

Waveguide QED

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This note isn't aimed for distribution.

QED in waveguides is discussed in details and examples are provided. [Link to problems](#)

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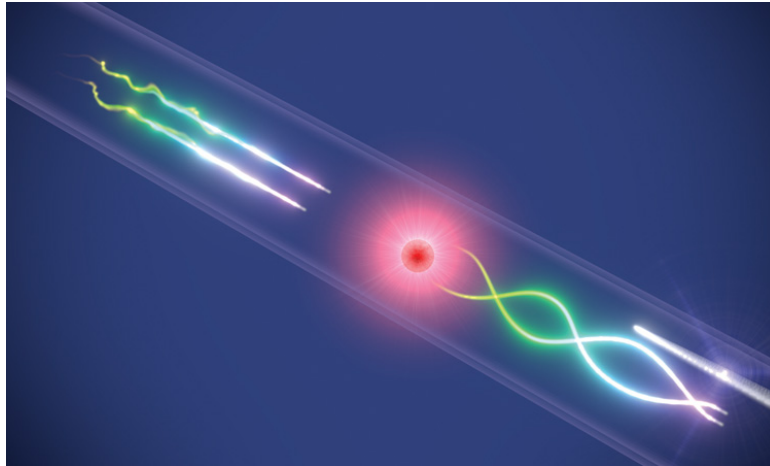
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1 Preface

1.1 Основная мотивация

(напишу потом, на самом деле многие этим занимаются, почему - не уверен.)

Фундаментальность фотонных явлений в волноводах



(пока это более всего мотивирует, потому что фундаментально многое можно решить и много уравнений получить. раскрою эту мысль потом.)

(тут примеры от Кирилла, что такие-то взаимодействия атома с светом можно рассматривать в этом формализме)

Множество приложений

Укажем приложения
(потом раскрою)

Удивительные факты

(потом раскрою)

Головоломки для мотивации

(потом раскрою)

2 Waveguide QED in Nutshell

2.1 Main formulas

2.1.1 Параметры и формализм для КЭД волноводов

Суть модели

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{V},$$

где

$$\mathcal{H}_0 := \omega_s a_s^\dagger a_s + \sum_{n=1}^{N_q} \Omega_n \sigma_+^{(n)} \sigma_-^{(n)}, \quad (\text{count energy})$$

$$\mathcal{V} := a_s^\dagger v_s + v_s^\dagger a_s \quad (\text{annihilate and excite})$$

Тут

$$s = (\mu, k) \quad (\text{multi-index}),$$

used the generalized summation convention: If two multiindices are repeated, summation over the channel index μ and integration with respect to the momentum k (over the relevant bandwidth B_μ) is implied.

$$v_s := \sum_{n=1}^{N_q} g_{\mu,n}(k) \sigma_-^{(n)} \quad (\text{bare interaction vertex})$$

имеет смысл (????)

Без сокращений модель имеет вид:

$$\mathcal{H}_0 := \sum_{n=1}^{N_q} \Omega_n \sigma_+^{(n)} \sigma_-^{(n)} + \sum_{\mu=1}^{N_c} \int_{B_\mu} dk \omega_\mu(k) a_\mu^\dagger(k) a_\mu(k); \quad \mathcal{V} = \sum_{\mu=1}^{N_c} \sum_{n=1}^{N_q} \int_{B_\mu} dk \left[g_{\mu,n}(k) a_\mu^\dagger(k) \sigma_-^{(n)} + \text{h.c.} \right]$$

V - dipole light-matter interaction in the RWA. Ω - константа, (??? смысл???) $g_{\mu,ns}$ - константа, (??? смысл???) (???? пояснение, почему такой гамильтониан?)

Operators $a_\mu^\dagger(k)$, $a_\mu(k)$ are bosonic creation and annihilation field operators of a photon with momentum k :

$$[a_\mu(k), a_{\mu'}^\dagger(k')] = \delta_{\mu,\mu'} \delta(k - k'), \quad [a_\mu^\dagger(k), a_{\mu'}^\dagger(k')] = [a_\mu(k), a_{\mu'}(k')] = 0.$$

И через них записываются все выражения далее.

Матрица рассеяния записывается через:

$$\mathcal{S} = 1_{\mathcal{H}} - 2\pi i \delta(\epsilon_i - \epsilon_f) \mathcal{T}(\epsilon_i), \quad \mathcal{T}(\epsilon) := \mathcal{V} + \mathcal{V} \mathcal{G}(\epsilon) \mathcal{V} \quad (\text{T-matrix})$$

$$\mathcal{G}(\epsilon) := \frac{1}{\epsilon - \mathcal{H} + i\eta} = \sum_{n=0}^{\infty} (\mathcal{G}_0(\epsilon) \mathcal{V})^n \mathcal{G}_0(\epsilon) \quad (\text{Gr f.}), \quad \mathcal{G}_0\{(\epsilon)\} = \frac{1}{\epsilon - \mathcal{H}_0 + i\eta}, \quad \eta \rightarrow 0^+ (\text{Bare Gr f.})$$

Decompositions:

$$\langle N'_p, g | \mathcal{T}^{(1)} | N_p, g \rangle = \sum_{n=0}^{\infty} \langle N'_p, g | a_{s'_1}^\dagger v_{s'_1} (\mathcal{G}_0 \mathcal{V} \mathcal{G}_0 \mathcal{V})^n \mathcal{G}_0 v_{s_1}^\dagger a_{s_1} | N_p, g \rangle$$

(тут про рассеяние, что такие-то функции от таких-то зависят.)

Типичные преобразования

$$a_s G_0(z) = G_0(\mathcal{H}_0 - \omega_s) a_s \quad \text{for} \quad G_0(z) := \frac{1}{z - \mathcal{H}_0},$$

По этим правилам и двигаем операторы для обнуления одних и вычисления других.

Следующая модель (????)

The dynamics of the system is generated by

$$\begin{aligned} \mathcal{H} &= \mathcal{H}_0 + \mathcal{V}, \\ \mathcal{H}_0 &= \sum_{\mu=\pm} \int_{-\infty}^{\infty} dx a_{\mu}^{\dagger}(x) (\eta i c \partial_x) a_{\mu}(x) + \sum_{n=0}^{N-1} \epsilon_n |n\rangle \langle n|, \\ \mathcal{V} &= \sum_{n=1}^{N-1} \sqrt{c \Gamma_n} \sum_{\mu=\pm} a_{\mu}^{\dagger}(0) |n-1\rangle \langle n| + \text{h.c.} \end{aligned}$$

(???? про смысл этой модели еще раз!!!) Here signs are $\mu = +$ or $-$, and $\eta = \mp$ for each $\mu = \pm$.

(????? тут напишу подробно, откуда такой гамильтониан взялся?)

Defining the momentum space field operators as

$$\begin{aligned} a_{\mu}(x) &= \int \frac{dk}{\sqrt{2\pi}} a_{\mu,k} e^{i k x}, \quad a_{\mu,k} := \int \frac{dx}{\sqrt{2\pi}} e^{i k x} a_{\mu}(x), \\ [a_{\mu,k}, a_{\mu',k'}^{\dagger}] &= \delta_{\mu,\mu'} \delta(k - k'), \quad [a_{\mu,k}^{\dagger}, a_{\mu',k'}^{\dagger}] = [a_{\mu,k}, a_{\mu',k'}] = 0, \end{aligned}$$

we find that

$$\begin{aligned} \mathcal{H}_0 &= \sum_{\mu=\pm} \int_{-\infty}^{\infty} dk \cdot ck \cdot a_{\mu,k}^{\dagger} a_{\mu,k} + \sum_{n=0}^{N-1} \epsilon_n |n\rangle \langle n|, \\ \mathcal{V} &= \sum_{n=1}^{N-1} \sqrt{\frac{\Gamma_n}{2\pi}} \sum_{\mu=\pm} \int dk a_{\mu,k}^{\dagger} |n-1\rangle \langle n| + \text{h.c.} \equiv \sum_{n=1}^{N-1} \sqrt{\frac{\Gamma_n}{2\pi}} \sum_{\mu=\pm} \int dk \left(a_{\mu,k}^{\dagger} |n-1\rangle \langle n| + a_{\mu,k} |n\rangle \langle n-1| \right) \end{aligned}$$

(? такая формула???)

It follows that we have to apply the usual diagrammatic rules with $\omega_s = \omega_{\mu,k} = ck, \mu = \pm$ and

$$v_s = v_{\mu,k} = \sum_{n=1}^{N-1} \sqrt{\frac{\Gamma_n}{2\pi}} |n-1\rangle \langle n|.$$

For example, consider the self-energy diagram

$$\begin{aligned} \Sigma(z) &= v_s^{\dagger} G_{\text{free}}(z - \omega_s) v_s = \\ &= \sum_{\mu=\pm} \int dk \underbrace{\left(\sum_{n''=1}^{N-1} \sqrt{\frac{\Gamma_{n''}}{2\pi}} |n''\rangle \langle n''-1| \right)}_{\text{absorption}} \underbrace{\frac{1}{z - \sum_{n=0}^{N-1} \epsilon_n |n\rangle \langle n| - ck}}_{\text{free propagation}} \underbrace{\left(\sum_{n'=1}^{N-1} \sqrt{\frac{\Gamma_{n'}}{2\pi}} |n'-1\rangle \langle n'| \right)}_{\text{emission}} = \\ &= \sum_{n=1}^{N-1} \frac{\Gamma_n}{\pi} \int dk \frac{1}{\omega - \epsilon_{n-1} - ck + i\eta} |n\rangle \langle n| = \\ &= -i \sum_{n=1}^{N-1} \Gamma_n |n\rangle \langle n|. \end{aligned}$$

Here we used that $z = \omega + i\eta, \eta = 0^+$ on the Bromwich contour and employed the Sokhotski-Plemelj theorem $\lim_{\eta \rightarrow 0^+} \int dx \frac{f(x)}{x \pm i\eta} = P \int dx \frac{f(x)}{x} \mp i\pi f(0)$.

(?? про вывод еще подумаю больше)

Due to the locality of our potential in position space $\propto \delta(x)$, it is possible to show that all of the higher-order diagrams vanish exactly. The dressed propagator is hence

$$G_{\text{dr}}(z) = \sum_{n=1}^{N-1} \frac{|n\rangle\langle n|}{z - \epsilon_n + i\Gamma_n} + \frac{|0\rangle\langle 0|}{z - \epsilon_0}.$$

Free propagator is

$$G_{\text{free}}(z - \omega_s) = \frac{1}{z - \sum_{n=0}^{N-1} \epsilon_n |n\rangle\langle n| - ck}$$

Note that the ground state of the emitter is the only subradiant (no broadening \implies no decay, i.e. there is nowhere to emit a photon from the ground state) subspace. In particular, one expects the spectral density of the photons emitted from such a system to be roughly given by

$$\rho(\omega) = -\frac{1}{\pi} \text{Im}\{\text{tr}[G(\omega + i\eta)]\} = \frac{1}{\pi} \sum_{n=1}^{N-1} \frac{\Gamma_n}{(\omega - \epsilon_n)^2 + \Gamma_n^2} + \delta(\omega - \epsilon_0),$$

which we shall prove in the next problem.

2.1.2 Fundamental physics in waveguide QED

(пропишу, очень важный раздел!!! пока отдельные дни сидеть на этом нужно.)

2.1.3 Суть диаграммного метода PP21 (????)

Суть метода (!!!!!)

Our model is as follows:

(????????????/)

Diagrammatic theory of scattering and dynamics of multiphoton states in waveguide QED works like this:

(?????)

The N_p -photon scattering matrices in single-qubit waveguide QED may be conveniently parametrized in terms of effective $(N_p - 1)$ -photon vertex functions and the equations satisfied by these vertex functions were established.

(??? тут основные формулы!!!)

Next, certain practical issues related to the direct sum representation of the S matrix, separation of elastic contributions to effective vertices, as well as the generalized cluster decomposition were discussed.

(??? тут основные формулы!!!)

Further, a generalization to the waveguide QED systems with more than a single qubit was given. Specifically, in the case of the two-qubit systems, it was established that the equations governing multiphoton vertex functions remain the same as in the case of a single qubit, up to the inclusion of higher-order vertex corrections.

Moreover, we have shown that once the integral equations governing N_q -photon scattering matrix in N_q waveguide QED, these equations hold for any system of qubits and established the generic equations governing two- and three-photon scattering operators by considering two- and three-photon scattering on two and three qubits, respectively.

Next, the diagrammatic theory of scattering was applied to a problem of scattering of a weakly coherent pulse on the giant acoustic atom. Namely, by expanding a coherent state

perturbatively in a coherence parameter up to third order in $|\alpha|$ and studying its scattering on the atom, we were able to establish the first-, second-, and third-order coherence functions of scattered radiation. Moreover, a set of approximation routines was suggested along with the exact method and the two were compared where appropriate. Further, the statistical properties of scattered surface acoustic waves were studied, and the effect of the non-Markovian nature of the setup on statistics was discussed.

Алгоритм, как использовать диаграммную технику Песочного и др.

Словарь определений выражений

$$\begin{aligned}\mathcal{S} &= 1_{\mathcal{H}} - 2\pi i \delta(\epsilon_i - \epsilon_f) \mathcal{T}(\epsilon_i), \\ \mathcal{T}(\epsilon) &:= \mathcal{V} + \mathcal{V} \mathcal{G}(\epsilon) \mathcal{V}, \\ \mathcal{G}(\epsilon) &= \frac{1}{\epsilon - \mathcal{H} + i\eta} = \sum_{n=0}^{\infty} (\mathcal{G}_0(\epsilon) \mathcal{V})^n \mathcal{G}_0(\epsilon), \\ \mathcal{G}_0(\epsilon) &= \frac{1}{\epsilon - \mathcal{H}_0 + i\eta}, \quad \eta \rightarrow 0^+\end{aligned}$$

Let's define the “self-energy operator” $\Sigma^{(1)}$ and the “effective potential energy operator” $\mathcal{R}^{(1)}$ to write

$$v_s^\dagger a_{s'} \mathcal{G}_0(\epsilon) a_s^\dagger v_s = \Sigma^{(1)}(\epsilon) + \mathcal{R}^{(1)}(\epsilon),$$

So they will be defined as:

$$\begin{aligned}\Sigma^{(1)}(\epsilon) &:= v_s^\dagger \mathcal{G}_0(\epsilon - \omega_s) v_s, & \mathcal{R}^{(1)}(\epsilon) &:= a_{s'}^\dagger \mathcal{R}_{s',s}^{(1)}(\epsilon) a_s, \\ & & \mathcal{R}_{s',s}^{(1)}(\epsilon) &:= v_s^\dagger \mathcal{G}_0(\epsilon - \omega_{s'} - \omega_s) v_{s'}\end{aligned}$$

By defining the generating operator

$$\mathcal{W}^{(1)} := \mathcal{R}^{(1)}(\epsilon) + \mathcal{R}^{(1)}(\epsilon) \mathcal{G}^{(1)} \mathcal{R}^{(1)}(\epsilon)$$

$$\mathcal{T}^{(1)}(\epsilon) = \sum_{n=1}^{\infty} T_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(\epsilon) a_{s'_1}^\dagger \dots a_{s'_n}^\dagger a_{s_n} \dots a_{s_1},$$

where we have defined the following functions:

$$\begin{aligned}T_{s'_1, s_1}^{(1,1)}(\epsilon) &:= \langle g | v_{s'_1} G^{(1)}(\epsilon) v_{s_1}^\dagger | g \rangle \\ &\vdots \\ T_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n>1)}(\epsilon) &:= \langle g | v_{s'_1} G^{(1)} \left(\epsilon - \sum_{l=2}^n \omega_{s'_l} \right) W_{s_2 \dots s'_n, s_2 \dots s_n}^{(1,n-1)}(\epsilon) G^{(1)} \left(\epsilon - \sum_{l=2}^n \omega_{s_l} \right) v_{s_1}^\dagger | g \rangle.\end{aligned}$$

which helps us to define the connected part of one-particle vertex function as

$$W_{s'_1, s_1}^{(1,1,C)}(\epsilon) = W_{s'_1, s_1}^{(1,1)}(\epsilon) + i\pi v_{s_1}^\dagger v_{s'_1} \delta(\epsilon - \omega_{s'_1} - \omega_{s_1}).$$

$$W_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n,C)}(\epsilon) = W_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(\epsilon) - W_{s'_1, s_1}^{(1,1)} \left(\epsilon - \sum_{l=2}^n \omega_{s'_l} \right) G^{(1)} \left(\epsilon - \omega_{s_1} - \sum_{l=2}^n \omega_{s_l} \right) W_{s_2 \dots s'_n, s_2 \dots s_n}^{(1,n-1)}(\epsilon - \omega_{s_1}).$$

with the help of the definition of components of T one may immediately deduce (???? сделаю это, пока не очевидно это) the following decomposition of the two-body transition operator:

$$T_{s'_1 s_2, s_1 s_2}^{(1,2)}(\omega_{s_1} + \omega_{s_2}) = -i\pi \delta(\omega_{s_1} - \omega_{s'_2}) T_{s'_1, s_1}^{(1,1)}(\omega_{s_1}) T_{s'_2, s_2}^{(1,1)}(\omega_{s_2}) + T_{s_1 s'_2, s_1 s_2}^{(1,2)}(\omega_{s_1} + \omega_{s_2}),$$

where $T^{(1,2,C)}$ is defined in precisely the same way as $T^{(1,2)}$ but with $W^{(1,1,C)}$ replacing $W^{(1,1)}$.

By plugging the representation (44) into the definition of the two-photon S matrix (38) we immediately arrive at the following cluster decomposition principle:

$$\mathcal{S}_2 = \left[\frac{1}{2} S_{s'_1, s_1}^{(1)} S_{s'_2, s_2}^{(1)} - 2\pi i T_{s'_1 s_2, s_1 s_2}^{(1,2,C)}(\omega_{s_1} + \omega_{s_2}) \delta(\omega_{s'_1} + \omega_{s'_2} - \omega_{s_1} - \omega_{s_2}) \right] a_{s_1}^\dagger a_{s_2}^\dagger a_{s_2} a_{s_1}.$$

Let us start with definition of the three-body component of the S matrix entering its direct sum representation (???? напишу конкретно формулы для этого!?!?!?) [throughout this Appendix, for simplicity it is assumed that $\omega_\mu(k) = \omega(k)$, $B_\mu = B, \forall \mu \in \{1, \dots, N_c\}$], namely

$$\begin{aligned} \mathcal{S}_3 = & \left[\frac{1}{3!} \delta_{s'_1, s_1} \delta_{s'_2, s_2} \delta_{s'_3, s_3} - 2\pi i \frac{1}{2!} \delta_{s'_2, s_2} \delta_{s'_3, s_3} T_{s'_1, s_1}^{(1,1)}(\omega(k_1)) \delta(\omega(k'_1) - \omega(k_1)) - \right. \\ & - 2\pi i \frac{1}{1!} \delta_{s'_3, s_3} T_{s'_1 s'_2, s_1 s_2}^{(1,2)}(\omega(k_1) + \omega(k_2)) \delta(\omega(k'_1) + \omega(k'_2) - \omega(k_1) - \omega(k_2)) - \\ & \left. - 2\pi i T_{s'_1 s'_2 s'_3, s_1 s_2 s_3}^{(1,3)}(\omega(k_1) + \omega(k_2) + \omega(k_3)) \delta(\omega(k'_1) + \omega(k'_2) + \omega(k'_3) - \omega(k_1) - \omega(k_2) - \omega(k_3)) \right] \cdot \\ & \cdot a_{s'_1}^\dagger a_{s'_2}^\dagger a_{s'_3}^\dagger a_{s_3} a_{s_2} a_{s_1}. \end{aligned}$$

$$\begin{aligned} T_{\mu'_1 k'_1, \mu'_2 k'_2, \mu'_3 k'_3; \mu_1 k_1, \mu_2 k_2, \mu_3 k_3}^{(1,3)}(\omega(k_1) + \omega(k_2) + \omega(k_3)) = \\ = g_{\mu_1}^*(k_1) g_{\mu_2}^*(k_2) g_{\mu_3}^*(k_3) g_{\mu'_1}(k'_1) g_{\mu'_2}(k'_2) g_{\mu'_3}(k'_3) \cdot \\ \cdot \tilde{G}^{(1)}(\omega(k_1)) \tilde{G}^{(1)}(\omega(k'_1)) F^{(1,2)}(k'_2, k'_3, k_2, k_3, \omega(k_1) + \omega(k_2) + \omega(k_3)), \end{aligned}$$

where $F^{(1,2)}(k'_2, k'_3, k_2, k_3, \omega(k_1) + \omega(k_2) + \omega(k_3))$ is not an entirely connected object defined via

$$F^{(1,2)}(k'_1, k'_2, k_1, k_2, \epsilon) := \frac{1}{g_{\mu'_1}(k'_1) g_{\mu'_2}(k'_2) g_{\mu_1}^*(k_1) g_{\mu_2}^*(k_2)} \left\langle g \left| W_{\mu'_1 k'_1 \mu'_2 k'_2, \mu_1 k_1 \mu_2 k_2}^{(1,2)}(\epsilon) \right| g \right\rangle$$

(???? и зачем мы умножаем и потом делим на одни и те же множители?????)

Separation of elastic contribution (43) translates into the following decomposition:

$$\begin{aligned} F^{(1,2)}(k'_2, k'_3, k_2, k_3, \omega(k_1) + \omega(k_2) + \omega(k_3)) = \\ = F^{(1,1)}(k'_2, k_2, \omega(k'_1) + \omega(k'_2)) \tilde{G}^{(1)}(\omega(k_1) + \omega(k_3) - \omega(k'_3)) F^{(1,1)}(k'_3, k_3, \omega(k_1) + \omega(k_3)) + \\ + \bar{F}^{(2,2)}(k'_2, k'_3, k_2, k_3, \omega(k_1) + \omega(k_2) + \omega(k_3)) \end{aligned}$$

In order to understand the difference between the singlequbit and the two-qubit theories, let us have a closer look at the equation defining $\mathcal{W}^{(2)}$:

$$\mathcal{W}^{(2)} = \mathcal{R}^{(1)} + a_{s'_1}^\dagger v_{s'_1} \mathcal{G}_0 v_{s_1}^\dagger a_{s_1} + \mathcal{R}^{(1)} \mathcal{G}^{(1)} \mathcal{W}^{(2)} + a_{s'_1}^\dagger v_{s'_1} \mathcal{G}_0 v_{s_1}^\dagger a_{s_1} \mathcal{G}^{(1)} \mathcal{W}^{(2)}.$$

(!!! оттренирую его, важный очень раздел для систематизации происходящего!!!)

Hierarchies

we arrive at the following hierarchy of integral equations:

$$W_{s'_1, s_1}^{(1,1)}(\epsilon) = R_{s'_1, s_1}^{(1)}(\epsilon) + R_{s'_1, s}^{(1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) W_{s, s_1}^{(1,1)}(\epsilon),$$

$$W_{s'_1, s_1}^{(1,2)}(\epsilon) = \text{напишу потом}$$

Since the lowest term in the expansion of $\mathcal{W}^{(2)}$ is again a single-photon operator

$$\mathcal{W}^{(2)} = \sum_{n=1}^{\infty} a_{s'_1}^{\dagger} \dots a_{s'_n}^{\dagger} \mathcal{W}_{s'_1 \dots s'_n, s_1 \dots s_n}^{(2,n)} a_{s_n} \dots a_{s_1}$$

we see that the hierarchy of equations satisfied by the twophoton vertex functions is precisely the same as (29) and (30) with $R^{(1)}$ being replaced by $R^{(2)}$ (see Fig. 4).

Типичный пример для иллюстрации диаграммного метода PP21

Giant acoustic atom as example for PP21

2.1.4 On coherence functions (??)

(смысл и формулы, там много всего)

2.1.5 Main mathematics for wQED (??)

Integrals for for wQED

- Sometimes use Sokhotski–Plemelj theorem

$$\lim_{\epsilon \rightarrow 0^+} \frac{1}{x \pm i\epsilon} = \mp i\pi\delta(x) + \mathcal{P} \left(\frac{1}{x} \right)$$

- Sometimes compute residues fast.

3 Theory

3.1 Fundamentals of Optics and Waveguides

(тут по идее общая подготовительная теория курса квантовой оптики и волноводов, которая подразумевается. Пройду когда-то - напишу)

3.2 Fundamentals of Waveguide QED

3.2.1 Physics of wQED and derivation of the model

(тут важные всякие обсуждения, что вообще происходит прежде чем начинаются эти модели.)

3.2.2 Hamiltonian, generalized summation convention, and the S matrix

Let us describe in details the model and the formalism.

Setting a model

Let us consider a collection of N_q qubits coupled to a waveguide with N_c radiation channels. The Hamiltonian of such a system assumes the form

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{V},$$

where the free Hamiltonian is:

$$\mathcal{H}_0 := \sum_{n=1}^{N_q} \Omega_n \sigma_+^{(n)} \sigma_-^{(n)} + \sum_{\mu=1}^{N_c} \int_{B_\mu} dk \omega_\mu(k) a_\mu^\dagger(k) a_\mu(k)$$

and dipole light-matter interaction term in Hamiltonian in the rotating wave approximation (RWA):

$$\mathcal{V} = \sum_{\mu=1}^{N_c} \sum_{n=1}^{N_q} \int_{B_\mu} dk \left[g_{\mu,n}(k) a_\mu^\dagger(k) \sigma_-^{(n)} + \text{h.c.} \right]$$

(?????? вот потом и выведу, как это связано с известным мне взаимодействием????)

(?????? почему именно зона Бриллюэна тут???? додумаю, важный вопрос, пока не понимаю.)

(??? другие мультипольные моменты почему не рассматриваются????)

Or explicitly (?? yes???) $\mathcal{V} = \sum_{\mu=1}^{N_c} \sum_{n=1}^{N_q} \int_{B_\mu} dk \left[g_{\mu,n}(k) a_\mu^\dagger(k) \sigma_-^{(n)} + g_{\mu,n}^*(k) a_\mu(k) \sigma_+^{(n)} \right]$.

(??? все еще вопрос, почему у нас ω в общем случае не ck ???)

In the above expression, Ω_n is the transition frequency of the n -th qubit, the dispersion relation $\omega_\mu(k)$ and the bandwidth B_μ characterize the radiation channel μ , while $a_\mu^\dagger(k)$ and $a_\mu(k)$ stand for the creation and annihilation field operators of a photon with momentum k and obey the standard bosonic commutation relations:

$$\begin{aligned} \left[a_\mu(k), a_{\mu'}^\dagger(k') \right] &= \delta_{\mu,\mu'} \delta(k - k'), \\ \left[a_\mu^\dagger(k), a_{\mu'}^\dagger(k') \right] &= [a_\mu(k), a_{\mu'}(k')] = 0. \end{aligned}$$

And σ -operators act on the Hilbert space of the n -th qubit, $\{\sigma_3^{(n)}, \sigma_+^{(n)}, \sigma_-^{(n)}\}$, they are defined according to $\sigma_l^{(n)} := 1_{\mathbb{C}^2}^{\otimes(n-1)} \otimes \sigma_l \otimes 1_{\mathbb{C}^2}^{\otimes(N_q-n)}$, with the σ matrices being chosen according to the standard convention $\sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$, $\sigma_+ = \sigma_-^\dagger = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$.

(Тут Пояснения, почему модель именно такая (!?!?!?!))

(ну там типа взаимодействует свет с кубтом, все такое, я хз, четко не понимаю это)

The RWA

The RWA is justified as long as the characteristic operational frequency ω_0 is such that the condition $|g_\mu^2(\omega_0)/\omega_0| \ll 1$ is satisfied [73]. (????)

One of the main benefits of this approximation is the conservation of the total number of excitations in the system, i.e., an operator

$$\mathcal{N} := \sum_{n=1}^{N_q} \sigma_+^{(n)} \sigma_-^{(n)} + \sum_{\mu=1}^{N_c} \int_{B_\mu} dk a_\mu^\dagger(k) a_\mu(k)$$

commutes with the full Hamiltonian

$$[\mathcal{N}, \mathcal{H}] = 0.$$

(???? why????)

This property allows us to simultaneously diagonalize \mathcal{H} and \mathcal{N} . Moreover, the eigenspaces of the Hamiltonian labeled by the eigenvalues of \mathcal{N} are certainly orthogonal, hence, there exists a direct sum decomposition of the total Hilbert space of the system

$$\mathcal{H} = \bigoplus_{N=0}^{\infty} \mathcal{H}_N$$

where \mathcal{H}_N is the $D(N, N_q) = \sum_{l=0}^{\min(N_q, N)} \frac{N_q!}{l!(N_q-l)!}$ dimensional subspace of all possible states with N excitations. Note that here $D(N, N_q)$ does not stand for the dimension of \mathcal{H}_N in the strict mathematical sense (??? why????). Instead, it is a number of ways to distribute N excitations in a system of N_q qubits [i.e., each single-photon infinite-dimensional vector space adds unity to $D(N, N_q)$]. Analogous direct sum decompositions hold for the Hamiltonian, unitary evolution operator, and the S matrix (to be introduced later). Moreover, such a decomposition considerably simplifies the problem since the calculations may be performed in all of the subspaces separately.

Пояснение, что такое RWA (???????) (пока этот метод не освоил, приведу примеры или подробнее о нем напишу)

Generalized summation convention for compactness (!!!)

To simplify our further analysis, it is useful to introduce compact notations. Thus, we define a multi-index $s = (\mu, k)$ and the generalized summation convention: If two multiindices are repeated, summation over the channel index μ and integration with respect to the momentum k (over the relevant bandwidth B_μ) is implied. We also introduce the following notation for the bare interaction vertex просто потому что это есть половина каждого члена в потенциале взаимодействия:

$$v_s := \sum_{n=1}^{N_q} g_{\mu,n}(k) \sigma_-^{(n)}.$$

Это очень важная формула, потому что дальше постоянно у нас v_s в формулах!

(добавлю еще пояснения, что типа важно так пользоваться обозначениями, иначе вообще с формулами никуда не уедешь!) Поэтому гамильтониан в изначальной форме мы и не используем, иначе все формулы были бы очень большими.

Using these conventions we rewrite parts the Hamiltonian $\mathcal{H} = \mathcal{H}_0 + \mathcal{V}$ as

$$\mathcal{H}_0 = \omega_s a_s^\dagger a_s + \sum_{n=1}^{N_q} \Omega_n \sigma_+^{(n)} \sigma_-^{(n)},$$

$$\mathcal{V} = a_s^\dagger v_s + v_s^\dagger a_s.$$

The scattering matrix, or the S matrix, is the main object of interest in the present section. It can be generally defined via the so-called transition operator, or the T matrix, in the following way:

$$S = 1_{\mathcal{H}} - 2\pi i \delta(\epsilon_i - \epsilon_f) \mathcal{T}(\epsilon_i),$$

$$\mathcal{T}(\epsilon) := \mathcal{V} + \mathcal{V} \mathcal{G}(\epsilon) \mathcal{V},$$

where the T matrix is put on shell, i.e., $\epsilon = \epsilon_i$, and the energies ϵ_i, ϵ_f , corresponding to initial and final states of the system, obey the energy conservation in the scattering processes, which is mathematically ensured by the delta function. (???? потом подумаю, почему действительно дельта функция не дает нам бесконечности?? также про оператор $1_{\mathcal{H}}$ точнее напишу. все это в квантмехе должно быть написано!)

In $\mathcal{T}(\epsilon)$ we have denoted by $\mathcal{G}(\epsilon)$ the retarded Green's operator defined according to

$$\mathcal{G}(\epsilon) = \frac{1}{\epsilon - \mathcal{H} + i\eta} = \sum_{n=0}^{\infty} (\mathcal{G}_0(\epsilon) \mathcal{V})^n \mathcal{G}_0(\epsilon),$$

$$\mathcal{G}_0(\epsilon) = \frac{1}{\epsilon - \mathcal{H}_0 + i\eta}, \quad \eta \rightarrow 0^+$$

3.2.3 Origin of special models in scope of wQED (???)

(типа откуда там взять дисперсии и величины ширин распада?? важное дополнение.)

Origin of V and Λ models

3.3 Diagrams for scattering in waveguide QED by Piasotski and Pletyukhov

3.3.1 Connection of this model with learned theory (????)

(потом пропишу, вопросы про это есть многие. мб уменьшу раздел, посмотрим.)

Вывод данного гамильтониана ил Лагранжиана КЭД (?????)

(пока это вообще не понимаю)

3.3.2 General properties of the scattering matrix in waveguide QED

(???? ничего пока не понял, супер сложно считается этот абзац)

Theory

Let us consider the scattering problem for the following initial state $|N_p\rangle \otimes |g\rangle$, where $|N_p\rangle$ is a N_p -photon state, and $|g\rangle = |0\rangle^{\otimes N_q}$ is the ground state of the scatterer. Due to the conservation of excitation-number operator, all of the possible $D(N_p, N_q)$ scattering outcomes must contain N_p excitations. (???? это не совсем понимаю, у нас один фотон большой энергии разве не может создать два фотона???)

Due to the fact that for any system of qubits the ground state $|g\rangle$ is the only nondecaying (subradiant) subspace, in the long-time limit (a priori assumed in scattering theory) all of the emitters will definitely decay into the continuum, leaving us with the only possibility for the system to end up in the state $|N'_p\rangle \otimes |g\rangle$ (here $|N'_p\rangle$ is again a N_p -photon state, with potentially redistributed momenta) [74].

If one wishes to extend the scattering theory to the systems with metastable ground states, such as, e.g., a Λ three-level system, one then has to consider calculating more matrix elements of the transition operator [75, 76]. (?? потом еще раз прочитаю, не понял)

Since the only matrix elements we are interested in are diagonal in both the photon and qubit spaces, due to the RWA, the only terms contributing to the perturbation expansion of the T matrix are those containing an even number of interactions \mathcal{V} , thus reducing the number of diagrams by half.

Another important feature to be mentioned is the nilpotency of the photon-qubit interaction vertex operator $v_{s_1}^\dagger \dots v_{s_{N_q+1}}^\dagger = v_{s_1} \dots v_{s_{N_q+1}} = 0$, which along with the property $v_s|g\rangle = \langle g|v_s^\dagger = 0$ and the fact that the number of v 's and v^\dagger 's have to be equal in each graph contributing to the expansion, significantly reduces the number of nonzero diagrams at each order in perturbation theory. In fact, as we are going to see in this section, all of the diagrams contributing to the series for any fixed N_q may be constructed out of a finite number of "clusters," in turn allowing, in principle, for the exact resummation of the perturbation series. One can also organize the calculation differently, namely, by fixing N_p and allowing N_q to vary instead. Calculation within this approach is facilitated in its turn by the fact that $a_{s_1} \dots a_{s_{N_p+1}}|N_p\rangle = \langle N_p|a_{s_1}^\dagger \dots a_{s_{N_p+1}}^\dagger = 0$ and the fact that the number of a 's and a^\dagger 's in each term of the perturbation series have to be equal.

Although, these two approaches are clearly dual due to the structure of interaction potential in RWA. This approach is beneficial when studying few-photon scattering on a large number of qubits. This assertion has to do with the fact that once the solution of N_p photon scattering problem on $N_q = N_p$ the scattering of N_p particles on $N_q > N_p$ follows the same lines. Indeed, since $v_s (v_s^\dagger)$ by itself contains the sum of all of the single-qubit lowering (raising) operators and the highest number of qubits that the N_p -photon pulse can excite equals to N_p , the normal ordered N_p -photon S matrix cannot contain projectors on subspaces with higher-excitation number than N_p .

Using this fact in the following we are going to derive the generic two- and three-photon scattering matrices by considering two- and three-particle scattering on two and three atoms, respectively.

(крч, надеюсь, что выше - просто слова, ничего супер важного.)

3.3.3 Scattering theory in $N_q = 1$ waveguide QED

In this section, we would like to make a detailed exposition of our general method by considering the simplest imaginable scenario of a single qubit coupled to a waveguide.

Идея разложения S -матрицы в диаграммы (????)

(???? почему такие разложения работают??? или всегда как-то можно разложить аналогично? пока не очень понимаю это.)

Разложение S -матрицы в диаграммы

In our formalism to solve the N_p -photon scattering problem, we shall determine the following matrix elements of the transition operator:

$$\begin{aligned}\langle N'_p, g | \mathcal{T}^{(1)}(\epsilon) | N_p, g \rangle &= \langle N'_p, g | \mathcal{V} \mathcal{G}(\epsilon) \mathcal{V} | N_p, g \rangle \\ &= \langle N'_p, g | a_{s'_1}^\dagger v_{s'_1} \mathcal{G}(\epsilon) v_{s_1}^\dagger a_{s_1} | N_p, g \rangle \\ &= \sum_{n=0}^{\infty} \langle N'_p, g | a_{s'_1}^\dagger v_{s'_1} (\mathcal{G}_0(\epsilon) \mathcal{V})^n \cdot \mathcal{G}_0(\epsilon) v_{s_1}^\dagger a_{s_1} | N_p, g \rangle\end{aligned}$$

where the superscript (1) refers to the $N_q = 1$ waveguide QED and we have used the fact that $\langle N'_p, g | \mathcal{V} | N_p, g \rangle = 0$. (??? еще раз отслежу, где это???)

Note that in what follows, whenever an argument of an object is omitted, we understand that its argument is ϵ , e.g., $\mathcal{G}^{(1)}$ stands for $\mathcal{G}^{(1)}(\epsilon)$, etc., however, when the argument of a given operator or vertex function is of importance, it would be explicitly stated (?? и когда это так? просто пишем или опускаем, все).

As it was mentioned above, due to RWA, only even terms (??? потом еще раз подумаю, почему???) contribute to the above geometric series, so that

$$\langle N'_p, g | \mathcal{T}^{(1)} | N_p, g \rangle = \sum_{n=0}^{\infty} \langle N'_p, g | a_{s'_1}^\dagger v_{s'_1} (\mathcal{G}_0 \mathcal{V} \mathcal{G}_0 \mathcal{V})^n \mathcal{G}_0 v_{s_1}^\dagger a_{s_1} | N_p, g \rangle$$

Now, let us consider the $\mathcal{G}_0 \mathcal{V} \mathcal{G}_0$ term in the brackets above:

$$\mathcal{V} \mathcal{G}_0 \mathcal{V} = a_{s'}^\dagger v_{s'} \mathcal{G}_0 a_s^\dagger v_s + a_{s'}^\dagger v_{s'} \mathcal{G}_0 v_s^\dagger a_s + v_{s'}^\dagger a_{s'} \mathcal{G}_0 v_s^\dagger a_s + v_{s'}^\dagger a_{s'} \mathcal{G}_0 a_s^\dagger v_s.$$

Here the terms with two v 's and two v^\dagger 's do not contribute (they are in fact zero) by the single-qubit nilpotency condition $v^2 = (v^\dagger)^2 = 0$. Among the “diagonal” terms, the only nonzero contribution comes from the $v^\dagger v$ term since the term vv^\dagger annihilates the state $v^\dagger |g\rangle$ and gives zero whenever it is multiplied with $v^\dagger v$ term.

(???? я что-то про крос диаг член не понял, почему он обнуляет??? нужно про g додумать это!!)

So we have:

$$\langle N'_p, g | \mathcal{T}^{(1)} | N_p, g \rangle = \sum_{n=0}^{\infty} \langle N'_p, g | a_{s'_1}^\dagger v_{s'_1} (\mathcal{G}_0 v_{s'}^\dagger a_{s'} \mathcal{G}_0 a_s^\dagger v_s)^n \mathcal{G}_0 v_{s_1}^\dagger a_{s_1} | N_p, g \rangle.$$

With our Hamiltonian we can interchange order with photon operators by the rule:

$$\begin{aligned}a_s f(\mathcal{H}_0) &= f(\mathcal{H}_0 + \omega_s) a_s & \leftrightarrow & & a_s G_0(z) &= G_0(\mathcal{H}_0 - \omega_s) a_s \text{ for } G_0(z) := \frac{1}{z - \mathcal{H}_0}, \\ f(\mathcal{H}_0) a_s^\dagger &= a_s^\dagger f(\mathcal{H}_0 - \omega_s),\end{aligned}$$

where f is some function admitting for the Maclaurin expansion $f(\mathcal{H}_0) = \sum_{n=0}^{\infty} f_n \mathcal{H}_0^n$. Proof is done by looking at n -th term of \mathcal{H}_0 without the qubit part, and knowing that

$$\begin{aligned}a_s \mathcal{H}_0 &= [a_s, \mathcal{H}_0] + \mathcal{H}_0 a_s = \omega_{s2} [a_s, a_{s2}^\dagger a_{s2}] + \mathcal{H}_0 a_s & [A, BC] &= [A, B]C + B[A, C] \\ &= \omega_{s2} \delta_{s,s2} a_s + \mathcal{H}_0 a_s = \omega_s a_s + \mathcal{H}_0 a_s = (\mathcal{H}_0 + \omega_s) a_s.\end{aligned}$$

that

$$a_s \mathcal{H}_0^n = a_s \mathcal{H}_0 \mathcal{H}_0^{n-1} = (\mathcal{H}_0 + \omega_s) a_s \mathcal{H}_0 = (\mathcal{H}_0 + \omega_s)^n a_s$$

So

$$a_s f(\mathcal{H}_0) = \sum_{n=0}^{\infty} a_s \mathcal{H}_0^n f_n = \sum_{n=0}^{\infty} f_n (\mathcal{H}_0 + \omega_s)^n$$

For $G_0(z) = \frac{1}{z - \mathcal{H}_0}$ we have

$$f(\mathcal{H}_0 + \omega_s) = \frac{1}{z - (\mathcal{H}_0 + \omega_s)} = \frac{1}{(z - \omega_s) - \mathcal{H}_0} \equiv G_0(z - \omega_s)$$

Also (??? докажу это позже)

$$f(\mathcal{H}_0) a_s^\dagger = a_s^\dagger f(\mathcal{H}_0 - \omega_s),$$

We see that

$$v_s^\dagger a_{s'} \mathcal{G}_0(\epsilon) a_s^\dagger v_s = v_s^\dagger \mathcal{G}_0(\epsilon - \omega_s) v_s + a_{s'}^\dagger v_s^\dagger \mathcal{G}_0(\epsilon - \omega_{s'} - \omega_s) v_{s'} a_s,$$

where in the last term here the contraction of the indices s and s' is not assumed.

Let's define the "self-energy operator" $\Sigma^{(1)}$ and the "effective potential energy operator" $\mathcal{R}^{(1)}$ to write

$$v_s^\dagger a_{s'} \mathcal{G}_0(\epsilon) a_s^\dagger v_s = \Sigma^{(1)}(\epsilon) + \mathcal{R}^{(1)}(\epsilon),$$

So they will be defined as:

$$\begin{aligned} \Sigma^{(1)}(\epsilon) &:= v_s^\dagger \mathcal{G}_0(\epsilon - \omega_s) v_s, & \mathcal{R}^{(1)}(\epsilon) &:= a_{s'}^\dagger \mathcal{R}_{s',s}^{(1)}(\epsilon) a_s, \\ & & \mathcal{R}_{s',s}^{(1)}(\epsilon) &:= v_s^\dagger \mathcal{G}_0(\epsilon - \omega_{s'} - \omega_s) v_{s'} \end{aligned}$$

so we have:

$$\begin{aligned} \langle N'_p, g | \mathcal{T}^{(1)} | N_p, g \rangle &= \langle N'_p, g | a_{s_1'}^\dagger v_{s_1'} \frac{1}{1 - \mathcal{G}^{(1)} \mathcal{R}^{(1)}(\epsilon)} \mathcal{G}^{(1)} v_{s_1}^\dagger a_{s_1} | N_p, g \rangle, \\ (\mathcal{G}^{(1)})^{-1}(\epsilon) &:= \mathcal{G}_0^{-1}(\epsilon) - \Sigma^{(1)}(\epsilon). \end{aligned}$$

(??? тоже еще раз проделаю этот вывод!)

By defining the generating operator

$$\mathcal{W}^{(1)} := \mathcal{R}^{(1)}(\epsilon) + \mathcal{R}^{(1)}(\epsilon) \mathcal{G}^{(1)} \mathcal{R}^{(1)}(\epsilon)$$

we arrive at the following result: (????? подумаю, как мы второй член дальше получили???? ряды что ли какие-то тут суммируются???? мб иначе \mathcal{W} определено должно быть?)

$$\langle N'_p, g | \mathcal{T}^{(1)} | N_p, g \rangle = \langle N'_p, g | a_{s_1'}^\dagger v_{s_1'} \mathcal{G}^{(1)} v_{s_1}^\dagger a_{s_1} | N_p, g \rangle + \langle N'_p, g | a_{s_1'}^\dagger v_{s_1'} \mathcal{G}^{(1)} \mathcal{W}^{(1)} \mathcal{G}^{(1)} v_{s_1}^\dagger a_{s_1} | N_p, g \rangle.$$

By analyzing the structure of $\mathcal{R}^{(1)}$, we conclude that $\mathcal{W}^{(1)}$ admits for the following series representation (????? почему???)

$$\mathcal{W}^{(1)} = \sum_{n=1}^{\infty} a_{s_1'}^\dagger \dots a_{s_n'}^\dagger \mathcal{W}_{s_1' \dots s_n', s_1 \dots s_n}^{(1,n)} a_{s_n} \dots a_{s_1},$$

where $\mathcal{W}^{(1,n)}$'s are the operator-valued functions (??? можно написать лучше, что за объект????), which depend only on $\epsilon - \mathcal{H}_0$ and $2n$ multi-indices $\{s_1', \dots, s_n', s_1, \dots, s_n\}$. Here

and below, we will use regular letters W, G, R instead of calligraphic ones to indicate that these objects are not operators but are rather their projections on the photonic vacuum (note that $W^{(1,n)}$'s are still acting as operators on the qubit space).

By inserting decomposition of $\mathcal{W}^{(1)}$ into the definition of $\mathcal{W}^{(1)}$ and taking the projections onto the particle subspaces (??? вот тут я не совсем понял, что за проекции??? мб догадаюсь, если подумаю???) we arrive at the following hierarchy of integral equations:

$$W_{s'_1, s_1}^{(1,1)}(\epsilon) = R_{s'_1, s_1}^{(1)}(\epsilon) + R_{s'_1, s}^{(1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) W_{s, s_1}^{(1,1)}(\epsilon),$$

$$W_{s'_1, s_1}^{(1,2)}(\epsilon) = \text{напишу потом}$$

⋮

$$\begin{aligned} W_{s'_1, \dots, s_1 \dots s_n}^{(1,n)}(\epsilon) &= R_{s'_1, s_1}^{(1)}\left(\epsilon - \sum_{l=2}^n \omega_{s'_l}\right) G^{(1)}\left(\epsilon - \omega_{s_1} - \sum_{l=2}^n \omega_{s'_l}\right) W_{s'_2 \dots s'_n, s_2 \dots s_n}^{(1,n-1)}(\epsilon - \omega_{s_1}) + \\ &+ R_{s'_1, s}^{(1)}\left(\epsilon - \sum_{l=2}^n \omega_{s'_l}\right) G^{(1)}\left(\epsilon - \omega_s - \sum_{l=2}^n \omega_{s'_l}\right) \left[W_{ss'_2 \dots s'_n, s_1 \dots s_n}^{(1,n)}(\epsilon) + \dots + W_{s_2 \dots s'_n s, s_1 \dots s_n}^{(1,n)}(\epsilon) \right]. \end{aligned}$$

(???? ну тут вообще место подумать!!! пока не полностью понимаю эту формулу, буду перевыводить ее сам еще раз)

Diagrammatic representation The collection of the integral equations for $W_{s'_1, \dots, s_1 \dots s_n}^{(1,n)}(\epsilon)$ may be conveniently represented diagrammatically. The objects will be as follows.

The $\Sigma^{(1)}$ bubble corresponds to the self-energy in a subspace of a single excitation used to define the dressed Green's function (represented by a double line) from the bare Green's function (depicted by the dashed line).

The $W^{(1,n)}$ bubbles (bubbles with $2n$ -amputated legs) represent effective n -photon vertex functions describing effective interaction between n photons induced by nonlinearity. Bare absorption v^\dagger and emission v vertices are represented by black dots with incoming and outgoing photon lines, respectively.

(see Fig. 1).

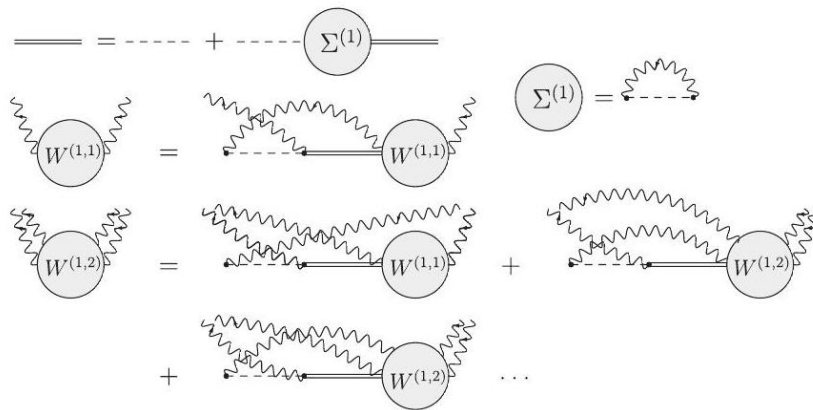


Figure 1: FIG. 1. Hierarchy of integral equations governing effective multiphoton vertex functions in $N_q = 1$ waveguide QED.

Diagrammatic rules may be formulated as follows:

- 1) To each dotted line associate the bare propagator $G_0(\epsilon)$.
- 2) To each wavy line with incoming (outgoing) arrow associate the bare absorption v^\dagger (emission v) vertex.
- 3) Whenever two wavy lines are contracted together, one has to integrate over all momentum and sum over all channels.
- 4) When a given wavy line passes over the propagator, its argument has to be shifted by the frequency carried by this line [which is a direct consequence of the intertwining property (20)].

For example, for the self-energy diagram we have:

$$\text{Diagram: a circle with a wavy line inside} = \text{Diagram: a wavy line with a dashed line inside} \rightarrow \Sigma^{(1)}(\epsilon) = v_s^\dagger G_0(\epsilon - \omega_s) v_s.$$

(???? окей, скоро про это подумаю.)

T -matrix again Now having identified the equations defining the components of $\mathcal{W}^{(1)}$, we may express the transition operator as follows:

$$\mathcal{T}^{(1)}(\epsilon) = \sum_{n=1}^{\infty} T_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(\epsilon) a_{s'_1}^\dagger \dots a_{s'_n}^\dagger a_{s_n} \dots a_{s_1},$$

where we have defined the following functions:

$$\begin{aligned} T_{s'_1, s_1}^{(1,1)}(\epsilon) &:= \langle g | v_{s'_1} G^{(1)}(\epsilon) v_{s_1}^\dagger | g \rangle \\ &\vdots \\ T_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n>1)}(\epsilon) &:= \langle g | v_{s'_1} G^{(1)}\left(\epsilon - \sum_{l=2}^n \omega_{s'_l}\right) W_{s_2 \dots s'_n, s_2 \dots s_n}^{(1,n-1)}(\epsilon) G^{(1)}\left(\epsilon - \sum_{l=2}^n \omega_{s_l}\right) v_{s_1}^\dagger | g \rangle. \end{aligned}$$

Note that we are working with the nonsymmetrized forms of operators and perform the symmetrization only when doing actual calculations. Also note that the dependence of $\mathcal{T}_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}$ on $\omega_s a_s^\dagger a_s$ may be omitted taking into account normal ordering, when S matrix is going to be finally contracted with the initial state (???? где конкретно????), all of the T matrix components are going to be eventually projected onto the photonic vacuum and energies are going to be put on shell. Using the above representation of the transition operator we immediately deduce that the scattering operator takes the following form:

$$\mathcal{S} = 1_{\mathcal{H}} - 2\pi i \sum_{n=1}^{\infty} T_{s'_1 \dots s'_n, s_1 \dots s_n}^{(n)} \left(\sum_{l=1}^n \omega_{s_l} \right) \delta \left(\sum_{l=1}^n \omega_{s'_l} - \sum_{l=1}^n \omega_{s_l} \right) a_{s'_1}^\dagger \dots a_{s'_n}^\dagger a_{s_n} \dots a_{s_1}.$$

Practically, when one contracts the S matrix with the initial N_p -photon state, only the first N_p terms in the above series contribute (??? тоже пока не понял, а почему?). It is, however, beneficial to represent the S matrix in terms of the direct sum of N -body operators which act solely in the N -particle subspaces

$$\mathcal{S} = 1_{\mathcal{H}} \oplus \bigoplus_{n=1}^{\infty} \mathcal{S}_n$$

where \mathcal{S}_n may be written as

$$\mathcal{S}_n = S_{s'_1 \dots s'_n, s_1 \dots s_n}^{(n)} a_{s'_1}^\dagger \dots a_{s'_n}^\dagger a_{s_n} \dots a_{s_1},$$

$$S_{s'_1 \dots s'_n, s_1 \dots s_n}^{(n)} = \frac{1}{n!} \prod_{l=1}^n \delta_{s'_l, s_l} - 2\pi i \sum_{m=1}^n \frac{1}{(n-m)!} T_{s'_1 \dots s'_m, s_1 \dots s_m}^{(n)} \left(\sum_{l=1}^m \omega_{s_l} \right) \delta \left(\sum_{l=1}^n \omega_{s'_l} - \sum_{l=1}^n \omega_{s_l} \right) \prod_{r=m+1}^n \delta_{s'_r, s_r}.$$

Note that the combinatorial prefactors $\frac{1}{(n-m)!}$, $m \in \{0, \dots, n\}$, and additional δ functions $\delta_{s'_r, s_r}$ are chosen to take into account the excess number of $(n-m)!$ Wick contractions. (??? тоже пока не очень понял, что за эти свертки???)

3.3.4 Generalized cluster decomposition

Let's illustrate how the generalized cluster decomposition in waveguide QED, extensively studied in [76, 77] (??? напишу про это тоже, что там такое вообще изучалось??), naturally follows from the results of the previous section.

(???? тут я пока ничего не понимаю, просто дальше продолжается та же теория)

Theory

The cluster decomposition is a way of separating the elastic and inelastic contributions to the S matrix. The elastic contribution physically corresponds to the scattering channel in which all photons scatter coherently, i.e., conserve their energy individually in the scattering process. On the other hand, the inelastic contribution corresponds to the incoherent scattering. Thereby the photons redistribute their initial energy between one another via effective photon-photon interaction which is mediated by their interaction with nonlinear scatterers (e.g., qubits). In contrast, in the case of a linear scatter (e.g., a cavity mode), the effective photon-photon interaction is not generated, and the n -photon S matrix simply factors out into the product of n single-particle S matrices.

The first step towards the cluster decomposition of the multiphoton S matrices is the realization that the multiphoton vertex functions $W^{(1,n)}$ contain the disconnected components. These, in turn, arise from the projections of $R_{s',s}^{(1)}$ on the ground state of the scatterer thus resulting in the (quasi)elastic contributions $\propto \delta(\epsilon - \dots)$ to $W^{(1,n)}$'s. Not only the separation of these contributions is crucial for the cluster decomposition but is of evident importance for both numerical and analytical treatment of the integral equations (29) and (30). It is the easiest to define the connected parts of the multiphoton vertex functions recursively.

First, we observe that

$$R_{s',s}^{(1)}(\epsilon) = v_s^\dagger G_0(\epsilon - \omega_{s'} - \omega_s) v_{s'} = -i\pi \delta(\epsilon - \omega_{s'} - \omega_s) v_s^\dagger v_{s'} + v_s^\dagger P \frac{1}{\epsilon - \omega_{s'} - \omega_s} v_{s'},$$

where P stands for the Cauchy principal value, which helps us to define the connected part of one-particle vertex function as

$$W_{s_1, s_1}^{(1,1,C)}(\epsilon) = W_{s'_1, s_1}^{(1,1)}(\epsilon) + i\pi v_{s_1}^\dagger v_{s'_1} \delta(\epsilon - \omega_{s'_1} - \omega_{s_1}).$$

By then analyzing the structure of the general equation in the hierarchy (30) and bearing in mind the equation satisfied by $W_{s_1, s_1}^{(1,1)}(\epsilon)$ one may easily deduce the connected part of n -photon effective vertex function may be defined in the following manner:

$$W_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n,C)}(\epsilon) = W_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(\epsilon) - W_{s'_1, s_1}^{(1,1)} \left(\epsilon - \sum_{l=2}^n \omega_{s'_l} \right) G^{(1)} \left(\epsilon - \omega_{s_1} - \sum_{l=2}^n \omega_{s_l} \right) W_{s_2 \dots s'_n, s_2 \dots s_n}^{(1,n-1)}(\epsilon - \omega_{s_1}).$$

Now, with the help of the definition of components of T one may immediately deduce (???? сделаю это, пока не очевидно это) the following decomposition of the two-body transition operator:

$$T_{s'_1 s_2, s_1 s_2}^{(1,2)}(\omega_{s_1} + \omega_{s_2}) = -i\pi \delta(\omega_{s_1} - \omega_{s'_2}) T_{s'_1, s_1}^{(1,1)}(\omega_{s_1}) T_{s'_2, s_2}^{(1,1)}(\omega_{s_2}) + T_{s_1 s'_2, s_1 s_2}^{(1,2)}(\omega_{s_1} + \omega_{s_2}),$$

where $T^{(1,2,C)}$ is defined in precisely the same way as $T^{(1,2)}$ but with $W^{(1,1,C)}$ replacing $W^{(1,1)}$.

By plugging the representation (44) into the definition of the two-photon S matrix (38) we immediately arrive at the following cluster decomposition principle:

$$\mathcal{S}_2 = \left[\frac{1}{2} S_{s'_1, s_1}^{(1)} S_{s'_2, s_2}^{(1)} - 2\pi i T_{s'_1 s_2, s_1 s_2}^{(1,2,C)}(\omega_{s_1} + \omega_{s_2}) \delta(\omega_{s'_1} + \omega_{s'_2} - \omega_{s_1} - \omega_{s_2}) \right] a_{s_1}^\dagger a_{s_2}^\dagger a_{s_2} a_{s_1}.$$

The physical meaning of the this expression is rather clear. The first term, being a product of one-particle S matrices, describes the coherent scattering of two particles, i.e., a scattering process in which there are no effective interactions between the photons. The second term, on the other hand, is completely connected and describes the incoherent scattering of photons in which the particles redistribute their initial energy by interaction. (???? тут возможно важная формула, подумаю про нее потом!!!)

A slightly more involved, but otherwise completely analogous, calculation may be done in the three-photon sector. As a result, one arrives at the following cluster decomposition of the three-body S matrix:

$$\mathcal{S}_3 = \left[\frac{1}{6} S_{s'_1, s_1}^{(1)} S_{s'_2, s_2}^{(1)} S_{s'_3, s_3}^{(1)} - 2\pi i T_{s'_1 s_2, s_1 s_2}^{(1,2,C)}(\omega_{s_1} + \omega_{s_2}) \delta(\omega_{s'_1} + \omega_{s'_2} - \omega_{s_1} - \omega_{s_2}) S_{s'_3, s_3}^{(1)} - \right. \\ \left. - 2\pi i T_{s'_1 s_2 s'_3, s_1 s_2 s_3}^{(1,3,C)}(\omega_{s_1} + \omega_{s_2} + \omega_{s_3}) \cdot \delta(\omega_{s'_1} + \omega_{s'_2} + \omega_{s'_3} - \omega_{s_1} - \omega_{s_2} - \omega_{s_3}) \right] \text{essentially,}$$

or more precisely:

$$\mathcal{S}_3 = \left[\frac{1}{6} S_{s'_1, s_1}^{(1)} S_{s'_2, s_2}^{(1)} S_{s'_3, s_3}^{(1)} - 2\pi i T_{s'_1 s_2, s_1 s_2}^{(1,2,C)}(\omega_{s_1} + \omega_{s_2}) \delta(\omega_{s'_1} + \omega_{s'_2} - \omega_{s_1} - \omega_{s_2}) S_{s'_3, s_3}^{(1)} - \right. \\ \left. - 2\pi i T_{s'_1 s_2 s'_3, s_1 s_2 s_3}^{(1,3,C)}(\omega_{s_1} + \omega_{s_2} + \omega_{s_3}) \cdot \delta(\omega_{s'_1} + \omega_{s'_2} + \omega_{s'_3} - \omega_{s_1} - \omega_{s_2} - \omega_{s_3}) \right] \cdot a_{s_1}^\dagger a_{s_2}^\dagger a_{s_3}^\dagger a_{s_3} a_{s_2} a_{s_1},$$

or exactly:

$$\mathcal{S}_3 = \left[\frac{1}{6} S_{s'_1, s_1}^{(1)} S_{s'_2, s_2}^{(1)} S_{s'_3, s_3}^{(1)} - 2\pi i T_{s'_1 s_2, s_1 s_2}^{(1,2,C)}(\omega_{s_1} + \omega_{s_2}) \delta(\omega_{s'_1} + \omega_{s'_2} - \omega_{s_1} - \omega_{s_2}) S_{s'_3, s_3}^{(1)} - \right. \\ \left. - 2\pi i T_{s'_1 s_2 s'_3, s_1 s_2 s_3}^{(1,3,C)}(\omega_{s_1} + \omega_{s_2} + \omega_{s_3}) \cdot \delta(\omega_{s'_1} + \omega_{s'_2} + \omega_{s'_3} - \omega_{s_1} - \omega_{s_2} - \omega_{s_3}) \right] \cdot a_{s_1}^\dagger a_{s_2}^\dagger a_{s_3}^\dagger a_{s_3} a_{s_2} a_{s_1},$$

where the connected part of the three-photon T matrix may be found by (??? which is done below).

Смысл этой формулы в том, что (!!!!!! напишу, как ее понимать, это же в 1 части!!!)

Cluster decomposition of three-photon S -matrix (!!!)

(!!!!!! многие формулы тут напишу в формате $A=B+C+D$, где $A=...$ $B=...$, иначе ничего не понятно, на страницу такое никогда не поместится!)

Let us start with definition of the three-body component of the S matrix entering its direct sum representation (???? напишу конкретно формулы для этого!?!?!?) [throughout this Appendix, for simplicity it is assumed that $\omega_\mu(k) = \omega(k)$, $B_\mu = B, \forall \mu \in \{1, \dots, N_c\}$], namely

$$\begin{aligned} \mathcal{S}_3 = & \left[\frac{1}{3!} \delta_{s'_1, s_1} \delta_{s'_2, s_2} \delta_{s'_3, s_3} - 2\pi i \frac{1}{2!} \delta_{s'_2, s_2} \delta_{s'_3, s_3} T_{s'_1, s_1}^{(1,1)}(\omega(k_1)) \delta(\omega(k'_1) - \omega(k_1)) - \right. \\ & - 2\pi i \frac{1}{1!} \delta_{s'_3, s_3} T_{s'_1 s'_2, s_1 s_2}^{(1,2)}(\omega(k_1) + \omega(k_2)) \delta(\omega(k'_1) + \omega(k'_2) - \omega(k_1) - \omega(k_2)) - \\ & \left. - 2\pi i T_{s'_1 s'_2 s'_3, s_1 s_2 s_3}^{(1,3)}(\omega(k_1) + \omega(k_2) + \omega(k_3)) \delta(\omega(k'_1) + \omega(k'_2) + \omega(k'_3) - \omega(k_1) - \omega(k_2) - \omega(k_3)) \right] \cdot \\ & \cdot a_{s'_1}^\dagger a_{s'_2}^\dagger a_{s'_3}^\dagger a_{s_3} a_{s_2} a_{s_1}. \end{aligned}$$

As before we write (??? видимо, это важная формула, которую в 1ю часть нужно добавить!! пока не знаком с такими разложениями.)

$$T_{s'_1 s'_2, s_1 s_2}^{(1,2)}(\omega(k_1) + \omega(k_2)) = -\pi i \delta(\omega(k'_1) - \omega(k_1)) T_{s'_1, s_1}^{(1,1)}(\omega(k_1)) T_{s'_2, s_2}^{(1,1)}(\omega(k_2)) + T_{s'_1 s'_2, s_1 s_2}^{(1,2,C)}(\omega(k_1) + \omega(k_2)).$$

Here, as before, the equality symbol is understood in the sense of permutation equivalence and on-shell condition.

Now let us start massaging the three-body transition operator. First of all, one has

$$\begin{aligned} T_{\mu'_1 k'_1, \mu'_2 k'_2, \mu'_3 k'_3; \mu_1 k_1, \mu_2 k_2, \mu_3 k_3}^{(1,3)}(\omega(k_1) + \omega(k_2) + \omega(k_3)) = \\ = g_{\mu_1}^*(k_1) g_{\mu_2}^*(k_2) g_{\mu_3}^*(k_3) g_{\mu'_1}(k'_1) g_{\mu'_2}(k'_2) g_{\mu'_3}(k'_3) \cdot \\ \cdot \tilde{G}^{(1)}(\omega(k_1)) \tilde{G}^{(1)}(\omega(k'_1)) F^{(1,2)}(k'_2, k'_3, k_2, k_3, \omega(k_1) + \omega(k_2) + \omega(k_3)), \end{aligned}$$

where $F^{(1,2)}(k'_2, k'_3, k_2, k_3, \omega(k_1) + \omega(k_2) + \omega(k_3))$ is not an entirely connected object defined via

$$F^{(1,2)}(k'_1, k'_2, k_1, k_2, \epsilon) := \frac{1}{g_{\mu'_1}(k'_1) g_{\mu'_2}(k'_2) g_{\mu_1}^*(k_1) g_{\mu_2}^*(k_2)} \left\langle g \left| W_{\mu'_1 k'_1 \mu'_2 k'_2, \mu_1 k_1 \mu_2 k_2}^{(1,2)}(\epsilon) \right| g \right\rangle$$

(???? и зачем мы умножаем и потом делим на одни и те же множители?????)

Separation of elastic contribution (43) translates into the following decomposition:

$$\begin{aligned} F^{(1,2)}(k'_2, k'_3, k_2, k_3, \omega(k_1) + \omega(k_2) + \omega(k_3)) = \\ = F^{(1,1)}(k'_2, k_2, \omega(k'_1) + \omega(k'_2)) \tilde{G}^{(1)}(\omega(k_1) + \omega(k_3) - \omega(k'_3)) F^{(1,1)}(k'_3, k_3, \omega(k_1) + \omega(k_3)) + \\ + \bar{F}^{(2,2)}(k'_2, k'_3, k_2, k_3, \omega(k_1) + \omega(k_2) + \omega(k_3)) \end{aligned}$$

Bearing in mind that $\bar{F}^{(2,2)}(k'_2, k'_3, k_2, k_3, \omega(k_1) + \omega(k_2) + \omega(k_3))$ is an analytic function we decompose the three-photon T matrix as follows:

$$\begin{aligned} T_{\mu'_1 k'_1, \mu'_2 k'_2, \mu'_3 k'_3; \mu_1 k_1, \mu_2 k_2, \mu_3 k_3}^{(1,3)}(\omega(k_1) + \omega(k_2) + \omega(k_3)) = \\ = \bar{T}_{\mu'_1 k'_1, \mu'_2 k'_2, \mu'_3 k'_3; \mu_1 k_1, \mu_2 k_2, \mu_3 k_3}^{(1,3)}(\omega(k_1) + \omega(k_2) + \omega(k_3)) + \\ + \hat{T}_{\mu'_1 k'_1, \mu'_2 k'_2, \mu'_3 k'_3; \mu_1 k_1, \mu_2 k_2, \mu_3 k_3}(\omega(k_1) + \omega(k_2) + \omega(k_3)) \end{aligned}$$

where we have defined the following objects:

$$\begin{aligned} \bar{T}_{\mu'_1 k'_1, \mu'_2 k'_2, \mu'_3 k'_3; \mu_1 k_1, \mu_2 k_2, \mu_3 k_3}^{(1,3)}(\omega(k_1) + \omega(k_2) + \omega(k_3)) := \\ = g_{\mu_1}^*(k_1) g_{\mu_2}^*(k_2) g_{\mu_3}^*(k_3) g_{\mu'_1}(k'_1) g_{\mu'_2}(k'_2) g_{\mu'_3}(k'_3) \cdot \\ \cdot \tilde{G}(\omega(k_1)) \tilde{G}(\omega(k'_1)) \bar{F}^{(1,2)}(k'_2, k'_3, k_2, k_3, \omega(k_1) + \omega(k_2) + \omega(k_3)) \end{aligned}$$

and

$$\begin{aligned} & \hat{T}_{\mu'_1 k'_1, \mu'_2 k'_2, \mu'_3 k'_3; \mu_1 k_1, \mu_2 k_2, \mu_3 k_3}^{(1,3)} (\omega(k_1) + \omega(k_2) + \omega(k_3)) := \\ & = g_{\mu_1}^* (k_1) g_{\mu_2}^* (k_2) g_{\mu_3}^* (k_3) g_{\mu'_1} (k'_1) g_{\mu'_2} (k'_2) g_{\mu'_3} (k'_3) \cdot \\ & \cdot \tilde{G}(\omega(k_1)) \tilde{G}(\omega(k'_1)) F^{(1,1)}(k'_2, k_2, \omega(k'_1) + \omega(k'_2)) \tilde{G}^{(1)}(\omega(k_1) + \omega(k_3) - \omega(k'_3)) F^{(1,1)}(k'_3, k_3, \omega(k_1) + \omega(k_3)) \end{aligned}$$

In the last equation we have

$$\begin{aligned} F^{(1,1)}(k'_2, k_2, \omega(k'_1) + \omega(k'_2)) &= \hat{G}_0(\omega(k'_1) - \omega(k_2)) + \bar{F}^{(1,1)}(k'_2, k_2, \omega(k'_1) + \omega(k'_2)) \\ F^{(1,1)}(k'_3, k_3, \omega(k_1) + \omega(k_3)) &= \hat{G}_0(\omega(k_1) - \omega(k'_3)) + \bar{F}^{(1,1)}(k'_3, k_3, \omega(k_1) + \omega(k_3)) \end{aligned}$$

The terms in (A8) containing \hat{G}_0 deserve a special attention since they can yield delta functions determining additional conservation of frequencies. (?????)

In particular, the terms with $\hat{G}_0 \bar{F}^{(1,1)}$ and $\bar{F}^{(1,1)} \hat{G}_0$ together give

$$\begin{aligned} & -2\pi i \delta(\omega(k'_3) - \omega(k_3)) T_{s'_3, s_3}^{(1,1)}(\omega(k_3)) \\ & \left[T_{s'_1 s'_2, s_1 s_2}^{(1,2,C)}(\omega(k_1) + \omega(k_2)) - g_{\mu_1}^* (k_1) g_{\mu_2}^* (k_2) g_{\mu'_1} (k'_1) g_{\mu'_2} (k'_2) \tilde{G}^{(1)}(\omega(k_1)) \tilde{G}^{(1)}(\omega(k'_1)) P\left(\frac{1}{\omega(k_1) - \omega(k'_2)}\right) \right] + \\ & + \\ & + g_{\mu_1}^* (k_1) g_{\mu_2}^* (k_2) g_{\mu_3}^* (k_3) g_{\mu'_1} (k'_1) g_{\mu'_2} (k'_2) g_{\mu'_3} (k'_3) \tilde{G}(\omega(k_1)) \tilde{G}(\omega(k'_1)) \tilde{G}^{(1)}(\omega(k_1) + \omega(k_3) - \omega(k'_3)) \\ & \left[P\left(\frac{1}{\omega(k'_1) - \omega(k_2)}\right) \bar{F}^{(1,1)}(k'_3, k_3, \omega(k_1) + \omega(k_3)) + \bar{F}^{(1,1)}(k'_2, k_2, \omega(k'_1) + \omega(k'_2)) P\left(\frac{1}{\omega(k_1) - \omega(k'_3)}\right) \right]. \end{aligned}$$

(???? почему $2\pi i$ у нас только в 1м члене????)

The term (A11) contributes to the $3 = 2 + 1$ cluster of the three-photon S matrix.

The term (A12) is completely connected and nonsingular. This property becomes explicitly visible if we reexpress it as

$$\begin{aligned} & \frac{g_{\mu_1}^* (k_1) g_{\mu_2}^* (k_2) g_{\mu_3}^* (k_3) g_{\mu'_1} (k'_1) g_{\mu'_2} (k'_2) g_{\mu'_3} (k'_3)}{\omega(k'_1) - \omega(k_1)} \cdot \\ & \cdot \left[\tilde{G}^{(1)}(\omega(k'_1)) \tilde{G}^{(1)}(\omega(k_3)) \tilde{G}^{(1)}(\omega(k'_3) + \omega(k'_1) - \omega(k_1)) \bar{F}^{(1,1)}(k'_2, k_2, \omega(k'_1) + \omega(k'_2) + \omega(k'_3) - \omega(k_1)) - \right. \\ & \left. - \tilde{G}^{(1)}(\omega(k_1)) \tilde{G}^{(1)}(\omega(k_1) + \omega(k_3) - \omega(k'_1)) \tilde{G}^{(1)}(\omega(k'_3)) \bar{F}^{(1,1)}(k'_2, k_2, \omega(k'_2) + \omega(k'_3)) \right]. \end{aligned}$$

This representation makes it obvious that in the limit $k'_1 \rightarrow k_1$ this function is finite.

Now, let us consider the contribution to (A8) containing $\hat{G}_0 \hat{G}_0$. It amounts to

$$\begin{aligned} & g_{\mu_1}^* (k_1) g_{\mu_2}^* (k_2) g_{\mu_3}^* (k_3) g_{\mu'_1} (k'_1) g_{\mu'_2} (k'_2) g_{\mu'_3} (k'_3) \\ & \tilde{G}(\omega(k_1)) \tilde{G}(\omega(k'_3)) \tilde{G}^{(1)}(\omega(k_2) + \omega(k_1) - \omega(k'_1)) \hat{G}_0(\omega(k'_3) - \omega(k_3)) \hat{G}_0(\omega(k_1) - \omega(k'_1)) = \\ & = \\ & = (-i\pi)^2 T_{s'_1, s_1}^{(1,1)}(\omega(k_1)) T_{s'_2, s_2}^{(1,1)}(\omega(k_2)) T_{s'_3, s_3}^{(1,1)}(\omega(k_3)) \delta(\omega(k'_1) - \omega(k_1)) \delta(\omega(k'_2) - \omega(k_2)) - \\ & - 2\pi i g_{\mu_1}^* (k_1) g_{\mu_2}^* (k_2) g_{\mu'_1} (k'_1) g_{\mu'_2} (k'_2) \\ & \tilde{G}^{(1)}(\omega(k_1)) \tilde{G}^{(1)}(\omega(k'_1)) T_{s'_3, s_3}^{(1,1)}(\omega(k_3)) \delta(\omega(k'_3) - \omega(k_3)) \\ & g_{\mu_1}^* (k_1) g_{\mu_2}^* (k_2) g_{\mu_3}^* (k_3) g_{\mu'_1} (k'_1) g_{\mu'_2} (k'_2) g_{\mu'_3} (k'_3) \\ & \tilde{G}(\omega(k'_3)) \tilde{G}(\omega(k_1)) \tilde{G}^{(1)}(\omega(k_2) + \omega(k_1) - \omega(k'_1)) P\left(\frac{1}{\omega(k'_3) - \omega(k_3)}\right) P\left(\frac{1}{\omega(k_1) - \omega(k'_1)}\right). \end{aligned}$$

The term (A14) contributes to the $3 = 1 + 1 + 1$ cluster. The term (A15) contributes to the $3 = 2 + 1$ cluster. The term (A16) requires a special consideration. Rewriting

$$\begin{aligned}
& \tilde{G}^{(1)}(\omega(k'_3)) \tilde{G}^{(1)}(\omega(k_2) + \omega(k_1) - \omega(k'_1)) \tilde{G}^{(1)}(\omega(k_1)) P\left(\frac{1}{\omega(k'_3) - \omega(k_3)}\right) P\left(\frac{1}{\omega(k_1) - \omega(k'_1)}\right) \\
&= \tilde{G}^{(1)}(\omega(k'_3)) \tilde{G}^{(1)}(\omega(k_1)) P\left(\frac{\tilde{G}^{(1)}(\omega(k_2) + \omega(k_1) - \omega(k'_1)) - \tilde{G}^{(1)}(\omega(k_2))}{\omega(k'_3) - \omega(k_3)}\right) \frac{1}{\omega(k_1) - \omega(k'_1)} \\
&+ \tilde{G}^{(1)}(\omega(k'_3)) \tilde{G}^{(1)}(\omega(k_2)) \tilde{G}^{(1)}(\omega(k_1)) P\left(\frac{1}{\omega(k'_3) - \omega(k_3)}\right) P\left(\frac{\tilde{G}^{(1)}(\omega(k_2) + \omega(k_1) - \omega(k'_1)) - \tilde{G}^{(1)}(\omega(k_2))}{\omega(k_1) - \omega(k'_1)}\right) \\
&= \tilde{G}^{(1)}(\omega(k'_3)) \tilde{G}^{(1)}(\omega(k_1)) P\left(\frac{1}{\omega(k'_3) - \omega(k_3)}\right) \frac{\tilde{G}_1^{(1)}(\omega(k'_3)) - \tilde{G}^{(1)}(\omega(k_3))}{\omega(k'_1)} P\left(\frac{1}{\omega(k_1) - \omega(k'_1)}\right) \\
&\quad + \tilde{G}^{(1)}(\omega(k_2)) \tilde{G}^{(1)}(\omega(k_1)) \frac{1}{1} P\left(\frac{1}{\omega(k_1) - \omega(k'_1)}\right),
\end{aligned}$$

we observe that the terms (A17) and (A18) give together a nonsingular contribution. In fact,

$$\begin{aligned}
& \tilde{G}^{(1)}(\omega(k'_3)) \tilde{G}^{(1)}(\omega(k_1)) P\left(\frac{1}{\omega(k'_3) - \omega(k_3)}\right) \frac{\tilde{G}^{(1)}(\omega(k_2) + \omega(k_1) - \omega(k'_1)) - \tilde{G}^{(1)}(\omega(k_2))}{\omega(k_1) - \omega(k'_1)} \\
&+ \tilde{G}^{(1)}(\omega(k_2)) \tilde{G}^{(1)}(\omega(k_1)) \frac{\tilde{G}^{(1)}(\omega(k'_3)) - \tilde{G}^{(1)}(\omega(k_3))}{\omega(k'_3) - \omega(k_3)} P\left(\frac{1}{\omega(k_1) - \omega(k'_1)}\right) \\
&= \tilde{G}^{(1)}(\omega(k'_3)) \tilde{G}^{(1)}(\omega(k_1)) \tilde{G}^{(1)}(\omega(k_2)) \tilde{G}^{(1)}(\omega(k'_2) + \omega(k'_3) - \omega(k_3)) \tilde{G}^{(1)}(\omega(k'_2)) \\
&\quad \cdot \frac{\left(\tilde{G}^{(1)}\right)^{-1}(\omega(k'_2)) - \left(\tilde{G}^{(1)}\right)^{-1}(\omega(k'_2) + \omega(k'_3) - \omega(k_3))}{\omega(k'_3) - \omega(k_3)} \frac{\left(\tilde{G}^{(1)}\right)^{-1}(\omega(k_2)) - \left(\tilde{G}^{(1)}\right)^{-1}(\omega(k_2) + \omega(k_1) - \omega(k'_1))}{\omega(k_1) - \omega(k'_1)} \\
&+ \tilde{G}^{(1)}(\omega(k_2)) \tilde{G}^{(1)}(\omega(k_3)) \tilde{G}^{(1)}(\omega(k'_3)) \frac{1}{\omega(k'_1) - \omega(k_1)} \left(\tilde{G}^{(1)}(\omega(k'_1))\right. \\
&\quad \cdot \left.\frac{\left(\tilde{G}^{(1)}\right)^{-1}(\omega(k_3)) - \left(\tilde{G}^{(1)}\right)^{-1}(\omega(k'_1) + \omega(k'_3) - \omega(k_1))}{\omega(k'_1) + \omega(k'_3) - \omega(k_1) - \omega(k_3)} - \tilde{G}^{(1)}(\omega(k_1)) \frac{\left(\tilde{G}^{(1)}\right)^{-1}(\omega(k_3)) - \left(\tilde{G}^{(1)}\right)^{-1}(\omega(k'_3))}{\omega(k'_3) - \omega(k_3)}\right)
\end{aligned}$$

In contrast, the term (A19) is singular and contributes to the $3 = 1 + 1 + 1$ cluster of the scattering matrix. To show this, we first fully symmetrize

$$\begin{aligned}
& \tilde{G}^{(1)}(\omega(k_3)) \tilde{G}^{(1)}(\omega(k_2)) \tilde{G}^{(1)}(\omega(k_1)) P\left(\frac{1}{\omega(k'_3) - \omega(k_3)}\right) P\left(\frac{1}{\omega(k_1) - \omega(k'_1)}\right) \\
&\rightarrow \\
&\rightarrow \frac{1}{3} \tilde{G}^{(1)}(\omega(k_3)) \tilde{G}^{(1)}(\omega(k_2)) \tilde{G}^{(1)}(\omega(k_1)) \left[P\left(\frac{1}{\omega(k'_3) - \omega(k_3)}\right) P\left(\frac{1}{\omega(k_1) - \omega(k'_1)}\right) \right. \\
&\quad \left. + P\left(\frac{1}{\omega(k'_2) - \omega(k_2)}\right) P\left(\frac{1}{\omega(k_3) - \omega(k'_3)}\right) + P\left(\frac{1}{\omega(k'_1) - \omega(k_1)}\right) P\left(\frac{1}{\omega(k_2) - \omega(k'_2)}\right) \right].
\end{aligned}$$

Owing to the Poincare-Bertrand distributional identity $P\left(\frac{1}{x}\right) P\left(\frac{1}{y}\right) = P\left(\frac{1}{y-x}\right) \left[P\left(\frac{1}{x}\right) - P\left(\frac{1}{y}\right) \right] +$

$\pi^2 \delta(x) \delta(y)$, we establish the identity

$$\begin{aligned} P\left(\frac{1}{\omega(k'_3) - \omega(k_3)}\right) P\left(\frac{1}{\omega(k_1) - \omega(k'_1)}\right) + P\left(\frac{1}{\omega(k'_2) - \omega(k_2)}\right) P\left(\frac{1}{\omega(k_3) - \omega(k'_3)}\right) + \\ + P\left(\frac{1}{\omega(k'_1) - \omega(k_1)}\right) P\left(\frac{1}{\omega(k_2) - \omega(k'_2)}\right) = \\ = \pi^2 \delta(\omega(k'_3) - \omega(k_3)) \delta(\omega(k'_1) - \omega(k_1)) \end{aligned}$$

leading us to the result

$$\frac{\pi^2}{3} \tilde{G}^{(1)}(\omega(k_3)) \tilde{G}^{(1)}(\omega(k_2)) \tilde{G}^{(1)}(\omega(k_1)) \cdot \delta(\omega(k'_3) - \omega(k_3)) \delta(\omega(k'_1) - \omega(k_1))$$

in (A21).

(??? мб ниже главная формула, которую в 1 часть и вынесу!)

Combining all of the above results, we arrive at the following decomposition of the three-photon T matrix:

$$\begin{aligned} T_{s'_1 s'_2 s'_3, s_1 s_2 s_3}^{(1,3)}(\omega(k_1) + \omega(k_2) + \omega(k_3)) = \\ = \frac{(-2\pi i)^2}{6} T_{s'_1, s_1}^{(1)}(\omega(k_1)) T_{s'_2, s_2}^{(1)}(\omega(k_2)) T_{s'_3, s_3}^{(1)}(\omega(k_3)) \delta(\omega(k'_1) - \omega(k_1)) \delta(\omega(k'_2) - \omega(k_2)) \\ - 2\pi i T_{s'_1 s'_2, s_1 s_2}^{(1,2,C)}(\omega(k_1) + \omega(k_2)) T_{s'_3, s_3}^{(1)}(\omega(k_3)) \delta(\omega(k'_3) - \omega(k_3)) \\ + T_{s'_1 s'_2 s'_3, s_1 s_2 s_3}^{(1,3,C)}(\omega(k_1) + \omega(k_2) + \omega(k_3)) \end{aligned}$$

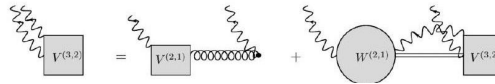
with the three-body connected part

$$\begin{aligned} T_{s'_1 s'_2 s'_3, s_1 s_2 s_3}^{(1,3,C)}(\omega(k_1) + \omega(k_2) + \omega(k_3)) = \\ = g_{\mu_1}^*(k_1) g_{\mu_2}^*(k_2) g_{\mu_3}^*(k_3) g_{\mu'_1}(k'_1) g_{\mu'_2}(k'_2) g_{\mu'_3}(k'_3) \cdot \\ \cdot \left\{ \tilde{G}^{(1)}(\omega(k'_3)) \tilde{G}^{(1)}(\omega(k_1)) \tilde{G}^{(1)}(\omega(k_2)) \tilde{G}^{(1)}(\omega(k'_2) + \omega(k'_3) - \omega(k_3)) \tilde{G}^{(1)}(\omega(k'_2)) \cdot \right. \\ \cdot \frac{(\tilde{G}^{(1)})^{-1}(\omega(k'_2)) - (\tilde{G}^{(1)})^{-1}(\omega(k'_2) + \omega(k'_3) - \omega(k_3))}{\omega(k'_3) - \omega(k_3)} \cdot \frac{(\tilde{G}^{(1)})^{-1}(\omega(k_2)) - (\tilde{G}^{(1)})^{-1}(\omega(k_2) + \omega(k_1) - \omega(k'_1))}{\omega(k_1) - \omega(k'_1)} + \\ + \frac{1}{\omega(k'_1) - \omega(k_1)} \left[\tilde{G}^{(1)}(\omega(k_2)) \tilde{G}^{(1)}(\omega(k_3)) \tilde{G}^{(1)}(\omega(k'_3)) \cdot \right. \\ \cdot \left(\tilde{G}^{(1)}(\omega(k'_1)) \frac{(\tilde{G}^{(1)})^{-1}(\omega(k_3)) - (\tilde{G}^{(1)})^{-1}(\omega(k'_1) + \omega(k'_3) - \omega(k_1))}{\omega(k'_1) + \omega(k'_3) - \omega(k_1) - \omega(k_3)} - \right. \\ \left. \left. - \tilde{G}^{(1)}(\omega(k_1)) \frac{(\tilde{G}^{(1)})^{-1}(\omega(k_3)) - (\tilde{G}^{(1)})^{-1}(\omega(k'_3))}{\omega(k'_3) - \omega(k_3)} \right) + \right. \\ \left. + \tilde{G}^{(1)}(\omega(k'_1)) \tilde{G}^{(1)}(\omega(k_3)) \tilde{G}^{(1)}(\omega(k'_3) + \omega(k'_1) - \omega(k_1)) \bar{F}^{(1,1)}(k'_2, k_2, \omega(k'_1) + \omega(k'_2) + \omega(k'_3) - \omega(k_1)) - \right. \\ \left. - \tilde{G}^{(1)}(\omega(k_1)) \tilde{G}^{(1)}(\omega(k'_3)) \tilde{G}^{(1)}(\omega(k_1) + \omega(k_3) - \omega(k'_1)) \bar{F}^{(1,1)}(k'_2, k_2, \omega(k'_2) + \omega(k'_3)) \right] + \\ + \tilde{G}(\omega(k_1)) \tilde{G}(\omega(k'_1)) \bar{F}^{(1,1)}(k'_2, k_2, \omega(k'_1) + \omega(k'_2)) \tilde{G}^{(1)}(\omega(k_1) + \omega(k_3) - \omega(k'_3)) \bar{F}^{(1,1)}(k'_3, k_3, \omega(k_1) + \omega(k_3)) \Big\} + \\ + \bar{T}_{s'_1 s'_2 s'_3, s_1 s_2 s_3}(\omega(k_1) + \omega(k_2) + \omega(k_3)). \end{aligned}$$

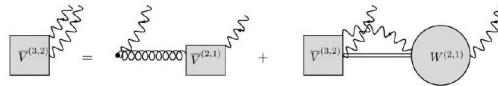
Plugging everything into the definition of the three-photon S matrix we finally obtain (еще раз, какая там формула основная???? забыл уже??? в 1й части укажу это тоже!)

$$\mathcal{S}_3 = \left[\frac{1}{3!} S_{s'_1, s_1}^{(1)} S_{s'_2, s_2}^{(1)} S_{s'_3, s_3}^{(1)} - \right. \\ \left. - 2\pi i T_{s'_1 s'_2, s_1 s_2}^{(1,2,C)} (\omega(k_1) + \omega(k_2)) S_{s'_3, s_3}^{(1)} \delta(\omega(k'_1) + \omega(k'_2) - \omega(k_1) - \omega(k_2)) \right. \\ \left. - 2\pi i T_{s'_1 s'_2 s'_3, s_1 s_2 s_3}^{(1,3,C)} (\omega(k_1) + \omega(k_2) + \omega(k_3)) \delta(\omega(k'_1) + \omega(k'_2) + \omega(k'_3) - \omega(k_1) - \omega(k_2) - \omega(k_3)) \right] \\ a_{s'_1}^\dagger a_{s'_2}^\dagger a_{s'_3}^\dagger a_{s_3} a_{s_2} a_{s_1}.$$

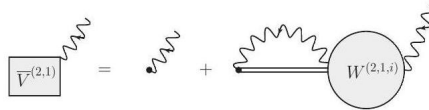
3.3.5 Examples of Diagrams



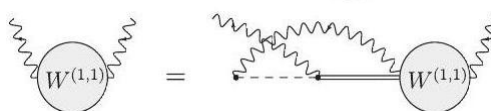
(тут ее формула и смысл)



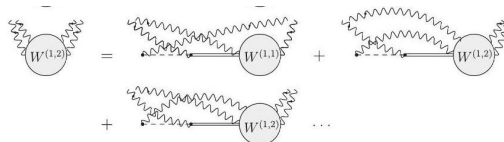
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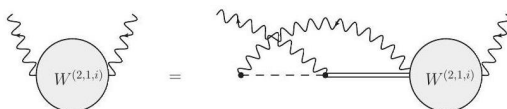
(тут ее формула и смысл)



(тут ее формула и смысл)



(тут ее формула и смысл)



(тут ее формула и смысл)

$$W^{(2,1,r)} = V^{(2,1)} \text{---} \text{---} V^{(2,1)}$$

(тут ее формула и смысл)

$$W^{(3,2)} = V^{(3,2)} \text{---} \text{---} \text{---} \text{---} V^{(3,2)}$$

(тут ее формула и смысл)

$$W^{(3,2)} = V^{(3,2)} \text{---} \text{---} \text{---} \text{---} V^{(3,2)}$$

$$\Sigma^{(2,0)} = \text{---} \text{---} + \text{---} \text{---} W^{(2,1,r)} \text{---} \text{---}$$

$$\Sigma^{(3,0)} = \text{---} \text{---} V^{(3,2)} + \text{---} \text{---} V^{(3,2)} = V^{(3,2)} \text{---} \text{---} + V^{(3,2)} \text{---} \text{---}$$

$$\text{---} \text{---} \text{---} = \text{---} + \text{---} \text{---} \Sigma^{(2,0)} \text{---} \text{---}$$

3.3.6 Closed-form solution in the Markovian limit

(??? вообще пока хз.)

Theory

Let us now consider the single-qubit scattering problem in the Markovian limit. Validity of Markovian approximation demands a number of assumptions: Linear dispersion relation in all of the channels $\omega_\mu(k) = \omega_{0\mu} + v_\mu k$, broad-band limit $B_\mu = \mathbb{R}, \forall \mu \in \{1, \dots, N_c\}$, and local couplings (i.e., independent of frequency) $g_\mu(k) = \sqrt{\gamma_\mu/\pi}$.

Within the above assumptions, the self-energy diagram reads as $\Sigma^{(1)}(\epsilon) = -i \sum_{\mu=1}^{N_c} \gamma_\mu / v_\mu |1\rangle\langle 1|$, which is independent of ϵ (here we have introduced the projector on the qubit's excited state $|1\rangle\langle 1| = \frac{1+\sigma_3}{2}$). By causality, all of the W functions are analytic in momentum (energy) variables in the lower (upper) half of the complex plane. By exploiting this analyticity along with the momentum independence of both coupling constants and self-energy, we can close all of the integration contours in the lower half of the complex momentum plane to render all of the integrals zero, thus promoting the integral equations into algebraic ones. As a result, we recover the solution obtained in [51]. Diagrammatically the above solution is equivalent to the so-called noncrossing approximation (which becomes exact in the Markovian limit) and it is represented in Fig. 2.

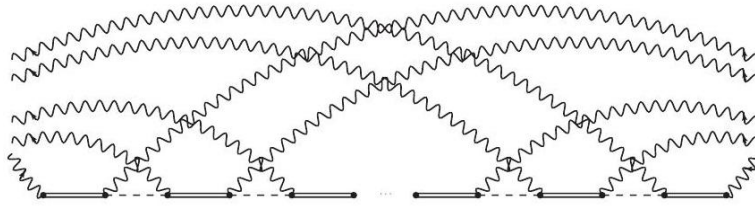


FIG. 2. Exact diagrammatic representation of the n -particle T matrix in the Markovian limit. The above diagrams also correspond to the noncrossing approximation discussed in Sec. II F. As opposed to the exact n -photon T matrix parametrized by the $(n - 1)$ -particle effective vertex function resumming an infinite number of emission and absorption processes in both direct and exchange channels, this approximation replaces the vertex by a sequence of $n - 2$ and $n - 1$ ($n \geq 2$) alternating excitations and deexcitations of the emitter.

Как было бы, если бы не было марковского лимита? (????) (просто пока не разобрался еще с ним.)

3.3.7 F. Approximation strategies

Theory

Although it is possible to write an entire hierarchy of exact equations for the multiphoton vertex functions, which in turn parametrize the exact S matrix, their analytical solution is in general only possible in the Markovian limit. To make some progress in solving the scattering problem, one has to resort to some kind of approximation routine. In this section we propose a couple of physically motivated resummation approaches, allowing one to avoid (or partially avoid) the solution of the exact integral equations.

The most basic approximation, which is accurate in the regime $\gamma\tau \lesssim 1$, where τ is a typical time delay in the system due to photons' propagation between two nearby scatterers, and γ is a typical decay rate of scatterers, is the so-called quasi-Markovian approximation. While in the quantum master-equation approach it has a long tradition (see, e.g., [22, 23]), it has been recently realized [51, 53] that in the diagrammatic approach it is mathematically equivalent to picking only noncrossing diagrams shown in Fig. 2 and thereby fully neglecting vertex corrections. To give a physical explanation of this equivalence, we view photons propagating in the waveguide as an effective reservoir. It is intuitively clear that a fast decay of time correlations between these photons is an essential feature of the Markovian regime (we add here the prefix "quasi" in order to indicate that the field values at positions of different scatterers can still differ from each other by a phase factor). On the other hand, these time correlations result from correlated virtual processes of emission and absorption of different photons at different scatterers, which are mathematically encoded in the vertex corrections. Thus, the neglect of vertex corrections is equivalent to making the quasi-Markovian approximation. It is also worth noting that this approximation for a single-photon scattering matrix coincides with its exact expression since in the absence of other photons the correlations in questions are not generated.

Below we give a step-by-step prescription how to implement the quasi-Markovian approximation in our diagrammatic approach. The exact n -photon transition matrices are represented by a $(n - 1)$ -particle effective vertex function inbetween two dressed Green's functions followed by emission and absorption vertices [see Eq. (34)]. In this approximation, the exact multiphoton vertex functions are simply replaced with a sequence of $n - 1$ bare and $n - 2$ dressed Green's functions interspersed with $2n - 2$ emission and absorption vertices. In particular, in the $n = 2$ case we get $W_{s'_1, s_1}^{(1,1)}(\epsilon) \rightarrow v_{s_1}^\dagger G_0(\epsilon - \omega_{s'_1} - \omega_{s_1}) v_{s'_1}$. In the $n = 3$ case we obtain $W_{s'_1 s'_2, s_1 s_2}^{(1,2)}(\epsilon) \rightarrow v_{s_1}^\dagger G_0(\epsilon - \omega_{s_1} - \omega_{s'_1} - \omega_{s'_2}) v_{s'_1} G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s'_2}) v_{s'_2}^\dagger G_0(\epsilon - \omega_{s_1} - \omega_{s_2} - \omega_{s'_2}) v_{s_2}$, and

so on. In this approximation, all of the nontrivial momentum dependence of the S matrix, comes entirely from the frequency dependence of the self-energy diagram. Note that the single-photon T matrix is completely determined by the dressed propagator $G^{(1)}(\epsilon)$ [see Eq. (33)]. This observation explicitly confirms the statement that the quasi-Markovian approximation becomes exact for a single propagating photon.

The second approximation routine, which is more accurate than the quasi-Markovian one for $\gamma\tau \gtrsim 1$, makes a partial account of the vertex corrections. In particular, this approximation is based on the resummation of the full single-photon vertex functions $W_{s',s}^{(1,1)}(\epsilon)$. Diagrammatically, this approximation amounts to the replacement of the dotted lines in Fig. 2 by the full single-particle bubbles; the resulting n -photon T matrix is shown in Fig. 3.

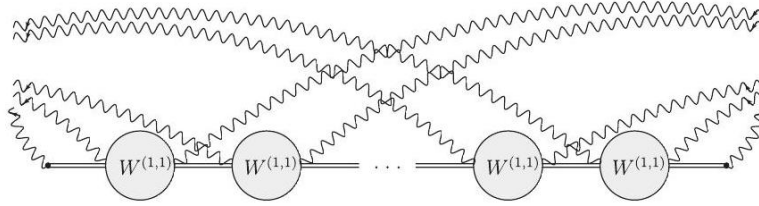


FIG. 3. Diagrammatic representation of n -particle transition matrix within the weak correlation approximation. Here two-particle bubbles correspond to a single-photon effective vertex function $W^{(1,1)}$. Opposite to the quasi-Markovian approximation, this approximation resums exactly all of the single-particle processes, ignoring all the connected diagrams corresponding to multiparticle scattering.

This approximation corresponds to resummation of all of the direct interaction diagrams (coming entirely from the single-particle sector), completely ignoring the exchange processes (encompassed by the connected parts of many-particle vertices). In order to clarify the matters, let us consider an integral equation governing the two-particle effective vertex shown in Fig. 1. Using the diagrammatic rules we deduce

$$\begin{aligned} W_{s'_1 s'_2, s_1 s_2}^{(1,2)}(\epsilon) &= R_{s'_1, s_1}^{(1)}(\epsilon - \omega_{s'_2}) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s'_2}) W_{s'_2, s_2}^{(1,1)}(\epsilon - \omega_1) + \\ &\quad + R_{s_1, s}^{(1)}(\epsilon - \omega_{s'_2}) G^{(1)}(\epsilon - \omega_s - \omega_{s'_2}) W_{s'_2, s_1 s_2}^{(1,2)} + \\ &\quad + R_{s_1, s}^{(1)}(\epsilon - \omega_{s'_2}) G^{(1)}(\epsilon - \omega_s - \omega_{s'_2}) W_{s'_2, s_1 s_2}^{(1,2)}. \end{aligned}$$

(потом цвета поставлю, лень уже)

Note that the last line above corresponds to the exchange interaction between that particles (see also Fig. 1). If we ignore the the last term completely and take into account the equation satisfied by $W^{(1,1)}$ it is easy to show that

$$W_{s'_1 s'_2, s_1 s_2}^{(1,2)}(\epsilon) = W_{s'_1, s_1}^{(1,1)}(\epsilon - \omega_{s'_2}) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s'_2}) W_{s'_2, s_2}^{(1,1)}(\epsilon - \omega_1)$$

is an exact solution of (47).

We expect this approximation to get worse as one increases the number of photons in the system since this approximation ignores a larger and larger fraction of diagrams with the increase in the number of particles involved in a scattering process. This approximation is beneficial since an integral equation for $W^{(1,1)}$ may be frequently solved analytically by means of the method developed in the Supplemental Material of [71]. Due to the nontrivial momentum dependence of $W^{(1,1)}$, we expect this approximation to be better than a quasi-Markovian one. In what follows, we refer to this approximation as to the weak correlation one. Note that as the quasi-Markovian approximation is exact in the single-particle sector, the weak correlation approximation is exact in the two-particle sector, thus in order to test its validity, one has to consider at least a three-photon scattering problem.

3.4 Systems with more than one qubit

Let's generalize the theory scattering for the systems with a larger number of qubits. In particular, we are going to focus our attention on the systems with two and three emitters. By deriving the equations governing two- and three-photon scattering matrices in two and three-qubit waveguide QED systems, respectively, we present the most general two- and three-particle equations, holding independently of the number of qubits (see the discussion in Sec. II B).

3.4.1 Case of $N_q = 2$ waveguide QED

(!! тут теперь у нас везде довечка!!! потом пойму, что конкретно новое изменилось????)

Theory

First, we would like to focus on the case of two emitters coupled to a waveguide since the generalization of the single-qubit results is the most apparent in this case. The starting point in the analysis is Eqs. (17) and (18). As opposed to the single-emitter case, now, clearly, both diagonal terms $v_s^\dagger a_{s'} \mathcal{G}_0 a_s^\dagger v_s$ and $a_{s'}^\dagger v_{s'} \mathcal{G}_0 v_s^\dagger a_s$ contribute to the geometric series for the transition operator. Nondiagonal ones still give zero since they both annihilate the state $v^\dagger |g\rangle$. By resumming the series and introducing the following set of objects

$$\begin{aligned}\mathcal{W}^{(2)} &= \mathcal{R}^{(2)} + \mathcal{R}^{(2)} \mathcal{G}^{(1)} \mathcal{W}^{(2)}, \\ \mathcal{R}^{(2)} &= a_{s_1}^\dagger \mathcal{R}_{s_1', s_1}^{(2)} a_{s_1}, \\ \mathcal{R}_{s_1', s_1}^{(2)} &= \mathcal{R}_{s_1', s_1}^{(1)} + v_{s_1} \mathcal{G}_0 v_{s_1}^\dagger,\end{aligned}$$

we render the matrix elements of the transition operator in the form (??? все как и было, только теперь довечки появляются??)

$$\langle N_p', g | \mathcal{T}^{(2)} | N_p, g \rangle = \langle N_p', g | a_{s_1}^\dagger v_{s_1} \mathcal{G}^{(1)} v_{s_1}^\dagger a_{s_1} | N_p, g \rangle + \langle N_p', g | a_{s_1}^\dagger v_{s_1} \mathcal{G}^{(1)} \mathcal{W}^{(2)} \mathcal{G}^{(1)} v_{s_1}^\dagger a_{s_1} | N_p, g \rangle.$$

Since the lowest term in the expansion of $\mathcal{W}^{(2)}$ is again a single-photon operator

$$\mathcal{W}^{(2)} = \sum_{n=1}^{\infty} a_{s_1}^\dagger \dots a_{s_n}^\dagger \mathcal{W}_{s_1' \dots s_n', s_1 \dots s_n}^{(2,n)} a_{s_n} \dots a_{s_1}$$

we see that the hierarchy of equations satisfied by the twophoton vertex functions is precisely the same as (29) and (30) with $R^{(1)}$ being replaced by $R^{(2)}$ (see Fig. 4).



FIG. 4. Diagrammatic representation of the replacement required to obtain $R_{s',s}^{(2)}$ from $R_{s',s}^{(1)}$. Note that the extra contribution to the effective potential energy vertex $R^{(2)}$ in two-qubit systems is not single-particle connected, i.e., it is possible to cut the intermediate propagator such that the diagram falls into two distinct pieces. This very fact makes the splitting (56)-(59) into reducible and irreducible contributions possible.

Отличие рассеяния на одном кубите от рассеяния на двух кубитах

In order to understand the difference between the singlequbit and the two-qubit theories, let us have a closer look at the equation defining $\mathcal{W}^{(2)}$:

$$\mathcal{W}^{(2)} = \mathcal{R}^{(1)} + a_{s'_1}^\dagger v_{s'_1} \mathcal{G}_0 v_{s_1}^\dagger a_{s_1} + \mathcal{R}^{(1)} \mathcal{G}^{(1)} \mathcal{W}^{(2)} + a_{s'_1}^\dagger v_{s'_1} \mathcal{G}_0 v_{s_1}^\dagger a_{s_1} \mathcal{G}^{(1)} \mathcal{W}^{(2)}.$$

Now let us perform the separation $\mathcal{W}^{(2)} = \mathcal{W}^{(2,i)} + \mathcal{W}^{(2,r)}$, where the superscripts i and r stand for the irreducible and reducible contributions, respectively, and $\mathcal{W}^{(2,i)}$ is chosen to satisfy Eq. (26). This leads one to the following equation satisfied by the reducible part:

$$\begin{aligned} \mathcal{W}^{(2,r)} &= a_{s'_1}^\dagger v_{s'_1} \mathcal{G}_0 v_{s_1}^\dagger a_{s_1} + \mathcal{R}^{(1)} \mathcal{G}^{(1)} \mathcal{W}^{(2,r)} + \\ &+ a_{s'_1}^\dagger v_{s'_1} \mathcal{G}_0 v_{s_1}^\dagger a_{s_1} \mathcal{G}^{(1)} \mathcal{W}^{(2,i)} + \\ &+ a_{s'_1}^\dagger v_{s'_1} \mathcal{G}_0 v_{s_1}^\dagger a_{s_1} \mathcal{G}^{(1)} \mathcal{W}^{(2,r)} \end{aligned}$$

The solution of above equation may then conveniently be parametrized as

$$W^{(2,r)}(\epsilon) = \mathcal{V}^{(2)}(\epsilon) \mathcal{G}^{(2)}(\epsilon) \bar{\mathcal{V}}^{(2)}(\epsilon),$$

(???? ПАЧИМУ???) where

$$\begin{aligned} \mathcal{G}^{(2)} &= \mathcal{G}_0 + \mathcal{G}_0 \Sigma^{(2)} \mathcal{G}^{(2)}, \\ \Sigma^{(2)} &= a_s v_s^\dagger \mathcal{G}^{(1)} v_{s'} a_{s'}^\dagger + a_s v_s^\dagger \mathcal{G}^{(1)} \mathcal{W}^{(2,i)} \mathcal{G}^{(1)} v_{s'} a_{s'}^\dagger, \\ \bar{\mathcal{V}}^{(2)} &= v_s^\dagger a_s + v_s^\dagger a_s \mathcal{G} \mathcal{W}^{(2,i)} =: \sum_{n=1}^{\infty} \bar{V}_{s_1 \dots s_n}^{(2,n)} a_{s_1} \dots a_{s_n}, \\ \mathcal{V}^{(2)} &= a_s^\dagger v_s + \mathcal{W}^{(2,i)} \mathcal{G} v_s a_s^\dagger =: \sum_{n=1}^{\infty} V_{s_1 \dots s_n}^{(2,n)} a_{s_1}^\dagger \dots a_{s_n}^\dagger \end{aligned}$$

The meaning of the above-defined objects is as follows. $\mathcal{G}^{(2)}(\epsilon)$ may be thought of as a Green's operator in the two-qubit excitation subspace since in practice, it is always projected there. $\Sigma^{(2)}(\epsilon)$ in its turn may be thought of as a selfenergy operator in the two-qubit excitation subspace. $\mathcal{V}(\epsilon)$ and $\bar{\mathcal{V}}(\epsilon)$ may be understood as the renormalized absorption and emission vertex operators.

As it was anticipated above, the equations governing a two-photon scattering on a pair of qubits hold in the case of a two-photon scattering for a general N_q system. Bearing this in mind, in Fig. 5 we present the system of exact integral equations governing the general two-photon scattering problem in waveguide QED (i.e., equations defining $W^{(2,1)}$). These equations were first obtained in [71] in relation with the two-photon scattering problem on two distant qubits.

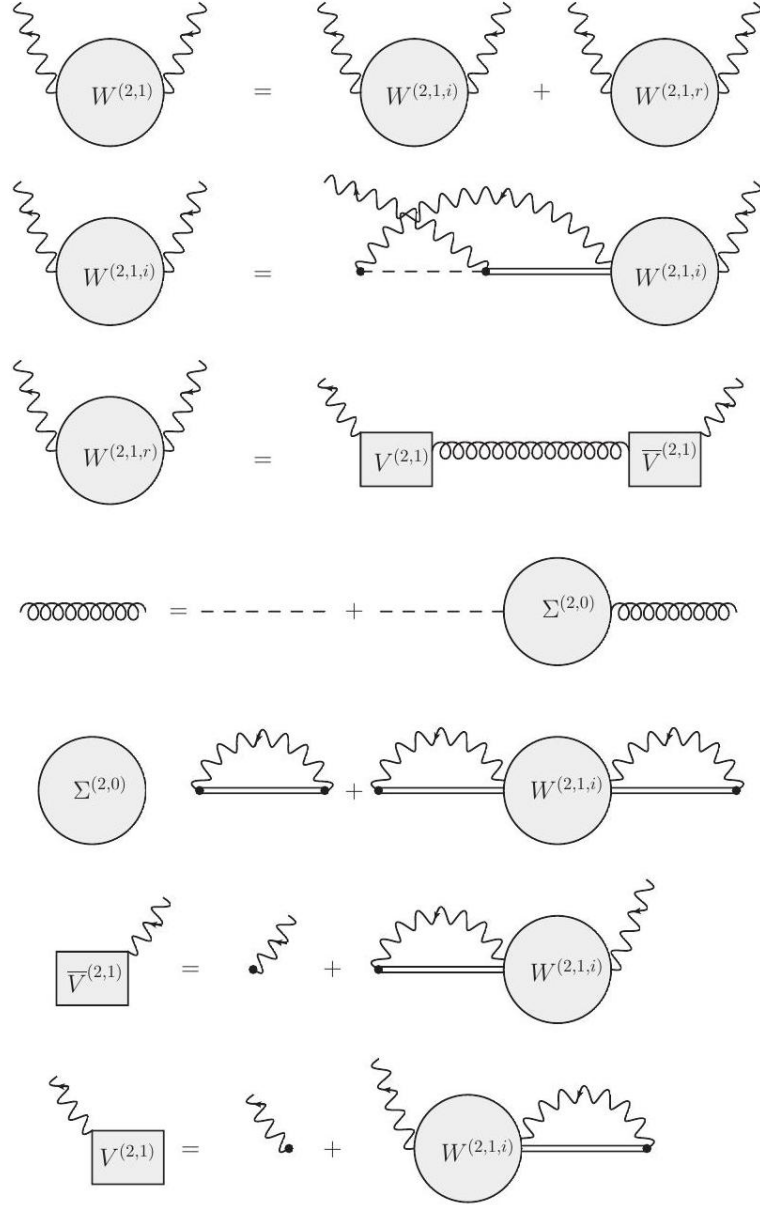


FIG. 5.

Equations corresponding to the general two-photon scattering problem. Equation in the first line describes the splitting of the effective single-particle vertex function $W^{(2,1)}$ in the generic twophoton scattering problem into its reducible $W^{(2,1,r)}$ and irreducible parts $W^{(2,1,i)}$. The irreducible part is generated from the fundamental process of the single-qubit waveguide QED $R^{(1)}$ (as shown in the second line) and thus satisfies the same integral equation as $W^{(1,1)}$. The reducible part, stemming from non-single-particle connectedness of the additional contribution to $R^{(2)}$ (see Fig. 4), is parametrized by the dressed Green's function $G^{(2,0)}$ in two-excitation subspace (shown as the curly line) as well as renormalized emission and absorption vertices (indicated by rectangles). As one can see, the entire system of equations boils down to the solution of the equation defining the irreducible part of the vertex function since its knowledge is sufficient to completely determine both the renormalized vertices $V^{(2,1)}$, $\bar{V}^{(2,1)}$ as well as the self-energy $\Sigma^{(2,0)}$ in the two-excitation subspace.

3.4.2 Case of $N_q = 3$ waveguide QED

Theory

Let us finally dedicate our attention to three-qubit waveguide QED systems. Due to the enormous increase in the computational complexity, we restrict ourselves to the first nontrivial subspace within such a setup: A three-excitation subspace. As before, the starting point of the analysis is Eq. (17). No doubt, both of the "diagonal" terms $\sim v^\dagger v$ and $\sim vv^\dagger$ give a nonzero contribution to the transition operator as it was the case in the previous section; however, one can clearly see that now the "off-diagonal" terms $(vv, v^\dagger v^\dagger)$ have to be also taken into account. By defining the operators

$$\mathcal{D}_+ = a_{s'}^\dagger v_{s'} \mathcal{G}_0 a_s^\dagger v_s, \quad \mathcal{D}_- = v_{s'}^\dagger a_{s'} \mathcal{G}_0 v_s^\dagger a_s$$

bearing in mind the rotating wave approximation, and resumming the series (17) to incorporate the diagonal terms and again making use of RWA, in the realm of $N_q = 3$ waveguide QED, we obtain

$$\begin{aligned} \langle N'_p, g | \mathcal{T}^{(3)} | N_p, g \rangle &= \left\langle N'_p, g \left| a_{s'_1}^\dagger v_{s'_1} \frac{1}{(\mathcal{G}^{(1)})^{-1} - \mathcal{R}^{(3)}} v_{s_1}^\dagger a_{s_1} \right| N_p, g \right\rangle \\ \mathcal{R}^{(3)} &= \mathcal{R}^{(2)} + \mathcal{D} \\ \mathcal{D} &= \mathcal{D}_+ \frac{1}{(\mathcal{G}^{(1)})^{-1} - \mathcal{R}^{(2)}} \mathcal{D}_- = \mathcal{R}^{(2)} + \mathcal{D}_+ \mathcal{G}^{(1)} \mathcal{D}_- + \mathcal{D}_+ \mathcal{G}^{(1)} \mathcal{W}^{(2)} \mathcal{G}^{(1)} \mathcal{D}_- \end{aligned}$$

As usual, we define the $\mathcal{W}^{(3)}$ operator according to

$$\mathcal{W}^{(3)} := \mathcal{D} + \mathcal{D} (\mathcal{G}^{(1)} + \mathcal{G}^{(1)} \mathcal{W}^{(2)} \mathcal{G}^{(1)}) \mathcal{W}^{(3)}$$

which brings the transition operator to the following form:

$$\langle N'_p, g | \mathcal{T}^{(3)} | N_p, g \rangle = \left\langle N'_p, g \left| \mathcal{T}^{(2)} + a_{s'_1}^\dagger v_{s'_1} \mathcal{G}^{(1)} (1 + \mathcal{W}^{(2)} \mathcal{G}^{(1)}) \mathcal{W}^{(3)} (\mathcal{G}^{(1)} \mathcal{W}^{(2)} + 1) \mathcal{G}^{(1)} v_{s_1}^\dagger a_{s_1} \right| N_p, g \right\rangle$$

Upon the projection, onto the three-photon subspace, we obtain the following set of equations governing the generic (see Sec. II B) three-particle T matrix (see Appendix C for the detailed derivation):

$$\begin{aligned} T_{s'_1 s'_2 s'_3, s_1 s_2 s_3}^{(3,3)}(\epsilon) &= \left\langle g \left| v_{s'_1} G^{(1)}(\epsilon - \omega_{s'_2} - \omega_{s'_3}) \left[W_{s'_2 s_3, s_2 s_3}^{(2,2)}(\epsilon) + V_{s'_2 s'_3}^{(3,2)}(\epsilon) G^{(3,0)}(\epsilon) \bar{V}_{s_2 s_3}^{(3,2)}(\epsilon) \right] G^{(1)}(\epsilon - \omega_{s_2} - \omega_{s_3}) v_{s_1}^\dagger \right| g \right\rangle \\ &=: \left\langle g \left| v_{s'_1} G^{(1)}(\epsilon - \omega_{s'_2} - \omega_{s'_3}) \left[W_{s'_2 s'_3, s_2 s_3}^{(2,2)}(\epsilon) + W_{s'_2 s_3, s_2 s_3}^{(3,2)}(\epsilon) \right] G^{(1)}(\epsilon - \omega_{s_2} - \omega_{s_3}) v_{s_1}^\dagger \right| g \right\rangle \\ G^{(3,0)}(\epsilon) &= G^{(1)}(\epsilon) + G^{(1)}(\epsilon) \Sigma^{(3,0)}(\epsilon) G^{(3,0)}(\epsilon) \\ \Sigma^{(3,0)}(\epsilon) &= \left[v_s^\dagger G_0(\epsilon - \omega_s) v_{s'}^\dagger + v_{s'}^\dagger G_0(\epsilon - \omega_{s'}) v_s^\dagger \right] G^{(1)}(\epsilon - \omega_s - \omega_{s'}) V_{ss'}^{(3,2)}(\epsilon) \\ &\equiv \bar{V}_{ss'}^{(3,2)}(\epsilon) G^{(1)}(\epsilon - \omega_s - \omega_{s'}) [v_{s'} G_0(\epsilon - \omega_s) v_s + v_s G_0(\epsilon - \omega_{s'}) v_{s'}] \\ \bar{V}_{s_1 s_2}^{(3,2)}(\epsilon) &= v_{s_1}^\dagger G^{(2,0)}(\epsilon) \bar{V}_{s_2}^{(2,1)}(\epsilon) + \bar{V}_{ss_1}^{(3,2)}(\epsilon) G^{(1)}(\epsilon - \omega_s) W_{s, s_2}^{(2,1)}(\epsilon) \\ V_{s'_1 s'_2}^{(3,2)}(\epsilon) &= V_{s'_1}^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon) v_{s'_2}^\dagger + W_{s'_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) V_{s'_2 s}^{(3,2)}(\epsilon) \end{aligned}$$

Here $G^{(2,0)}(\epsilon)$ is the projection of (56) onto the photon vacuum state. As usual, the above equation may be compactly represented diagrammatically as shown in Fig. 6.

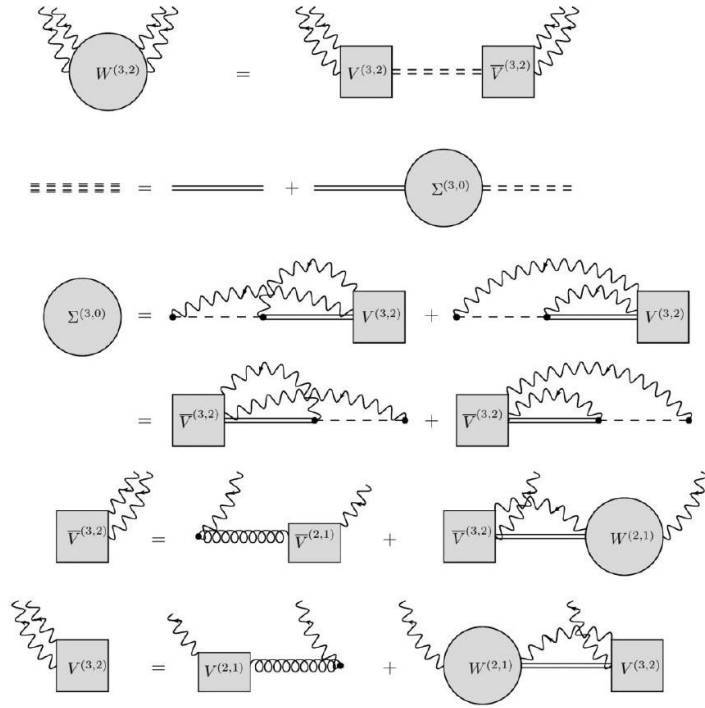


FIG. 6.

Equations corresponding to the general three-photon scattering problem. Here the first line defines the effective two-body vertex function $W^{(3,2)}$ in terms of the dressed Green's function in three-excitation subspace shown as a double dashed line as well as effective two-photon absorption and emission vertices depicted by square boxes with a pair of incoming and outgoing amputated photon legs (note that these vertices correspond to the absorption and emission of photon pairs by a system as a whole). As it is shown in the last five lines the effective two-photon emission and absorption vertices as well as the self-energy bubble defining the Green's function in the three-excitation subspace satisfy a closed hierarchy of self-consistent equations, the validity of which is directly proven in Appendix C. Curly lines as well as the rectangular boxes with single amputated photon lines are precisely defined in Fig. 5.

3.4.3 Вывод диаграммной техники на простом примере (!?!?!?)

Вывод

(а то так в общем формализме и утонуть просто запросто можно. нет, пока не усвоил это.)

3.4.4 Diagrammatic representation of the generic 3-body transition operator (?????)

In this Appendix we start our analysis with Eq. (64). Taking matrix elements of (64) in the three-particle subspace we arrive at the following integral equation:

$$\begin{aligned}
W_{s_1 s'_2, s_1 s_2}^{(3,2)}(\epsilon) &= D_{s'_1 s'_2, s_1 s_2}^{(2)}(\epsilon) + \left[D_{s'_1 s'_2, \bar{s}_2 \bar{s}'_1}^{(2)}(\epsilon) + D_{s'_1 s'_2, \bar{s}'_1 \bar{s}_2}^{(2)}(\epsilon) \right] G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) W_{\bar{s}'_1 \bar{s}_2, s_1 s_2}^{(3,2)}(\epsilon) \\
&+ D_{s'_1 s'_2, \bar{s}'_1 \bar{s}_2}^{(2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) W_{\bar{s}_2, \bar{s}'_2}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) W_{\bar{s}'_1 \bar{s}_2, s_1 s_2}^{(3,2)}(\epsilon) \\
&+ D_{s'_1 s'_2, \bar{s}_1 \bar{s}'_1}^{(2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}_1} - \omega_{\bar{s}'_1}) W_{\bar{s}_1, \bar{s}'_2}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) W_{\bar{s}'_1 \bar{s}_2, s_1 s_2}^{(3,2)}(\epsilon) \\
&+ D_{s'_1 s'_2, \bar{s}_1 \bar{s}_2}^{(2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}_1} - \omega_{\bar{s}_2}) W_{\bar{s}_1, \bar{s}'_1}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) W_{\bar{s}'_1 \bar{s}_2, s_1 s_2}^{(3,2)}(\epsilon) \\
&+ D_{s'_1 s'_2, \bar{s}'_2 \bar{s}_2}^{(2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_2} - \omega_{\bar{s}_2}) W_{\bar{s}_2, \bar{s}'_1}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) W_{\bar{s}'_1 \bar{s}_2, s_1 s_2}^{(3,2)}(\epsilon) \\
&+ D_{s'_1 s'_2, \bar{s}_1 \bar{s}_2}^{(2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}_1} - \omega_{\bar{s}_2}) W_{\bar{s}_2 \bar{s}_1, \bar{s}'_2 \bar{s}'_1}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) W_{\bar{s}'_1 \bar{s}'_2, s_1 s_2}^{(3,2)}(\epsilon) \\
&+ D_{s'_1 s'_2, \bar{s}_1 \bar{s}_2}^{(2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}_1} - \omega_{\bar{s}_2}) W_{\bar{s}_1 \bar{s}_2, \bar{s}'_2 \bar{s}'_1}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) W_{\bar{s}'_1 \bar{s}'_2, s_1 s_2}^{(3,2)}(\epsilon) \\
&+ D_{s'_1 s'_2, \bar{s}_1 \bar{s}_2}^{(2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}_1} - \omega_{\bar{s}_2}) W_{\bar{s}_1 \bar{s}_2, \bar{s}'_1 \bar{s}'_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) W_{\bar{s}'_1 \bar{s}'_2, s_1 s_2}^{(3,2)}(\epsilon) \\
&+ D_{s'_1 s'_2, \bar{s}_1 \bar{s}_2}^{(2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}_1} - \omega_{\bar{s}_2}) W_{\bar{s}'_2 \bar{s}_1, \bar{s}'_1 \bar{s}'_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) W_{\bar{s}'_1 \bar{s}'_2, s_1 s_2}^{(3,2)}(\epsilon),
\end{aligned}$$

where the projection of \mathcal{D} onto the two-particle subspace is given by

$$D_{s'_1 s'_2, s_1 s_2}^{(2)}(\epsilon) = v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2} G^{(1)}(\epsilon) v_{s_2}^\dagger G_0(\epsilon - \omega_{s_2}) v_{s_1}^\dagger$$

Keeping this in mind we make the following ansatz:

$$W_{s'_1 s'_2, s_1 s_2}^{(3,2)}(\epsilon) = v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2} G^{(3,0)}(\epsilon) v_{s_2}^\dagger G_0(\epsilon - \omega_{s_2}) v_{s_1}^\dagger$$

This, in turn, leads to the following Dyson equation:

$$G^{(3,0)}(\epsilon) = G^{(1)}(\epsilon) + G^{(1)}(\epsilon) \Sigma^{(3,0)}(\epsilon) G^{(3,0)}(\epsilon)$$

where the self-energy in the three-excitation subspace is given by

$$\begin{aligned}
\Sigma^{(3,0)}(\epsilon) &= \left[v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_2}^\dagger + v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger \right] G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2} \\
&+ v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) W_{s_2, s'_2}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2} \\
&+ v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_2}^\dagger G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s'_1}) W_{s_1, s'_2}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2} \\
&+ v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s'_2}) W_{s_1, s'_1}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2} \\
&+ v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_2}^\dagger G^{(1)}(\epsilon - \omega_{s'_2} - \omega_{s_2}) W_{s_2, s'_1}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2} \\
&+ v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) W_{s_2 s_1, s'_2 s'_1}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2} \\
&+ v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) W_{s_1 s_2, s'_2 s'_1}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2} \\
&+ v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) W_{s_1 s_2, s'_1 s'_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2} \\
&+ v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) W_{s_2 s_1, s'_1 s'_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) v_{s'_1} G_0(\epsilon - \omega_{s'_2}) v_{s'_2}.
\end{aligned}$$

Let us now consider the expression (65) for the transition operator. Concentrating on the three-photon subspace we obtain

$$\begin{aligned}
T_{s'_1 s_2 s'_3, s_1 s_2 s_3}^{(3)}(\epsilon) &= \langle g | v_{s'_1} G^{(1)}(\epsilon - \omega_{s'_2} - \omega_{s'_3}) \left[W_{s'_2 s'_3, s_2 s_3}^{(2,2)}(\epsilon) + V_{s'_2 s'_3}^{(3,2)}(\epsilon) G^{(3,0)}(\epsilon) \bar{V}_{s_2 s_3}^{(3,2)}(\epsilon) \right] G^{(1)}(\epsilon - \omega_{s_2} - \omega_{s_3}) v_{s_1}^\dagger | g \rangle, \\
V_{s'_1 s'_2}^{(3,2)} &= v_{s'_1} G_0(\epsilon) v_{s'_2} + W_{s'_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) v_s G_0(\epsilon) v_{s'_2} + W_{s'_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) v_{s'_2} G_0(\epsilon - \omega_s) v_s \\
&+ W_{s'_1 s'_2, \bar{s}'_1 \bar{s}_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) v_{\bar{s}'_1} G_0(\epsilon - \omega_{\bar{s}_2}) v_{\bar{s}_2} \\
&+ W_{s'_1 s'_2, \bar{s}'_2 \bar{s}_1}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{\bar{s}'_1} - \omega_{\bar{s}_2}) v_{\bar{s}'_1} G_0(\epsilon - \omega_{\bar{s}_2}) v_{\bar{s}_2} \\
\bar{V}_{s_1 s_2}^{(3,2)} &= v_{s_1} G_0(\epsilon) v_{s_2} + v_{s_1}^\dagger G_0(\epsilon) v_{s_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1}) W_{s'_1, s_2}^{(2,1)}(\epsilon) + v_{s_1}^\dagger G_0(\epsilon - \omega_{s_1}) v_{s_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1}) W_{s'_1, s_2}^{(2,1)}(\epsilon) \\
&+ v_{s_2}^\dagger G_0(\epsilon - \omega_{s_2}) v_{s_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) W_{\bar{s}_1 \bar{s}_2, s_1 s_2}^{(2,2)}(\epsilon) \\
&+ v_{s_2}^\dagger G_0(\epsilon - \omega_{s_2}) v_{s_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) W_{\bar{s}_2 \bar{s}_1, s_1 s_2}^{(2,2)}(\epsilon).
\end{aligned}$$

Now, our goal is to rewrite the renormalized two-particle emission $V_{s'_1 s'_2}$ and absorption $\bar{V}_{s_1 s_2}$ vertices, as well as the self-energy in three-excitation subspace $\Sigma^{(3,3)}$ in terms of full Green's and vertex functions, as it is presented in the main text.

First, we note the following identity:

$$\begin{aligned}
v_{s'_1} G_0(\epsilon) v_{s'_2} + W_{s'_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) v_s G_0(\epsilon) v_{s'_2} &= v_{s'_1} G_0(\epsilon) v_{s'_2} + W_{s'_1, s}^{(2,1,i)}(\epsilon) G^{(1)}(\epsilon - \omega_s) v_s G_0(\epsilon) v_{s'_2} \\
+ V_{s'_1}^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon) \bar{V}_s^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) v_s G_0(\epsilon) v_{s'_2} &= v_{s'_1} G_0(\epsilon) v_{s'_2} + W_{s'_1, s}^{(2,1,i)}(\epsilon) G^{(1)}(\epsilon - \omega_s) v_s G_0(\epsilon) v_{s'_2} \\
+ V_{s'_1}^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon) \Sigma^{(2,0)} G_0(\epsilon) v_{s'_2} &= v_{s'_1} G_0(\epsilon) v_{s'_2} + W_{s'_1, s}^{(2,1,i)}(\epsilon) G^{(1)}(\epsilon - \omega_s) v_s G_0(\epsilon) v_{s'_2} \\
+ V_{s'_1}^{(2,1)}(\epsilon) [G^{(2,0)}(\epsilon) - G_0(\epsilon)] v_{s'_2} &= V_{s'_1}^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon) v_{s'_2}.
\end{aligned}$$

Analogously

$$v_{s'_1}^\dagger G_0(\epsilon) v_{s'_2}^\dagger + v_{s'_1}^\dagger G_0(\epsilon) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'}) W_{s', s_2}^{(2,1)}(\epsilon) = v_{s'_1}^\dagger G^{(2,0)}(\epsilon) \bar{V}_{s_2}^{(2,1)}(\epsilon)$$

Analyzing the structure of equations satisfied by $W^{(2,1)}$ and $W^{(2,2)}$ one easily concludes that

$$W_{s_1 s'_2, s_1 s_2}^{(2,2)}(\epsilon) = W_{s'_1, s_1}^{(2,1)}(\epsilon) G^{(1)}(\epsilon) W_{s'_2, s_2}^{(2,1)}(\epsilon) + W_{s'_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) W_{s'_2, s_1 s_2}^{(2,2)}(\epsilon)$$

$$W_{s'_1 s'_2, s_1 s_2}^{(2,2)}(\epsilon) = W_{s'_1, s_1}^{(2,1)}(\epsilon) G^{(1)}(\epsilon) W_{s'_2, s_2}^{(2,1)}(\epsilon) + W_{s'_1 s'_2, s s_1}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_s) W_{s, s_2}^{(2,1)}(\epsilon)$$

Multiplying (C11) and (C12) by $G^{(1)}(\epsilon) v_{s_2} G_0(\epsilon) v_{s_1}$ from the right and by $v_{s'_2}^\dagger G_0(\epsilon) v_{s'_1}^\dagger G^{(1)}(\epsilon)$ from the left, respectively, and contracting the relevant indices, we obtain

$$\begin{aligned}
W_{s'_1 s'_2, s_1 s_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) v_{s_2} G_0(\epsilon - \omega_{s_2}) v_{s_1} &= W_{s'_1, s_1}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1}) [V_{s'_2}^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon - \omega_{s_1}) v_{s_1} \\
- v_{s'_2}^\dagger G_0(\epsilon - \omega_{s_1}) + W_{s'_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) W_{s'_2, s_1 s_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) v_{s_2} G_0(\epsilon - \omega_{s_1}) v_{s_1}, \\
v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) W_{s'_1 s'_2, s_1 s_2}^{(2,2)}(\epsilon) &= [v_{s'_2}^\dagger G^{(2,0)}(\epsilon - \omega_{s'_2}) \bar{V}_{s_1}^{(2,1)}(\epsilon) - v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger] \\
\cdot G^{(1)}(\epsilon - \omega_{s'_2}) W_{s'_2, s_2}^{(2,2)} + v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) &W_{s'_1 s'_2, s s_1}^{(2,2)} G^{(1)}(\epsilon - \omega_s) W_{s, s_2}^{(2,1)}(\epsilon).
\end{aligned}$$

Now, defining the objects

$$\begin{aligned}
K_{s'_1 s'_2}^{(d)}(\epsilon) &= W_{s'_1 s'_2, s_1 s_2}^{(\epsilon, 2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_2} - \omega_{s_1}) v_{s_2} G_0(\epsilon - \omega_{s_1}) v_{s_1} + W_{s'_1, s_1}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1}) v_{s'_2} G_0(\epsilon - \omega_{s_1}) v_{s_1}, \\
\bar{K}_{s_1 s_2}^{(d)}(\epsilon) &= v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) W_{s'_1 s'_2, s_1 s_2}^{(2,2)}(\epsilon) + v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'_2}) W_{s'_2, s_2}^{(2,1)}(\epsilon),
\end{aligned}$$

we establish the following equations:

$$\begin{aligned}
K_{s'_1 s'_2}^{(d)}(\epsilon) &= W_{s'_1, s_1}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1}) V_{s'_2}^{(2,1)}(\epsilon - \omega_{s_1}) G^{(2,0)}(\epsilon - \omega_{s_1}) v_{s_1} \\
&+ W_{s'_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) [K_{s'_2 s}^{(d)}(\epsilon) - W_{s'_2, s_1}^{(2,1)}(\epsilon - \omega_s) G^{(1)}(\epsilon - \omega_{s_1} - \omega_s) v_s G_0(\epsilon - \omega_{s_1}) v_{s_1}], \\
\bar{K}_{s_1 s_2}^{(d)}(\epsilon) &= v_{s'_2}^\dagger G^{(2,0)}(\epsilon - \omega_{s'_2}) \bar{V}_{s_1}^{(2,1)}(\epsilon - \omega_{s'_2}) G^{(1)}(\epsilon - \omega_{s'_2}) W_{s'_2, s_2}^{(1,0)}(\epsilon) \\
&+ [\bar{K}_{s s_1}^{(d)}(\epsilon) - v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_s^\dagger G^{(1)}(\epsilon - \omega_{s'_2} - \omega_s) W_{s'_2, s_1}^{(2,1)}(\epsilon - \omega_s)] G^{(1)}(\epsilon - \omega_s) W_{s, s_2}^{(2,1)}(\epsilon).
\end{aligned}$$

Analogously, multiplying (C11) and (C12) by $G^{(1)}(\epsilon) v_{s_1} G_0(\epsilon) v_{s_2}$ from the right and by $v_{s'_1}^\dagger G_0(\epsilon) v_{s'_2}^\dagger G^{(1)}(\epsilon)$ from the left, respectively, contracting the $s_{1,2}$ indices, and defining

$$\begin{aligned}
K_{s'_1 s'_2}^{(e)}(\epsilon) &= W_{s'_1 s'_2, s_1 s_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) v_{s_1} G_0(\epsilon - \omega_{s_2}) v_{s_2}, \\
\bar{K}_{s_1 s_2}^{(e)}(\epsilon) &= v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_2}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) W_{s'_1 s'_2, s_1 s_2}^{(2,2)}(\epsilon),
\end{aligned}$$

we deduce

$$\begin{aligned}
K_{s'_1 s'_2}^{(e)}(\epsilon) &= W_{s'_1, s_1}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1}) W_{s'_2, s_2}^{(2,1)}(\epsilon - \omega_{s_1}) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) v_{s_1} G_0(\epsilon - \omega_{s_2}) v_{s_2} + W_{s'_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) K_{s'_2 s}^{(e)}(\epsilon), \\
\bar{K}_{s_1 s_2}^{(e)}(\epsilon) &= v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_2}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) W_{s'_1, s_1}^{(2,1)}(\epsilon - \omega_{s'_2}) G^{(1)}(\epsilon - \omega_{s'_2}) W_{s'_2, s_2}^{(2,1)}(\epsilon) + \bar{K}_{s s_1}^{(e)}(\epsilon) G^{(1)}(\epsilon - \omega_s) W_{s, s_2}^{(2,1)}(\epsilon)
\end{aligned}$$

Further, we define

$$\begin{aligned}
K_{s'_1 s'_2}(\epsilon) &= K_{s'_1 s'_2}^{(d)}(\epsilon) + K_{s'_1 s'_2}^{(e)}(\epsilon), \\
\bar{K}_{s_1 s_2}(\epsilon) &= \bar{K}_{s_1 s_2}^{(d)}(\epsilon) + \bar{K}_{s_1 s_2}^{(e)}(\epsilon).
\end{aligned}$$

With these definitions it is easy to show that the two-particle emission and absorption vertices are given by

$$\begin{aligned}
V_{s'_1 s'_2}^{(3,2)}(\epsilon) &= V_{s'_1}^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon) V_{s'_2}^{(2,1)}(\epsilon) + \tilde{K}_{s'_1 s'_2}(\epsilon), \\
\bar{V}_{s_1 s_2}^{(3,2)}(\epsilon) &= \bar{V}_{s_1}^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon) \bar{V}_{s_2}^{(2,1)}(\epsilon) + \tilde{\bar{K}}_{s_1 s_2}(\epsilon),
\end{aligned}$$

Where

$$\begin{aligned}
\tilde{K}_{s'_1 s'_2}(\epsilon) &= K_{s'_1 s'_2}(\epsilon) - V_{s'_1}^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon) W_{s'_2, s'_1}^{(2,1,i)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1}) v_{s_1}, \\
\tilde{\bar{K}}_{s_1 s_2}(\epsilon) &= \bar{K}_{s_1 s_2}(\epsilon) \\
&\quad - v_{s'_2}^\dagger G^{(1)}(\epsilon - \omega_{s'_2}) W_{s'_2, s_1}^{(2,1,i)}(\epsilon) G^{(2,0)}(\epsilon) \bar{V}_{s_2}^{(2,1)}(\epsilon)
\end{aligned}$$

obey the following integral equations:

$$\begin{aligned}
\tilde{K}_{s_1 s'_2}(\epsilon) &= W_{s'_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) V_{s'_2}^{(2,1)}(\epsilon - \omega_s) G^{(2,0)}(\epsilon - \omega_s) V_s^{(2,1)}(\epsilon) - V_{s'_1}^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon) W_{s'_2, s}^{(2,1,i)}(\epsilon) G^{(1)}(\epsilon - \omega_s) v_s \\
&\quad + W_{s_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) \tilde{K}_{s'_2 s}(\epsilon), \\
\tilde{\bar{K}}_{s_1 s_2}(\epsilon) &= \bar{V}_s^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon - \omega_s) V_{s_1}^{(2,1)}(\epsilon - \omega_s) G^{(1)}(\epsilon - \omega_s) W_{s, s_2}^{(2,1)}(\epsilon) - v_s^\dagger G^{(1)}(\epsilon - \omega_s) W_{s, s_1}^{(2,1,i)}(\epsilon) G^{(2,0)}(\epsilon) \bar{V}_{s_2}^{(2,1)}(\epsilon) \\
&\quad + \tilde{\bar{K}}_{s s_1}(\epsilon) G^{(1)}(\epsilon - \omega_s) W_{s, s_2}^{(2,1)}(\epsilon).
\end{aligned}$$

Using Eqs. (C25) and (C26) together with (C29) and (C30), we finally arrive at the following equations:

$$\begin{aligned}
V_{s_1 s'_2}^{(3,2)}(\epsilon) &= V_{s'_1}^{(2,1)}(\epsilon) G^{(2,0)}(\epsilon) v_{s'_2} + W_{s_1, s}^{(2,1)}(\epsilon) G^{(1)}(\epsilon - \omega_s) V_{s'_2}^{(3,2)}(\epsilon), \\
\bar{V}_{s_1 s_2}^{(3,2)}(\epsilon) &= v_{s_1} G^{(2,1)}(\epsilon) \bar{V}_{s_2}(\epsilon) + \bar{V}_{s s_1}^{(3,2)}(\epsilon) G^{(1)}(\epsilon - \omega_s) W_{s, s_2}^{(2,1)}(\epsilon),
\end{aligned}$$

which are precisely Eqs. (70) and (71) stated in the main text.

Now, we turn our attention to the self-energy bubble. Let us show that Eqs. (68) and (69) hold via direct substitution. One has

$$\begin{aligned}
\Sigma^{(3,0)}(\epsilon) &= \left[v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_2}^\dagger + v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger \right] G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) V_{s'_1 s'_2}^{(3,2)}(\epsilon) \\
&= v_{s'_2}^\dagger \left[G^{(2,0)}(\epsilon - \omega_{s'_2}) - G_0(\epsilon - \omega_{s_2}) \right] v_{s'_2} - v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_s) v_{s'_1} G_0(\epsilon - \omega_s) v_s \\
&\quad + v_{s'_1}^\dagger G_0(\epsilon - \omega_{s_1}) v_{s'_2}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s_2}) V_{s'_1}^{(2,1)}(\epsilon - \omega_{s'_2}) G^{(2,0)}(\epsilon - \omega_{s'_2}) v_{s'_2} \\
&\quad + v_{s'_1}^\dagger G^{(2,0)}(\epsilon - \omega_{s'_1}) \bar{V}_s^{(2,1)}(\epsilon - \omega_{s'_1}) G^{(1)}(\epsilon - \omega_s - \omega_{s'_1}) v_{s'_1} G_0(\epsilon - \omega_s) v_s \\
&\quad + v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) W_{s'_2, s}^{(2,1)}(\epsilon - \omega_{s'_1}) G^{(1)}(\epsilon - \omega_{s'_1} - \omega_s) v_{s'_1} G_0(\epsilon - \omega_s) v_s \\
&\quad + v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_2}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) W_{s'_1 s'_2, s'}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'} - \omega_s) v_{s'} G_0(\epsilon - \omega_s) v_s \\
&\quad + v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_2}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) W_{s'_1 s'_2, s' s}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'} - \omega_s) v_{s'} G_0(\epsilon - \omega_s) v_s \\
&\quad + v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) W_{s'_1 s_2, s' s}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'} - \omega_s) v_{s'} G_0(\epsilon - \omega_s) v_s \\
&\quad + v_{s'_2}^\dagger G_0(\epsilon - \omega_{s'_2}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s'_2}) W_{s'_1 s_2, s' s'}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s'} - \omega_s) v_{s'} G_0(\epsilon - \omega_s) v_s, \\
\Sigma^{(3,0)}(\epsilon) &= \bar{V}_{s_1 s_2}^{(3,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) (v_{s_1} G_0(\epsilon - \omega_{s_2}) v_{s_2} + v_{s_2} G_0(\epsilon - \omega_{s_1}) v_{s_1}) \\
&= v_{s'_2}^\dagger \left[G^{(2,0)}(\epsilon - \omega_{s_2}) - G_0(\epsilon - \omega_{s_2}) \right] v_{s_2} - v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s'_1}) v_{s'_1} G_0(\epsilon - \omega_{s_1}) v_{s_1} \\
&\quad + v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s'_1}) V_{s'_1}^{(2,1)}(\epsilon - \omega_{s_1}) G^{(2,0)}(\epsilon - \omega_{s_1}) v_{s_1} \\
&\quad + v_{s'_2}^\dagger G^{(2,0)}(\epsilon - \omega_{s_2}) \bar{V}_{s_1}^{(2,1)}(\epsilon - \omega_{s_2}) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) v_{s_2} G_0(\epsilon - \omega_{s_1}) v_{s_1} \\
&\quad + v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_{s'_1} - \omega_{s_1}) W_{s'_1, s_2}^{(2,1)}(\epsilon - \omega_{s_1}) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) v_{s_1} G_0(\epsilon - \omega_{s_2}) v_{s_2} \\
&\quad + v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_s - \omega_{s'_1}) W_{s s', s_1 s_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) v_{s_1} G_0(\epsilon - \omega_{s_2}) v_{s_2} \\
&\quad + v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_s - \omega_{s'_1}) W_{s s', s_1 s_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) v_{s_1} G_0(\epsilon - \omega_{s_2}) v_{s_2} \\
&\quad + v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_s - \omega_{s'_1}) W_{s s', s_1 s_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) v_{s_2} G_0(\epsilon - \omega_{s_1}) v_{s_1} \\
&\quad + v_{s'_1}^\dagger G_0(\epsilon - \omega_{s'_1}) v_{s'_1}^\dagger G^{(1)}(\epsilon - \omega_s - \omega_{s'_1}) W_{s s', s_1 s_2}^{(2,2)}(\epsilon) G^{(1)}(\epsilon - \omega_{s_1} - \omega_{s_2}) v_{s_2} G_0(\epsilon - \omega_{s_1}) v_{s_1}.
\end{aligned}$$

This, together with identities (C9) and (C10), justifies the proposed representation of the self-energy.

3.5 Coherence functions

Let's consider the non-Markovian scattering setup: A giant acoustic atom, extensively studied theoretically and experimentally in [19, 59, 60, 78 – 81] (see also [82] for a detailed review). (???? добавлю из этих статей теорию про это! мб там многое полезного!)

3.5.1 Model and conventions (!!!!!!!)

(по идее это один из самых важных разделов!)

Theory

A giant acoustic atom may be defined as a two-level system coupled to an acoustical waveguide, in which the radiation is carried by the surface acoustic waves (SAW), at two distant points $x = \pm R/2$. The Hamiltonian of such a system may be written as $\mathcal{H} = \mathcal{H}_1 + \mathcal{V}$:

$$\begin{aligned}\mathcal{H}_0 &= \Omega\sigma_+\sigma_- - iv \sum_{\mu=1,2} \int dx c_\mu b_\mu^\dagger(x) \partial_x b_\mu(x), \\ \mathcal{V} &= \sum_{\mu=1,2} \left[\sqrt{\Gamma_1} b_\mu^\dagger(-R/2) + \sqrt{\Gamma_2} b_\mu^\dagger(R/2) \right] \sigma_- + \text{H.c.}\end{aligned}$$

Here $b_\mu(x), b_\mu^\dagger(x)$ are the position space field operators of phonons, the index μ distinguishes between the right $\mu = 1$ and left $\mu = 2$ moving fields, and $c_\mu = (-1)^{\mu-1}$. Note that we have made use of the common assumption of the mode dispersion being linear in the vicinity of the relevant energy scale $\sim \Omega$ and the bandwidth being infinite. Defining the Fourier transformation as

$$b_\mu(x) = \frac{1}{\sqrt{2\pi}} \int dk e^{ic_\mu kx} a_\mu(k),$$

we bring the Hamiltonian in to the forms (1) and (2):

$$\begin{aligned}\mathcal{H}_0 &= \Omega\sigma_+\sigma_- + v \sum_{\mu=1,2} \int dk k a_\mu^\dagger(k) a_\mu(k), \\ \mathcal{V} &= \sum_{\mu=1,2} \int dk g_\mu(k) a_\mu(k) \sigma_- + \text{H.c.} , \\ g_\mu(k) &= \sqrt{\frac{\Gamma_1}{2\pi}} e^{-ic_\mu kR/2} + \sqrt{\frac{\Gamma_2}{2\pi}} e^{ic_\mu kR/2}.\end{aligned}$$

In the following subsections we are going to study the scattering of a coherent pulse in the form of a wave packet centered around the frequency vk_0 (see Sec. III B), for that sake it is convenient to perform the following time-dependent gauge transformation:

$$\mathcal{U}(t) = \exp \left(-ivk_0 \left[\int dk a_\mu^\dagger(k) a_\mu(k) + \sigma_+\sigma_- \right] t \right)$$

The Hamiltonian transforms as $\mathcal{H} \rightarrow \tilde{\mathcal{H}} = \mathcal{U}^\dagger(t) \mathcal{H} \mathcal{U}(t) - i\mathcal{U}^\dagger(t) \frac{d\mathcal{U}(t)}{dt} =: \tilde{\mathcal{H}}_0 + \tilde{\mathcal{V}}$, resulting in final form of the Hamiltonian we are going to work with:

$$\begin{aligned}\tilde{\mathcal{H}}_0 &= -\Delta\sigma_+\sigma_- + v \sum_{\mu=1,2} \int dk k \tilde{a}_\mu^\dagger(k) \tilde{a}_\mu(k), \\ \tilde{\mathcal{V}} &= \sum_{\mu=1,2} \int dk \tilde{g}_\mu(k) \tilde{a}_\mu(k) \sigma_- + \text{H.c.} , \\ \tilde{g}_\mu(k) &= \sqrt{\frac{\Gamma_1}{2\pi}} e^{-ic_\mu(k+k_0)R/2} + \sqrt{\frac{\Gamma_2}{2\pi}} e^{ic_\mu(k+k_0)R/2}, \\ \tilde{a}_\mu(k) &= a_\mu(k+k_0), \quad \Delta = \omega_0 - \omega, \quad \omega_0 = vk_0.\end{aligned}$$

In the following we adopt the system of units such that $v = 1$, for simplicity we will also assume $\Gamma_1 = \Gamma_2 = \gamma/2$. Furthermore, we shall also drop the tilde symbols out of operators for notational convenience.

3.5.2 Problem formulation

Theory

In order to formulate the scattering problem, we define the following wave-packet operators:

$$A_\mu^\dagger = \int dk \varphi_L(k) a_\mu^\dagger(k)$$

where $\varphi_L(k) = \sqrt{\frac{2}{\pi L}} \frac{\sin(kL/2)}{k}$ is the Fourier transform of the rectangular pulse of length L , with the property $\varphi_L(k) \sim \sqrt{\frac{2\pi}{L}} \delta(k)$, $L \rightarrow \infty$ [obviously, it is possible to choose any other nascent δ function for $\varphi_L(k)$]. Note that since we are working in the frame of reference rotating with frequency k_0 , peaking of $\varphi_L(k)$ at $k = 0$ corresponds to a pulse centered at $k = k_0$ in the original one. Note that throughout this section we focus on the zero detuning setup $\Delta = 0$, i.e., the initial k_0 is chosen to be equal to Ω . The effect of nonzero detuning of atom from radiation is studied in Appendix D. Definition of these wave-packet operators is crucial since the eigenstates of the bare Hamiltonian \mathcal{H}_0 are not normalizable. Hence, in order to avoid the ascent of the undefinable quantities such as $\delta(0)$, $(\delta(0))^2, \dots$ coming from the elastic clusters of the S matrix in the calculation of the observables, one has to work with the normalizable states and take the plane-wave limit $L \rightarrow \infty$ at the very end. Having defined the Fock creation operators A_μ^\dagger , we can define the coherent state as a displaced vacuum

$$|\alpha\rangle_\mu = e^{-|\alpha|^2/2} e^{\alpha A_\mu^\dagger} |\Omega\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |\Phi_\mu^{(n)}\rangle$$

where $\alpha \in \mathbb{C}$ is the so-called coherence parameter, defined such that $|\alpha|^2$ is the average photon number (power), and the normalized n -particle Fock states $|\Phi_\mu^{(n)}\rangle$ were defined according to

$$|\Phi_\mu^{(n)}\rangle = \frac{1}{\sqrt{n!}} (A_\mu^\dagger)^n |\Omega\rangle$$

In what follows, we assume that $|\alpha| \ll 1$ in such a way that the terms of order $|\alpha|^4$ are negligible:

$$|\alpha\rangle_\mu \approx e^{-|\alpha|^2/2} \left(|\Omega\rangle + \frac{\alpha}{\sqrt{1!}} |\Phi_\mu^{(1)}\rangle + \frac{\alpha^2}{\sqrt{2!}} |\Phi_\mu^{(2)}\rangle + \frac{\alpha^3}{\sqrt{3!}} |\Phi_\mu^{(3)}\rangle + O(|\alpha|^4) \right) \equiv |\alpha\rangle_\mu^{(3)}.$$

The factor $e^{-|\alpha|^2/2}$ has to be retained until various overlaps of states are calculated to ensure the normalization of both the initial and final states as well as the power conservation [here the normalization is again assumed in the power perturbative regime, that is up to order $O(|\alpha|^8)$]. With this in hand, we formulate the scattering problem as follows. We assume that the initial state of the system is given by $|\psi_i\rangle = |\alpha\rangle_1^{(3)} \otimes |0\rangle$, that is, a leftwards-propagating weakly coherent pulse $|\alpha\rangle_1^{(3)}$ is incident on a two-level system which is initially in its ground state $|0\rangle$. According to the theory developed above, the final state of the systems has the following form:

$$|\psi_f\rangle = e^{-|\alpha|^2/2} \left(|\Omega\rangle + \frac{\alpha}{\sqrt{1!}} \mathcal{S}_1 |\Phi_1^{(1)}\rangle + \frac{\alpha^2}{\sqrt{2!}} \mathcal{S}_2 |\Phi_1^{(2)}\rangle + \frac{\alpha^3}{\sqrt{3!}} \mathcal{S}_3 |\Phi_1^{(3)}\rangle \right) \otimes |0\rangle$$

Inelastic contributions to the n -phonon S matrices (discussed in Sec. IID) introduce a nontrivial momentum redistribution of the incident phonons (note that owing to the linear dispersion relation and our choice of units energy and momentum may be used interchangeably), leading to the nontrivial phonon correlations in the final state. As it is well known, the phononic correlations may be conveniently examined with the help of the so-called coherence functions introduced by Glauber [83] in 1963. Defining the Fourier transform of the field operators according to

$$a_\mu(\tau) = \int dk \frac{e^{ik\tau}}{\sqrt{2\pi}} a(k)$$

one constructs the first-order coherence function as

$$\begin{aligned} C_\mu^{(1)}(\tau) &= \langle \psi_f | a_\mu^\dagger(\tau) a_\mu(0) | \psi_f \rangle \\ &= \left(1 - |\alpha|^2 + \frac{|\alpha|^4}{2} \right) |\alpha|^2 C_\mu^{(1,1)}(\tau) + (1 - |\alpha|^2) \frac{|\alpha|^4}{2} C_\mu^{(1,2)}(\tau) + \frac{|\alpha|^6}{6} C_\mu^{(1,3)}(\tau) + O(|\alpha|^8), \end{aligned}$$

where we have introduced the n -particle Fock state first-order correlation functions as

$$C_\mu^{(1,n)}(\tau) = \langle \Phi_1^{(n)} | (\mathcal{S}_n)^\dagger a_\mu^\dagger(\tau) a_\mu(0) \mathcal{S}_n | \Phi_1^{(n)} \rangle.$$

With the help of the first-order coherence function, one may define the spectral power density as the Fourier transform of (89):

$$S_\mu(k) = \int d\tau \frac{e^{-ik\tau}}{2\pi} C_\mu^{(1)}(\tau)$$

$S_\mu(k)$ is understood as a momentum-space distribution of power in the scattered state of radiation, that is to a given mode k (supported by the μ th channel) it associates a certain power $S_\mu(k)$. The power conservation condition

$$\sum_{\mu=1,2} \int dk S_\mu(k) \rightarrow \Phi, \quad \Phi = \frac{|\alpha|^2}{L}$$

is automatically satisfied due to the unitarity of the S matrix. In a linear system, where the n -body S matrix factorizes into the product of single-particle S matrices, the first-order coherence function is a constant, thus leading to the purely elastic power density $S_\mu(k) \propto \delta(k)$. Since a qubit is an intrinsically nonlinear system, we are going to see that the spectral power density admits for the following decomposition $S(k) = S^{\text{el}}(k) + S^{\text{inel}}(k)$, where $S^{\text{el}}(k) \propto \delta(k)$ is the elastic contribution to the spectral density, and $S^{\text{inel}}(k)$, in turn, is the inelastic part of spectral power density with a nontrivial momentum dependence.

Further, we define the normalized second- and third-order coherence functions:

$$\begin{aligned} C_{\mu,\mu'}^{(2)}(\tau) &= \frac{\langle \psi_f | a_\mu^\dagger(0) a_{\mu'}^\dagger(\tau) a_{\mu'}(\tau) a_\mu(0) | \psi_f \rangle}{C_\mu^{(1)}(0) C_{\mu'}^{(1)}(0)} = \\ &= \left(1 - \frac{|\alpha|^2}{2} \right) \frac{1}{2} C_{\mu,\mu'}^{(2,2)}(\tau) + \frac{|\alpha|^2}{6} C_{\mu,\mu'}^{(2,3)}(\tau) + O(|\alpha|^4), \\ C_{\mu,\mu',\mu''}^{(3)}(\tau, \tau') &= \frac{\langle \psi_f | a_\mu^\dagger(0) a_{\mu'}^\dagger(\tau) a_{\mu''}^\dagger(\tau') a_{\mu''}(\tau') a_{\mu'}(\tau) a_\mu(0) | \psi_f \rangle}{C_\mu^{(1)}(0) C_{\mu'}^{(1)}(0) C_{\mu''}^{(1)}(0)} = \\ &= \frac{1}{6} C_{\mu,\mu',\mu''}^{(3,3)}(\tau, \tau') + O(|\alpha|^2), \\ C_{\mu_1, \dots, \mu_m}^{(m,n)}(\tau_1, \dots, \tau_{m-1}) &= \frac{\langle \Phi_1^{(n)} | \mathcal{S}_n^\dagger a_{\mu_1}^\dagger(0) \dots a_{\mu_m}^\dagger(\tau_{m-1}) a_{\mu_m}(\tau_{m-1}) \dots a_{\mu_1}(0) \mathcal{S}_n | \Phi_1^{(n)} \rangle}{\prod_{l=1}^m C_{\mu_l}^{(1)}(0)}. \end{aligned}$$

For pairs of phonons, the normalized second-order coherence function is defined as the arrival probability of the second particle as a function of the delay τ following the detection of the first one, normalized by the individual photon probabilities. Likewise, for particle triples, the normalized third-order coherence function is defined as the arrival probability of the third

and second particle as a function of delays τ', τ following the detection of the first one, normalized by the individual phonon probabilities. A perfectly coherent source is characterized by a uniform arrival probability, yielding the correlation functions of all orders equal to unity. Whenever correlation functions exceed unity, particle statistics is said to be superPoissonian and the particles are said to be bunched together, whereas in the case of correlation functions falling below unity, the statistics of particles is said to be sub-Poissonian and particles are correspondingly said to be antibunched.

In the following subsections, we are going to use the ideas developed in Sec. II C in order to compute the abovediscussed observables to the lowest order in $|\alpha|$ exactly.

3.5.3 Spectral power density (???)

(???? я хз, что тут вообще происходит, это отдельно много учить еще нужно.)

Theory

Let us begin with the analysis of the power spectrum of the SAW scattered by the giant atom. We start by considering the Fock state first-order coherence functions defined via (90). In order to establish $C_\mu^{(1,1)}(\tau)$ one first has to find the matrix elements of the single-particle S matrix, which, in turn, demands the knowledge of the dressed propagator in the single-excitation subspace $G^{(1)}(\epsilon)$. The self-energy diagram may be evaluated straightforwardly to yield

$$\Sigma^{(1)}(\epsilon) = -i\gamma (1 + e^{i(\epsilon+k_0)R}) \sigma_+ \sigma_-,$$

in accordance with Ref. [59]. With this in hand, the singlephonon scattering operator may be easily established with the help of Eqs. (33), (37), and (38):

$$\begin{aligned} \mathcal{S}_1 &= \sum_{\mu', \mu} \int dk dk' S_{\mu'k', \mu k}^{(1)} a_{\mu'}^\dagger(k') a_\mu(k), \\ S_{\mu'k', \mu k}^{(1)} &= \delta(k - k') S_{\mu', \mu}^{(1)}(k) \sigma_- \sigma_+ \\ S_{\mu', \mu}^{(1)}(k) &= \left(\delta_{\mu, \mu'} - 2\pi i g_\mu^*(k) g_{\mu'}(k) \tilde{G}^{(1)}(k) \right) \end{aligned}$$

Here the tilde symbol denotes the projection onto the excited state in the qubit space, and $G^{(1)}(\epsilon) = G_0^{-1}(\epsilon) - \Sigma^{(1)}(\epsilon)$ in accordance with the definition in Sec. IIC. Performing a straightforward calculation, we obtain

$$\begin{aligned} C_\mu^{(1)}(\tau) &= |\alpha|^2 C_\mu^{(1,1)}(\tau) + O(|\alpha|^4) \\ &= \Phi \left| S_{\mu 0, 10}^{(1)} \right|^2 + O(\Phi^2) \\ \rightarrow S_\mu(k) &= \Phi \left| S_{\mu 0, 10}^{(1)} \right|^2 \delta(k) + O(\Phi^2). \end{aligned}$$

As we can see there exists no inelastic contribution to the spectral density in single-photon sector. In general the phenomenon of resonance fluorescence [84], leading to the inelastic power spectrum, is underpinned by the possibility of the two-level system to emit into the modes other than the incident one. This naturally allows the photons incident on the atom to exchange their energy between one another (while conserving the total energy) due to the higher-order emission and absorption processes, leading to the inelastic power spectrum. In the case of the single-photon, however, the particle ought to conserve its energy individually [as mathematically prescribed by the δ function in Eq. (98)] leading to the purely elastic spectrum.

In order to obtain the leading-order inelastic contribution to the spectral power density, we thus have to consider the contribution of the multiparticle states in the expansion (87), so that to allow for the interparticle interaction. In this case, the information about the inelastic scattering is entirely contained in the connected component of the two-phonon T matrix (see Sec. IID), which captures the nonlinear acoustic effects via the effective single-particle vertex

function. Contracting the cluster decomposed S matrix (45) with the two-particle Fock state we arrive at the following result:

$$\sum_{\mu,\mu'} \left(\frac{1}{\sqrt{2}} \int dk dk' \varphi(k) \varphi(k') S_{\mu,1}^{(1)}(k) S_{\mu',1}^{(1)}(k') a_{\mu}^{\dagger}(k) a_{\mu'}^{\dagger}(k') - \frac{8\pi^2 i}{L\sqrt{2}} \int dk T_{\mu k, \mu' -k, 10, 10}^{(2,C)}(0) a_{\mu}^{\dagger}(k) a_{\mu'}^{\dagger}(-k) \right) |\Omega\rangle \otimes |0\rangle$$

Again we would like to emphasize that at this point the planewave limit ($L \rightarrow \infty$) may only be taken in the term containing the connected component of the S matrix since in this limit the first part of the state (102) is clearly non-normalizable. With the help of the final two-particle state derived above one may easily establish

$$C_{\mu}^{(1,2)}(\tau) = 16\pi^2 \sum_{\mu'} \text{Im} \left\{ M_{\mu',\mu}(0) \left(S_{\mu',1}^{(1)}(0) S_{\mu,1}^{(1)}(0) \right)^* \right\} \\ + 32\pi^3 \sum_{\mu'} \int dk e^{ik\tau} |M_{\mu',\mu}(k)|^2,$$

where $M_{\mu',\mu}(k)$ is the symmetric part of $T_{\mu k, \mu' -k, 10, 10}^{(2,C)}(0)$, i.e., $M_{\mu',\mu}(k) = M_{\mu,\mu'}(-k) = \left[T_{\mu' k, \mu -k, 10, 10}^{(2,C)}(0) + T_{\mu -k, \mu' k, 10, 10}^{(2,C)}(0) \right] / 2$. Performing the Fourier transform of (103) we arrive at the following expressions for the elastic $S^{\text{el}}(k)$ and inelastic $S^{\text{inel}}(k)$ spectral power densities valid to order Φ^3 :

$$S_{\mu}^{\text{el}}(k) = \delta(k) \left(\Phi \left| S_{\mu,1}^{(1)}(0) \right|^2 + 16\pi^2 \Phi^2 \right. \\ \left. \cdot \sum_{\mu'} \text{Im} \left\{ M_{\mu',\mu}(0) \left(S_{\mu',1}^{(1)}(0) S_{\mu,1}^{(1)}(0) \right)^* \right\} \right), \\ S_{\mu}^{\text{inel}}(k) = 32\pi^3 \Phi^2 \sum_{\mu'} |M_{\mu',\mu}(k)|^2.$$

The inelastic spectral densities are shown in Fig. 7 for different interleg separations ($R = 1, 3, 5$). As one can see, the inelastic power spectrum develops a couple of sharp peaks near the origin of momentum space followed by infinitely many smaller side peaks. In order to interpret the nature of these peaks, we adopt the physical picture discussed in [21, 85, 86] for an "atom in front of a mirror" system. One can interpret this system as a leaky cavity formed by the two connection points of a giant atom. In this picture these peaks may be thought of as being located at the renormalized excitation frequencies of the effective cavity broadened by the renormalized decay rates. The resulting effect is the formation of sharp, bound-state-like peaks in the intensity of the scattered phonons, corresponding to cavity resonances. As the delay γR increases, the peaks get closer to $\omega = 0$, and get sharper, corresponding to a decrease of the effective cavity linewidth $\simeq 1/(\gamma R)$, that is effective cavity resonances approach the resonance of the two-level system, thus making atomic connection points better and better mirrors and hence increasing the quality factor of the effective cavity (quality factor is a common physical measure of both the rate of Inelastic spectral power density (scaled by Φ^2) of SAW scattered by a giant acoustic atom as a function of frequency $\omega = k$ for a variety of interleg separations $\gamma R = 1, 3, 5$).

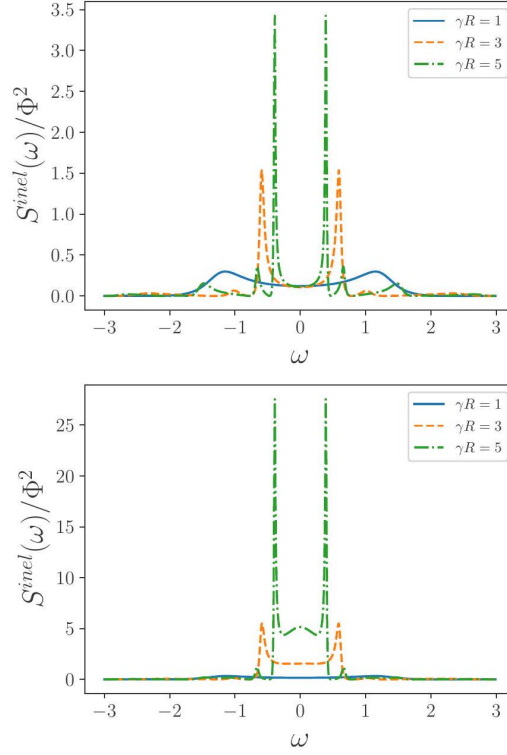


FIG. 7.

Top panel: Exact solution; bottom panel: Quasi-Markovian approximation. Other model parameters: $k_0 R = \pi/4 \bmod 2\pi$, and $\Delta = 0$. Here, the limit $L \rightarrow \infty$ was taken.

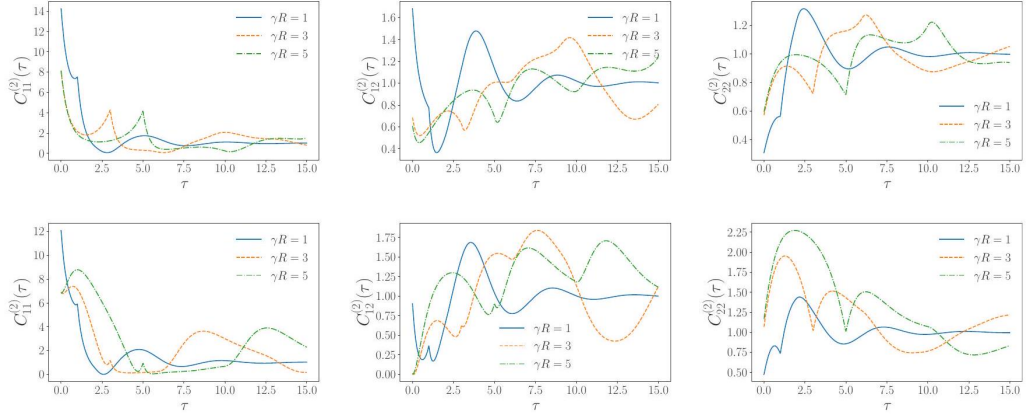


FIG. 8.

The figure demonstrates the independent components of the normalized second-order coherence function $C_{11}^{(2)}$, $C_{12}^{(2)}$, $C_{22}^{(2)}$ for various interleg separations $\gamma R = 1, 3, 5$. As before the top panel corresponds to an exact solution, the bottom one to its quasi-Markovian approximation, and $k_0 R = \pi/4 \bmod 2\pi$, $\Delta = 0$. Here the limit $L \rightarrow \infty$ was taken and by definition $C^{(2)}$ is dimensionless.

excitation damping and the rate of energy loss of an oscillator or a cavity)

Additionally, spectral densities based on the approximate solution of the scattering problem in the quasi-Markovian approximation are shown in Fig. 7. As it was mentioned in Sec. IIF, quasi-Markovian results show a good agreement with an exact solution in $\gamma R \ll 1$ parameter regime. As the delay time increases $\gamma R \geq 1$, the discrepancy between the approximate and complete solutions becomes dramatic. One can clearly see the tendency of the quasi-Markovian theory to enhance the scattering into the incoming frequency states $\omega = 0$. Indeed, in contrast to the exact solution, taking into account infinitely many excursions of phonons to the qubit, the quasi-Markovian approximation is based on the assumption of a single scattering event after which each phonon immediately leaves the system, thus leading to a more elastic result.

3.5.4 Second-order coherence

Theory

Let us now consider the second-order coherence function to the lowest order in $\Phi : O(\Phi^0)$. Performing the relevant Wick contractions we arrive at the following simple expression for the normalized second-order coherence:

$$C_{\mu',\mu}^{(2)}(\tau) = \left| 1 - \frac{4\pi i}{S_{\mu',1}^{(1)}(0)S_{\mu,1}^{(1)}(0)} \int dk e^{ik\tau} M_{\mu',\mu}(k) \right|^2.$$

The independent components of second-order coherence function's components are presented in Fig. 8.

As it was mentioned above, the higher-order coherence functions provide the information about the statistics of radiation scattered by a giant acoustic atom. Since $C_{1,1}^{(2)}(0) > 1$, one can clearly see that the statistics of back-scattered phonons is super-Poissonian, i.e., the particles tend to bunch together. Indeed, this result agrees with the physical expectation that at zero detuning $\Delta = 0$ the power extinction $1 - |S_{11}(0)|^2$ is enhanced even in the presence of pure dephasing [13, 87]. This assertion also explains the antibunching of forwardly scattered photons $C_{2,2}^{(2)}(0)$. Another clear feature of the second-order coherence function shown in Fig. 8 is presence of long-range quantum correlations of phonons, i.e., the components of $C^{(2)}$ do not decay to unity even for delays significantly exceeding the interleg separation $\tau \gg 1$. Note that this correlation effect becomes more and more pronounced with the increase in R , where correlation functions exhibit slightly damped oscillations around unity.

Another interesting feature of the second-order coherence is the presence of the nondifferentiable peaks at natural multiples of the interleg separation $\tau_n = nR, n \in \mathbb{N}$. Physically, this property may again be understood with the help of the simple picture of a leaky cavity formed by the scatterer. Indeed, once a phonon is trapped between the legs of the atom, it may bounce off the cavity's walls back and forth multiple times, leading to the formation of the nonanalytical structures present in the second-order coherence. The fact that the nondifferentiable peaks are more pronounced at smaller values of n is a direct manifestation of the fact that the quality factor of the effective cavity is not infinite. This property is indeed of interest since the second-order coherence function is an experimentally measurable quantity which makes these sharp peaks a potentially observable effect.

Alongside the exact solution, the results based on the quasi-Markovian approximation are presented in Fig. 8 (lower panel). The discrepancy between the two is apparent. Another feature typical of this approximation is the tendency to overestimate the amplitudes of oscillation as was first pointed out in the Supplemental Material of Ref. [71].

3.5.5 Third-order coherence

Theory

Let us finally consider the third-order coherence function. The full expression for the third-order coherence function $C_{\mu,\mu',\mu''}^{(3)}(\tau, \tau')$ in terms of the symmetrized components of two- and three-particle transition matrices may be found in Appendix B. Although in general, $C_{\mu,\mu',\mu''}^{(3)}$ has eight

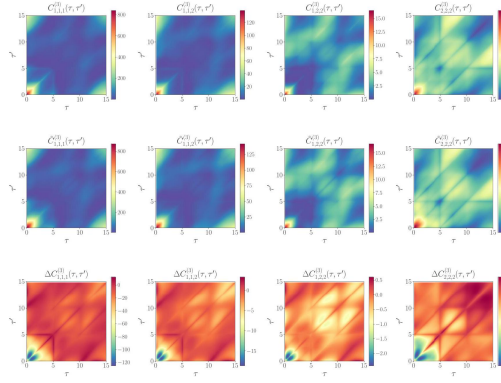


FIG. 9. Independent components $(\mu, \mu', \mu'') = (1, 1, 1), (1, 1, 2), (1, 2, 2), (2, 2, 2)$ of the third-order coherence function of phonons scattered by a giant acoustic atom. Top, central, and bottom panels correspond to the exact solution $C_{\mu, \mu', \mu''}^{(3)}(\tau, \tau')$, weak correlation approximation $\tilde{C}_{\mu, \mu', \mu''}^{(3)}(\tau, \tau')$, and their difference $\Delta C_{\mu, \mu', \mu''}^{(3)}(\tau, \tau') = C_{\mu, \mu', \mu''}^{(3)}(\tau, \tau') - \tilde{C}_{\mu, \mu', \mu''}^{(3)}(\tau, \tau')$, respectively. Here $\gamma R = 5$, $k_0 R = \pi/4 \bmod 2\pi$, and $\Delta = 0$. Here the limit $L \rightarrow \infty$ was taken and by definition $C^{(2)}$ is dimensionless.

independent components in the case of two radiation channels, due to our particular choice of the coupling $\Gamma_1 = \Gamma_2 = \gamma/2$, only four independent components remain:

$$\begin{aligned} & C_{1,1,1}^{(3)}(\tau, \tau'), \quad C_{2,2,2}^{(3)}(\tau, \tau'), \\ & C_{1,1,2}^{(3)}(\tau, \tau') = C_{1,2,1}^{(3)}(\tau, \tau') = C_{2,1,1}^{(3)}(\tau, \tau'), \\ & C_{1,2,2}^{(3)}(\tau, \tau') = C_{2,2,1}^{(3)}(\tau, \tau') = C_{2,1,2}^{(3)}(\tau, \tau'). \end{aligned}$$

Independent components of $C^{(3)}$ for a system with $R = 5$, $k_0 R = \pi/4 \bmod 2\pi$, and $\Delta = 0$ are shown in the top panel of Fig. 9. First, we note that the individual components of third-order coherence at $\tau, \tau' = 0$ significantly exceed unity, signifying the bunching of phonons. This effect can be attributed to the fact that a single two-level system can only emit and absorb a single quantum of radiation at a time, which, in turn, significantly increases the probability of simultaneous detection of a pair of phonons in the waveguide. Moreover, this effect is more pronounced in those components of the correlation function, describing correlations with phonons in the channel of incident radiation $\mu = 1$. This artifact again has to do with the fact of the enhancement of power extinction by an atom at zero detuning.

Another interesting feature of $C^{(3)}$ to be noticed is the presence of clear peak and downfall structures located on the lines $\tau' - \tau = nR, n \in \mathbb{Z}$. Physically, $\delta\tau = \tau' - \tau$ corresponds to the average delay time between the second and third phonon detection events upon detection of the first one at zero time. The quantization of $\delta\tau$ in the units of deterministic time delay is the characteristic feature of the system under consideration and may be potentially observed in future experiments via the observation of enhancement or diminution of the conditional probability of arrival of the third particle. In fact, the peak and downfall structures discussed above are nondifferentiable, as it was the case with the second-order coherence function, and again this phenomenon may be understood with the help of a simple picture of an effective cavity discussed in Secs. IIIC1 and III C.

Aside from the exact solution $C_{\mu, \mu', \mu''}^{(3)}(\tau, \tau')$, the solution based on the weak-correlation (WC) approximation $\tilde{C}_{\mu, \mu', \mu''}^{(3)}(\tau, \tau')$ as well as the difference between the exact solution and the WC one

$$\Delta C_{\mu, \mu', \mu''}^{(3)} = C_{\mu, \mu', \mu''}^{(3)} - \tilde{C}_{\mu, \mu', \mu''}^{(3)}$$

are shown in Fig. 9 in central and bottom panels, respectively. As one can anticipate, the WC approximation tends to notably overestimate the amplitude of the third-order coherence function. This effect is especially apparent in the vicinity of $\tau, \tau' = 0$, where the WC approximation significantly overestimates the phononic bunching. Away from the temporal origin, though, the approximation becomes adequate and only slightly deviates from the exact result, as one may infer from the plots in the bottom panel of Fig. 9. The discrepancy between the exact solution and its WC approximation is not hard to understand. Weak-correlation approximation

ignores an infinite diagrammatic channel, consisting of exchange interaction diagrams between the phonons, which are, of course, of importance when one studies the statistical properties of particles.

3.5.6 Effect of the non-zero detuning

In this Appendix we analyze the effect on nonzero detuning of the atom from radiation on the observable quantities. In particular, we focus on the spectral power density and the second-order coherence function. As it was discussed in Sec. III C, the sharp bound-state-like peaks in the line shape of spectral density may be understood with a simple physical picture of an effective cavity. When one increases (or decreases) the detuning from zero value, one effectively changes the modes supported by the cavity and thus one expects the position of the peaks to be shifted. The precise location of the resonances in the spectral density as function of Δ and k for various values of $k_0 R$ is shown in Fig. 10. As we can see, for nonzero dephasing $k_0 R \neq 0$, the spectrum is not a symmetric function of Δ . For negative dephasing we find that emission into the zero modes is enhanced for a negatively detuned atom $\Delta < 0$, whereas the picture is opposite for pos-

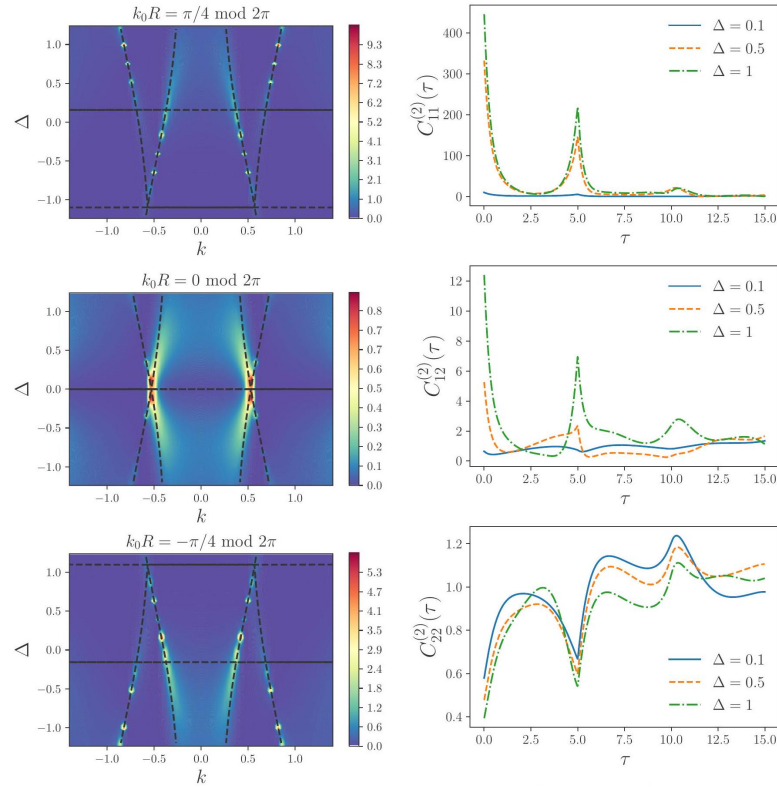


FIG. 10. Spectral power density (scaled by $1/\Phi^2$) for the giant atom model as a function of Δ, k for various values of $k_0 R$ and $\gamma R = 5$. Here the dashed black lines indicate the pole position of the dressed Green's function in the single-excitation subspace.

itive $k_0 R$. In general, we can clearly resolve a pair of sharp peaks which eventually merge together at certain values of parameters (e.g., $k_0 R = \Delta = 0$). It is interesting to note that the location of these peaks is almost entirely determined by the poles of the dressed propagator in the single-excitation subspace $(G^{(1)}(k))^{-1} = k + \Delta + i\gamma(1 + e^{i(k+k_0)R}) = 0$. This

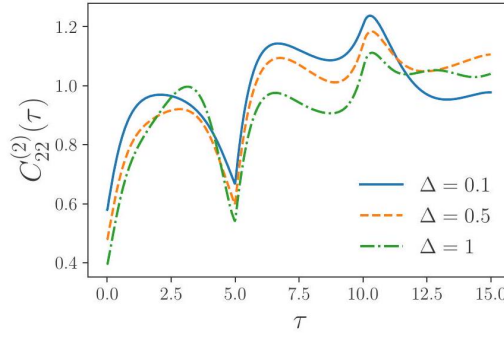


FIG. 11. Second-order coherence function for the system with $k_0 R = 3\pi/11$, $\gamma R = 5$, $\Delta = 0.1, 0.5, 1.0$ (as before, the second-order coherence function is dimensionless).
equation is solved by

$$k = \pm i \frac{R\gamma - iR\Delta - W_n(-\gamma R e^{i(k_0 - \Delta - i\gamma)R})}{R}$$

where $W_n(z)$ is the n th branch of the Lambert W function, also known as the product logarithm. The real part of (D1) with $n = 0, \pm 1$ is plotted as black dashed lines in Fig. 10. The vertical lines in Fig. 10 represent the discontinuous jumps of the Lambert function across the branch cut. As one may

3.5.7 Appendix on 3-order coherence function

The formula for the third-order coherence function of phonons in the giant atom model is obtained as follows. Using the formula (A28) with $\omega(k) = k$ along with the notations introduced in Sec. III, we obtain the following result upon contraction with the three-phonon Fock state:

$$\mathcal{S}_3 |\Phi_1^{(3)}\rangle = \frac{1}{\sqrt{6}} \sum_{\{\mu'_i\}} (A - B - C),$$

where only here:

$$\begin{aligned} A &:= \int_{k_1 k_2 k_3} \varphi(k_1) \varphi(k_2) \varphi(k_3) S_{\mu'_1,1}^{(1)}(k_1) S_{\mu'_2,1}^{(1)}(k_2) S_{\mu'_3,1}^{(1)}(k_3) a_{\mu'_1}^\dagger(k_1) a_{\mu'_2}^\dagger(k_2) a_{\mu'_3}^\dagger(k_3) |\Omega\rangle, \\ B &:= -12\pi i \int_{k'_1 k'_2 k'_3} \varphi(k_1) \varphi(k_2) \varphi(k_3) T_{\mu'_1 k'_1, \mu'_2 k'_2, \mu'_3 k'_3}^{(2,C)}(k_1 + k_2) \delta(k'_1 + k'_2 - k_1 - k_2) \cdot S_{\mu'_3,1}^{(1)}(k_3) a_{\mu'_1}^\dagger(k'_1) a_{\mu'_2}^\dagger(k'_2) a_{\mu'_3}^\dagger(k'_3) |\Omega\rangle; \\ C &:= -12\pi i \left(\frac{2\pi}{L}\right)^{3/2} \int_{k'_1 k'_2 k'_3} Q(k'_1, k'_2, k'_3) \delta(k'_1 + k'_2 + k'_3) a_{\mu'_1}^\dagger(k'_1) a_{\mu'_2}^\dagger(k'_2) a_{\mu'_3}^\dagger(k'_3) |\Omega\rangle. \end{aligned}$$

and here we have introduced the following symmetrized version of the connected three-phonon transition operator:

$$\begin{aligned} Q(k'_1, k'_2, k'_3) &:= \frac{1}{6} \left[T_{\mu'_1 k'_1, \mu'_2 k'_2, \mu'_3 k'_3}^{(3,C)}(0) T_{\mu'_1 k'_1, \mu'_3 k'_3, \mu'_2 k'_2}^{(3)}(0) + T_{\mu'_3 k'_3, \mu'_2 k'_2, \mu'_1 k'_1}^{(3,C)}(0) \right. \\ &\quad \left. + T_{\mu'_3 k'_3, \mu'_1 k'_1, \mu'_2 k'_2}^{(3,C)}(0) T_{\mu'_2 k'_2, \mu'_1 k'_1, \mu'_3 k'_3}^{(3,C)}(0) + T_{\mu'_2 k'_2, \mu'_3 k'_3, \mu'_1 k'_1}^{(3,C)}(0) \right]. \end{aligned}$$

Here we have suppressed the dependence of $Q(k'_1, k'_2, k'_3)$ on $\{\mu'\}$ since in the giant atom model the coupling constants are independent of the channel index.

Now we consider

$$a_{\mu''}(\tau_3) a_{\mu'}(\tau_2) a_{\mu}(\tau_1) \mathcal{S}_3 |\Phi_1^{(3)}\rangle = \frac{\sqrt{6}}{L^{3/2}} S_{\mu'',1}^{(1)}(0) S_{\mu',1}^{(1)}(0) S_{\mu,1}^{(1)}(0) (1 - A - B)$$

$$A := 4\pi i \left[\frac{I_{\mu'',\mu'}^{(1)}(\tau_3 - \tau_2)}{S_{\mu'',1}^{(1)}(0) S_{\mu',1}^{(1)}(0)} + \frac{I_{\mu,\mu'}^{(1)}(\tau_2 - \tau_1)}{S_{\mu,1}^{(1)}(0) S_{\mu',1}^{(1)}(0)} + \frac{I_{\mu'',\mu}^{(1)}(\tau_3 - \tau_1)}{S_{\mu'',1}^{(1)}(0) S_{\mu,1}^{(1)}(0)} \right]; \quad B := 12\pi i \frac{I^{(2)}(\tau_3 - \tau_1, \tau_2 - \tau_1)}{S_{\mu'',1}^{(1)}(0) S_{\mu',1}^{(1)}(0) S_{\mu,1}^{(1)}(0)}.$$

where the following functions were defined:

$$\begin{aligned} I_{\mu',\mu}^{(1)}(t_1) &= \int_k e^{ikt_1} M_{\mu',\mu}(k), \\ I^{(2)}(t_2, t_1) &= \int_{k,q} e^{iqt_2} e^{ikt_1} Q(-k - q, k, q), \end{aligned}$$

where $M_{\mu,\mu'}(k) = [T_{\mu',\mu-k,10,10}^{(2,C)}(0) + T_{\mu-k,\mu',10,10}^{(2,C)}(0)]/2$, as before. By introducing the following variables $\tau' = \tau_3 - \tau_1$, $\tau = \tau_2 - \tau_1$, we can immediately write the normalized third-order coherence function to the lowest order in φ as

$$C_{\mu'',\mu',\mu}^{(3)}(t',t) = |1 - A - B|^2,$$

where only here

$$A := 4\pi i \left[\frac{I_{\mu'',\mu'}^{(1)}(t'-t)}{S_{\mu'',1}^{(1)}(0)S_{\mu',1}^{(1)}(0)} + \frac{I_{\mu,\mu'}^{(1)}(t)}{S_{\mu,1}^{(1)}(0)S_{\mu',1}^{(1)}(0)} + \frac{I_{\mu'',\mu}^{(1)}(t')}{S_{\mu'',1}^{(1)}(0)S_{\mu,1}^{(1)}(0)} \right]; \quad B := 12\pi i \frac{I^{(2)}(t',t)}{S_{\mu'',1}^{(1)}(0)S_{\mu',1}^{(1)}(0)S_{\mu,1}^{(1)}(0)}.$$

3.6 Giant Acoustic Atom Model

Let's consider the non-Markovian scattering setup: A giant acoustic atom, extensively studied theoretically and experimentally in [19, 59, 60, 78 – 81] (see also [82] for a detailed review).
(???? добавлю из этих статей теорию про это! мб там многое полезного!)
(из выше теории соберу про это сюда суть. выше - фокус на методы, тут - на эту модель.)

3.7 Real-Time Dynamics in Waveguide QED: Theory and Practice

(по магистерской Кирилла. по идее именно это мне и нужно для статьи, да что ли?)

3.7.1 Introduction and Generalities

3.7.2 Resummation of the Perturbation Series for the Propagator in $Q = 1$ Waveguide QED

3.7.3 5.3 General Dynamics in Single Excitation Subspace

3.7.4 5.4 Spontaneous Emission of a Giant Acoustic Atom

3.7.5 5.5 Dynamics of Single Excitation States in the System of Two Distant Qubits

3.7.6 5.6 Spontaneous Emission of a Qubit Into an Array of Coupled Resonators

5.6.1 Infinite Single Band System

5.6.2 Semi-Infinite Single Band System

3.8 Typical Phenomena of Waveguide QED

(мб потом вставляю выше, пока не занимался ими, так что поставил сюда, чтобы не отвлекаться)

3.8.1 Эффект Парселла

мотивация

некоторые люди изучают его вот.

обзор

(вики)

Эффект Парселла - в квантовой электродинамике увеличение скорости испускания осциллятора в резонаторе по сравнению со скоростью спонтанного излучения в свободное пространство.

Скорость испускания осциллятора в резонаторе умножается на коэффициент Парселла:

$$F_p = \frac{3}{4\pi^2} \left(\frac{\lambda_c}{n} \right)^3 \frac{Q}{V}$$

где $\frac{\lambda_c}{n}$ — длина волны в среде резонатора, Q — его добротность, V — модовый объём. Квантовый эмиттер (атом, ион, квантовая точка и т. д.), помещённый в добротный резонатор малого объёма, меняет направленность и скорость спонтанного излучения.

Эффект зависит от плотности мод в резонаторе. Это свойство используется для эффективного согласования излучения квантовых эмиттеров с приёмниками излучения (оптическое волокно, волноводы и т. д.)

Пример изменения коэффициента Парселла можно найти в работе Акимова и др., где показано, что излучение квантовой точки, размещённой вблизи серебряной нанопроволочки почти полностью «засасывается» проволочкой[2].

Статья Парселла, в которой был впервые введён этот коэффициент, является одной из самых коротких (один абзац) и одновременно активно цитируемой в современной физике. По данным ISI Web of Knowledge на 2011 год статья цитировалась почти 1700 раз.

модель

пока не актуально, потом мб буду разбирать.

3.8.2 О других известных явлениях (???)

(пока хз. по квантовой оптике нужно подготовиться.)

3.9 Scattering of massless particles in 1D chiral channel by Pleteukhov

(мб потом вставлю выше, пока не занимался ими, так что поставил сюда, чтобы не отвлекаться)

3.9.1 General solution

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4 Examples and Problems

4.1 Single-excitation subspace, Markovian systems

(!?!?! казалось бы, можно было бы многое решить, в том числе через формализм PP21, а я и не решал, и даже пока задачи придумать не готов.)

4.1.1 Qubit emission

For a single qubit we have

$$v_{\mu,k} = \sqrt{\frac{\Gamma_1}{2\pi}} |g\rangle \langle e|, \quad (4.1)$$

such that

$$\Sigma(z) = \Gamma_1 |e\rangle \langle e| \sum_{\mu} \int \frac{dk}{2\pi} \frac{1}{z-k} = -i\Gamma_1 |e\rangle \langle e|. \quad (4.2)$$

Such that

$$|\psi(t)\rangle = \oint_{C_{\eta}} \frac{dz}{2\pi i} \frac{e^{-izt}}{z - \Delta + i\Gamma_1} |e\rangle |\Omega\rangle \quad (4.3)$$

$$+ \sqrt{\frac{\Gamma_1}{2\pi}} \sum_{\mu=\pm} \oint_{C_{\eta}} \frac{dz}{2\pi i} \frac{1}{z-k} \frac{e^{-izt}}{z - \Delta + i\Gamma_1} a_{\mu,k}^{\dagger} |g\rangle |\Omega\rangle \quad (4.4)$$

$$= e^{-i\Delta t} e^{-\Gamma_1 t} |e\rangle |\Omega\rangle + \sqrt{\frac{\Gamma_1}{2\pi}} \sum_{\mu=\pm} \frac{e^{-ikt} - e^{-i\Delta t} e^{-\Gamma_1 t}}{k - \Delta + i\Gamma_1} a_{\mu,k}^{\dagger} |g\rangle |\Omega\rangle \quad (4.5)$$

it follows that

$$P_e(t) = e^{-2\Gamma t}, \quad P_g(t) = 1 - e^{-2\Gamma t}. \quad (4.6)$$

(ТУТ УСЛОВИЕ)

Wave functions for $N = 2$ emission case

We assume that the entire system is prepared in the following initial state

$$|\psi_0\rangle = |1\rangle \otimes |\Omega_{\text{phot.}}\rangle,$$

where $|1\rangle$ is the excited state of the qubit and $|\Omega_{\text{phot.}}\rangle$ is the vacuum state of photons. The state of the system at later times $t > 0$ is given by

$$|\psi(t)\rangle = \psi^{(1)}(t) |1\rangle \otimes |\Omega_{\text{phot.}}\rangle + \sum_{\mu=\pm} \int dk \psi_{\mu}^{(0)}(t, k) a_{\mu,k}^{\dagger} |0\rangle \otimes |\Omega_{\text{phot.}}\rangle,$$

where

$$\begin{aligned} \psi^{(1)}(t) &= \oint_{C_{\eta}} \frac{dz}{2\pi i} \langle 1 | G(z) | 1 \rangle e^{-izt}, \\ \psi_{\mu}^{(0)}(t, k) &= \oint_{C_{\eta}} \frac{dz}{2\pi i} \langle 0 | G(z - \omega_{\mu,k}) v_{\mu,k} G(z) | 1 \rangle e^{-izt}. \end{aligned}$$

Here C_{η} is a contour such that it is a counterclockwise semi-circle running $i\eta$ above the real axis (from $\infty + i\eta$ to $-\infty + i\eta$) and closing in the lower-half of the complex plane.

Problem of $N = 2$ emission statement

a) Calculate the wave functions, and measure the following hermitian operator $P_1 = |1\rangle\langle 1|$ (a projector on the excited state), i.e. the probability to find the system in the excited state at time t :

$$\langle \psi(t) | P_1 | \psi(t) \rangle = \left| \psi^{(1)}(t) \right|^2 = ?$$

b) Measure also the photon number operator

$$\mathcal{N} := \sum_{\mu=\pm} \int dk a_{\mu,k}^\dagger a_{\mu,k}$$

to show that

$$\langle \psi(t) | \mathcal{N} | \psi(t) \rangle = \sum_{\mu=\pm} \int dk \left| \psi_\mu^{(0)}(t, k) \right|^2 = 1 - \left| \psi^{(1)}(t) \right|^2.$$

This is a manifestation of the unitarity of quantum theory (all probabilities add to one).

c) Consider now the second moment of the number operator

$$\langle \psi(t) | \mathcal{N}^2 | \psi(t) \rangle - ?$$

d) Does the photon number fluctuate? That is:

$$\langle \psi(t) | \mathcal{N}^2 | \psi(t) \rangle - \langle \psi(t) | \mathcal{N} | \psi(t) \rangle^2 \neq 0?$$

e) Calculate the momentum space probability distribution of photons at time $t > 0$

$$P_\mu(k, t) = \langle \psi(t) | a_{\mu,k}^\dagger a_{\mu,k} | \psi(t) \rangle = \left| \psi_\mu^{(0)}(t, k) \right|^2,$$

what does it approach at times $t \gg 1/\Gamma_1$?

Probability of system in the excited state

Using $G(z) = \sum_{n=1}^{N-1} \frac{|n\rangle\langle n|}{z - \epsilon_n + i\Gamma_n} + \frac{|0\rangle\langle 0|}{z - \epsilon_0}$, we have

$$\langle \psi(t) | P_1 | \psi(t) \rangle = \left| \psi^{(1)}(t) \right|^2 = \left| \oint_{C_\eta} \frac{dz}{2\pi i} \frac{e^{-izt}}{z - \epsilon_n + i\Gamma_n} \right|^2 \stackrel{\text{res}}{=} \left| e^{-it(\epsilon_1 - i\Gamma_1)} \right|^2 = e^{-2\Gamma_1 t}$$

Photon number

$$\langle \psi(t) | \mathcal{N} | \psi(t) \rangle =$$

$$\begin{aligned} & \left(\langle 1 | \otimes \langle \Omega_{\text{phot.}} | \psi^{(1)*}(t) + \langle 0 | \otimes \langle \Omega_{\text{phot.}} | \sum_{\mu=\pm} \int dk \psi_\mu^{(0)*}(t, k) a_{\mu,k} \right) \cdot \\ & \cdot \left(\sum_{\mu=\pm} \int dk a_{\mu,k}^\dagger a_{\mu,k} \right) \cdot \\ & \cdot \left(\psi^{(1)}(t) | 1 \rangle \otimes | \Omega_{\text{phot.}} \rangle + \sum_{\mu=\pm} \int dk \psi_\mu^{(0)}(t, k) a_{\mu,k}^\dagger | 0 \rangle \otimes | \Omega_{\text{phot.}} \rangle \right) = \\ & = \\ & = \langle 0 | \otimes \langle \Omega_{\text{phot.}} | \sum_{\mu_1, \mu_2, \mu_3=\pm} \int dk_1 dk_2 dk_3 \psi_{\mu_1}^{(0)*}(t, k_1) \psi_{\mu_2}^{(0)}(t, k_2) a_{\mu_3, k_3}^\dagger a_{\mu_1, k_1} a_{\mu_2, k_2} a_{\mu_3, k_3}^\dagger | 0 \rangle \otimes | \Omega_{\text{phot.}} \rangle \end{aligned}$$

Тут красное уходит потому что справа у нас вакуум $|\Omega_{\text{phot.}}\rangle$, так что после действия оператора уничтожения в центре у нас получается ноль. Слева красное уходит, потому что справа у нас только состояние с невозбужденной двухуровневой системой. Во всех суммах индекс μ должен быть одинаков, то есть или только (+) одновременно, или только (-) одновременно, потому что иначе левый оператор

уничтожения будет уничтожать вакуум и будет ноль. По этой же причине только при одном и том же k для трех интегралов все не нулевое, поэтому остается один интеграл.

Нере (пакуль тут індексы толькі 1 і 2, але верныя папросту потым можна расставіць.)

$$\begin{aligned}
& a_{\mu,k} a_{\mu,k}^\dagger a_{\mu,k} a_{\mu,k}^\dagger = \\
& = (a_{\mu,k}^\dagger a_{\mu,k} + \delta_{\mu,\mu'} \delta(k_1 - k_2)) (a_{\mu,k}^\dagger a_{\mu,k} + \delta_{\mu,\mu'} \delta(k_1 - k_2)) = \\
& = \delta_{\mu,\mu'} \delta(k_1 - k_2) \delta_{\mu,\mu'} \delta(k_1 - k_2) + \delta_{\mu,\mu'} \delta(k_1 - k_2) a_{\mu,k}^\dagger a_{\mu,k} + \delta_{\mu,\mu'} \delta(k_1 - k_2) a_{\mu,k}^\dagger a_{\mu,k} + a_{\mu,k}^\dagger a_{\mu,k} a_{\mu,k}^\dagger a_{\mu,k} = \\
& = \delta_{\mu,\mu'} \delta(k_1 - k_2) \cdot \delta_{\mu,\mu'} \delta(k_1 - k_2) + a_{\mu,k}^\dagger (\delta_{\mu,\mu'} \delta(k_1 - k_2) + a_{\mu,k}^\dagger a_{\mu,k}) a_{\mu,k} = \\
& = \delta_{\mu,\mu'} \delta(k_1 - k_2) \cdot \delta_{\mu,\mu'} \delta(k_1 - k_2)
\end{aligned}$$

$$\begin{aligned}
& \langle \psi(t) | \mathcal{N} | \psi(t) \rangle = \\
& = \langle 0 | \otimes \langle \Omega_{\text{phot.}} | \sum_{\mu_1, \mu_2, \mu_3 = \pm} \int dk_1 dk_2 dk_3 \psi_{\mu}^{(0)*}(t, k) \psi_{\mu}^{(0)}(t, k) \delta_{\mu_1, \mu_2} \delta(k_1 - k_2) \cdot \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) | 0 \rangle \otimes | \Omega_{\text{phot.}} \rangle = \\
& = \sum_{\mu = \pm} \int dk \left| \psi_{\mu}^{(0)}(t, k) \right|^2
\end{aligned}$$

Left side for N

We set $\omega_{\mu,k} = k, c \equiv 1$. From another side,

$$\begin{aligned}
\psi_{\mu}^{(0)}(t, k) &= \oint_{C_{\eta}} \frac{dz}{2\pi i} \langle 0 | G(z - \omega_{\mu,k}) v_{\mu,k} G(z) | 1 \rangle e^{-izt} \stackrel{\text{diag. rules}}{=} \\
&= \oint_{C_{\eta}} \frac{dz}{2\pi i} \left\langle 0 \left| \left(\sum_{n=1}^{N-1} \frac{|n\rangle \langle n|}{z - k - \epsilon_n + i\Gamma_n} + \frac{|0\rangle \langle 0|}{z - k - \epsilon_0} \right) \left(\sqrt{\frac{\Gamma}{2\pi}} |0\rangle \langle 1| \right) \left(\sum_{n=1}^{N-1} \frac{|n\rangle \langle n|}{z - \epsilon_n + i\Gamma_n} + \frac{|0\rangle \langle 0|}{z - \epsilon_0} \right) \right| 1 \right\rangle e^{-izt} = \\
&= \sqrt{\frac{\Gamma}{2\pi}} \oint_{C_{\eta}} \frac{dz}{2\pi i} \frac{e^{-izt}}{(z - k - \epsilon_0)(z - \epsilon_1 + i\Gamma)} \stackrel{\text{close count.}}{=} \text{down, res} \\
&= \sqrt{\frac{\Gamma}{2\pi}} \cdot \left(\frac{e^{-i(k+\epsilon_0)t}}{k + \epsilon_0 - \epsilon_1 + i\Gamma} + \frac{e^{-i(\epsilon_1 - i\Gamma)t}}{\epsilon_1 - i\Gamma - k - \epsilon_0} \right) \\
&= \sqrt{\frac{\Gamma}{2\pi}} \cdot \frac{e^{-ikt - i\epsilon_0 t} - e^{-i\epsilon_1 t - \Gamma t}}{k + \epsilon_0 - \epsilon_1 + i\Gamma} = \\
&= \sqrt{\frac{\Gamma}{2\pi}} e^{-i\epsilon_0 t} \cdot \frac{e^{-ikt} - e^{-i\Delta \cdot t - \Gamma t}}{k - \Delta + i\Gamma}
\end{aligned}$$

Here $\Gamma_1 \equiv \Gamma, \Delta \equiv \epsilon_1 - \epsilon_0$.

Then for $t > 0$

$$\begin{aligned}
\int dk \left| \psi_{\mu}^{(0)}(t, k) \right|^2 &= \frac{\Gamma}{2\pi} \int dk \frac{(e^{ikt} - e^{i\Delta \cdot t - \Gamma t})(e^{-ikt} - e^{-i\Delta \cdot t - \Gamma t})}{(k - \Delta + i\Gamma)(k - \Delta - i\Gamma)} = \\
&= \frac{\Gamma}{2\pi} \int dk \left(\frac{1 - e^{-2\Gamma t}}{(k - \Delta + i\Gamma)(k - \Delta - i\Gamma)} - \frac{e^{-ikt} e^{i\Delta \cdot t - \Gamma t}}{(k - \Delta + i\Gamma)(k - \Delta - i\Gamma)} - \frac{e^{ikt} e^{-i\Delta \cdot t - \Gamma t}}{(k - \Delta + i\Gamma)(k - \Delta - i\Gamma)} \right) = \\
&= \frac{\Gamma}{2\pi} \frac{2\pi i (1 + e^{-2\Gamma t})}{2i\Gamma} - \frac{\Gamma}{2\pi} \frac{(-1)2\pi i e^{-i(\Delta - i\Gamma)t} e^{-i\Delta \cdot t - \Gamma t}}{(-1)2i\Gamma} - \frac{\Gamma}{2\pi} \frac{2\pi i e^{i(\Delta + i\Gamma)t} e^{-i\Delta \cdot t - \Gamma t}}{2i\Gamma} = \\
&= \frac{1 + e^{-2\Gamma t}}{2} - \frac{e^{-2\Gamma t}}{2} - \frac{e^{-2\Gamma t}}{2} = \frac{1 - e^{-2\Gamma t}}{2}
\end{aligned}$$

Here first contour could be closed up or down, second we should close down, third - up.

$$\sum_{\mu = \pm} \int dk \left| \psi_{\mu}^{(0)}(t, k) \right|^2 = 1 - e^{-2\Gamma t}$$

Right side for N

From another side

$$\begin{aligned}\psi^{(1)}(t) &= \oint_{C_\eta} \frac{dz}{2\pi i} \langle 1 | \left(\sum_{n=1}^{N-1} \frac{|n\rangle\langle n|}{z - \epsilon_n + i\Gamma_n} + \frac{|0\rangle\langle 0|}{z - \epsilon_0} \right) | 1 \rangle e^{-izt} = \\ &= \oint_{C_\eta} \frac{dz}{2\pi i} \frac{1}{z - \epsilon_1 + i\Gamma} e^{-izt} = \\ &= e^{-i(\epsilon_1 - i\Gamma)t} = e^{-i\epsilon_1 t - \Gamma t}\end{aligned}$$

And

$$\left| \psi^{(1)}(t) \right|^2 = \psi^{(1)*}(t) \psi^{(1)}(t) = e^{-2\Gamma t}$$

We see that left-side equals to the right side, thus

$$\langle \psi(t) | \mathcal{N} | \psi(t) \rangle = \sum_{\mu=\pm} \int dk \left| \psi_\mu^{(0)}(t, k) \right|^2 = 1 - \left| \psi^{(1)}(t) \right|^2.$$

Expression for N^2 and squared dispersion of photos

$$\begin{aligned}\langle \psi(t) | \mathcal{N}^2 | \psi(t) \rangle &= \left(\langle 1 | \otimes \langle \Omega_{\text{phot.}} | \psi^{(1)*}(t) + \langle 0 | \otimes \langle \Omega_{\text{phot.}} | \sum_{\mu_1=\pm} \int dk_1 \psi_{\mu_1}^{(0)*}(t, k_1) a_{\mu_1, k_1} \right) \cdot \\ &\quad \cdot \left(\sum_{\mu_2=\pm} \int dk_2 a_{\mu_2, k_2}^\dagger a_{\mu_2, k_2} \right) \left(\sum_{\mu_3=\pm} \int dk_3 a_{\mu_3, k_3}^\dagger a_{\mu_3, k_3} \right) \cdot \\ &\quad \cdot \left(\psi^{(1)}(t) | 1 \rangle \otimes | \Omega_{\text{phot.}} \rangle + \sum_{\mu_4=\pm} \int dk_4 \psi_{\mu_4}^{(0)}(t, k_4) a_{\mu_4, k_4}^\dagger | 0 \rangle \otimes | \Omega_{\text{phot.}} \rangle \right) = \\ &= \langle 0 | \otimes \langle \Omega_{\text{phot.}} | \sum_{\mu_1, \mu_2, \mu_3, \mu_4=\pm} \int dk_1 \dots dk_4 \psi_{\mu_1}^{(0)*}(t, k_1) \psi_{\mu_2}^{(0)}(t, k_2) a_{\mu_1, k_1} a_{\mu_2, k_2}^\dagger a_{\mu_3, k_3}^\dagger a_{\mu_3, k_3} a_{\mu_4, k_4}^\dagger | 0 \rangle \otimes | \Omega_{\text{phot.}} \rangle\end{aligned}$$

Тут

$$\begin{aligned}a_{\mu_1, k_1} a_{\mu_2, k_2}^\dagger a_{\mu_2, k_2} a_{\mu_3, k_3}^\dagger a_{\mu_3, k_3} a_{\mu_4, k_4}^\dagger &= \\ &= (a_{\mu_2, k_2}^\dagger a_{\mu_1, k_1} + \delta_{\mu_1, \mu_2} \delta(k_1 - k_2)) (a_{\mu_3, k_3}^\dagger a_{\mu_2, k_2} + \delta_{\mu_2, \mu_3} \delta(k_2 - k_3)) (a_{\mu_4, k_4}^\dagger a_{\mu_3, k_3} + \delta_{\mu_3, \mu_4} \delta(k_3 - k_4)) = \\ &= \left(a_{\mu_2, k_2}^\dagger a_{\mu_1, k_1} a_{\mu_3, k_3}^\dagger a_{\mu_2, k_2} + a_{\mu_2, k_2}^\dagger a_{\mu_1, k_1} \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) + a_{\mu_3, k_3}^\dagger a_{\mu_2, k_2} \delta_{\mu_1, \mu_2} \delta(k_1 - k_2) + \right. \\ &\quad \left. + \delta_{\mu_1, \mu_2} \delta(k_1 - k_2) \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) \right) (a_{\mu_4, k_4}^\dagger a_{\mu_3, k_3} + \delta_{\mu_3, \mu_4} \delta(k_3 - k_4)) = \\ &= a_{\mu_2, k_2}^\dagger a_{\mu_1, k_1} a_{\mu_3, k_3}^\dagger a_{\mu_2, k_2} a_{\mu_4, k_4}^\dagger a_{\mu_3, k_3} + a_{\mu_2, k_2}^\dagger a_{\mu_1, k_1} a_{\mu_4, k_4}^\dagger a_{\mu_3, k_3} \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) + \\ &\quad + a_{\mu_3, k_3}^\dagger a_{\mu_2, k_2} a_{\mu_4, k_4}^\dagger a_{\mu_3, k_3} \delta_{\mu_1, \mu_2} \delta(k_1 - k_2) + a_{\mu_4, k_4}^\dagger a_{\mu_3, k_3} \delta_{\mu_1, \mu_2} \delta(k_1 - k_2) \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) + \\ &\quad + a_{\mu_2, k_2}^\dagger a_{\mu_1, k_1} a_{\mu_3, k_3}^\dagger a_{\mu_2, k_2} \delta_{\mu_3, \mu_4} \delta(k_3 - k_4) + a_{\mu_2, k_2}^\dagger a_{\mu_1, k_1} \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) \delta_{\mu_3, \mu_4} \delta(k_3 - k_4) + \\ &\quad + a_{\mu_3, k_3}^\dagger a_{\mu_2, k_2} \delta_{\mu_1, \mu_2} \delta(k_1 - k_2) \delta_{\mu_3, \mu_4} \delta(k_3 - k_4) + \delta_{\mu_1, \mu_2} \delta(k_1 - k_2) \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) \delta_{\mu_3, \mu_4} \delta(k_3 - k_4) = \\ &= \delta_{\mu_1, \mu_2} \delta(k_1 - k_2) \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) \delta_{\mu_3, \mu_4} \delta(k_3 - k_4),\end{aligned}$$

потому что у нас в других слагаемых (кроме оставшегося) справа уже стоит a - оператор уничтожения, так что каждое из этих слагаемых после действия на вакуум даст нуль.

В итоге

$$\langle \psi(t) | \mathcal{N}^2 | \psi(t) \rangle = \langle 0 | \otimes \langle \Omega_{\text{phot.}} | \sum_{\mu=\pm} \int dk \psi_\mu^{(0)*}(t, k) \psi_\mu^{(0)}(t, k) | 0 \rangle \otimes | \Omega_{\text{phot.}} \rangle$$

$$\langle \psi(t) | \mathcal{N}^2 | \psi(t) \rangle = \langle \psi(t) | \mathcal{N} | \psi(t) \rangle$$

Momentum space probability

$$\begin{aligned}
 P_\mu(k, t) &= \left\langle \psi(t) \left| a_{\mu,k}^\dagger a_{\mu,k} \right| \psi(t) \right\rangle = \left| \psi_\mu^{(0)}(t, k) \right|^2 = \frac{\Gamma}{2\pi} \frac{e^{-ikt} - e^{-i\Delta \cdot t - \Gamma t}}{k - \Delta + i\Gamma} \frac{e^{ikt} - e^{i\Delta \cdot t - \Gamma t}}{k - \Delta - i\Gamma} = \\
 &= \frac{\Gamma}{2\pi} \frac{1 - e^{-ikt} e^{i\Delta \cdot t - \Gamma t} - e^{-ikt} e^{-i\Delta \cdot t - \Gamma t} + e^{-2\Gamma t}}{(k - \Delta)^2 + \Gamma^2} = \\
 &= \frac{\Gamma}{2\pi} \frac{1 + e^{-2\Gamma t} - 2 \cos((k - \Delta)t) e^{-\Gamma t}}{(k - \Delta)^2 + \Gamma^2} =
 \end{aligned}$$

(я тут построил графики, но не уверен в них, потому что нужно примерно реальные величины Γ и др. брать.)
 При $\Gamma t \gg 1$ экспонента мелкая, так что

$$P_\mu(k, t) \approx \frac{\Gamma}{2\pi} \frac{1}{(k - \Delta)^2 + \Gamma^2}.$$

4.1.2 Problems for $N = 3$ emission

Problem statement

We assume that the entire system is prepared in the following initial state

$$|\psi_0\rangle = |2\rangle \otimes |\Omega\rangle,$$

where $|2\rangle$ is the second excited state of the atom. The state of the system at later times $t > 0$ is given by

$$|\psi(t)\rangle = \psi^{(2)}(t)|2\rangle \otimes |\Omega\rangle + \sum_{\mu=\pm} \int dk dk' \psi_\mu^{(1)}(t, k) a_{\mu,k}^\dagger |1\rangle \otimes |\Omega\rangle + \sum_{\mu, \mu'=\pm} \int dk dk' \psi_{\mu, \mu'}^{(0)}(t, k, k') a_{\mu,k}^\dagger a_{\mu',k'}^\dagger |0\rangle \otimes |\Omega\rangle,$$

where

$$\begin{aligned}
 \psi^{(2)}(t) &= \oint_{C_\eta} \frac{dz}{2\pi i} \langle 2 | G(z) | 2 \rangle e^{-izt}, \\
 \psi_\mu^{(1)}(t, k) &= \oint_{C_\eta} \frac{dz}{2\pi i} \langle 1 | G(z - \omega_{\mu,k}) v_{\mu,k} G(z) | 2 \rangle e^{-izt}, \\
 \psi_{\mu, \mu'}^{(0)}(t, k, k') &= \oint_{C_\eta} \frac{dz}{2\pi i} \langle 0 | G(z - \omega_{\mu,k} - \omega_{\mu',k'}) v_{\mu',k'} G(z - \omega_{\mu,k}) v_{\mu,k} G(z) | 2 \rangle e^{-izt},
 \end{aligned}$$

Here C_η is the contour that is a counterclockwise semi-circle running $i\eta$ above the real axis (from $\infty + i\eta$ to $-\infty + i\eta$) and closing in the lower-half of the complex plane.

- Calculate the wave functions, and measure the following hermitian operators $P_n = |n\rangle\langle n|$, $n = 0, 1, 2$.
- Measure the photon number operator

$$\mathcal{N} = \sum_{\mu=\pm} \int dk a_{\mu,k}^\dagger a_{\mu,k},$$

- Consider the second moment of the number operator

$$\langle \psi(t) | \mathcal{N}^2 | \psi(t) \rangle - ?$$

Does the photon number fluctuate in this case?

- Determine the spectrum of the photons

$$P_\mu(k, t) = \left\langle \psi(t) \left| a_{\mu,k}^\dagger a_{\mu,k} \right| \psi(t) \right\rangle,$$

what does it approach at times $t \gg 1/\min\{\Gamma_1, \Gamma_2\}$? As $t \gg 1/\min\{\Gamma_1, \Gamma_2\}$, show that the system finds itself in an entangled two-photon state.

Photon number

$$\begin{aligned}
& \langle \psi(t) | \mathcal{N} | \psi(t) \rangle = \\
& \left(\psi^{(2)*}(t) | 2 \rangle \otimes | \Omega \rangle + \sum_{\mu_1=\pm} \int dk_1 \psi_{\mu_1}^{(1)*}(t, k_1) a_{\mu_1, k_1} \langle 1 | \otimes \langle \Omega | + \sum_{\mu_2, \mu'_2=\pm} \int dk_2 dk'_2 \psi_{\mu_2, \mu'_2}^{(0)*}(t, k_2, k'_2) a_{\mu_2, k_2} a_{\mu'_2, k'_2} \langle 0 | \otimes \langle \Omega | \right) \cdot \\
& \cdot \left(\sum_{\mu_3=\pm} \int dk_3 a_{\mu_3, k_3}^\dagger a_{\mu_3, k_3} \right) \cdot \\
& \cdot \left(\psi^{(2)}(t) | 2 \rangle \otimes | \Omega \rangle + \sum_{\mu_4=\pm} \int dk_4 \psi_{\mu_4}^{(1)}(t, k_4) a_{\mu_4, k_4}^\dagger | 1 \rangle \otimes | \Omega \rangle + \sum_{\mu_5, \mu'_5=\pm} \int dk_5 dk'_5 \psi_{\mu_5, \mu'_5}^{(0)}(t, k_5, k'_5) a_{\mu_5, k_5}^\dagger a_{\mu'_5, k'_5}^\dagger | 0 \rangle \otimes | \Omega \rangle \right).
\end{aligned}$$

The same way as before,

$$\begin{aligned}
\langle \psi(t) | \mathcal{N} | \psi(t) \rangle &= \sum_{\mu_i=\pm} \int d^4 k \psi_{\mu_1}^{(1)*}(t, k) \psi_{\mu_4}^{(1)}(t, k) a_{\mu_1, k_1} a_{\mu_3, k_3}^\dagger a_{\mu_3, k_3} a_{\mu_4, k_4}^\dagger + \\
&+ \sum_{\mu_j=\pm} \int d^6 k \psi_{\mu_2, \mu'_2}^{(0)*}(t, k_2, k'_2) \psi_{\mu_5, \mu'_5}^{(0)}(t, k_5, k'_5) a_{\mu_2, k_2} a_{\mu'_2, k'_2} a_{\mu_3, k_3}^\dagger a_{\mu_3, k_3} a_{\mu_5, k_5}^\dagger a_{\mu'_5, k'_5}^\dagger
\end{aligned}$$

Тут i пробегает такие-то значения, j пробегает такие-то значения, а dk это сокращение от всех k .

Тут первый член - абсолютно то же, что и для двух фотонов, поэтому

$$\sum_{\mu_i=\pm} \int d^4 k \psi_{\mu_1}^{(1)*}(t, k) \psi_{\mu_4}^{(1)}(t, k) a_{\mu_1, k_1} a_{\mu_3, k_3}^\dagger a_{\mu_3, k_3} a_{\mu_4, k_4}^\dagger = \sum_{\mu=\pm} \int dk \left| \psi_{\mu}^{(1)}(t, k) \right|^2$$

Во втором члене имеем следующее. Ниже я сразу буду опускать все, что зануляется.

$$\begin{aligned}
& a_{\mu_2, k_2} a_{\mu'_2, k'_2} a_{\mu_3, k_3}^\dagger a_{\mu_3, k_3} a_{\mu_5, k_5}^\dagger a_{\mu'_5, k'_5}^\dagger = a_{\mu_2, k_2} a_{\mu'_2, k'_2} a_{\mu_3, k_3}^\dagger (a_{\mu_5, k_5}^\dagger a_{\mu_3, k_3} + \delta_{\mu_3, \mu_5} \delta(k_3 - k_5)) a_{\mu'_5, k'_5}^\dagger = \\
&= a_{\mu_2, k_2} a_{\mu'_2, k'_2} a_{\mu_3, k_3}^\dagger a_{\mu_5, k_5}^\dagger a_{\mu_3, k_3} a_{\mu'_5, k'_5}^\dagger + \delta_{\mu_3, \mu_5} \delta(k_3 - k_5) a_{\mu_2, k_2} a_{\mu'_2, k'_2} a_{\mu_3, k_3}^\dagger a_{\mu'_5, k'_5}^\dagger = \\
&= a_{\mu_2, k_2} a_{\mu'_2, k'_2} a_{\mu_3, k_3}^\dagger a_{\mu_5, k_5}^\dagger (a_{\mu'_5, k'_5}^\dagger a_{\mu_3, k_3} + \delta_{\mu_3, \mu'_5} \delta(k_3 - k'_5)) + \\
&\quad + \delta_{\mu_3, \mu'_5} \delta(k_3 - k'_5) a_{\mu_2, k_2} (a_{\mu_3, k_3}^\dagger a_{\mu'_2, k'_2} + \delta_{\mu_3, \mu'_2} \delta(k_3 - k'_2)) a_{\mu'_5, k'_5}^\dagger = \\
&= \delta_{\mu_3, \mu'_5} \delta(k_3 - k'_5) a_{\mu_2, k_2} (a_{\mu_3, k_3}^\dagger a_{\mu'_2, k'_2} + \delta_{\mu_3, \mu'_2} \delta(k_3 - k'_2)) a_{\mu'_5, k'_5}^\dagger + \\
&\quad + \delta_{\mu_3, \mu_5} \delta(k_3 - k_5) a_{\mu_2, k_2} a_{\mu'_2, k'_2} a_{\mu'_5, k'_5}^\dagger + \delta_{\mu_3, \mu_5} \delta(k_3 - k_5) \delta_{\mu_3, \mu'_2} \delta(k_3 - k'_2) a_{\mu_2, k_2} a_{\mu'_5, k'_5}^\dagger = \\
&= \delta_{\mu_3, \mu'_5} \delta(k_3 - k'_5) a_{\mu_2, k_2} a_{\mu_3, k_3}^\dagger a_{\mu'_2, k'_2} a_{\mu'_5, k'_5}^\dagger + \delta_{\mu_3, \mu'_5} \delta(k_3 - k'_5) \delta_{\mu_3, \mu'_2} \delta(k_3 - k'_2) a_{\mu_2, k_2} a_{\mu'_5, k'_5}^\dagger + \\
&\quad + \delta_{\mu_3, \mu_5} \delta(k_3 - k_5) \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) \delta_{\mu'_2, \mu'_5} \delta(k'_2 - k'_5) + \\
&\quad + \delta_{\mu_3, \mu_5} \delta(k_3 - k_5) \delta_{\mu_3, \mu'_2} \delta(k_3 - k'_2) (a_{\mu'_5, k'_5}^\dagger a_{\mu_2, k_2} + \delta_{\mu_2, \mu'_5} \delta(k_2 - k'_5)) = \\
&= \delta_{\mu_3, \mu'_5} \delta(k_3 - k'_5) a_{\mu_2, k_2} a_{\mu_3, k_3}^\dagger (a_{\mu'_2, k'_2} a_{\mu'_5, k'_5}^\dagger + \delta_{\mu_5, \mu'_2} \delta(k_5 - k'_2)) + \\
&\quad + \delta_{\mu_3, \mu'_5} \delta(k_3 - k'_5) \delta_{\mu_3, \mu'_2} \delta(k_3 - k'_2) (a_{\mu'_5, k'_5}^\dagger a_{\mu_2, k_2} + \delta_{\mu_5, \mu_2} \delta(k_5 - k_2)) + \\
&\quad + \delta_{\mu_3, \mu_5} \delta(k_3 - k_5) \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) \delta_{\mu'_2, \mu'_5} \delta(k'_2 - k'_5) + \delta_{\mu_3, \mu_5} \delta(k_3 - k_5) \delta_{\mu_3, \mu'_2} \delta(k_3 - k'_2) \delta_{\mu_2, \mu'_5} \delta(k_2 - k'_5) = \\
&= \delta_{\mu_3, \mu'_5} \delta(k_3 - k'_5) \delta_{\mu_5, \mu'_2} \delta(k_5 - k'_2) \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) + \\
&\quad + \delta_{\mu_3, \mu'_5} \delta(k_3 - k'_5) \delta_{\mu_3, \mu'_2} \delta(k_3 - k'_2) \delta_{\mu_5, \mu_2} \delta(k_5 - k_2) + \\
&\quad + \delta_{\mu_3, \mu_5} \delta(k_3 - k_5) \delta_{\mu_2, \mu_3} \delta(k_2 - k_3) \delta_{\mu'_2, \mu'_5} \delta(k'_2 - k'_5) + \\
&\quad + \delta_{\mu_3, \mu_5} \delta(k_3 - k_5) \delta_{\mu_3, \mu'_2} \delta(k_3 - k'_2) \delta_{\mu_2, \mu'_5} \delta(k_2 - k'_5)
\end{aligned}$$

То есть тут у нас есть 5 индексов, и в каждой комбинации дельт у нас 3 каждых равны между собой, а оставшиеся 2 равны между собой, но не равны трем другим.

Thus the second term is

$$\begin{aligned}
& \sum_{\mu_j=\pm} \int d^6 k \psi_{\mu_2, \mu'_2}^{(0)*}(t, k_2, k'_2) \psi_{\mu_5, \mu'_5}^{(0)}(t, k_5, k'_5) a_{\mu_2, k_2} a_{\mu'_2, k'_2}^\dagger a_{\mu_3, k_3} a_{\mu_3, k_3}^\dagger a_{\mu_5, k_5} a_{\mu'_5, k'_5}^\dagger = \\
& = \sum_{\mu_3, \mu_5=\pm} \int dk_3 dk_5 \psi_{\mu_3, \mu_5}^{(0)*}(t, k_3, k_5) \psi_{\mu_5, \mu_3}^{(0)}(t, k_5, k_3) + \\
& + \sum_{\mu_3, \mu_2=\pm} \int dk_3 dk_2 \psi_{\mu_2, \mu_3}^{(0)*}(t, k_2, k_3) \psi_{\mu_2, \mu_3}^{(0)}(t, k_2, k_3) + \\
& + \sum_{\mu_3, \mu_2=\pm} \int dk_3 dk_2 \psi_{\mu_2, \mu_3}^{(0)*}(t, k_2, k_3) \psi_{\mu_3, \mu_2}^{(0)}(t, k_3, k_2) + \\
& + \sum_{\mu_3, \mu'_5=\pm} \int dk_3 dk'_5 \psi_{\mu_3, \mu'_5}^{(0)*}(t, k_3, k'_5) \psi_{\mu_3, \mu'_5}^{(0)}(t, k_3, k'_5).
\end{aligned}$$

Теперь сменим обозначения:

$$\begin{aligned}
& \sum_{\mu_j=\pm} \int d^6 k \psi_{\mu_2, \mu'_2}^{(0)*}(t, k_2, k'_2) \psi_{\mu_5, \mu'_5}^{(0)}(t, k_5, k'_5) a_{\mu_2, k_2} a_{\mu'_2, k'_2}^\dagger a_{\mu_3, k_3} a_{\mu_3, k_3}^\dagger a_{\mu_5, k_5} a_{\mu'_5, k'_5}^\dagger = \\
& = \sum_{\mu_1, \mu_2=\pm} \int dk_1 dk_2 \psi_{\mu_1, \mu_2}^{(0)*}(t, k_1, k_2) \psi_{\mu_2, \mu_1}^{(0)}(t, k_2, k_1) + \\
& + \sum_{\mu_1, \mu_2=\pm} \int dk_1 dk_2 \psi_{\mu_2, \mu_1}^{(0)*}(t, k_2, k_1) \psi_{\mu_2, \mu_1}^{(0)}(t, k_2, k_1) + \\
& + \sum_{\mu_1, \mu_2=\pm} \int dk_1 dk_2 \psi_{\mu_2, \mu_1}^{(0)*}(t, k_2, k_1) \psi_{\mu_1, \mu_2}^{(0)}(t, k_1, k_2) + \\
& + \sum_{\mu_1, \mu_2=\pm} \int dk_1 dk'_2 \psi_{\mu_1, \mu_2}^{(0)*}(t, k_1, k_2) \psi_{\mu_1, \mu_2}^{(0)}(t, k_1, k_2) \\
& = \\
& 4 \sum_{\mu_1, \mu_2=\pm} \int dk_1 dk'_2 \psi_{\mu_1, \mu_2}^{(0)*}(t, k_1, k_2) \psi_{\mu_1, \mu_2}^{(0)}(t, k_1, k_2).
\end{aligned}$$

В итоге:

$$\begin{aligned}
& \langle \psi(t) | \mathcal{N} | \psi(t) \rangle = \\
& = \sum_{\mu=\pm} \int dk \left| \psi_{\mu}^{(1)}(t, k) \right|^2 + \\
& + \sum_{\mu_1, \mu_2=\pm} \int dk_1 dk_2 \psi_{\mu_1, \mu_2}^{(0)*}(t, k_1, k_2) \psi_{\mu_2, \mu_1}^{(0)}(t, k_2, k_1) + \\
& + \sum_{\mu_1, \mu_2=\pm} \int dk_1 dk_2 \psi_{\mu_2, \mu_1}^{(0)*}(t, k_2, k_1) \psi_{\mu_2, \mu_1}^{(0)}(t, k_2, k_1) + \\
& + \sum_{\mu_1, \mu_2=\pm} \int dk_1 dk_2 \psi_{\mu_2, \mu_1}^{(0)*}(t, k_2, k_1) \psi_{\mu_1, \mu_2}^{(0)}(t, k_1, k_2) + \\
& + \sum_{\mu_1, \mu_2=\pm} \int dk_1 dk_2 \psi_{\mu_1, \mu_2}^{(0)*}(t, k_1, k'_2) \psi_{\mu_1, \mu_2}^{(0)}(t, k_1, k_2).
\end{aligned}$$

Photon number's second moment

Spectrum of photons

4.1.3 Λ -system

We have

$$v_{\mu, k} = \sqrt{\frac{\Gamma_1}{2\pi}} |g_1\rangle \langle e| + \sqrt{\frac{\Gamma_2}{2\pi}} |g_2\rangle \langle e|, \quad (4.7)$$

with the energies $\epsilon_{0,1} = -\Delta_1$ and $\epsilon_{0,2} = -\Delta_2$ we find

$$\Sigma(z) = |e\rangle \langle e| \frac{\Gamma_1}{2\pi} \sum_{\mu} \int dk \frac{1}{z + \Delta_1 - k} + |e\rangle \langle e| \frac{\Gamma_2}{2\pi} \sum_{\mu} \int dk \frac{1}{z + \Delta_2 - k} \quad (4.8)$$

$$= -i(\Gamma_1 + \Gamma_2) |e\rangle \langle e|. \quad (4.9)$$

The state at times $t > 0$ is given by

$$|\psi(t)\rangle = \oint_{C_{\eta}} \frac{dz}{2\pi i} \frac{e^{-izt}}{z + i(\Gamma_1 + \Gamma_2)} |e\rangle |\Omega\rangle \quad (4.10)$$

$$+ \sqrt{\frac{\Gamma_2}{2\pi}} \oint_{C_{\eta}} \frac{dz}{2\pi i} \frac{1}{z - k + \Delta_2} \frac{e^{-izt}}{z + i(\Gamma_1 + \Gamma_2)} a_{\mu,k}^{\dagger} |g_2\rangle |\Omega\rangle \quad (4.11)$$

$$+ \sqrt{\frac{\Gamma_1}{2\pi}} \oint_{C_{\eta}} \frac{dz}{2\pi i} \frac{1}{z - k + \Delta_1} \frac{e^{-izt}}{z + i(\Gamma_1 + \Gamma_2)} a_{\mu,k}^{\dagger} |g_1\rangle |\Omega\rangle \quad (4.12)$$

$$= e^{-(\Gamma_1 + \Gamma_2)t} |e\rangle |\Omega\rangle \quad (4.13)$$

$$+ \sqrt{\frac{\Gamma_1}{2\pi}} \frac{(e^{-i(k-\Delta_1)t} - e^{-(\Gamma_1 + \Gamma_2)t})}{k - \Delta_1 + i(\Gamma_1 + \Gamma_2)} a_{\mu,k}^{\dagger} |g_1\rangle |\Omega\rangle \quad (4.14)$$

$$+ \sqrt{\frac{\Gamma_2}{2\pi}} \frac{(e^{-i(k-\Delta_2)t} - e^{-(\Gamma_1 + \Gamma_2)t})}{k - \Delta_2 + i(\Gamma_1 + \Gamma_2)} a_{\mu,k}^{\dagger} |g_2\rangle |\Omega\rangle. \quad (4.15)$$

It follows that

$$P_e(t) = e^{-2(\Gamma_1 + \Gamma_2)t}, \quad (4.16)$$

$$P_{g_1}(t) = (1 - e^{-2(\Gamma_1 + \Gamma_2)t}) \frac{\Gamma_1}{\Gamma_1 + \Gamma_2}, \quad P_{g_2}(t) = (1 - e^{-2(\Gamma_1 + \Gamma_2)t}) \frac{\Gamma_2}{\Gamma_1 + \Gamma_2}. \quad (4.17)$$

The reduced density matrix of the system is given by

$$\rho_{\Lambda}(t) = P_e(t) |e\rangle \langle e| + P_{g_1}(t) |g_1\rangle \langle g_1| + P_{g_2}(t) |g_2\rangle \langle g_2| \quad (4.18)$$

$$+ f(t) |g_1\rangle \langle g_2| + f^*(t) |g_2\rangle \langle g_1|, \quad (4.19)$$

where

$$f(t) = \sum_{\mu=\pm} \int dk \psi_{\mu,k}^{g_1}(t) \psi_{\mu,k}^{g_2\dagger}(t) = 2i\sqrt{\Gamma_1\Gamma_2} \frac{(e^{i(\Delta_1 - \Delta_2)t} - e^{-2(\Gamma_1 + \Gamma_2)t})}{\Delta_2 - \Delta_1 + 2i(\Gamma_1 + \Gamma_2)} \quad (4.20)$$

The eigenvalues of the reduced density matrix are

$$\lambda_e(t) = P_e(t), \quad \lambda_{g,\pm}(t) = \frac{1}{2} (P_{g_1}(t) + P_{g_2}(t)) \pm \frac{1}{2} \sqrt{(P_{g_1}(t) - P_{g_2}(t))^2 + 4|f(t)|^2}, \quad (4.21)$$

yielding the following expression for the entropy

$$S = - \sum_{\lambda} \lambda(t) \log(\lambda(t)). \quad (4.22)$$

For a symmetric Λ -system $\Delta_1 = \Delta_2$ we find that

$$\lambda_{g,+}(t) = (1 - e^{-2(\Gamma_1 + \Gamma_2)t}), \quad \lambda_{g,-}(t) = 0. \quad (4.23)$$

4.1.4 V-system

We consider $v_s = \sqrt{\frac{\Gamma_1}{2\pi}} |g\rangle \langle e_1| + \sqrt{\frac{\Gamma_2}{2\pi}} |g\rangle \langle e_2|$, with $\epsilon_0 = 0$ and $\epsilon_{1,1} = \Delta_1$, $\epsilon_{1,2} = \Delta_2$. One has

$$\begin{aligned} \Sigma^{(1)} &= -i \left(\sqrt{\Gamma_1} |e_1\rangle + \sqrt{\Gamma_2} |e_2\rangle \right) \left(\sqrt{\Gamma_1} \langle e_1| + \sqrt{\Gamma_2} \langle e_2| \right) \\ &= -i \begin{pmatrix} \Gamma_1 & \sqrt{\Gamma_1\Gamma_2} \\ \sqrt{\Gamma_1\Gamma_2} & \Gamma_2 \end{pmatrix}. \end{aligned} \quad (4.24)$$

With this in our hands, we find

$$[G^{(1)}(z)]^{-1} = \begin{pmatrix} z - \Delta_1 + i\Gamma_1 & i\sqrt{\Gamma_1\Gamma_2} \\ i\sqrt{\Gamma_1\Gamma_2} & z - \Delta_2 + i\Gamma_2 \end{pmatrix}, \quad (4.25)$$

or

$$G^{(1)}(z) = \frac{1}{(z - \Delta_1 + i\Gamma_1)(z - \Delta_2 + i\Gamma_2) + \Gamma_1\Gamma_2} \begin{pmatrix} z - \Delta_2 + i\Gamma_2 & -i\sqrt{\Gamma_1\Gamma_2} \\ -i\sqrt{\Gamma_1\Gamma_2} & z - \Delta_1 + i\Gamma_1 \end{pmatrix} \quad (4.26)$$

$$= \frac{(z - \Delta_2 + i\Gamma_2)|e_1\rangle\langle e_1| + (z - \Delta_1 + i\Gamma_1)|e_2\rangle\langle e_2|}{(z - \Delta_1 + i\Gamma_1)(z - \Delta_2 + i\Gamma_2) + \Gamma_1\Gamma_2} \quad (4.27)$$

$$- i\sqrt{\Gamma_1\Gamma_2} \frac{|e_1\rangle\langle e_2| + |e_2\rangle\langle e_1|}{(z - \Delta_1 + i\Gamma_1)(z - \Delta_2 + i\Gamma_2) + \Gamma_1\Gamma_2}. \quad (4.28)$$

The pole equation

$$(z - \Delta_1 + i\Gamma_1)(z - \Delta_2 + i\Gamma_2) + \Gamma_1\Gamma_2 = 0 \quad (4.29)$$

admits for the following solutions

$$z_{\pm} = \frac{1}{2} \left[(\Delta_1 + \Delta_2 - i\Gamma_1 - i\Gamma_2) \pm \sqrt{(\Delta_1 + \Delta_2 - i\Gamma_1 - i\Gamma_2)^2 - 4((\Delta_1 - i\Gamma_1)(\Delta_2 - i\Gamma_2) + \Gamma_1\Gamma_2)} \right]. \quad (4.30)$$

We note that in the symmetric situation $\Delta_1 = \Delta_2 = \Delta$ the system admits for and atom-photon bound state, since

$$z_+ = \Delta, \quad z_- = \Delta - i(\Gamma_1 + \Gamma_2). \quad (4.31)$$

We suppose that the initial state of the system is given by

$$|\psi_0\rangle = \cos\vartheta |e_1\rangle + e^{i\varphi/2} \sin\vartheta |e_2\rangle. \quad (4.32)$$

The state of the system at later times

$$|\psi(t)\rangle = \psi_{e_1}(t) |e_1\rangle |\Omega\rangle + \psi_{e_2}(t) |e_2\rangle |\Omega\rangle + \sum_{\mu=\pm} \int dk \psi_{\mu,k}^g(t) a_{\mu,k}^\dagger |g\rangle |\Omega\rangle, \quad (4.33)$$

where

$$\psi_{e_1}(t) = \oint_{C_\eta} \frac{dz}{2\pi i} e^{-izt} \frac{(z - \Delta_2 + i\Gamma_2) \cos\vartheta}{(z - z_+)(z - z_-)} - \oint_{C_\eta} \frac{dz}{2\pi i} e^{-izt} \frac{ie^{i\varphi/2} \sin\vartheta \sqrt{\Gamma_1\Gamma_2}}{(z - z_+)(z - z_-)} \quad (4.34)$$

$$= ((z_+ - \Delta_2 + i\Gamma_2)e^{-iz_+t} - (z_- - \Delta_2 + i\Gamma_2)e^{-iz_-t}) \frac{\cos\vartheta}{(z_+ - z_-)} \quad (4.35)$$

$$- (e^{-iz_+t} - e^{-iz_-t}) \frac{ie^{i\varphi/2} \sin\vartheta \sqrt{\Gamma_1\Gamma_2}}{(z_+ - z_-)}, \quad (4.36)$$

$$\psi_{e_2}(t) = \oint_{C_\eta} \frac{dz}{2\pi i} e^{-izt} \frac{(z - \Delta_1 + i\Gamma_1)e^{i\varphi/2} \sin\vartheta}{(z - z_+)(z - z_-)} - \oint_{C_\eta} \frac{dz}{2\pi i} e^{-izt} \frac{i\sqrt{\Gamma_1\Gamma_2} \cos\vartheta}{(z - z_+)(z - z_-)} \quad (4.37)$$

$$= ((z_+ - \Delta_1 + i\Gamma_1)e^{-iz_+t} - (z_- - \Delta_1 + i\Gamma_1)e^{-iz_-t}) \frac{e^{i\varphi/2} \sin\vartheta}{(z_+ - z_-)} \quad (4.38)$$

$$- \left(e^{-iz_+t} \frac{i\sqrt{\Gamma_1\Gamma_2} \cos\vartheta}{(z_+ - z_-)} + e^{-iz_-t} \frac{i\sqrt{\Gamma_1\Gamma_2} \cos\vartheta}{(z_- - z_+)} \right) \quad (4.39)$$

4.1.5 Second pair (???)

In the following, we consider a problem of two distant emitters. We assume that $\omega_{\mu,k} = k$, and that

$$g_{\mu,k}^{(n)} = \sqrt{\frac{\Gamma_n}{2\pi}} e^{-ic_n \mu k R/2}, \quad c_n = (-1)^{n+1}. \quad (4.40)$$

The Green's function in zero-excitation subspace is simply

$$G^{(0)}(z) = \frac{1}{z + \Delta_+}, \quad \Delta_{\pm} = \frac{\Delta_1 \pm \Delta_2}{2}. \quad (4.41)$$

The Green's function in one-excitation subspace is written as

$$G^{(1)}(z) = \frac{g_1^{(1)}(z) |10\rangle \langle 10| + g_2^{(1)}(z) |01\rangle \langle 01| + g_1^{(1)}(z) g_2^{(1)}(z) m(z) (\sigma_+^{(1)} \sigma_-^{(2)} + \sigma_+^{(2)} \sigma_-^{(1)})}{1 - g_1^{(1)}(z) g_2^{(1)}(z) m^2(z)}, \quad (4.42)$$

$$m(z) = -i\sqrt{\Gamma_1 \Gamma_2} e^{i(z+\Delta_+)R}, \quad g_n^{(1)}(z) = \frac{1}{z - c_n \Delta_- + i\Gamma_n}. \quad (4.43)$$

Let us consider the special case $\Delta_1 = \Delta_2 =: \Delta$ and $\Gamma_1 = \Gamma_2 =: \Gamma$. In that case $g_1(z) = g_2(z) =: g(z)$. We obtain

$$G^{(1)}(z) = g^{(1)}(z) \frac{|10\rangle \langle 10| + |01\rangle \langle 01| + g^{(1)}(z) m(z) (\sigma_+^{(1)} \sigma_-^{(2)} + \sigma_+^{(2)} \sigma_-^{(1)})}{1 - (g^{(1)}(z) m(z))^2}. \quad (4.44)$$

We consider the second pair of Bell states

$$|\Phi_{\pm}\rangle = \frac{|10\rangle \pm |01\rangle}{\sqrt{2}}. \quad (4.45)$$

One has

$$|10\rangle \langle 10| + |01\rangle \langle 01| = |\Phi_+\rangle \langle \Phi_+| + |\Phi_-\rangle \langle \Phi_-|, \quad (4.46)$$

$$\sigma_+^{(1)} \sigma_-^{(2)} + \sigma_+^{(2)} \sigma_-^{(1)} = |\Phi_+\rangle \langle \Phi_+| - |\Phi_-\rangle \langle \Phi_-|. \quad (4.47)$$

It thus follows

$$G^{(1)}(z) = g_+^{(1)}(z) |\Phi_+\rangle \langle \Phi_+| + g_-^{(1)}(z) |\Phi_-\rangle \langle \Phi_-|, \quad g_{\pm}^{(1)}(z) = \frac{1}{z + i\Gamma(1 \pm e^{i(z+\Delta)R})}. \quad (4.48)$$

The emission vertex is expressed as

$$v_{\mu,k} = \sqrt{\frac{\Gamma}{2\pi}} \sum_{n=1,2} e^{-ic_n \mu k R/2} \sigma_-^{(n)} = \sqrt{\frac{\Gamma}{\pi}} \cos(kR/2) \frac{(\sigma_-^{(1)} + \sigma_-^{(2)})}{\sqrt{2}} \quad (4.49)$$

$$-i\sqrt{\frac{\Gamma}{\pi}} \mu \sin(kR/2) \frac{(\sigma_-^{(1)} - \sigma_-^{(2)})}{\sqrt{2}} \quad (4.50)$$

Using

$$\sigma_-^{(1)} = |00\rangle \langle 10| + |01\rangle \langle 11|, \quad \sigma_-^{(2)} = |00\rangle \langle 01| + |10\rangle \langle 11|, \quad (4.51)$$

we deduce

$$\frac{\sigma_-^{(1)} \pm \sigma_-^{(2)}}{\sqrt{2}} = |00\rangle \langle \Phi_{\pm}| \pm |\Phi_{\pm}\rangle \langle 11|. \quad (4.52)$$

It hence follows

$$P^{(0)} v_{\mu,k} P^{(1)} = \sqrt{\frac{\Gamma}{\pi}} |00\rangle (\cos(kR/2) \langle \Phi_+| - i\mu \sin(kR/2) \langle \Phi_-|). \quad (4.53)$$

Assuming that the state of the system at initial time $t_0 = 0$ is given by

$$|\psi_0\rangle = |\Phi_p\rangle, \quad (4.54)$$

the state at latter times $t > t_0 = 0$ is given by

$$|\psi_0\rangle = \psi_p^{(1)}(t) |\Phi_p\rangle + \sum_{\mu=\pm} \int dk \psi_{p,\mu,k}^{(0)}(t) a_{\mu,k}^\dagger |\Omega\rangle |00\rangle, \quad (4.55)$$

where

$$\psi_p^{(1)}(t) = \oint_{C_\eta} \frac{dz}{2\pi i} g_p^{(1)}(z) e^{-izt}, \quad \psi_{\mu,k}^{(0)}(t) = \oint_{C_\eta} \frac{dz}{2\pi i} g^{(0)}(z-k) \quad (4.56)$$

$$\times \sqrt{\frac{\Gamma}{\pi}} \begin{cases} \cos(kR/2), & p = +, \\ -i\mu \sin(kR/2), & p = - \end{cases} \times g_p^{(1)}(z) \quad (4.57)$$

The Green's function is given by

$$g_p(z) = \frac{1}{z + i\Gamma(1 + pe^{i(z+\Delta)R})}. \quad (4.58)$$

Let us try to find real pole solutions z , this essentially implies

$$z = p\Gamma \sin((z + \Delta)R), \quad \cos((z + \Delta)R) = -p. \quad (4.59)$$

For $\cos((z + \Delta)R) = \pm 1$ we have $\sin((z + \Delta)R) = 0$, leading us to the solution

$$z = 0, \quad \cos(\Delta R) = -p. \quad (4.60)$$

The condition $\cos(\Delta R) = -p$ basically implies destructive interference and leads to the formation of an atom-photon bound state, sitting at zero energy.

The Laplace transform of the Green's function is given by

$$\psi_p^{(1)}(t) = \sum_{n=0}^{\infty} \frac{(-p\Gamma e^{i\Delta R})^n}{n!} \Theta(t - nR) (t - nR)^n e^{-\Gamma(t - nR)}. \quad (4.61)$$

For all Δ such that $\cos(\Delta R) \neq -p$ this series approaches 0. For $\cos(\Delta R) = -p$, on the contrary

$$\psi_p^{(1)}(t) = \sum_{n=0}^{\infty} \frac{1}{n!} \Theta(t - nR) (\Gamma(t - nR))^n e^{-\Gamma(t - nR)} \rightarrow \frac{1}{1 + \Gamma R}. \quad (4.62)$$

The projection of the survival amplitude on the interval $t \in [nR, (n+1)R]$ is given by

$$\sum_{l=0}^n \frac{(pe^{i\Delta R})^l}{l!} \frac{\partial^l}{\partial y^l} e^{-y\Gamma(t-lR)} \Big|_{y=1}. \quad (4.63)$$

The reduced density matrix of qubits is given by

$$\rho_Q^{(p)}(t) = |\psi_p^{(1)}(t)|^2 |\Phi^{(p)}\rangle \langle \Phi^{(p)}| + N(t) |00\rangle \langle 00|, \quad (4.64)$$

$$N(t) = \sum_{\mu=\pm} \int dk |\psi_{\mu,k}^{(0)}(t)|^2 = 1 - |\psi_p^{(1)}(t)|^2. \quad (4.65)$$

Leading to the following expression for the von Neumann entropy

$$S_{\text{vN}}(t) = -|\psi_p^{(1)}(t)|^2 \log(|\psi_p^{(1)}(t)|^2) - (1 - |\psi_p^{(1)}(t)|^2) \log(1 - |\psi_p^{(1)}(t)|^2), \quad (4.66)$$

which has the property $S(t=0) = S(t \rightarrow \infty) = 0$ unless $\cos(\Delta R) = -p$. When the destructive interference condition is satisfied $\cos(\Delta R) = -p$, the entropy reaches

$$S_{\text{vN}}(t) \rightarrow \frac{(1 + \Gamma R)^2 \log[(1 + \Gamma R)^2] - [(1 + \Gamma R)^2 - 1] \log[(1 + \Gamma R)^2 - 1]}{(1 + \Gamma R)^2}. \quad (4.67)$$

The maximum entropy is achieved at

$$R = \frac{\sqrt{2} - 1}{\Gamma}. \quad (4.68)$$

Now let us consider the photonic part of the wave function

$$\psi_{\mu,k}^{(0)}(t) = g_{\mu,k}^{(p)} \oint_{C_\eta} \frac{dz}{2\pi i} \frac{1}{z + \Delta - k} \frac{1}{z + i\Gamma(1 + pe^{i(z+\Delta)R})} e^{-izt} \quad (4.69)$$

$$= g_{\mu,k}^{(p)} \sum_{n=0}^{\infty} \Theta(t - nR) \frac{(-i\Gamma pe^{i\Delta R})^n}{(k - \Delta + i\Gamma)^{n+1}} \left(e^{-i(k-\Delta)(t-nR)} \right. \quad (4.70)$$

$$\left. - e^{-\Gamma(t-nR)} \sum_{m=0}^n \frac{((\Gamma - i[k - \Delta])(t - nR))^{n-m}}{(n-m)!} \right). \quad (4.71)$$

For all Δ such that $\cos(\Delta R) \neq -p$ this series approaches

$$\psi_{\mu,k}^{(0)}(t) \rightarrow g_{\mu,k}^{(p)} \frac{1}{k - \Delta + i\Gamma(1 + pe^{ikR})} e^{-i(k-\Delta)t}, \quad t \rightarrow \infty. \quad (4.72)$$

In the case of atom-photon bound states $\cos(\Delta R) = -p$, photonic wave function approaches

$$\psi_{\mu,k}^{(0)}(t) \rightarrow g_{\mu,k}^{(p)} \frac{1}{k - \Delta + i\Gamma(1 + pe^{ikR})} e^{-i(k-\Delta)t} - g_{\mu,k}^{(p)} \frac{1}{k - \Delta} \frac{1}{1 + \Gamma R}, \quad t \rightarrow \infty. \quad (4.73)$$

The first-order coherence is given by

$$C_{\mu,\mu'}^{(1)}(x, x'|t, t') = \langle \psi_0 | a_\mu^\dagger(x, t) a_{\mu'}(x', t') | \psi_0 \rangle = \psi_\mu^{(0)*}(t, x) e^{i\Delta(t-t')} \psi_{\mu'}^{(0)}(t', x') \quad (4.74)$$

Now we introduce $\tau = t - t'$ and $T = \frac{t+t'}{2}$, so that $t = T + \tau/2$, $t' = T - \tau/2$. One has

$$\begin{aligned} C_{\mu,\mu'}^{(1)}(x, x'|T, \tau) &= \psi_\mu^{(0)*}(T + \tau/2, x) \psi_{\mu'}^{(0)}(T - \tau/2, x') e^{i\Delta\tau} \\ &= \int dk \int dk' \frac{e^{-i\mu kx}}{\sqrt{2\pi}} \frac{e^{i\mu' k' x'}}{\sqrt{2\pi}} \psi_{\mu,k}^{(0)*}(T + \tau/2) \psi_{\mu',k'}^{(0)}(T - \tau/2) e^{i\Delta\tau}. \end{aligned} \quad (4.75)$$

The local spectral density at time T may be defined via

$$S_\mu^{\text{emission}}(x, T|\nu) = \int \frac{d\tau}{2\pi} e^{-i\nu\tau} C_{\mu,\mu}^{(1)}(x, x|T, \tau), \quad (4.76)$$

implying that the total spectrum of emitted radiation is given by

$$\begin{aligned} S_\mu^{\text{emission}}(T|\nu) &= \int \frac{d\tau}{2\pi} e^{-i\nu\tau} \int dx C_{\mu,\mu}^{(1)}(x, x|T, \tau) \\ &= \int \frac{d\tau}{2\pi} \int dk \psi_{\mu,k}^{(0)*}(T + \tau/2) \psi_{\mu,k}^{(0)}(T - \tau/2) e^{i\Delta\tau} e^{-i\nu\tau}. \end{aligned} \quad (4.77)$$

Using

$$\psi_{\mu,k}^{(0)}(t) = i \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \hat{\psi}_{\mu,k}^{(0)}(\omega) e^{-i\omega t}, \quad (4.78)$$

we obtain

$$S_\mu^{\text{emission}}(T|\nu) = \int dk \int \frac{d\omega}{2\pi^2} \hat{\psi}_{\mu,k}^{(0)*}(\nu - \Delta - \omega) \hat{\psi}_{\mu,k}^{(0)}(\nu - \Delta + \omega) e^{-2i\omega T}$$

Now, using

$$\hat{\psi}_{\mu,k}^{(0)}(z) = g_{\mu,k}^{(p)} \frac{1}{z + \Delta - k} \frac{1}{z + i\Gamma(1 + pe^{i(z+\Delta)R})} \quad (4.79)$$

we cast

$$\begin{aligned} S_\mu^{\text{emission}}(T|\nu) &= -\frac{\Gamma}{2\pi} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi i} \frac{1}{\omega + i\eta} \\ &\quad \times \frac{1 + p \cos(\nu R) e^{i\omega R}}{\omega - (\nu - \Delta) + i\Gamma + i\Gamma p e^{-i\nu R} e^{i\omega R}} \frac{1}{\omega + (\nu - \Delta) + i\Gamma + i\Gamma p e^{i\nu R} e^{i\omega R}} e^{-2i\omega T}. \end{aligned} \quad (4.80)$$

Now using the fact that

$$\frac{i\Gamma + i\Gamma p \cos(\nu R) e^{i\omega R}}{\omega - (\nu - \Delta) + i\Gamma + i\Gamma p e^{-i\nu R} e^{i\omega R}} \frac{1}{\omega + (\nu - \Delta) + i\Gamma + i\Gamma p e^{i\nu R} e^{i\omega R}} \quad (4.81)$$

$$= \frac{1}{2} \left(\frac{1}{\omega - (\nu - \Delta) + i\Gamma + i\Gamma p e^{-i\nu R} e^{i\omega R}} + \frac{1}{\omega + (\nu - \Delta) + i\Gamma + i\Gamma p e^{i\nu R} e^{i\omega R}} \right) \quad (4.82)$$

$$- \frac{\omega}{\omega - (\nu - \Delta) + i\Gamma + i\Gamma p e^{-i\nu R} e^{i\omega R}} \frac{1}{\omega + (\nu - \Delta) + i\Gamma + i\Gamma p e^{i\nu R} e^{i\omega R}}, \quad (4.83)$$

we rewrite the emission spectral density as

$$S_{\mu}^{\text{emission}}(T|\nu) = \frac{1}{2\pi i} \int_{+\infty}^{-\infty} \frac{d\omega}{2\pi i} \frac{1}{\omega - (\nu - \Delta) + i\Gamma + i\Gamma p e^{-i\nu R} e^{i\omega R}} \times \frac{1}{\omega + (\nu - \Delta) + i\Gamma + i\Gamma p e^{i\nu R} e^{i\omega R}} e^{-2i\omega T} \quad (4.84)$$

$$- \frac{1}{4\pi i} \int_{+\infty}^{-\infty} \frac{d\omega}{2\pi i} \frac{1}{\omega + i\eta} \frac{1}{\omega - (\nu - \Delta) + i\Gamma + i\Gamma p e^{-i\nu R} e^{i\omega R}} e^{-2i\omega T} \quad (4.85)$$

$$- \frac{1}{4\pi i} \int_{+\infty}^{-\infty} \frac{d\omega}{2\pi i} \frac{1}{\omega + i\eta} \frac{1}{\omega + (\nu - \Delta) + i\Gamma + i\Gamma p e^{i\nu R} e^{i\omega R}} e^{-2i\omega T}. \quad (4.86)$$

As the "observation time" T tends to infinity $T \rightarrow \infty$, unless $\cos(\Delta R) = -p$, we pick up a pole at $\omega = 0$ only, so that the emission power spectrum approaches

$$S_{\mu}^{\text{emission}}(T|\nu) = \frac{1}{4\pi i} \left(\frac{1}{(\nu - \Delta) - i\Gamma - i\Gamma p e^{-i\nu R}} - \frac{1}{(\nu - \Delta) + i\Gamma + i\Gamma p e^{i\nu R}} \right) = \frac{\Gamma}{2\pi} \frac{1 + p \cos(\nu R)}{[(\nu - \Delta) + i\Gamma + i\Gamma p e^{i\nu R}]^2}. \quad (4.87)$$

In the case, the atom-photon bound states are present $\cos(\Delta R) = -p$, we have to account for additional poles

$$S_{\mu}^{\text{emission}}(T|\nu) = \frac{1}{\pi} \frac{\cos(2\bar{\nu}T)}{1 + \Gamma R} \frac{-\Gamma(1 - \cos(2\bar{\nu}R))}{|2\bar{\nu} + i\Gamma(1 - e^{2i\bar{\nu}R})|^2} + \frac{1}{\pi} \frac{\sin(2\bar{\nu}T)}{1 + \Gamma R} \left(\frac{1}{2\bar{\nu}} - \frac{2\bar{\nu} + \Gamma \sin(2\bar{\nu}R)}{|2\bar{\nu} + i\Gamma(1 - e^{2i\bar{\nu}R})|^2} \right) \quad (4.88)$$

$$+ \frac{\Gamma}{2\pi} \frac{1 - \cos(\bar{\nu}R)}{|\bar{\nu} + i\Gamma - i\Gamma e^{i\bar{\nu}R}|^2} \quad (4.89)$$

$$+ \frac{1}{2} \delta(\bar{\nu}) \frac{\Gamma R}{(1 + \Gamma R)^2}, \quad \bar{\nu} = \nu - \Delta \quad (4.90)$$

4.2 General dynamics in $\bar{N}_{max} = 1$ systems

4.2.1 Exact resummation of perturbation theory for the propagator

In this section, we derive the full Green's operator in $\bar{N}_{max} = 1$ waveguide QED. Our starting point is the following representation of the Green's operator in terms of the transition operator $\mathcal{T}(z)$:

$$\mathcal{G}(z) = \mathcal{G}^{(0)}(z) + \mathcal{G}^{(0)}(z) \mathcal{T}(z) \mathcal{G}^{(0)}(z), \quad (4.91)$$

where the T -operator satisfies

$$\mathcal{T}(z) = \mathcal{V} + \mathcal{V} \mathcal{G}(z) \mathcal{V}. \quad (4.92)$$

Now we define the following states

$$|N_p, 0\rangle = \frac{1}{\sqrt{N_p!}} \psi_{s_1 \dots s_{N_p}} a_{s_1}^\dagger \dots a_{s_{N_p}}^\dagger |\Omega\rangle \otimes |g\rangle, \quad (4.93)$$

$$|N_p - 1, 1\rangle = \frac{1}{\sqrt{(N_p - 1)!}} \psi_{s_1 \dots s_{N_p-1}} a_{s_1}^\dagger \dots a_{s_{N_p-1}}^\dagger |\Omega\rangle \otimes |e\rangle, \quad (4.94)$$

where $|\Omega\rangle$ is the vacuum state, $|g\rangle$, $|e\rangle$ are used symbolically to indicate some state belonging to either ground or excited manifolds, respectively, and s is the multi-index $s = (k, \mu)$ subject to the generalized summation convention

$$A_s B_s := \sum_{\mu=1}^{N_c} \int_{B_\mu} dk A_\mu(k) B_\mu(k). \quad (4.95)$$

Above, we defined a family of N_p -photon test-functions

$$\psi_{s_1 \dots s_{N_p}} = \psi_{\mu_1, \dots, \mu_{N_p}}(k_1, \dots, k_{N_p}), \quad \psi_{s_1 \dots s_{N_p}} = \psi_{\sigma(s_1) \dots \sigma(s_{N_p})}, \quad \sigma \in S_{N_p}, \quad |\psi_{s_1 \dots s_{N_p}}|^2 = 1, \quad (4.96)$$

on the N_p -photon Hilbert space.

The N -excitation subspace is thus spanned by

$$|N, g\rangle, \quad |N-1, e\rangle. \quad (4.97)$$

Our final goal is to represent the \mathcal{T} -operator in all of the N -subspaces separately. For this, we consider the matrix elements of $\mathcal{T}(z)$ in a pair of the above states, keeping N arbitrary.

The diagonal matrix element $\langle N'_p, g | \mathcal{T}(z) | N_p, g \rangle$ was determined in our previous work and may be expressed as

$$\langle N'_p, g | \mathcal{T}(z) | N_p, g \rangle = \langle N'_p, g | a_{s'_1}^\dagger v_{s'_1} \mathcal{G}^{(1)}(z) v_{s_1}^\dagger a_{s_1} | N_p, g \rangle \quad (4.98)$$

$$+ \langle N'_p, g | a_{s'_1}^\dagger v_{s'_1} \mathcal{G}^{(1)}(z) \mathcal{W}^{(1)}(z) \mathcal{G}^{(1)}(z) v_{s_1}^\dagger a_{s_1} | N_p, g \rangle, \quad (4.99)$$

where

$$\mathcal{W}^{(1)}(z) = \sum_{n=1}^{\infty} a_{s'_1}^\dagger \dots a_{s'_n}^\dagger \mathcal{W}_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(z) a_{s_n} \dots a_{s_1}, \quad \mathcal{G}^{(1)}(z) = \mathcal{G}^{(0)}(z) + \mathcal{G}^{(0)}(z) \Sigma^{(1)}(z) \mathcal{G}^{(1)}(z), \quad (4.100)$$

$$\Sigma^{(1)}(z) = v_s^\dagger \mathcal{G}^{(0)}(z - \omega_s) v_s, \quad v_s \equiv v_\mu(k) := \sum_{n=1}^{N_q} g_{\mu,n}(k) \sigma_-^{(n)} \equiv g_\mu(k) \sigma_-. \quad (4.101)$$

Furthermore, $\mathcal{G}^{(0)}(z)$ and $\mathcal{W}_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(z)$ are the operator-valued functions, dependent on the field operators via the complex frequency z , as $z - \mathcal{H}_0$. The effective vertex functions $\mathcal{W}_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(z)$ satisfy

$$\begin{aligned} \mathcal{W}_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(z) &= \mathcal{R}_{s'_1, s_1}^{(1)} \left(z - \sum_{l=2}^n \omega_{s'_l} \right) \mathcal{G}^{(1)} \left(z - \omega_{s_1} - \sum_{l=2}^n \omega_{s'_l} \right) \mathcal{W}_{s'_2 \dots s'_n, s_2 \dots s_n}^{(1,n-1)}(z - \omega_{s_1}) \\ &+ \mathcal{R}_{s'_1, s}^{(1)} \left(z - \sum_{l=2}^n \omega_{s'_l} \right) \mathcal{G}^{(1)} \left(z - \omega_s - \sum_{l=2}^n \omega_{s'_l} \right) [\mathcal{W}_{s'_2 \dots s'_n, s_1 \dots s_n}^{(1,n)}(z) + \\ &\dots + \mathcal{W}_{s'_2 \dots s'_n, s_1 \dots s_n}^{(1,n)}(z)]. \end{aligned} \quad (4.102)$$

We note that in the case N_p (say the highest photon number expected to emerge in the problem) is fixed, the hierarchy of integral equations is closed, meaning that one has to solve only the first $N_p - 1$ equations to completely determine the matrix element. Before further taking the matrix elements of (4.99), we shall first express other matrix elements in the form analogous to (4.99). As we shall see, the entire T -matrix may be *completely specified* with the help of the vertex functions $\mathcal{W}_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(z)$.

We start with the other "diagonal" matrix element

$$\begin{aligned} \langle (N_p - 1)', e | \mathcal{T}(z) | N_p - 1, e \rangle &= \left\langle (N_p - 1)', e \left| a_{s'} v_{s'}^\dagger \mathcal{G}(z) v_s a_s^\dagger \right| N_p - 1, e \right\rangle \\ &= \sum_{n=0}^{\infty} \left\langle (N_p - 1)', e \left| a_{s'} v_{s'}^\dagger (\mathcal{G}_0(z) \mathcal{V})^n \mathcal{G}_0(z) v_s a_s^\dagger \right| N_p - 1, e \right\rangle \\ &= \sum_{n=0}^{\infty} \left\langle (N_p - 1)', e \left| a_{s'} v_{s'}^\dagger (\mathcal{G}_0(z) \mathcal{V} \mathcal{G}_0(z) \mathcal{V})^n \mathcal{G}_0(z) v_s a_s^\dagger \right| N_p - 1, e \right\rangle \\ &= \sum_{n=0}^{\infty} \left\langle (N_p - 1)', e \left| a_{s'} v_{s'}^\dagger (\mathcal{G}_0(z) v_{s'_1}^\dagger a_{s'_1}^\dagger \mathcal{G}_0(z) a_{s_1} v_{s_1}^\dagger)^n \mathcal{G}_0(z) v_s a_s^\dagger \right| N_p - 1, e \right\rangle, \end{aligned} \quad (4.103)$$

where we made use of the $N_{max} = 1$ nilpotency condition $v_s v_{s'} = v_s^\dagger v_{s'}^\dagger = 0$ and the fact that due to the RWA, only the terms even in the interaction potential do contribute to the above geometric series. We further have

$$\begin{aligned}
& \langle (N_p - 1)', e | \mathcal{T}(z) | N_p - 1, e \rangle \\
&= \sum_{n=0}^{\infty} \left\langle (N_p - 1)', e \left| [\mathcal{G}^{(0)}(z)]^{-1} \mathcal{G}^{(0)}(z) a_{s'} v_{s'}^\dagger (\mathcal{G}^{(0)}(z) v_{s_1'} a_{s_1'}^\dagger \mathcal{G}^{(0)}(z) a_{s_1} v_{s_1}^\dagger)^n \mathcal{G}^{(0)}(z) v_s a_s^\dagger \mathcal{G}^{(0)}(z) [\mathcal{G}^{(0)}(z)]^{-1} \right| N_p - 1, e \right\rangle \\
&= \sum_{n=1}^{\infty} \left\langle (N_p - 1)', e \left| [\mathcal{G}^{(0)}(z)]^{-1} (\mathcal{G}^{(0)}(z) a_{s_1} v_{s_1}^\dagger \mathcal{G}^{(0)}(z) v_{s_1'} a_{s_1'}^\dagger)^n \mathcal{G}^{(0)}(z) [\mathcal{G}^{(0)}(z)]^{-1} \right| N_p - 1, e \right\rangle \\
&= \sum_{n=0}^{\infty} \left\langle (N_p - 1)', e \left| [\mathcal{G}^{(0)}(z)]^{-1} (\mathcal{G}^{(0)}(z) [\Sigma^{(1)}(z) + \mathcal{R}^{(1)}(z)])^n \mathcal{G}^{(0)}(z) [\mathcal{G}^{(0)}(z)]^{-1} \right| N_p - 1, e \right\rangle \\
&= \left\langle (N_p - 1)', e \left| [\mathcal{G}^{(0)}(z)]^{-1} \right| N_p - 1, 1 \right\rangle = \left\langle (N_p - 1)', e \left| [\mathcal{G}^{(0)}(z)]^{-1} \mathcal{G}^{(1)}(z) [\mathcal{G}^{(0)}(z)]^{-1} \right| N_p - 1, e \right\rangle \\
&+ \left\langle (N_p - 1)', e \left| [\mathcal{G}^{(0)}(z)]^{-1} \mathcal{G}^{(1)}(z) \mathcal{W}^{(1)}(z) \mathcal{G}^{(1)}(z) [\mathcal{G}^{(0)}(z)]^{-1} \right| N_p - 1, e \right\rangle - \left\langle (N_p - 1)', e \left| [\mathcal{G}^{(0)}(z)]^{-1} \right| N_p - 1, e \right\rangle. \tag{4.104}
\end{aligned}$$

Now, let us consider the off-diagonal matrix elements. As opposed to the diagonal case, the only terms in the Neumann series allowed by RWA are the odd ones

$$\langle (N_p - 1)', e | \mathcal{T}(z) | N_p, g \rangle = \langle (N_p - 1)', e | \mathcal{V} | N_p, g \rangle + \langle (N_p - 1)', e | \mathcal{V} \mathcal{G}(z) \mathcal{V} | N_p, g \rangle = \langle (N_p - 1)', e | a_s v_s^\dagger | N_p, g \rangle \tag{4.105}$$

$$\begin{aligned}
& + \sum_{n=0}^{\infty} \left\langle (N_p - 1)', e \left| a_{s'} v_{s'}^\dagger (\mathcal{G}^{(0)}(z) \mathcal{V} \mathcal{G}^{(0)}(z) \mathcal{V})^n \mathcal{G}^{(0)}(z) \mathcal{V} \mathcal{G}^{(0)}(z) a_s v_s^\dagger \right| N_p, g \right\rangle \\
&= \langle (N_p - 1)', e | a_s v_s^\dagger | N_p, g \rangle \\
& + \sum_{n=0}^{\infty} \left\langle (N_p - 1)', e \left| a_{s'} v_{s'}^\dagger (\mathcal{G}^{(0)}(z) v_{s_1} a_{s_1}^\dagger \mathcal{G}^{(0)}(z) v_{s_1'} a_{s_1'}^\dagger)^n \mathcal{G}^{(0)}(z) v_{s''} a_{s''}^\dagger \mathcal{G}^{(0)}(z) a_s v_s^\dagger \right| N_p, g \right\rangle \\
&= \sum_{n=0}^{\infty} \left\langle (N_p - 1)', e \left| [\mathcal{G}^{(0)}(z)]^{-1} (\mathcal{G}_0(z) a_{s_1} v_{s_1}^\dagger \mathcal{G}^{(0)}(z) v_{s_1'} a_{s_1'}^\dagger)^n \mathcal{G}^{(0)}(z) a_s v_s^\dagger \right| N_p, g \right\rangle \\
&= \left\langle (N_p - 1)', e \left| [\mathcal{G}^{(0)}(z)]^{-1} \mathcal{G}^{(1)}(z) a_s v_s^\dagger \right| N_p, g \right\rangle + \left\langle (N_p - 1)', e \left| [\mathcal{G}^{(0)}(z)]^{-1} \mathcal{G}^{(1)}(z) \mathcal{W}^{(1)}(z) \mathcal{G}^{(1)}(z) a_s v_s^\dagger \right| N_p, g \right\rangle. \tag{4.106}
\end{aligned}$$

Finally, we consider

$$\begin{aligned}
& \langle N_p', g | \mathcal{T}(z) | N_p - 1, e \rangle = \langle N_p', g | a_s^\dagger v_s | N_p - 1, e \rangle + \langle N_p', g | a_s^\dagger v_s \mathcal{G}(z) a_{s'}^\dagger v_{s'} | N_p - 1, e \rangle \\
&= \langle N_p', g | a_s^\dagger v_s | N_p - 1, e \rangle + \sum_{n=0}^{\infty} \left\langle N_p', g \left| a_s^\dagger v_s (\mathcal{G}^{(0)}(z) \mathcal{V} \mathcal{G}^{(0)}(z) \mathcal{V})^n \mathcal{G}^{(0)}(z) \mathcal{V} \mathcal{G}^{(0)}(z) a_{s'}^\dagger v_{s'} \right| N_p - 1, e \right\rangle \\
&= \langle N_p', g | a_s^\dagger v_s | N_p - 1, e \rangle + \sum_{n=0}^{\infty} \left\langle N_p', g \left| a_s^\dagger v_s (\mathcal{G}^{(0)}(z) v_{s_2} a_{s_2}^\dagger \mathcal{G}^{(0)}(z) v_{s_1'} a_{s_1'}^\dagger)^n \mathcal{G}^{(0)}(z) v_{s_1} a_{s_1}^\dagger \mathcal{G}^{(0)}(z) a_{s'}^\dagger v_{s'} \right| N_p - 1, e \right\rangle \\
&= \sum_{n=0}^{\infty} \left\langle N_p', g \left| a_s^\dagger v_s (\mathcal{G}^{(0)}(z) v_{s_1}^\dagger a_{s_1} \mathcal{G}^{(0)}(z) a_{s_1'}^\dagger v_{s_1'})^n \mathcal{G}^{(0)}(z) [\mathcal{G}^{(0)}(z)]^{-1} \right| N_p - 1, e \right\rangle \\
&= \left\langle N_p', g \left| a_s^\dagger v_s \mathcal{G}^{(1)}(z) [\mathcal{G}^{(0)}(z)]^{-1} \right| N_p - 1, e \right\rangle + \left\langle N_p', g \left| a_s^\dagger v_s \mathcal{G}^{(1)}(z) \mathcal{W}^{(1)}(z) \mathcal{G}^{(1)}(z) [\mathcal{G}^{(0)}(z)]^{-1} \right| N_p - 1, e \right\rangle. \tag{4.107}
\end{aligned}$$

Quite remarkably, we see that all of the non-trivial information about the dynamics may be drawn from the knowledge of $\mathcal{G}^{(1)}(z)$ and $\mathcal{W}^{(1)}(z)$ as it is the case in the theory of scattering. Let us also remark that the above calculation proves that all of the T -matrix elements apart from $\langle N_p, 0 | \mathcal{T}(z) | N_p, 0 \rangle$ vanish when being put on shell, as was claimed in (?).

Now, by making use of the relation between the Green's function and the transition operator, we are ready to write the former as

$$\mathcal{G}(z) = \sum_{\sigma, \sigma' = g, e} \mathcal{G}_{\sigma\sigma'}(z) \tag{4.108}$$

where

$$\mathcal{G}_{ee}(z) = P^{(e)}(\mathcal{G}^{(1)}(z) + \mathcal{G}^{(1)}(z)\mathcal{W}^{(1)}(z)\mathcal{G}^{(1)}(z))P^{(e)}, \quad (4.109)$$

$$\begin{aligned} \mathcal{G}_{gg}(z) = & P^{(g)}(\mathcal{G}^{(0)}(z) + \mathcal{G}^{(0)}(z)a_{s'_1}^\dagger v_{s'_1} \mathcal{G}^{(1)}(z)v_{s_1}^\dagger a_{s_1} \mathcal{G}^{(0)}(z) \\ & + \mathcal{G}^{(0)}(z)a_{s'_1}^\dagger v_{s'_1} \mathcal{G}^{(1)}(z)\mathcal{W}^{(1)}(z)\mathcal{G}^{(1)}(z)v_{s_1}^\dagger a_{s_1} \mathcal{G}^{(0)}(z))P^{(g)}, \end{aligned} \quad (4.110)$$

$$\mathcal{G}_{eg}(z) = P^{(e)}(\mathcal{G}^{(1)}(z)a_{s_1}v_s^\dagger \mathcal{G}^{(0)}(z) + \mathcal{G}^{(1)}(z)\mathcal{W}^{(1)}(z)\mathcal{G}^{(1)}(z)a_{s_1}v_s^\dagger \mathcal{G}^{(0)}(z))P^{(g)}, \quad (4.111)$$

$$\mathcal{G}_{ge}(z) = P^{(g)}(\mathcal{G}^{(0)}(z)a_s^\dagger v_s \mathcal{G}^{(1)}(z) + \mathcal{G}^{(0)}(z)a_s^\dagger v_s \mathcal{G}^{(1)}(z)\mathcal{W}^{(1)}(z)\mathcal{G}^{(1)}(z))P^{(e)}. \quad (4.112)$$

Above, we have defined the projections

$$P^{(\sigma)} = \sum_{j=1}^{S_\sigma} |\sigma, j\rangle \langle \sigma, j|, \quad (4.113)$$

onto the $\sigma = g$ ground and $\sigma = e$ excited states. With the help of the vertex expansion (4.100), we obtain

$$\begin{aligned} \mathcal{G}_{ee}(z) = & P^{(e)}(\mathcal{G}^{(1)}(z) + \mathcal{G}^{(1)}(z)\mathcal{W}^{(1)}(z)\mathcal{G}^{(1)}(z))P^{(e)} \\ = & P^{(e)}(\mathcal{G}^{(1)}(z) + \sum_{n=1}^{\infty} \mathcal{G}^{(1)}(z)a_{s'_1}^\dagger \dots a_{s'_n}^\dagger \mathcal{W}_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(z)a_{s_n} \dots a_{s_1} \mathcal{G}^{(1)}(z))P^{(e)} \\ = & P^{(e)}\left(\mathcal{G}^{(1)}(z) + \sum_{n=1}^{\infty} a_{s'_1}^\dagger \dots a_{s'_n}^\dagger \mathcal{G}^{(1)}\left(z - \sum_{l'=1}^n \omega_{s_{l'}}\right) \mathcal{W}_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}(z)\mathcal{G}^{(1)}\left(z - \sum_{l=1}^n \omega_{s_l}\right) a_{s_n} \dots a_{s_1}\right)P^{(e)}. \end{aligned} \quad (4.114)$$

When acting upon the N_p -photon state, only the first N_p terms in the above series survive. Instead, we wish to represent the above operator as the direct sum of N_p -photon operators. For that sake, we need to inset the complements of the identity operator on each n -particle subspace

$$\frac{1}{(N_p - n)!} a_{s_{n+1}}^\dagger \dots a_{s_{N_p}}^\dagger a_{s_{N_p}} \dots a_{s_{n+1}}. \quad (4.115)$$

Choosing $N_p = N - 1$, we obtain

$$\begin{aligned} G_{ee}^{s'_1 \dots s'_{N-1}, s_1 \dots s_{N-1}}(z) = & P^{(e)}\left(\frac{1}{(N-1)!} G^{(1)}\left(z - \sum_{l=1}^{N-1} \omega_{s_l}\right) \prod_{p=1}^{N-1} \delta_{s_p, s'_p} \right. \\ & \left. + \sum_{n=1}^{N-1} \frac{\prod_{p=n+1}^{N-1} \delta_{s_p, s'_p}}{(N-n-1)!} G^{(1)}\left(z - \sum_{l'=1}^{N-1} \omega_{s_{l'}}\right) W_{s'_1 \dots s'_n, s_1 \dots s_n}^{(1,n)}\left(z - \sum_{l''=n+1}^{N-1} \omega_{s_{l''}}\right) G^{(1)}\left(z - \sum_{l=1}^{N-1} \omega_{s_l}\right)\right)P^{(e)}, \end{aligned} \quad (4.116)$$

such that the corresponding component of the Green's function transforms to

$$\bar{P}_{N-1} P^{(e)} \mathcal{G}(z) P^{(e)} \bar{P}_{N-1} = G_{ee}^{s'_1 \dots s'_{N-1}, s_1 \dots s_{N-1}}(z) a_{s'_1}^\dagger \dots a_{s'_{N-1}}^\dagger a_{s_{N-1}} \dots a_{s_1}. \quad (4.117)$$

Above we used ordinary letters G , W instead of calligraphic ones \mathcal{G} , \mathcal{W} , to signify that these objects are no longer operators on the photon space, but are rather their vacuum projections (e.g. $G^{(1)}(z) = \langle \Omega | \mathcal{G}^{(1)}(z) | \Omega \rangle$).

Likewise, we represent

$$\bar{P}_N P^{(g)} \mathcal{G}(z) P^{(g)} \bar{P}_N = G_{gg}^{s'_1 \dots s'_N, s_1 \dots s_N}(z) a_{s'_1}^\dagger \dots a_{s'_N}^\dagger a_{s_N} \dots a_{s_1}, \quad (4.118)$$

$$\bar{P}_{N-1} P^{(e)} \mathcal{G}(z) P^{(g)} \bar{P}_N = G_{eg}^{s'_1 \dots s'_{N-1}, s_1 \dots s_N}(z) a_{s'_1}^\dagger \dots a_{s'_{N-1}}^\dagger a_{s_N} \dots a_{s_1}, \quad (4.119)$$

$$\bar{P}_N P^{(g)} \mathcal{G}(z) P^{(e)} \bar{P}_{N-1} = G_{ge}^{s'_1 \dots s'_N, s_1 \dots s_{N-1}}(z) a_{s'_1}^\dagger \dots a_{s'_N}^\dagger a_{s_{N-1}} \dots a_{s_1}, \quad (4.120)$$

where the vertices are given by

4.2.2 General dynamics in single-excitation subspace

In single excitation subspace, an arbitrary quantum system interacts with one photon only, meaning that the resummation theory coincides with that of the single qubit in the single-excitation subspace up to replacement of emission v_s and absorption v_s^\dagger vertices. Assuming that $\{|\epsilon_n\rangle\}_{n=1,\dots,N_e}$ span the single-excitation subspace of our quantum system, whereas the ground-states into which they are allowed to decay are parametrized as $\{|\mathfrak{g}_m\rangle\}_{m=1,\dots,N_g}$, we may parametrize the emission vertex as

$$v_s = \sum_{n=1}^{N_e} \sum_{m=1}^{N_g} g_{\mu,n,m}(k) |\mathfrak{g}_m\rangle \langle \epsilon_n|. \quad (4.121)$$

The self-energy in the single-excitation subspace is given by

$$\Sigma^{(1)}(z) = v_s^\dagger G^{(0)}(z - \omega_s) v_s = \sum_{n=1}^{N_e} \sum_{n'=1}^{N_e} |\epsilon_n\rangle \langle \epsilon_{n'}| \sum_{\mu=1}^{N_c} \sum_{m=1}^{N_g} \int_{B_\mu} dk \frac{g_{\mu,n,m}(k) g_{\mu,n',m}^*(k)}{z - \omega_\mu(k) - \epsilon_{\mathfrak{g}_m}}. \quad (4.122)$$

The renormalized Green's function in the single excitation subspace is given by

$$G^{(1)}(z) = [[P^{(e)} G^{(0)}(z) P^{(e)}]^{-1} - \Sigma^{(1)}(z)]^{-1}. \quad (4.123)$$

The Green's function typically possesses poles and branch cuts on the complex z plane. The contribution of the poles located on the lower half of the complex plane $z = \epsilon + i\Gamma$, $\Gamma \neq 0$ lead to the exponential decay, whereas the contribution of the branch cut integral typically lead to the long potential tails t^α weighted with the appropriate exponential decay $t^\alpha e^{-\Gamma t}$. The poles of the Green's function on the real axis, on the other hand, correspond to atom-photon bound states, widely studied in quantum-optical and quantum-electronic applications.

Let us consider the following initial state

$$|\psi_0\rangle = \sum_{n=1}^{N_e} \psi_n^{(e,0)} |\Omega\rangle |\epsilon_n\rangle + \sum_{m=1}^{N_g} \sum_{\mu=1}^{N_c} \int_{B_\mu} dk \psi_{\mu,m}^{(g,0)}(k) a_{\mu,k}^\dagger |\Omega\rangle |\mathfrak{g}_m\rangle. \quad (4.124)$$

Due to the conservation of the total excitation number operator, the state at later times $t > 0$ is given by

$$|\psi(t)\rangle = \sum_{n=1}^{N_e} \psi_n^{(e)}(t) |\Omega\rangle |\epsilon_n\rangle + \sum_{m=1}^{N_g} \sum_{\mu=1}^{N_c} \int_{B_\mu} dk \psi_{\mu,m}^{(g)}(k, t) a_{\mu,k}^\dagger |\Omega\rangle |\mathfrak{g}_m\rangle. \quad (4.125)$$

The occupation probability of the n^{th} excited state is given by

$$P_n(t) = \langle \psi(t) | \epsilon_n \rangle \langle \epsilon_n | \psi(t) \rangle = |\psi_n^{(e)}(t)|^2. \quad (4.126)$$

The total number of photons in channel μ is given by

$$N_\mu(t) = \int_{B_\mu} dk \langle \psi(t) | a_{\mu,k}^\dagger a_{\mu,k} | \psi(t) \rangle = \sum_{m=1}^{N_g} \int_{B_\mu} dk |\psi_{\mu,m}^{(g)}(k, t)|^2. \quad (4.127)$$

The integrands, by themselves, define the spectral density of photons in channel μ at time $t > 0$

$$S_\mu^{(1)}(k, t) = \sum_{m=1}^{N_g} |\psi_{\mu,m}^{(g)}(k, t)|^2. \quad (4.128)$$

In order to determine the exact wave functions, we apply the theory developed in Section 4.2.1. In particular,

$$\begin{aligned} \psi_n^{(e)}(t) &= \sum_{n'=1}^{N_e} \oint_{C_\eta} \frac{dz}{2\pi i} \langle \epsilon_n | G^{(1)}(z) | \epsilon_{n'} \rangle \psi_{n'}^{(e,0)} e^{-izt} \\ &\quad + \sum_{n'=1}^{N_e} \sum_{m=1}^{N_g} \sum_{\mu=1}^{N_c} \int_{B_\mu} dk \oint_{C_\eta} \frac{dz}{2\pi i} \langle \epsilon_n | G^{(1)}(z) | \epsilon_{n'} \rangle \frac{g_{\mu,n',m}^*(k) \psi_{\mu,m}^{(g,0)}(k)}{z - \omega_\mu(k) - \epsilon_m^{(g)}} e^{-izt}, \end{aligned} \quad (4.129)$$

$$\begin{aligned} \psi_{\mu,m}^{(g)}(k, t) &= \sum_{n=1}^{N_e} \sum_{n'=1}^{N_e} \oint_{C_\eta} \frac{dz}{2\pi i} \frac{g_{\mu,n,m}(k)}{z - \omega_\mu(k) - \epsilon_m^{(g)}} \langle \epsilon_n | G^{(1)}(z) | \epsilon_{n'} \rangle \psi_{n'}^{(e,0)} e^{-izt} \\ &\quad + G^{(0)}(z - \omega_\mu(k)) \psi_{\mu,m}^{(g,0)}(k) \\ &\quad + \sum_{m'=1}^{N_g} \sum_{\mu'=1}^{N_c} \int_{B_{\mu'}} dk' G^{(0)}(z - \omega_{\mu'}(k')) \psi_{\mu',m'}^{(g,0)}(k') \end{aligned} \quad (4.130)$$

4.2.3 Spontaneous emission from the second pair of Bell pairs

Let us consider a system comprised of a pair of equivalent qubits separated by distance R . We assume the qubits to be coupled to a one-dimensional transmission line supporting two distinct types of excitations corresponding to the chirality degree of freedom $\mu = \pm$. The corresponding Hamiltonian is written as

$$\mathcal{H}_0 = \Delta(\sigma_+^{(1)}\sigma_-^{(1)} + \sigma_+^{(2)}\sigma_-^{(2)}) + \sum_{\mu=\pm} \int_{-\infty}^{\infty} dk ck a_{k,\mu}^\dagger a_{k,\mu}, \quad (4.131)$$

where Δ is the detuning of qubits, we assumed the excitations of the transmission line to be linearly dispersing $\omega_{\mu,k} = ck$ around the operational frequency, and in the following we set $c = 1$. The interaction between qubits and the transmission line is described via the following bare emission vertex

$$v_s \equiv v_{k,\mu} = \sum_{n=1,2} e^{-i\mu k R_n} \sigma_-^{(n)}, \quad R_n = (-1)^n R/2. \quad (4.132)$$

The position space operators are related to the momentum space ones via

$$a_\mu(x) = \int_{-\infty}^{\infty} dk \frac{e^{i\mu k x}}{\sqrt{2\pi}} a_{k,\mu}, \quad a_{k,\mu} = \int_{-\infty}^{\infty} dx \frac{e^{-i\mu k x}}{\sqrt{2\pi}} a_\mu(x). \quad (4.133)$$

We assume that the system is initially prepared in one of the following two states

$$|\psi(0)\rangle = |\Omega\rangle \otimes |\Phi_\pm\rangle, \quad |\Phi_\pm\rangle = \frac{1}{\sqrt{2}}(|10\rangle \pm |01\rangle). \quad (4.134)$$

5 Other topics

A Adds

A.1 Введение и обзор

A.1.1 Другая мотивация

Польза в плане развития как профессионала

(потом раскрою)

Польза в плане саморазвития

(потом раскрою)

A.1.2 Мышление профессионала в КЭД волноводах

(потом напишу, пока не до этого раздела)

Взгляд на КЭД волноводов

Не нужно знать много другой физики и математики для КЭД волноводов, потому что в статьях очень схожий формализм и делают они почти одно и то же. Так что можно просто начать читать статьи и крутиться в этой теме. В 2023м году (да и скорее всего последние 10 лет тоже это так) очень много статей, так что можно читать их и понимать глубже и глубже этот предмет. Вообще не сложно.

И просто начинаешь про это думать, пару раз в неделю додумываешь детали - так за пару месяцев вообще без проблем и напрягов все понимается. Просто не нужно заниматься лишним и не нужно общие основы предметов собирать, можно спокойно исследовать многое, не так уж глубоко понимая основы, которые стоят за методами, которые тут используются.

А то можно и не дойти до этого предмета, если рыться в основах физики. По факту все тут нужное в статьях и написано.

(?? мб это общее соображение для всех предметов, тогда это в орг записи оставлю.)

Появление предмета в нашей картине мира

Использование предмета в обычной жизни (!) Укажем, как предмет используется в обычной жизни.

Особенности работы с КЭД волноводов

Для первой записи формул пишем без индексов и упрощенно, потому что иначе индексы и детали займут очень много времени (раскрою эту мысль, так и делаю. слишком уж тут много индексов. Окажется, что я неправ - изменю этот раздел.)

Все-таки, диаграммы для описания КЭД волноводов нужны и полезны или нет?

(по идее там будет раздел с приложениями вдали, тут обзорно, словами)

О применениях в квантовой когерентности, квантовых компьютерах (????)
(воспроизведу ответ Кирилла, я слишком мало про это думал, чтобы понять пока что.)

Актуальнейшие приложения

Построение с нуля

(потом раскрою, еще я не профессионал, а вопрос этот самый профессиональный)

Способы догадаться до всех главных идей

незаменимая часть нормального понимания предмета.

(потом раскрою)

Мышление для эффективного изучения

Осудим, какое мышление наиболее эффективное для усвоение предмета.

Способы изучения предмета (потом раскрою)

Необходимые темы для (потом раскрою)

Дополнительные темы для (потом раскрою)

А.1.3 Литература

Основная

[1] K. Piasotski, M. Pletyukhov Diagrammatic approach to scattering of multiphoton states in waveguide QED

То, откуда я начинаю изучать формализм для этих задач

Piasotski, Kiryl Master's degree thesis

Много объяснений происходящего и много теории. В открытом доступе нет, нужно Кириллу писать для нее.

[2] Mikhail Pletyukhov, Vladimir Gritsev Scattering of massless particles in one-dimensional chiral channel 2012

Еще одна статья, которую смотрел, мб там тоже много очень хорошего сделано, просто пока не до нее, отдельную минимум неделю нужно на ней сидеть, чтобы понять.

K. Lalumiere, B. C. Sanders, A. F. van Loo, A. Fedorov, A. Wallraff, and A. Blais, Input-output theory for waveguide QED with an ensemble of inhomogeneous atoms, Phys. Rev. A 88, 043806 (2013)

Известная статья, первая, на которую Кирилл ссылается, почитаю тоже ее.

Другие тоже содержательные статьи

[3] P-O Guimond and M Pletyukhov and H Pichler and P Zoller Delayed coherent quantum feedback from a scattering theory and a matrix product state perspective

Очень полезная тоже статья, вроде о том же, что уже пройдено, но посидеть над ней тоже нужно.

R. H. Lehmberg, Radiation from an N-atom system. I. general formalism, Phys. Rev. A 2, 883 (1970)

Первая статья про формализм излучения (так говорил Кирилл), и в 3д пространстве аж! Потом почитаю, в открытом доступе нет, так что нужно просить кого-то скачать ее.

Задачники

Статьи по схожим темам и методам

В помощь по физике и математике (!!!)

(тут скорее всего много всего будет)

О приложениях

A.1.4 Обзор

(потом раскрою)

Обзор применений и моделей описания

(тут то, что можно и потом прочитать супер внимательно, суть метода в частях ниже)

Waveguide quantum electrodynamics (QED) is a modern field of research focused on the study of light-matter interactions in one dimension. The confinement of electromagnetic radiation to a single spatial dimension allows one to achieve a significant enhancement of the coupling between atoms and fields, as well as to attain a better matching between the spatial modes of the emitting and absorbing atoms [1,2].

Apart from the purely academic interest in the study of strong light-matter coupling, a great deal of motivation in this field of research comes from the technological sector, namely, from the quantum computing [3-8]. One of the most prominent examples is the so-called quantum network: a system of quantum processors interconnected by quantum radiation channels propagating quantum information and entanglement between them [9].

Although photons are the excellent carriers of quantum information, capable of high-fidelity entanglement and information transfer [10-12], recent advancement in quantum electronics offers a large variety of alternatives. Most commonly, in 2020-s waveguide QED setups are realized in the experiments with superconducting quantum circuits, where superconducting transmission lines act as quantum radiation channels, whereas the Josephson-junction-based superconducting quantum bits play the role of quantum emitters [13-15]. Other examples include superconducting qubits coupled to propagating phonons (surface acoustic waves) employing the piezoelectric effect [16-19], and surface plasmons coupled to quantum dots [20].

Theoretically, the atom-field interactions in waveguide QED can often be accurately treated in the so-called Markovian limit $\gamma\tau \ll 1$, where γ and τ stand for the characteristic decay rate and time delay in the system [21] (??? разберусь, что они конкретно значат??). In the course of the last few decades, a significant number of theoretical approaches allowing one to tackle the waveguide QED problems within this limit was proposed. In particular, the Markovian waveguide QED systems are commonly examined theoretically with help of master-equation-based approaches [1,22-27]. Indeed, within the framework of the associated input-output formalism [1,28,29], Lindblad-type equation approaches allow one to study transmission and reflection characteristics, as well as the photonic correlations for arbitrary initial photon states, including coherent, thermal, and Fock ones. Moreover, at a rather modest expense, a substantial variety of theoretical tools are available for a derivation of master equations:

(??? okay, посмотрю их потом, мб сделаю разделы на эти методы. тут просто обзор, типа ну такое вот разное вообще есть. Интересно, конечно, но это можно вообще не знать и 1 метод додумать и все.)

Equation-of-motionbased methods [1,22,23], path-integral techniques [30], SLH formalism [31] (a popular formalism for the systematic construction of markovian master equations governing the evolution of cascaded quantum systems from S -matrix, coupling vector - L , and the Hamiltonian $-H$), to mention just a few. In 2020-s, master-equation-based approach was

generalized to capture the effects of temporal modulation of the system parameters [32, 33], such as the light-matter coupling strength and the transition frequencies of quantum emitters.

Another frequenter method of studying waveguide QED systems within Markov approximation is the coordinate space Bethe ansatz [34-41]. Within this approach, one is able to determine the exact stationary eigenstates of the system's Hamiltonian in a subspace of a given excitation number, which, in turn, enables one to calculate stationary observables as well as photonic correlation functions exactly. Moreover, the Bethe ansatz technique was shown to be applicable to the studies of real-time dynamics of few-photon states [36, 42, 43], systems where the photon-photon bound states occur [41, 44], and systems with delayed coherent feedback [45]. Despite its scalability to the cases of multiple emitters and emitters with complicated level structures, this approach is known to be strongly limited by the number of excitations in the system due to the rapid increase of complexity of the resulting Bethe wave functions [34, 36, 46, 47].

Another group of systematic methods of studying the waveguide QED systems in the limit of the negligible delay times is comprised of the field-theory-based approaches. For example, in [48-50], by representing the atomic operators in terms of the slave fermions, the authors were able to employ the path-integral representation of the field correlation functions, from which the S matrix may be established by means of the celebrated Lehmann-Symanzik-Zimmermann reduction formula. Another field-theoretical method to be mentioned is the so-called diagrammatic resummation theory developed in [51-54]. Within the framework of resummation theory, one sums the perturbative series of Feynman diagrams for the matrix elements of the transition operator to infinite orders, which, in turn, allows one to determine the exact S matrix, with the help of which all of the stationary observables may be calculated [52].

(в абзаце ниже - хз, что, что-то не легко читается, оставил.)

Although the physics behind waveguide QED systems is easily accessible in the Markovian limit using a large variety of theoretical tools, there exist a number of problems forcing one to go beyond this approximation [21, 55-58]. As it is well known, in the single-excitation subspace, all of the dynamical and stationary information about the system may be easily obtained (either analytically or numerically) by means of Bethe ansatz for a system of arbitrary complexity [59-62]. Primarily, this assertion has to do with the fact that it is relatively easy to conceive a closed system of (delay) differential equations governing the evolution of the system. Even though it is possible to proceed in the same manner in higher excitation subspaces [63], the calculations become much more cumbersome and lack systematicity. In the course of the last decade, a number of theoretical approaches allowing one to overcome these difficulties were put forward. On the numerical side, for example, significant progress in the dynamical simulation of the non-Markovian one-dimensional (1D) quantum systems was achieved within the framework of matrix product state ansatz [64-67]. Despite the complexity associated with the non-Markovian waveguide QED systems, a few analytical methods were also recently suggested. In particular, it is a common practice to generalize the Lindblad-type equation approaches to the non-Markovian realm [30, 68-70]. Although generalized master equations can only provide exact results in the case of linear scatterers, they allow for systematic approximate treatment of systems with nonlinearities such as qubits.

Another common approach to waveguide QED problems with delayed coherent quantum feedback is based on the diagrammatic resummation theory. In recent years resummation ideas were successfully applied to solve the two-photon scattering and dynamics in the systems with two distant qubits [71], a single qubit in front of a mirror [21], a giant acoustic atom [59], and a qubit coupled to a resonator array [72].

Описание метода (!?!?!?!)

(!?! тут нужно внимательно почитать!!)

In this paper, we present a systematic generalization of the diagrammatic approach to scattering of multiphoton states in waveguide QED. Our approach is based on the exact resummation of the perturbation theory for the transition operator which turns out to be possible due to the conservation of excitation number guaranteed by the rotating wave approximation.

The advantage of our approach is its insensitivity to the form of light-matter coupling constants, thus allowing one to potentially examine any kinds of waveguide QED systems, including the systems with delayed coherent quantum feedback. We start by making an exposure of the method by the direct example of one-qubit waveguide QED. This framework lays down a basis for further calculations, in particular general qubit number two and three-photon scattering theory. We then apply the developed theory to a weakly coherent pulse scattering on a giant acoustic atom, an intrinsically non-Markovian system.

In particular, we consider the scattering of a coherent state with small enough coherence parameter $|\alpha| \ll 1$ chosen such that the terms of order $|\alpha|^4$ can be ignored.

With the help of the general methods developed in Sec. II we compute an exact output state of radiation and study the particle correlations in it with the help of the theory of optical coherence. In particular, we compute the first-, second-, and third-order coherence functions to the lowest order in $|\alpha|$ and discuss the impact of the non-Markovianity of the scatterer on the observable quantities.

SCATTERING THEORY section description

In this section, we first set up the notations used throughout the paper. Next, we introduce the general formalism in the framework of the single-qubit waveguide QED. In particular, we extend the findings of the preceding papers [21, 51, 53, 59] to the realm of non-Markovian models by allowing for arbitrary momentum dependence of waveguide modes and radiation-qubit couplings. This development, in turn, allows one to study multiphoton scattering problems in systems with nonlinear dispersion of the modes supported by the radiation channels, as well as the systems with artificial feedback loops, such as a qubit placed in front of a mirror or a giant acoustic atom, for example.

Further on, we generalize the scattering formalism to the systems with a higher number of qubits, where the quantum feedback loops are naturally present due to the finiteness of time required for a photon to propagate between a given pair of distant emitters. Specifically, we discuss two- and three-photon scattering problems on an arbitrary number of emitters, extending the approach of [71].

Alongside this, we discuss several practical issues, such as the separation of elastic contributions to the scattering matrices and the generalized cluster decomposition.

Введение в двух словах (?????)

We give an exposure to diagrammatic techniques in waveguide quantum electrodynamics (QED) systems. A particular emphasis is placed on the systems with delayed coherent quantum feedback. Specifically, we show that the N -photon scattering matrices in single-qubit waveguide QED systems, within the rotating wave approximation, admit for a parametrization in terms of $(N - 1)$ -photon effective vertex functions and provide a detailed derivation of a closed hierarchy of generalized Bethe-Salpeter equations satisfied by these vertex functions. (???? про Бете-Солпитера отдельный разговор, я в этом не разбираюсь, пока считаю, что нет, это ложь, тут нет этого уравнения, оно о чем-то другом.)

The advantage of this method is that the above-mentioned integral equations hold independently of the number of radiation channels, their bandwidth, the dispersion of the modes they are supporting, and the structure of the radiation-qubit coupling interaction, thus enabling one to study multiphoton scattering problems beyond the Born-Markov approximation. Fur-

ther, we generalize the diagrammatic techniques to the systems containing more than a single emitter by presenting an exact set of equations governing the generic two- and three-photon scattering operators. The above-described theoretical machinery is then showcased on the example of a three-photon scattering on a giant acoustic atom, recently studied experimentally [G. Andersson et al., Nat.

Обзор диаграммных техник

один большой раздел

такой-то набор следствий

Связи с другими науками

Обсудим связи с разделами
(потом раскрою)

Обзор дальнейших развитий

Обзор теоретических подходов

такие-то есть, такие полезные, такие - нет.

Описание записи

Общее описание записи

Общие особенности записи

Особенности глав и разделов

Первая часть про предмет в двух словах

Вторая часть

Часть про приложения какие вообще приложения я разбирал?

Обозначения и константы

A.1.5 Головоломки

Обсудим в порядке интересности задачи и вопросы

Бытовые головоломки

Принципиальные головоломки

Головоломки о деталях

A.1.6 Короткий исторический обзор

Обсудим вкратце историю развития электродинамики волноводов.

A.2 Mathematics for Waveguide QED

On Poincare-Bertrand identity

B Bibliography

- [1] Piasotski, Kiryl and Pletyukhov, Mikhail: *Diagrammatic approach to scattering of multi-photon states in waveguide qed*. Phys. Rev. A, 104:023709, Aug 2021. <https://link.aps.org/doi/10.1103/PhysRevA.104.023709>.
- [2] Pletyukhov, Mikhail and Gritsev, Vladimir: *Scattering of massless particles in one-dimensional chiral channel*. New Journal of Physics, 14(9):095028, sep 2012. <https://dx.doi.org/10.1088/1367-2630/14/9/095028>.
- [3] Guimond, P O, Pletyukhov, M, Pichler, H, and Zoller, P: *Delayed coherent quantum feedback from a scattering theory and a matrix product state perspective*. Quantum Science and Technology, 2(4):044012, sep 2017. <https://dx.doi.org/10.1088/2058-9565/aa7f03>.