

Lecture notes
Quantum Theory of Solids

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Foreword to the digitalized lecture notes

Digitalized lecture notes for the course “TFY4210 - Quantum Theory of Many-Particle Systems” held by Prof. Asle Sudbø spring 2020. These notes follow that of the hand written lecture notes, which are based upon the lecture notes for the course “FY8302 - Quantum Theory of Solids”, written in 1996 or so.

There may be a few extra comments to the text and / or figures that is based on the lectures themselves.

Course website: <https://www.ntnu.edu/studies/courses/TFY4210>

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Contents

1	Introduction	3
2	Many-particle states, fermions	6
2.1	N-particle vacuum state	6
2.2	Completeness relation	8
2.3	Operators	8
3	Perturbation theory	16
3.1	Time-evolution of states	16
3.2	The S-matrix	18
3.3	Single-particle Green's function	23
3.3.1	Fermions	24
3.3.2	Bosons	29
4	Quasi-particles in interacting electron-systems. Fermi-liquids.	29
4.1	Fermi-liquids	29
4.2	Screening of the Coulomb-interaction	29
4.3	Phonon mediated electron-electron interaction	29
4.4	Magnons	31
5	The Cooper problem	35
6	BCS-theory	39
7	The Meissner Effect	51

1 Introduction

Many-particle systems are systems where interactions between the particle-constituents of the system are important. When quantum effects are important, we talk about quantum many-body systems. The sort of systems we will consider in this course are made up of aggregate states of various atoms, and may typically be separated, a priori, into interacting states of electrons and ions:

1. Electrons interacting among themselves.
2. Ions interacting among themselves.
3. Interactions between electrons and ions.

What we seek to explain, is what determines the various physical states such a system may take up. Why are some materials metals, insulators, superfluids, superconductors, ferromagnets, antiferromagnets? The plethora of states appears quite bewildering. A major objective of this course is to see how to give a unifying description of all these systems, a "theory of everything" (almost).

In principle, the answer to the above question is obtained by solving the Schrödinger-equation for the many-body quantum-mechanical state $|\psi\rangle$:

$$H|\psi\rangle = i\hbar \frac{\partial |\psi\rangle}{\partial t} \quad (1.1)$$

H : Operator that generates dynamics. Here, H is the Hamiltonian of the system, this H consists of three parts:

1. H_{e-e} : Describes the electrons with interactions among themselves.
2. H_{i-i} : Describes the ions with interactions among themselves.
3. H_{e-i} : Describes the interactions between ions and electrons.

The Hamiltonian we consider will furthermore describe a priori non-relativistic systems, which means we can separate H into kinetic energy, T , and potential energy, V ,

$$H = T + V \quad (1.2)$$

$$H_{e-e} = \sum_i \frac{\vec{p}_i^2}{2m} + \sum_{i,j} V_{e-e}^{Coulomb}(\vec{r}_i - \vec{r}_j) \quad (1.3)$$

m : Electron mass

\vec{p}_i : Electron momentum

\vec{r}_i : Electron coordinate

$V_{e-e}^{Coulomb}(\vec{r}) = \frac{e^2}{4\pi\epsilon_0} \frac{1}{r}$ - e : Electron charge (e defined as positive)

ϵ_0 : Vacuum-permittivity

$$H_{i-i} = \sum_i \frac{\vec{P}_i^2}{2M} + \sum_{i,j} V_{i-i}^{Coulomb}(\vec{R}_i - \vec{R}_j) \quad (1.4)$$

M : Ion mass

\vec{P}_i : Ion momentum

\vec{R}_i : Ion coordinate

$V_{i-i}^{Coulomb}(\vec{R}) = \frac{Z^2 e^2}{4\pi\epsilon_0} \frac{1}{R}$

Ze : Ionic charge

$$H_{e-i} = \sum_{i,j} V_{e-i}^{Coulomb}(\vec{R}_i - \vec{r}_j) \quad (1.5)$$

$$V_{e-i}^{Coulomb}(\vec{R}) = \frac{-Ze^2}{4\pi\epsilon_0} \frac{1}{R}$$

NB! Note that the kinetic energy of the entire system is the sum of kinetic energies of each individual particle. The potential energy of the system is the sum of potential energy of pairs of particles, this later statement is an approximation. In principle, we can include three-, four-, five-, ... body interactions, but these will be ignored to a good approximation. Thus, the total Hamiltonian for a many-body system is a sum of one-particle terms and two-particle terms. This is an enormous simplification. NB!! There exists physical systems in condensed matter physics where this may not be a good approximation.

Observables are represented by operators \hat{O} . A measurable quantity is then

$$\langle \hat{O} \rangle = \langle \psi | \hat{O} | \psi \rangle, \quad (1.6)$$

which is the expectation value of \hat{O} in the many-body quantum state. $|\psi\rangle$ is computed at zero temperature $T=0$; i.e. $|\psi\rangle$ is a ground state. Often, we would like to compute expectation-values of \hat{O} at $T > 0$. This can be done by introducing a statistical parameter

$$\beta = \frac{1}{k_b T}; \quad (1.7)$$

k_b : Boltzman's constant.

Partition function:

$$Z = Tr(e^{-\beta H}) \quad (1.8)$$

$$\langle \hat{O} \rangle_T = \frac{1}{Z} Tr(\hat{O} e^{-\beta H}) \quad (1.9)$$

Thermal average involves also excited states.

The systems are assumed to be overall charge-neutral. The above Hamiltonian is formulated as a classical Hamiltonian in terms of coordinates and momenta of electrons and ions. We are seeking a quantum formulation of such a system, which means we need to find a useful formalism of operators and states in order to proceed.

For the systems that will be considered in this course, quantum particles come in two varieties:

- i) Fermions.
- ii) Bosons.

We first proceed by setting up a formulation for fermions (electrons are fermions).

2 Many-particle states, fermions

2.1 N-particle vacuum state

Many-particle states will be built up by constructing a basis using products of single-particle states. Let λ be some set of quantum numbers that uniquely specifies a single-particle quantum state.

Example: λ could be the set of quantum numbers of the hydrogen-atom.

$\lambda = (n, l, m, \sigma)$

n : Main quantum number.

l : Orbital angular momentum quantum number.

m : Quantization of angular momentum along z-axis.

σ : Spin quantum number.

Motion in 3 dimensions \implies 3 quantum numbers : (n, l, m)

Spin: 1 quantum number.

Corresponding state: $|n_\lambda\rangle$

Adjoint state: $\langle n_\lambda| = (|n_\lambda\rangle)^\dagger$

Vacuum-state (unoccupied state): $|0_\lambda\rangle$

Introduce creation and annihilation operators.

Creation: c_λ^\dagger

Annihilation: c_λ

$$|1_\lambda\rangle = c_\lambda^\dagger |0_\lambda\rangle$$

$$|0_\lambda\rangle = c_\lambda |1_\lambda\rangle$$

$$0 = c_\lambda |0_\lambda\rangle$$

In general, we will use a set of quantum numbers that are convenient. Exactly what this means in practice will become clear later, when we start looking at specific systems.

Many-body state:

$$|N\rangle = |n_{\lambda_1}, n_{\lambda_2}, n_{\lambda_3}, \dots, n_{\lambda_N}\rangle$$

N-particle vacuum-state:

$$|0\rangle = |0_{\lambda_1}, 0_{\lambda_2}, \dots, 0_{\lambda_N}\rangle \tag{2.1}$$

$|N\rangle$: Fock-basis

We regard fermions as quantized excitations of a matter field, in the same way as we regard photons as quantized excitations of an electromagnetic field.

Field operators for a fermion: $\psi^\dagger(x, t)$: Creates a fermion in some quantum state at point $(\vec{r}, s) = x$ at time t .

$$\psi^\dagger(x, t) = \sum_{\lambda} c_{\lambda}^\dagger(t) \varphi_{\lambda}^*(x) \quad (2.2)$$

$\varphi_{\lambda}(\vec{r}, s)$: Wave-function for quantum state with quantum numbers $\underline{\lambda}$.

Quantization:

$$\{\psi^\dagger(x, t), \psi(x, t)\} = \delta(\vec{r} - \vec{r}') \delta(s, s') \quad (2.3)$$

Note that t is the same in ψ^\dagger and ψ !

$$\{A, B\} = AB + BA \quad (2.4)$$

The set of wavefunctions $\varphi_{\lambda}(\vec{r})$ are assumed to constitute a complete set i.e. any function $f(\vec{r})$ can be expressed in terms of $\{\varphi_{\lambda}(\vec{r})\}$

$$f(\vec{r}, s) = \sum_{\lambda} a_{\lambda} \varphi_{\lambda}(\vec{r}, s) \quad (2.5)$$

$\{\varphi_{\lambda}(\vec{r}, s)\}$ is furthermore assumed to be orthonormalized

$$\sum_{\vec{r}, s} \varphi_{\lambda}^*(\vec{r}, s) \varphi_{\lambda'}(\vec{r}, s) = \delta_{\lambda, \lambda'}, \quad (2.6)$$

where

$$\delta_{\lambda, \lambda'} = \begin{cases} 1; & \lambda = \lambda' \\ 0; & \lambda \neq \lambda' \end{cases}$$

$$\begin{aligned} \sum_{\vec{r}} \varphi_{\lambda'}^*(\vec{r}, s) f(\vec{r}, s) &= \sum_{\lambda} \sum_{\vec{r}} \varphi_{\lambda'}^*(\vec{r}, s) \varphi_{\lambda}(\vec{r}, s) \\ &= \sum_{\lambda} \delta_{\lambda, \lambda'} \\ &= \lambda' \end{aligned}$$

$$\begin{aligned} f(\vec{r}, s) &= \sum_{\lambda} \sum_{\vec{r}', s'} \varphi_{\lambda}^*(\vec{r}', s') f(\vec{r}', s') \varphi_{\lambda}(\vec{r}, s) \\ &= \sum_{\vec{r}', s'} \left[\sum_{\lambda} \varphi_{\lambda}^*(\vec{r}', s') \varphi_{\lambda}(\vec{r}, s) \right] f(\vec{r}', s') \\ &= \sum_{\vec{r}', s'} \delta(\vec{r} - \vec{r}') \delta_{s, s'} f(\vec{r}', s') \end{aligned}$$

2.2 Completeness relation

$$\sum_{\lambda} \varphi_{\lambda}^*(\vec{r}', s) \varphi_{\lambda}(\vec{r}, s) = \delta(\vec{r}' - \vec{r}) \delta_{s, s'} \quad (2.7)$$

Futhermore:

$$\begin{aligned} \{\psi^{\dagger}(x', t), \psi(x, t)\} &= \delta_{x', x} \\ &= \sum_{\lambda_1} \sum_{\lambda_2} \{c_{\lambda_1}^{\dagger}, c_{\lambda_2}\}(\vec{r}, s) \varphi_{\lambda_1}^*(\vec{r}', s) \varphi_{\lambda_2} \end{aligned} \quad (2.8)$$

If $\{c_{\lambda_1}^{\dagger}, c_{\lambda_2}\} = \delta_{\lambda_1, \lambda_2}$ then equation (2.8) is satisfied.

$$\{c_{\lambda_1}^{\dagger}, c_{\lambda_2}\} = \delta_{\lambda_1, \lambda_2} \quad (2.9)$$

In addition:

$$\{\psi^{\dagger}(x', t), \psi^{\dagger}(x, t)\} = 0 \implies \{c_{\lambda'}^{\dagger}, c_{\lambda}\} = 0 \quad (2.10)$$

$$\{\psi(x', t), \psi(x, t)\} = 0 \implies \{c_{\lambda'}, c_{\lambda}\} = 0 \quad (2.11)$$

$$c_{\lambda}^{\dagger} c_{\lambda}^{\dagger} |0\rangle = 0 \quad (2.12)$$

Cannot create more than one fermion in one single-particle state. (Pauli-principle) \implies

$$c_{\lambda} c_{\lambda} |n_{\lambda}\rangle = 0$$

$$\{c_{\lambda_1}^{\dagger}, c_{\lambda_2}\} = \delta_{\lambda_1, \lambda_2}$$

$$\lambda_1 \neq \lambda_2 :$$

$$|n_{\lambda_1} n_{\lambda_2}\rangle = -|n_{\lambda_2} n_{\lambda_1}\rangle$$

A fermionic two-particle sstate is antisymmetric under interchange of the constituent single-particle states.

The next step is now to express operators representing observables in terms of creation and destruction operators. This is called second quantization.

2.3 Operators

Definitions:

1. One-particle operator is an operator representing an observable of the following classical form

$$U = \sum_{i=1}^N U_i(\vec{r}_i, \vec{p}_i). \quad (2.13)$$

U_i depends only on the coordinate and momentum of one particle (\vec{r}_i, \vec{p}_i) .

2. Two-particle operator is an operator representing an observable of the following classical form

$$V = \sum_{i,j} V_{ij}(\vec{r}_i, \vec{p}_i, \vec{r}_j, \vec{p}_j). \quad (2.14)$$

V_{ij} depends on the coordinates and momenta of two particles, (\vec{r}_i, \vec{p}_i) and (\vec{r}_j, \vec{p}_j) . For the situations we will consider V_{ij} will depend only on \vec{r}_i and \vec{r}_j , not \vec{p}_i, \vec{p}_j .

Matrix elements of single-particle operators.

$$\hat{U} |N\rangle = \sum_i \hat{U}_i |N\rangle$$

\hat{U}_i Only works on one element in $|N\rangle$:

$$\hat{U}_i = \hat{U}_i \left| n_{\lambda_1}, \dots, n_{\lambda_i}, \dots, n_{\lambda_N} \right\rangle$$

Works on this element only

Examples of one-particle operators:

1. Kinetic energy T

$$\hat{T} = \sum_{i=1}^N \frac{\hat{p}_i^2}{2m} |N\rangle, \quad (2.15)$$

spin-independent (does not involve spin-coordinate).

2. Crystal potential that electrons move through in a solid

$$\hat{V} = \sum_i \hat{V}_i |N\rangle \quad (2.16)$$

$$\hat{V}_i = \sum_j \hat{V}_{ij}(\vec{r}_i - \vec{R}_j), \quad (2.17)$$

spin-independent, (no spin-coordinate).

\vec{r}_i : Electron-coordinate

\vec{R}_j : Ion-coordinate

The matrix element of a 1-p operator sandwiched between two many-particle states:

$$\begin{aligned}
 \langle N' | \hat{U} | N \rangle &= \sum_i \langle N' | \hat{U}_i | N \rangle \\
 &= \sum_i \left\langle n'_1, \dots, n'_i, \dots, n'_N \left| \hat{U}_i \right| n_1, \dots, n_i, \dots, n_N \right\rangle \\
 &\quad \text{--- i-th element ---} \\
 &= \sum_i \left\langle \tilde{N}' \left| \tilde{N} \right\rangle \langle n'_i | U_i | n_i \rangle \right. \\
 &\quad \left. \left| \tilde{N} \right\rangle = \prod_{k \neq i} |n_k\rangle \right. \\
 &\quad \left. \left| \tilde{N}' \right\rangle = \prod_{k \neq i} |n'_k\rangle \right.
 \end{aligned} \tag{2.18}$$

Normalization:

$$\begin{aligned}
 \frac{\langle N' | \hat{U} | N \rangle}{\langle N' | N \rangle} &= \sum_i \frac{\langle \tilde{N}' | \tilde{N} \rangle}{\langle \tilde{N}' | \tilde{N} \rangle} \cdot \frac{\langle n'_i | \hat{U}_i | n_i \rangle}{\langle n'_i | n_i \rangle} \\
 &= \sum_i \frac{\langle n'_i | \hat{U}_i | n_i \rangle}{\langle n'_i | n_i \rangle}
 \end{aligned} \tag{2.19}$$

One-particle operators are defined by matrix-elements in a one-particle Hilbert-space $\{|n_i\rangle\}$, $i = 1, \dots, N$.

Matrix elements of two-particle operators

$$\hat{V} | N \rangle = \sum_{i,j} \hat{V}_{ij} | n_1, \dots, n_i, \dots, n_j, \dots, n_N \rangle \tag{2.20}$$

Works only on these two elements

Example: Coulomb-interactions

Matrix element:

$$\langle N' | \hat{V} | N \rangle = \sum_{i,j} \langle n'_1, \dots, n'_i, \dots, n'_j, \dots, n'_N | \hat{V}_{ij} | n_1, \dots, n_i, \dots, n_j, \dots, n_N \rangle \tag{2.21}$$

$$= \sum_{i,j} \prod_{k \neq (i,j)} \langle n'_k | n_k \rangle \langle n'_i, n'_j | \hat{V}_{ij} | n_i, n_j \rangle \tag{2.22}$$

Normalization:

$$\frac{\langle N' | \hat{V} | N \rangle}{\langle N' | N \rangle} = \sum_{ij} \frac{\langle n'_i, n'_j | \hat{V}_{ij} | n_i, n_j \rangle}{\langle n'_i, n'_j | n_i, n_j \rangle} \quad (2.23)$$

Matrix elements of two-particle operators are computed in a Hilbert-space of two-particle states.

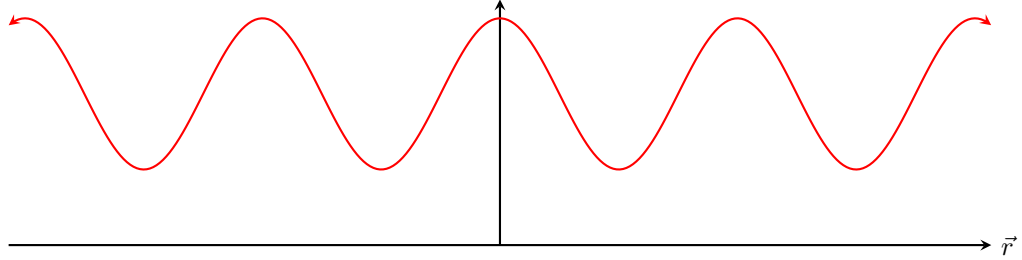
For the 2-particle operators we consider

$$\hat{V}_{ij} = \hat{V}_{ji}, \quad i \neq j \quad (2.24)$$

$$\text{If } i = j \implies \hat{V}_{ij} = 0,$$

because otherwise a 2-particle operator would operate on a 1-particle state, which it does not.

Interacting electron gas in a periodic crystal potential $U(\vec{r})$



$$H = \sum_i \left[\frac{\vec{p}_i^2}{2m} + U(\vec{r}_i) \right] + \sum_{ij} V_{e-e}^C(\vec{r}_i - \vec{r}_j) \quad (2.25)$$

This is, in general, a very hard problem to solve. In particular, it is the Coulomb-term which makes it really hard.

One-particle term:

$$H_1 = \sum_i H_1(\vec{r}_i, \vec{p}_i) \quad (2.26)$$

$$H_1(\vec{r}_i, \vec{p}_i) = \frac{\vec{p}_i^2}{2m} + U(\vec{r}_i) \quad (2.27)$$

Two-particle term:

$$H_2 = \sum_{ij} V_{e-e}^C(\vec{r}_i - \vec{r}_j) \quad (2.28)$$

We will first work out the second-quantized form of the two terms in $H_1(\vec{r}_i, \vec{p}_i)$.

We define $\varphi_\lambda(\vec{r}, s)$ as follows: Solutions to the single-particle Schrödinger-equation

$$H_1 \varphi_\lambda = \varepsilon_\lambda \varphi_\lambda \quad (2.29)$$

$$H_1 = -\frac{\hbar^2}{2m} \vec{\nabla}^2 + U(\vec{r}); \quad \vec{\nabla}^2 : \text{Laplace-operator} \quad (2.30)$$

The task is now to find a second-quantized form of H_1 which will yield the same matrix elements as 2.30.

Consider:

$$\langle \lambda_1 | H_1 | \lambda_2 \rangle; \quad \langle \lambda_1 | \lambda_2 \rangle = \delta_{\lambda_1, \lambda_2} \quad (2.31)$$

Completeness relation:

$$\langle \vec{r}, s | \lambda_1 \rangle = \varphi_{\lambda_1} \quad (\text{some wavefunction})$$

$$\text{Normalized states: } \langle \lambda | \lambda \rangle = 1$$

$$\sum_{\lambda} \varphi_{\lambda}^*(\vec{r}, s) \varphi_{\lambda}(\vec{r}', s') = \delta(\vec{r} - \vec{r}') \delta_{s, s'} \quad (2.32)$$

$$\sum_{\vec{r}, s} \varphi_{\lambda'}^*(\vec{r}, s) \varphi_{\lambda}(\vec{r}, s) = \delta_{\lambda, \lambda'} \quad (2.33)$$

$$\langle \lambda | \lambda' \rangle = \delta_{\lambda, \lambda'} \implies \sum_{\vec{r}, s} |\vec{r}, s\rangle \langle \vec{r}, s| = 1; \quad \sum_x |x\rangle \langle x| = 1 \quad (2.34)$$

Now we use this version of the completeness relations to evaluate the matrix element $\langle \lambda_1 | H_1 | \lambda_2 \rangle$

$$\begin{aligned} \langle \lambda_1 | H_1 | \lambda_2 \rangle &= \sum_{\vec{r}, s} \sum_{\vec{r}', s'} \langle \lambda_1 | \vec{r}, s \rangle \langle \vec{r}, s | H_1 | \vec{r}', s' \rangle \langle \vec{r}' | \lambda_2 \rangle \\ &= \sum_{\vec{r}, s} \sum_{\vec{r}', s'} \varphi_{\lambda_1}^*(\vec{r}, s) \langle \vec{r}, s | H_1 | \vec{r}', s' \rangle \varphi_{\lambda_2}(\vec{r}', s') \end{aligned} \quad (2.35)$$

$$H_1 = \frac{\vec{p}^2}{2m} + U(\vec{r}) \quad \text{Classical} \quad (2.36)$$

$$\vec{p} = \frac{\hbar}{i} \vec{\nabla}; \quad \vec{\nabla} : \text{Gradient operator} \quad (2.37)$$

$$H_1 = -\frac{\hbar^2 \vec{\nabla}^2}{2m} + U(\hat{r}) \quad \text{Quantum mechanical} \quad (2.38)$$

$$U(\hat{r}) |r\rangle = U(\vec{r}) |r\rangle \quad (2.39)$$

\vec{r} : Position : eigenvalue of the position operator

$$\hat{r} |\vec{r}, s\rangle = \vec{r} |\vec{r}, s\rangle \quad (2.40)$$

$$U(\hat{r}) |\vec{r}, s\rangle = U(\vec{r}) |\vec{r}, s\rangle \quad (2.41)$$

$$\langle \vec{r}, s | H_1 | \vec{r}', s' \rangle = \left[-\frac{\hbar^2}{2m} \vec{\nabla}^2 + U(\vec{r}) \right] \delta_{\vec{r}, \vec{r}'} \delta_{s, s'} \quad (2.42)$$

$$\begin{aligned} \langle \lambda_1 | H_1 | \lambda_2 \rangle &= \sum_{\vec{r}, s} \varphi_{\lambda_1}^*(\vec{r}, s) \left[-\frac{\hbar^2}{2m} \vec{\nabla}^2 + U(\vec{r}) \right] \varphi_{\lambda_2}(\vec{r}, s) \\ &\equiv \varepsilon_{\lambda_1, \lambda_2} \end{aligned} \quad (2.43)$$

$\varphi_{\lambda}(\vec{r}, s)$: Some complete set of functions, by assumption.

Let us now give an alternative form of H_1 , which will yield the same matrix elements.

Anzats:

$$H_1 = \sum_{\lambda_1, \lambda_2} h_{\lambda_1, \lambda_2} c_{\lambda_1}^\dagger c_{\lambda_2} \quad (2.44)$$

where h_{λ_1, λ_2} is some complex number. Then:

$$\begin{aligned} \langle \lambda_1 | H_1 | \lambda_2 \rangle &= \langle 0 | c_{\lambda_1} \left(\sum_{\lambda'_1, \lambda'_2} h_{\lambda'_1, \lambda'_2} c_{\lambda'_1}^\dagger c_{\lambda'_2} \right) c_{\lambda_2}^\dagger | 0 \rangle \\ &= \sum_{\lambda'_1, \lambda'_2} h_{\lambda'_1, \lambda'_2} \langle 0 | c_{\lambda_1} c_{\lambda'_1}^\dagger c_{\lambda'_2} c_{\lambda_2}^\dagger | 0 \rangle \\ &= \sum_{\lambda'_1, \lambda'_2} h_{\lambda'_1, \lambda'_2} \langle 0 | (\delta_{\lambda_1, \lambda'_1} - c_{\lambda'_1}^\dagger c_{\lambda_1}) (\delta_{\lambda_2, \lambda'_2} - c_{\lambda'_2}^\dagger c_{\lambda_2}) | 0 \rangle \\ &= \sum_{\lambda'_1, \lambda'_2} h_{\lambda'_1, \lambda'_2} \delta_{\lambda_1, \lambda'_1} \delta_{\lambda_2, \lambda'_2} \langle 0 | 0 \rangle \quad (c_{\lambda} | 0 \rangle = 0) \\ &= h_{\lambda_1, \lambda_2} \end{aligned} \quad (2.45)$$

Choose $h_{\lambda_1, \lambda_2} = \varepsilon_{\lambda_1, \lambda_2} \implies$ Same matrix-elements for

$$H_1 = -\frac{\hbar^2}{2m} \vec{\nabla}^2 + U(\hat{r}) \quad (2.46)$$

and

$$H_1 = \sum_{\lambda_1, \lambda_2} \varepsilon_{\lambda_1, \lambda_2} c_{\lambda_1}^\dagger c_{\lambda_2} \quad (2.47)$$

Thus, 2.47 is a useful 2nd quantized form of H_1 .

This expression may be simplified. Consider now a judicious choice of the complete set $\{\varphi_\lambda(x)\}$:

Let φ_λ be defined by

$$\left(-\frac{\hbar^2}{2m}\vec{\nabla}^2 + U(\vec{r})\right)\varphi_\lambda(x) = \varepsilon_\lambda\varphi_\lambda(x) \quad (2.48)$$

i.e. φ_λ are eigenfunctions of H_1

Then:

$$\begin{aligned} \varepsilon_{\lambda_1, \lambda_2} &= \sum_x \varphi_{\lambda_1}^*(x) \left(-\frac{\hbar^2}{2m}\vec{\nabla}^2 + U(\vec{r})\right) \varphi_{\lambda_2}(x) \\ &= \sum_x \varphi_{\lambda_1}^*(x) \varepsilon_{\lambda_2} \varphi_{\lambda_2}(x) \\ &= \varepsilon_{\lambda_2} \sum_x \varphi_{\lambda_1}^*(x) \varphi_{\lambda_2}(x) \\ &= \varepsilon_{\lambda_2} \delta_{\lambda_1, \lambda_2} \end{aligned} \quad (2.49)$$

giving that,

$$H_1 = \sum_{\lambda_1} \varepsilon_{\lambda_1} c_{\lambda_1}^\dagger c_{\lambda_1} \quad (2.50)$$

This form of H_1 has an intuitively appealing form: $c_{\lambda_1}^\dagger c_{\lambda_1}$ is a number operator. It counts the number of particles in state $|\lambda_1\rangle$.

ε_λ is the single-particle energy in this state. Thus, H_1 is an operator that counts the energy in the system coming from all the possible states of the system.

General one-particle operators:

$$T(x, \vec{p}) = T(x, \frac{\hbar}{i}\vec{\nabla}) \quad (2.51)$$

Could in principle depend on spin-coordinate s !

$$\langle \lambda_1 | T | \lambda_2 \rangle = \sum_x \varphi_{\lambda_1}^*(x) T(x, \frac{\hbar}{i}\vec{\nabla}) \varphi_{\lambda_2}(x) \quad (2.52)$$

$$\begin{aligned} T &= \sum_{\lambda_1, \lambda_2} \langle \lambda_1 | T(x, \vec{p}) | \lambda_2 \rangle c_{\lambda_1}^\dagger c_{\lambda_2} \\ &= \sum_{\lambda_1, \lambda_2} t_{\lambda_1, \lambda_2} c_{\lambda_1}^\dagger c_{\lambda_2} \end{aligned} \quad (2.53)$$

This expression for H_1 and T in second quantized form applies for any choice of sets of quantum numbers λ .

We next proceed by setting up a general form of second quantized form of 2-particle operators.

3 Many-particle perturbation theory

We assume that we are considering a system with a Hamiltonian \mathcal{H} , containing a part \mathcal{H}_0 that we can write the following way

$$\mathcal{H}_0 = \sum_{k,\sigma} \varepsilon_k c_{k\sigma}^\dagger c_{k\sigma} \quad (\text{Fermions}) \quad (3.1)$$

$$\mathcal{H}_0 = \sum_{q,\lambda} \omega_{q\lambda} a_{q\lambda}^\dagger a_{q\lambda} \quad (\text{Bosons}) \quad (3.2)$$

Suppose $\mathcal{H} = \mathcal{H}_0 + V$, and we want to describe the quantitative changes in observables when $\mathcal{H} = \mathcal{H}_0 \rightarrow \mathcal{H}_0 + V$, when we cannot solve the problem with $V \neq 0$ exactly. One then has to resort to more or less systematic approaches.

Examples of V:

i)

$$V = \sum_{k,q,\sigma} g_{q\lambda} \left(a_{-q,\lambda}^\dagger + a_{q,\lambda} \right) c_{k+q,\sigma}^\dagger c_{k,\sigma}$$

ii)

$$V = \sum_{\substack{k,k',q \\ \sigma,\sigma'}} \tilde{V}(q) c_{k+q,\sigma}^\dagger c_{k'-q,\sigma'}^\dagger c_{k',\sigma'} c_{k,\sigma}$$

iii) Hubbard-interaction

iv) etc

3.1 Time-evolution of states

i) Schrödinger-picture:

Operators are time-independent. States are time-dependent.

$$\begin{aligned} \hat{O}(t) &= \hat{O}(0) \\ i \frac{d}{dt} |\psi\rangle &= \mathcal{H} |\psi\rangle \\ |\psi(t)\rangle &= e^{-i\mathcal{H}t} |\psi(0)\rangle \end{aligned}$$

ii) Heisenberg-picture:

Operators are time-dependent. States are time-independent

$$\hat{O}(t) = e^{i\mathcal{H}t} \hat{O}(0) e^{-i\mathcal{H}t} \quad (3.3)$$

$$|\psi(t)\rangle = |\psi(0)\rangle \quad (3.4)$$

Notice that $\langle \psi(0) | \hat{O}(t) | \psi(0) \rangle = \langle \psi(t) | \hat{O}(0) | \psi(t) \rangle$, i.e Matrix-elements are the same in both the Heisenberg- and Schrödinger-picture. This suggests a considerable degree of freedom in choosing how to time-evolve operators and states, and the choice is to some extent dictated by convenience. For developing a (in principle!) systematic perturbation theory for observables in many-body systems, it turns out that a picture which is a hybrid of the Schrödinger- and Heisenberg picture, is convenient. In this picture “most of” the time-evolution the time-evolution is put in the operators, and “a little bit” of the time-evolution is put in the states;

$$\begin{aligned} O(t) &= e^{i\mathcal{H}_0 t} \hat{O}(0) e^{-i\mathcal{H}_0 t} \\ |\psi(t)\rangle &= e^{i\mathcal{H}_0 t} e^{-i\mathcal{H} t} |\psi(0)\rangle. \end{aligned} \quad (3.5)$$

The relations in eq. (3.5) give the same matrix-elements as in the Schrödinger and Heisenberg pictures. The non-trivial operator evolving $|\psi(t)\rangle$ is

$$\begin{aligned} U(t) &= e^{i\mathcal{H}_0 t} e^{-i\mathcal{H} t} \\ |\psi(t)\rangle &= U(t) |\psi(0)\rangle. \end{aligned} \quad (3.6)$$

We would, ideally, like to establish a perturbation series in V in U . Note that in general, $[\mathcal{H}_0, V] \neq 0$ such that

$$e^{-i\mathcal{H}_0 t} e^{i\mathcal{H} t} \neq e^{-iV t}!$$

Proceed as follows:

$$\begin{aligned} \frac{dU(t)}{dt} &= i\mathcal{H}_0 e^{i\mathcal{H}_0 t} e^{-i\mathcal{H} t} - i e^{i\mathcal{H}_0 t} e^{-i\mathcal{H} t} \mathcal{H} \\ &= i e^{i\mathcal{H}_0 t} \underbrace{(\mathcal{H}_0 - \mathcal{H})}_{-V} e^{-i\mathcal{H} t} \\ &= -i \underbrace{e^{i\mathcal{H}_0 t} V e^{-i\mathcal{H}_0 t}}_{V(t)} \underbrace{e^{i\mathcal{H}_0 t} e^{-i\mathcal{H} t}}_{=U(t)} \\ &= -i V(t) U(t) \\ \int_{\tilde{t}}^t dt' \frac{dU(t')}{dt'} &= -i \int_{\tilde{t}}^t dt' V(t') U(t') \\ U(t) &= U(\tilde{t}) - i \int_{\tilde{t}}^t dt' V(t') U(t') \\ U(0) &= 1, \quad \text{Choose } \tilde{t} = 0 \\ U(t) &= 1 - i \int_0^t dt V(t') U(t') \end{aligned}$$

This equation can be solved by iteration to generate a power series in V . This is essentially what we will do, but before doing so, it will be convenient to introduce a slightly more general evolution-operator.

3.2 The S-matrix

The S-matrix is defined as follows:

$$|\psi(t)\rangle = S(t, t') |\psi(t')\rangle$$

$$S(t, 0) = U(t)$$

$$|\psi(t)\rangle = S(t, t') U(t') |\psi(0)\rangle$$

$$U(t) = S(t, t') U(t')$$

$$S(t, t') = U(t) U^\dagger(t')$$

Using that $U^\dagger = U^{-1}$ (by the definition of U) we get

$$S(t, t') = U(t) U^\dagger(t') \quad (3.8)$$

Some properties of S :

i)

$$S(t, t') = 1$$

ii)

$$S^\dagger(t, t') = S(t', t) \quad (3.9)$$

iii)

$$\begin{aligned} |\psi(t)\rangle &= S(t, t') |\psi(t')\rangle \\ &= S(t, t') S(t', t'') |\psi(t'')\rangle \\ &= S(t, t'') |\psi(t'')\rangle \\ S(t, t'') &= S(t, t') S(t', t'') \end{aligned} \quad (3.10)$$

The equation for S is

$$\begin{aligned} \frac{\partial S(t, t')}{\partial t} &= \frac{\partial U}{\partial t} U^\dagger(t') \\ &= -V(t) U(t) U^\dagger(t') \\ &= -iV(t) S(t, t') \\ \int_{\tilde{t}}^t dt'' \frac{\partial S}{\partial t''} &= -i \int_{\tilde{t}}^t dt'' V(t'') S(t'', t') \\ S(t, t') &= S(\tilde{t}, t') - i \int_{\tilde{t}}^t V(t'') S(t'', t') \end{aligned}$$

Now choose $\tilde{t} = t'$ and use that $S(t', t') = 1$ to obtain

$$S(t, t') = 1 - i \int_{t'}^t dt'' V(t'') S(t'', t') \quad (3.11)$$

This we will solve by iteration to produce a power series in V for S . This power-series for S will then generate a power-series in V for any observable.

Iteration:

0th order:

$$S_0(t, t') = 1$$

1st order:

$$\begin{aligned} S_1(t, t') &= 1 - i \int_{t'}^t dt'' V(t'') S_0(t'', t') \\ &= 1 - i \int_{t'}^t dt'' V(t'') \end{aligned}$$

2nd order:

$$\begin{aligned} S_2(t, t') &= 1 - i \int_{t'}^t dt'' V(t'') S_1(t'', t') \\ &= 1 + (-i) \int_{t'}^t dt'' V(t'') + (-i)^2 \int_{t'}^t dt'' V(t'') \int_{t'}^{t''} dt''' V(t''') \end{aligned}$$

Infinite order:

$$S(t, t') = 1 + \sum_{n=1}^{\infty} (-i)^n \int_{t'}^t dt_1 \int_{t'}^{t_1} dt_2 \cdots \int_{t'}^{t_{n-1}} dt_n V(t_1) \cdots V(t_n) \quad (3.12)$$

Note: Lower integration limits are all the same, but the upper ones are different. We will now transform this integral into one where also all upper limits are the same, by introducing the time-ordering operator. \tilde{T} : time-ordering operator for fermions.

$$\tilde{T} [A(t_1) B^\dagger(t_2)] = \begin{cases} A(t_1) B^\dagger(t_2), & t_1 > t_2 \\ -B^\dagger(t_2) A(t_1), & t_2 > t_1 \end{cases} \quad (3.13)$$

Consider now the second-order in V -term in eq. (3.12), and work backwards, starting with

$$\frac{1}{2!} \int_{t'}^t dt_1 \int_{t'}^{t_1} dt_2 \tilde{T}[V(t_1) V(t_2)].$$

For $V(t)$, we assume that it is composed of fermion- or boson-operators in such a way that

$$\tilde{T}[V(t_1) V(t_2)] = \begin{cases} V(t_1) V(t_2), & t_1 > t_2 \\ V(t_2) V(t_1), & t_2 > t_1 \end{cases} \quad (3.14)$$

$$\begin{aligned} &\frac{1}{2!} \int_{t'}^t dt' \int_{t'}^{t_1} dt_2 V(t_1) V(t_2) \\ &+ \frac{1}{2!} \int_{t'}^t dt_1 \int_{t_1}^{t_2} dt_2 V(t_2) V(t_1) \end{aligned}$$

Now let $t_1 \leftrightarrow t_2$ in the second term

$$\Rightarrow \int_{t'}^t dt_1 \int_{t'}^{t_1} dt_2 V(t_1)V(t_2) = \frac{1}{2!} \int_{t'}^t dt_1 \int_{t'}^t dt_2 \tilde{T}[V(t_1)V(t_2)] \quad (3.15)$$

In the same way,

$$\begin{aligned} & \frac{1}{n!} \int_{t'}^t dt_1 \int_{t'}^t dt_2 \cdots \int_{t'}^t dt_n \tilde{T}[V(t_1) \cdots V(t_n)] \\ &= \int_{t'}^t dt_1 \cdots \int_{t'}^{t_{n-1}} dt_n V(t_1) \cdots V(t_n) \end{aligned} \quad (3.16)$$

Thus, we have for $S(t, t')$

$$\begin{aligned} S(t, t') &= 1 + \sum_{n=1}^{\infty} \frac{(-i)^n}{n!} \int_{t'}^t dt_1 \cdots \int_{t'}^t dt_n \tilde{T}[V(t_1) \cdots V(t_n)] \\ &= 1 + \tilde{T} \left\{ \sum_{n=1}^{\infty} \frac{(-i)^n}{n!} \left[\int_{t'}^t dt'' V(t'') \right]^n \right\} \\ &\Rightarrow S(t, t') = \tilde{T} \left[\exp \left\{ -i \int_{t'}^t dt'' V(t'') \right\} \right]. \end{aligned} \quad (3.17)$$

Typically, what we want to compute is some matrix-element of the form

$$\begin{aligned} & \langle \psi(0) | \hat{O}(t) | \psi(0) \rangle && \text{Heisenberg-picture} \\ &= \langle \psi(t) | \hat{O}(0) | \psi(t) \rangle && \text{Schrödinger-picture} \\ &= \langle \psi(t) | O(t) | \psi(t) \rangle && \text{Interaction-picture} \end{aligned} \quad (3.18)$$

where \hat{O} is an operator representing som observable. The main problem is that $|\psi\rangle$ is unknown. What we know how to find, is Φ_0 by

$$\mathcal{H}_0 |\Phi_0\rangle = E_0 |\Phi_0\rangle. \quad (3.19)$$

$|\Phi_0\rangle$: Eigenstate of the non-interacting system. The idea now is to replace $\langle \psi | \hat{O} | \psi \rangle$ with $\langle \Phi_0 | \hat{A} | \Phi_0 \rangle$, where we at least can find a power series in V for \hat{A} . Since Φ_0 is known, the necessary matrix-elements can be computed. It is the S -matrix that will facilitate this replacement. So we need to relate ψ and Φ_0 .

Imagine that at $t = -\infty$ (distant past, “way before the dinosaurs”), $V(t) = 0$. Then $\mathcal{H} = \mathcal{H}_0$, $\mathcal{H} |\psi\rangle = \mathcal{H}_0 |\psi\rangle = E_0 |\Phi_0\rangle$.

$$|\psi(-\infty)\rangle = |\Phi_0\rangle.$$

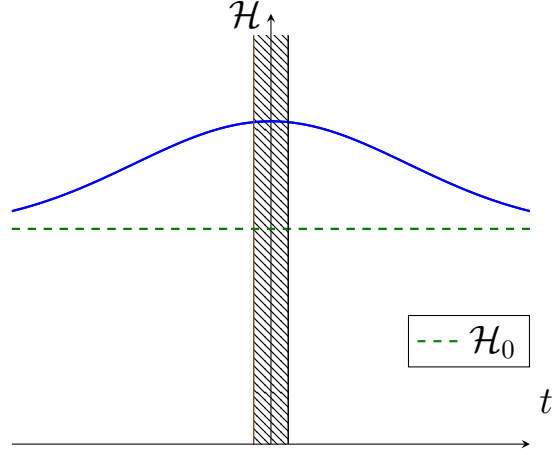


Figure 1: The shaded region represents the time interval of interest.

Next, bring in perturbation adiabatically.

$$\mathcal{H} = \mathcal{H}_0 + V e^{-\varepsilon|t|}$$

For $|t| \ll \varepsilon^{-1}$, $\mathcal{H} = \mathcal{H}_0 + V$, while for $|t| \gg \varepsilon^{-1}$, $\mathcal{H} = \mathcal{H}_0$. **TODO: Sett inn figur her.**

$$|\psi(t)\rangle = S(t, -\infty) |\Phi_0\rangle \quad (3.20)$$

What is $|\psi(+\infty)\rangle$? In the interaction picture, we have

$$\langle\psi(t)|O(t)|\psi(t)\rangle = \langle\Phi_0|S(-\infty, t)O(t)S(t, -\infty)|\Phi_0\rangle \quad (3.21)$$

If the leftmost factor of S had been $S(+\infty, t)$, then $SO(t)S$ would have been time-ordered. Therefore, we will try to bring in $S(+\infty, t)$ on the left, instead of $S(-\infty, t)$. We do this as follows:

$$\begin{aligned} |\psi(\infty)\rangle &= S(\infty, -\infty) |\psi(-\infty)\rangle \\ &= S(\infty, -\infty) |\Phi_0\rangle \\ &= e^{iL} |\Phi_0\rangle \\ \langle\Phi_0|\Phi_0\rangle &= 1 \\ \implies e^{iL} &= \langle\Phi_0|\psi(+\infty)\rangle \\ &= \langle\Phi_0|S(\infty, -\infty)|\Phi_0\rangle \\ |\psi(-\infty)\rangle &= S(-\infty, \infty) |\psi(+\infty)\rangle, \end{aligned}$$

where eq. (3.9) was used in the last step.

NB:

$$|\Phi_0\rangle = e^{iL} S(-\infty, \infty) |\Phi_0\rangle.$$

Now, we have what we need! By inserting $\langle \Phi_0 | = e^{-iL} \langle \Phi_0 | S(\infty, -\infty)$ in eq. (3.21), we get

$$\langle \Phi_0 | S(-\infty, t) O(t) S(t, -\infty) | \Phi_0 \rangle = e^{-iL} \langle \Phi_0 | S(+\infty, t) O(t) S(t, -\infty) | \Phi_0 \rangle$$

and finally

$$\langle \psi(t) | O(t) | \psi(t) \rangle = \frac{\langle \Phi_0 | S(+\infty, t) O(t) S(t, -\infty) | \Phi_0 \rangle}{\langle \Phi_0 | S(\infty, -\infty) | \Phi_0 \rangle} \quad (3.22)$$

with

$$O(t) = e^{i\mathcal{H}_0 t} \hat{O}(0) e^{-i\mathcal{H}_0 t}$$

(as in eq. (3.5)). Perturbation-expansion for $S \implies$ perturbation-expansion for matrix-element of $O(t)$. We also know the states with which to compute the matrix-elements. Notice that we may write

$$S(+\infty, t) O(t) S(t, -\infty)$$

as

$$\tilde{T}[O(t) S(+\infty, t) S(t, -\infty)] = \tilde{T}[O(t) S(\infty, -\infty)].$$

Therefore, we also have

$$\langle \psi(t) | O(t) | \psi(t) \rangle = \frac{\langle \Phi_0 | \tilde{T}[O(t) S(\infty, -\infty)] | \Phi_0 \rangle}{\langle \Phi_0 | S(\infty, -\infty) | \Phi_0 \rangle}. \quad (3.23)$$

Recall the relations for the different pictures eq. (3.18)

$$\begin{aligned} \langle \psi(0) | \hat{O}(t) | \psi(0) \rangle & \quad \text{Heisenberg-picture} \\ = \langle \psi(t) | \hat{O}(0) | \psi(t) \rangle & \quad \text{Schrödinger-picture} \\ = \langle \psi(t) | O(t) | \psi(t) \rangle & \quad \text{Interaction-picture.} \end{aligned}$$

The above was done for an operator $O(t)$ working at one time t . We need to generalize this to a product of operators working at different times t . To accomplish this, it is best to start in the Heisenberg-picture (otherwise, which times to use in $|\psi(t)\rangle$?

$$\begin{aligned} \hat{O}(t_i) &= e^{i\mathcal{H}t_i} \hat{O}(0) e^{-i\mathcal{H}t_i} \\ &= e^{i\mathcal{H}t_i} e^{-i\mathcal{H}_0 t_i} e^{i\mathcal{H}_0 t_i} \hat{O}(0) e^{-i\mathcal{H}_0 t_i} e^{i\mathcal{H}_0 t_i} e^{-i\mathcal{H}t_i} \\ &= U^\dagger(t_i) O(t_i) O(t_i) \\ &= S^\dagger(t_i, 0) O(t_i) S(t_i, 0) \\ &= \underline{S(0, t_i) O(t_i) S(t_i, 0)} \end{aligned} \quad (3.24)$$

$$\begin{aligned}
\hat{O}(t_1)\hat{O}(t_2) &= S(0, t_1)O(t_1) \underbrace{S(t_1, 0)S(0, t_2)}_{=S(t_1, t_2)} O(t_2)S(t_2, 0) \\
&= S(0, t_1)O(t_1)S(t_1, t_2)O(t_2)S(t_2, 0)
\end{aligned} \tag{3.25}$$

$$\begin{aligned}
\tilde{T}[\hat{O}(t_1)\hat{O}(t_2)] &= \tilde{T}[O(t_1)O(t_2) \underbrace{S(0, t_1)S(t_1, t_2)S(t_2, 0)}_{=S(0, 0)=1}] \\
&= \tilde{T}[O(t_1)O(t_2)]
\end{aligned} \tag{3.26}$$

This generalises to an arbitrary number of operators. Finally, we therefore have

$$\langle \psi(0) | \tilde{T}[\hat{O}_1(t_1) \dots \hat{O}_n(t_n)] | \psi(0) \rangle = \frac{\langle \Phi_0 | \tilde{T}[O_1(t_1) \dots O_n(t_n)S(\infty, -\infty)] | \Phi_0 \rangle}{\langle \Phi_0 | S(\infty, -\infty) | \Phi_0 \rangle} \tag{3.27}$$

So also the expectation values of such more complicated objects have a perturbation series generated by the perturbation series for S . **Equation (3.27) applies to bosons as well as fermions.** We are now set to compute expectation values of any observable in a systematic perturbation expansion. We will focus on a particularly important quantity, namely the **single-particle Green's function**. This quantity is extremely important, since it gives direct information about the exact excitation spectrum of for instance electrons or magnetic excitations, and can be measured with a number of well-established highly accurate and sophisticated techniques. Examples of such techniques are

1. Small-angle neutron scattering (SANS)
2. Angle-resolved photoemmission spectroscopy (ARPES)
3. Tunneling Electron Microscopy (TEM)
4. etc.

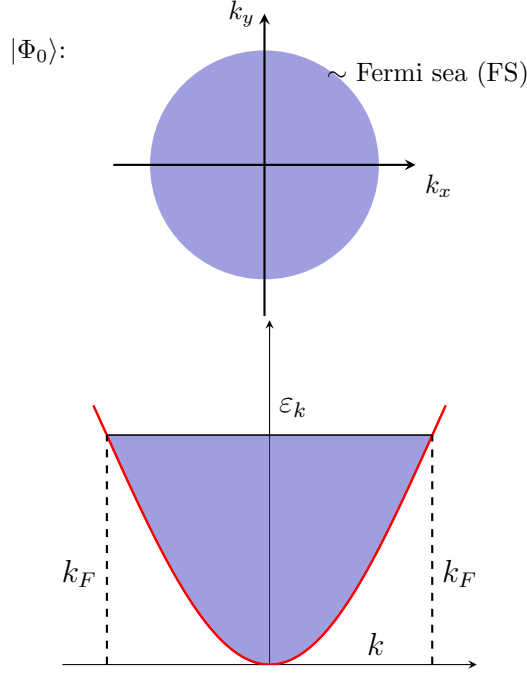
3.3 Single-particle Green's function

Let $(c_\lambda^\dagger, c_\lambda)$ be the creation or destruction operator for a fermion or boson in state λ . Define the single-particle Green's function $G(\lambda_1, t_1; \lambda_2, t_2)$ as follows

$$G(\lambda_1, t_1; \lambda_2, t_2) \equiv -i \langle \psi(0) | \tilde{T}[\hat{c}_{\lambda_2}(t_2)\hat{c}_{\lambda_1}^\dagger(t_1)] | \psi(0) \rangle \tag{3.28}$$

Notice that the basic formulation is in the Heisenberg-picture, since G involves a time-ordered product of operators (at different times). Using our general result in eq. (3.27), we immediately formulate G as

$$G(\lambda_1, t_1; \lambda_2, t_2) = -i \frac{\langle \Phi_0 | \tilde{T}[c_{\lambda_2}(t_2)c_{\lambda_1}^\dagger(t_1)S(\infty, -\infty)] | \Phi_0 \rangle}{\langle \Phi_0 | S(\infty, -\infty) | \Phi_0 \rangle}. \tag{3.29}$$



(a) States are filled up to the energy ε_F at $k = k_F$ according to the Pauli-principle.

Physical interpretation of G : It is the probability amplitude that if a particle is created in state λ_1 at time t_1 , it is found in state λ_2 at time t_2 . Green's function for the **non-interacting case**: $G_0(\lambda_1, t_1; \lambda_2, t_2)$. To get some more intuition for what G means, let us compute G_0 explicitly.

$$V = 0 \implies S(t, t') = 1 \implies$$

$$G_0(\lambda_1, t_1; \lambda_2, t_2) = -i \langle \Phi_0 | \tilde{T} [c_{\lambda_2}(t_2) c_{\lambda_1}^\dagger(t_1)] | \Phi_0 \rangle \quad (3.30)$$

$$c_\lambda(t) = e^{i\mathcal{H}_0 t} c_\lambda e^{-i\mathcal{H}_0 t} \quad (3.31)$$

$$c_\lambda^\dagger(t) = e^{i\mathcal{H}_0 t} c_\lambda^\dagger e^{-i\mathcal{H}_0 t} \quad (3.32)$$

$$\mathcal{H}_0 |\Phi_0\rangle = E_0 |\Phi_0\rangle \quad (3.33)$$

To proceed further, we now have to treat fermions and bosons separately, both because of the different effects \tilde{T} has, but also because of the vast difference in $|\Phi_0\rangle$.

3.3.1 Fermions

$\lambda = \mathbf{k}, \sigma$

$$\mathcal{H}_0 = \sum_{\mathbf{k}, \sigma} \varepsilon_{\mathbf{k}} c_{\mathbf{k}\sigma}^\dagger c_{\mathbf{k}\sigma} \quad (3.34)$$

i) Consider first $t_2 > t_1$:

$$\begin{aligned}
G_0(\lambda_1, t_1, \lambda_2, t_2) &= -i\theta(t_2 - t_1) \langle \Phi_0 | c_{k_2, \sigma_2}(t_2) c_{k_1, \sigma_1}^\dagger(t_1) | \Phi_0 \rangle \\
&= -i\theta(t_2 - t_1) \langle \Phi_0 | e^{i\mathcal{H}_0 t_2} c_{k_2, \sigma_2} e^{-i\mathcal{H}_0 t_2} e^{i\mathcal{H}_0 t_1} c_{k_1, \sigma_1}^\dagger e^{-i\mathcal{H}_0 t_1} | \Phi_0 \rangle \\
&= -i\theta(t_2 - t_1) \langle \Phi_0 | e^{i(E_0 + \varepsilon_{k_1} - \varepsilon_{k_2})t_2} c_{k_2, \sigma_2} e^{-i(E_0 + \varepsilon_{k_1})t_2} e^{i(E_0 + \varepsilon_{k_1})t_1} c_{k_1, \sigma_1}^\dagger e^{-E_0 t_1} | \Phi_0 \rangle \\
&= -i\theta(t_2 - t_1) e^{i(\varepsilon_{k_1} - \varepsilon_{k_2})t_2} e^{-i\varepsilon_{k_1}(t_2 - t_1)} \underbrace{\langle \Phi_0 | c_{k_2, \sigma_2} c_{k_1, \sigma_1}^\dagger | \Phi_0 \rangle}_{\delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \theta(\varepsilon_{k_1} - \varepsilon_{k_F})} \\
&= -i\theta(t_2 - t_1) e^{-i\varepsilon_{k_1}(t_2 - t_1)} \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \theta(\varepsilon_{k_1} - \varepsilon_{k_F})
\end{aligned}$$

ii) $t_1 > t_2$:

$$\begin{aligned}
G_0(\lambda_1, t_1, \lambda_2, t_2) &= -i\theta(t_1 - t_2)(-1) \langle \Phi_0 | c_{k_1, \sigma_1}^\dagger(t_1) c_{k_2, \sigma_2}(t_2) | \Phi_0 \rangle \\
&= i\theta(t_1 - t_2) \langle \Phi_0 | e^{i\mathcal{H}_0 t_1} c_{k_1, \sigma_1}^\dagger e^{-i\mathcal{H}_0 t_1} e^{i\mathcal{H}_0 t_2} c_{k_2, \sigma_2} e^{-i\mathcal{H}_0 t_2} | \Phi_0 \rangle \\
&= i\theta(t_1 - t_2) \langle \Phi_0 | e^{i(E_0 + \varepsilon_{k_1} - \varepsilon_{k_2})t_1} c_{k_1, \sigma_1}^\dagger e^{-i(E_0 - \varepsilon_{k_2})t_1} e^{i(E_0 - \varepsilon_{k_2})t_2} c_{k_2, \sigma_2} e^{-E_0 t_2} | \Phi_0 \rangle \\
&= i\theta(t_1 - t_2) e^{i\varepsilon_{k_1} t_1} e^{-i\varepsilon_{k_2} t_2} \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \theta(\varepsilon_{k_F} - \varepsilon_{k_1}) \\
&= i\theta(t_1 - t_2) \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \theta(\varepsilon_{k_F} - \varepsilon_{k_1}) e^{-i\varepsilon_{k_1}(t_2 - t_1)}
\end{aligned}$$

Therefore,

$$\begin{aligned}
G_0(k_1 \sigma_1, t_1; k_2 \sigma_2, t_2) &= -i\theta(t_2 - t_1) \theta(\varepsilon_{k_1} - \varepsilon_{k_F}) \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} e^{-i\varepsilon_{k_1}(t_2 - t_1)} \\
&\quad + i\theta(t_1 - t_2) \theta(\varepsilon_{k_F} - \varepsilon_{k_1}) \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} e^{-i\varepsilon_{k_1}(t_2 - t_1)} \quad (3.35)
\end{aligned}$$

This is a rather unwieldy expression, so to simplify a bit, we set $t_2 - t_1 = t$ and introduce Fourier-transformed G_0 .

$$\begin{aligned}
G_0(k_1 \sigma_1; k_2 \sigma_2; \omega) &= \int_{-\infty}^{\infty} dt G_0(k_1 \sigma_1; k_2 \sigma_2; t) e^{i\omega t} \\
&= -i\theta(\varepsilon_{k_1} - \varepsilon_{k_F}) \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \int_0^{\infty} dt e^{-i\varepsilon_{k_1} t} \underbrace{e^{-\delta t}}_{\delta=0^+} e^{i\omega t} \\
&\quad + i\theta(\varepsilon_{k_F} - \varepsilon_{k_1}) \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \int_{-\infty}^0 dt e^{-i\varepsilon_{k_1} t} \underbrace{e^{\delta t}}_{\delta=0^+} e^{i\omega t} \\
&= -i\theta(\varepsilon_{k_1} - \varepsilon_{k_F}) \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \int_0^{\infty} dt e^{i(\omega - \varepsilon_{k_1} + i\delta)t} \\
&\quad + i\theta(\varepsilon_{k_F} - \varepsilon_{k_1}) \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \int_{-\infty}^0 dt e^{i(\omega - \varepsilon_{k_1} - i\delta)t} \\
&= \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \left(\frac{\theta(\varepsilon_{k_1} - \varepsilon_{k_F})}{\omega - \varepsilon_{k_1} + i\delta} + \frac{\theta(\varepsilon_{k_F} - \varepsilon_{k_1})}{\omega - \varepsilon_{k_1} - i\delta} \right)
\end{aligned}$$

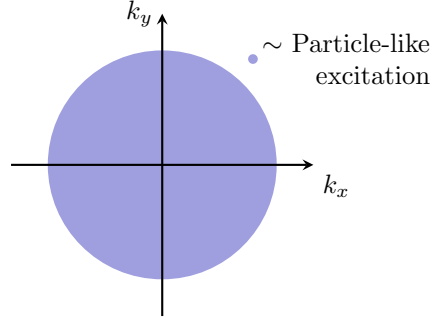


Figure 3: Particle excitation above the Fermi-surface.

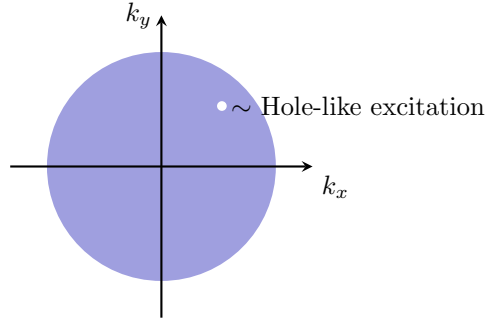


Figure 4: Hole excitation below the Fermi-surface.

- The first term in the Green's function involves excitations above the Fermi-surface (particles), depicted in fig. 3. Particle created first, then destroyed later. Particle moves forward in time. This is seen directly from the expression for G_0 in the time-domain, eq. (3.35), when $t_2 > t_1$ (particle created first at time t_1 , then destroyed later at time t_2).
- The second term in the Green's function involves excitations below the Fermi-surface (holes), depicted in fig. 4. Particle destroyed first, then created later. Particle moves backwards in time. This is again seen directly in eq. (3.35).
- The part of G_0 that moves a particle forward in time is often referred to as a retarded Green's function G_0^R .
- The part of G_0 that moves a particle backwards in time is often referred to as a advanced Green's function G_0^A .

$$G_0^R(k_1, \sigma_1; k_2, \sigma_2; \omega) = \frac{\theta(\varepsilon_{k_1} - \varepsilon_F)}{\omega - \varepsilon_{k_1} + i\delta} \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \quad (3.36)$$

$$G_0^A(k_1, \sigma_1; k_2, \sigma_2; \omega) = \frac{\theta(\varepsilon_F - \varepsilon_{k_1})}{\omega - \varepsilon_{k_1} - i\delta} \delta_{k_1 k_2} \delta_{\sigma_1 \sigma_2} \quad (3.37)$$

With the understanding that in G_0 , we must have $k_1 = k_2$; $\sigma_1 = \sigma_2$ and $\varepsilon_{k_1} > \varepsilon_F$ in G^R , $\varepsilon_{k_1} < \varepsilon_F$ in G^A , we may write

$$G_0^R(k, \omega) = \frac{1}{\omega - \varepsilon_k + i\delta} \quad (3.38)$$

$$G_0^A(k, \omega) = \frac{1}{\omega - \varepsilon_k - i\delta}, \quad (3.39)$$

which is summarized by

$$G_0(k, \omega) = \frac{1}{\omega - \varepsilon_k + i\delta_k}, \quad (3.40)$$

where $\delta_k = \delta \text{sign}(\varepsilon_k - \varepsilon_F)$.

Note that the single-particle excitation energies appear as simple poles in the Green's function!

To get a bit more perspective on things, consider $G_0^R(k, \omega)$ a bit further. $G_{0,R}^{-1} = \omega - \varepsilon_k + i\delta$ Imagine that we now introduce $V \neq 0$. What will happen is that the excitation spectrum ε_k will change, due to the perturbation $G_{0R}^{-1} \rightarrow G_R^{-1}(k, \omega)$.

$$G_R^{-1}(k, \omega) = \omega - \varepsilon_k - \Sigma(k, \omega), \quad (3.41)$$

$$\Sigma(k, \omega) = \Sigma_{\text{Re}}(k, \omega) + i\Sigma_{\text{Im}}(k, \omega).$$

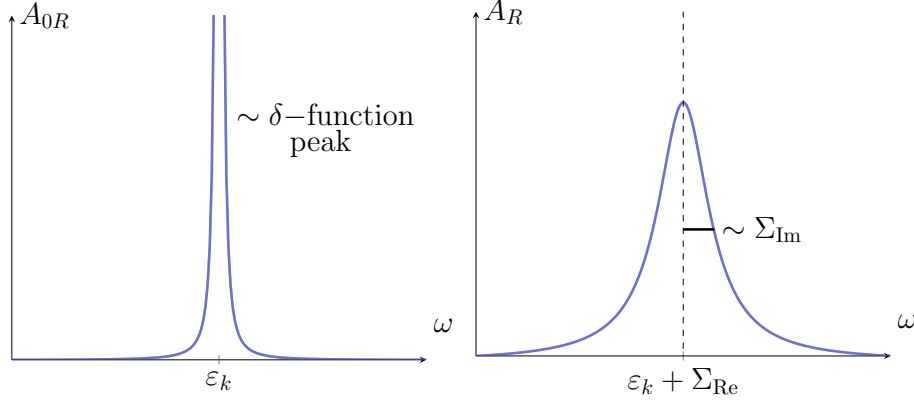
$\Sigma_{\text{Re}} :$	Real part of Σ
$\Sigma_{\text{Im}} :$	Imaginary part of Σ

Physical interpretation of G_R : Create a particle in (k, σ) at $t = 0$. What is the probability amplitude of finding the particle in the same state at $t > 0$?
Answer: G_R . $\Sigma(k, \omega)$ is the single particle self-energy. Note: $G_R^{-1} = G_{0R}^{-1} - \Sigma$

$$\begin{aligned} G_R &= \frac{1}{G_{0R}^{-1} - \Sigma} = \frac{G_{0R}}{1 - G_{0R}\Sigma} \\ &= G_{0R} + G_{0R}\Sigma G_{0R} + G_{0R}\Sigma G_{0R}\Sigma G_{0R} + \dots \end{aligned}$$

We can generate a perturbation expansion for G_R by a much simpler perturbation expansion for Σ ! Define the spectral weight $A_R(k, \omega)$

$$A_R(k, \omega) = -\frac{1}{\pi} \text{Im}\{G_R(k, \omega)\} \quad (3.42)$$



(a) Non-interacting system.

(b) Interacting system.

Figure 5: Spectral weights for both interacting and non-interacting system.

This is the quantity one measures in ARPES

$$A_R(k, \omega) = -\frac{1}{\pi} \frac{\Sigma_{\text{Im}}}{(\omega - \varepsilon_k - \Sigma_{\text{Re}})^2 - \Sigma_{\text{Im}}^2} \quad (3.43)$$

In the non-interacting case: $\Sigma_{\text{Im}} = 0, \Sigma_{\text{Im}} = -\delta; \delta = 0^+$

$$A_{0R}(k, \omega) = -\frac{1}{\pi} \frac{-\delta}{(\omega - \varepsilon_k)^2 + \delta^2} = \delta(\omega - \varepsilon_k), \quad (3.44)$$

which is a Dirac δ -function, shown in fig. 5a. Send in photons of different energies and momenta to map out ε_k . For $V \neq 0$: Peak position is shifted, narrow peak is broadened, as shown in fig. 5b. From maximum in peak: $\varepsilon_k + \Sigma_{\text{Re}} = \tilde{\varepsilon}_k$. From width of peak: Σ_{Im} . $\Sigma = \Sigma_{\text{Re}} + i\Sigma_{\text{Im}}$. Σ_{Re} and Σ_{Im} are related via the Kramers-Kronig relations

$$\Sigma_R(k, \omega) = \frac{1}{\pi} \mathcal{P} \int_{-\infty}^{\infty} d\omega' \frac{\Sigma_{\text{Im}}(k, \omega')}{\omega' - \omega}. \quad (3.45)$$

Therefore, from width of peak $\rightarrow \Sigma_{\text{Im}}$. From Kramers-Kronig: Σ_{Re} . This allows an ARPES experiment to uniquely determine both Σ_{Im} and Σ_{Re} from one measurement, and thus to back out the many-body effect in $\tilde{\varepsilon}_k$, the quasiparticle excitation spectrum. Note: For Kramers-Kronig to hold, $\Sigma(k, \omega)$ need to be analytic in the upper half-plane when ω is viewed as a complex variable. Moreover, Σ must fall off faster than $\frac{1}{|\omega|}$ when $|\omega| \rightarrow \infty$. For the perturbations we will consider, this will be the case.

Our goal will therefore be to compute Σ in many-body perturbation theory.

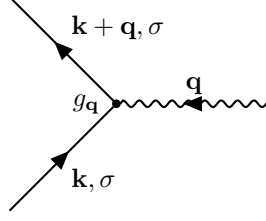


Figure 6: Diagram of electron-phonon vertex

Before we go into this, it will be turn out to be necessary to also consider bosonic Green's functions, and we start with the non-interacting case

3.3.2 Bosons

$$\begin{aligned} D(q, t - t') &= -i \langle \Psi(0) | \tilde{T} [\hat{A}_q(t) \hat{A}_q^\dagger(t')] | \Psi(0) \rangle \\ &= -i \frac{\langle \Phi_0 | \tilde{T} [\hat{A}_q(t) \hat{A}_q^\dagger(t')] S(\infty, -\infty) | \Phi_0 \rangle}{\langle \Phi_0 | S(\infty, -\infty) | \Phi_0 \rangle}. \end{aligned}$$

$|\Phi_0\rangle$: Unperturbed ground state of bosonic system.

$$D_0(q, t - t') = -i \langle \Phi_0 | \tilde{T} [\hat{A}_q(t) \hat{A}_q^\dagger(t')] | \Phi_0 \rangle. \quad (3.46)$$

Retarded boson-propagator: $t' < t$. Advanced boson-propagator: $t' > t$. At $T = 0$, the lowest energy state is occupied by all bosons (material particles), or there are no bosons.

4 Quasi-particles in interacting electron-systems. Fermi-liquids.

4.1 Fermi-liquids

4.2 Screening of the Coulomb-interaction

4.3 Phonon mediated electron-electron interaction

Due to the electron-phonon coupling depicted in fig. 6, we will get an effective phonon-mediated interaction between electrons, depicted in fig. 7

This is an exchange of a virtual phonon. The above diagram is the effective interaction to second order in g_q if we regard the wavy line $\sim\sim\sim$ as a bare phonon Green's function. We could also imagine that we replaced this by

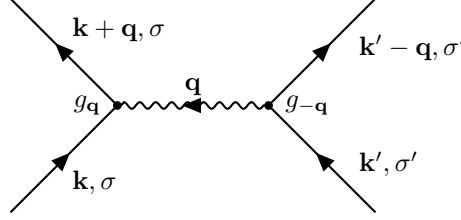
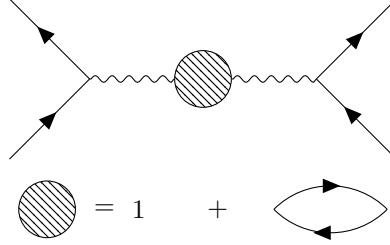


Figure 7: Diagram of the effective electron-phonon interaction



which would include an effective interaction computed correctly up to order $\mathcal{O}(g^4)$. In fact, we might replace $D_0 + D_0\Pi D_0 + \dots$ by $D!$ Thus computing the effective interaction up to infinite order in g . Another, often used approach would be to replace \sim by **TODO: SETT INN DIAGRAM**

Here, we have resummed a subset of diagrams to infinite order in g in order to get an effective interaction between electrons. Under the assumption that g is weak, we will keep terms only to $\mathcal{O}(g^2)$.

$$V_{\text{eff}}(q, \omega) = |g_q|^2 \frac{2\omega_q}{\omega^2 - \omega_q^2} \quad (4.1)$$

Thus, the interaction part of the Hamiltonian becomes

$$\mathcal{H} = \sum_{\substack{k, k', q \\ \sigma, \sigma'}} V_{\text{tot}}(q, \omega) c_{k+q, \sigma}^\dagger c_{k', \sigma'}^\dagger c_{k', \sigma'} c_{k, \sigma} \quad (4.2)$$

$$V_{\text{tot}}(q, \omega) = \frac{e^2}{4\pi\epsilon q^2} + V_{\text{eff}}(q, \omega), \quad (4.3)$$

where the first term is the Coulomb-interaction. Furthermore, ω is the energy transfer between scattering electrons when they exchange a phonon

$$\omega = \epsilon_{k+q} - \epsilon_k \quad (4.4)$$

TODO: Sett inn figur

Note the singularities in V_{tot} when $|\omega| \rightarrow \omega_q$. In particular, note the negative singularity when $|\omega| \rightarrow \omega_q^-$. This singularity persists when Coulomb-repulsion is included. For most frequencies, the Coulomb-interaction completely dominates.

However, in a narrow ω -region close to ω_q , the extremely weak electron-phonon coupling will always beat the Coulomb-interaction! This frequency is slightly smaller than ω_q . For small ω , V_{tot} is repulsive. For large ω , V_{tot} is repulsive. For $|\omega| \lesssim \omega_q$, V_{tot} is attractive.

Let us try to give a physical picture for this: When an electron moves past an ion, they interact. The electron pulls slightly on the heavy, positively charged ion. Electrons are light, and move much faster than the heavy ions. The electron thus moves quickly out of the scattering zone, while the ion relaxes slowly back to its equilibrium position. The ion in its out-of-equilibrium position represents excessive positive charge in that position, which can pull another electron towards it. This is effectively a charge-dipole interaction. If the second electron “waits” a little for the first electron to get away (thus reducing Coulomb-repulsion) but does not wait for too long (such that the ion has relaxed back to its equilibrium position), then the second electron can be attracted to the scattering region. Effectively, the second electron is attracted to the scattering region because the first electron was there. This is an effective electron-electron attraction. It only works if the electron waits a little, but not for too long. A minimum time corresponds to a maximum frequency, while a maximum time corresponds to a minimum frequency. This implies that V_{tot} is attractive if $\omega_{\text{min}} < \omega < \omega_{\text{max}}$, as depicted in **TODO: Sett in figurer og referanse til figuren (s.7)** We may view the effective electron-electron attraction as a result of an electron locally deforming an elastic medium. Think of a rubber membrane that you put a little metal sphere on. The membrane is stretched, dipping down where you put the first sphere. If you put another little sphere on the membrane, it will fall into the dip, i.e. it will be attracted to the first particle. This is also how gravity works: A mass deforms space-time (an elastic medium) and thus attracts another mass.

Disclaimer: The above two analogs are classical. There will be an important quantum effect coming into play here, which we will come back to. here, it will suffice to not that, classically, one can keep adding particles to the dip, such that all particles will be gathered in the same one, forming a large heavy object. This is not how it works quantum mechanically with fermions. Note also that in V_{tot} , and the two different simplified models for \bar{V} , they are only attractive up to a maximum ω , i.e. only after a minimum amount of time. The second particle has to wait a minimum amount of time for the interaction to be attractive. This is called retardation.

The electrons avoid the Coulomb-interactions by avoiding each other, not in space, but in time.

4.4 Magnon mediated electron-electron interaction

We have seen how a boson (a phonon) with a linear coupling to electrons could give an effective attractive interaction among electrons. What if we couple the electrons linearly to other bosons? One obvious thing to investigate, is to con-

sider the coupling of electrons to magnons. For simplicity, we consider itinerant electrons coupled to spin-fluctuations in a ferromagnetic insulator. (FMI) The question is if the spin-fluctuations of the FMI can give rise to an attractive interaction among electrons. We therefore consider a system of itinerant electrons with Hamiltonian

$$\mathcal{H}_{\text{el}} = \sum_{k,\sigma} (\varepsilon_k - \mu) c_{k\sigma}^\dagger c_{k\sigma}. \quad (4.5)$$

In this system, we envisage a regular lattice of localized spins with ferromagnetic coupling, with Hamiltonian

$$\mathcal{H}_{\text{spin}} = -J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j. \quad (4.6)$$

The localized spins are denoted by capital letter \mathbf{S} . The coupling between the localized spins (FMI) and the itinerant electron spins \mathbf{s}_i (lower case) is given by

$$\mathcal{H}_{\text{el-spin}} = -J_{sd} \sum_i \mathbf{S}_i \cdot \mathbf{s}_i. \quad (4.7)$$

As a minimal model, we have assumed that the electrons are hopping around on the same regular lattice that the localized spins are located. Using the Holstein-Primakoff transformation, ignoring the classical ground-state energy, and expressing operators in momentum space, we have

$$\mathcal{H}_{\text{spin}} = \sum_q \omega_q a_q^\dagger a_q \quad (4.8)$$

$$\omega_q = 2JS(z - \gamma(\mathbf{q})) \quad (4.9)$$

$$\gamma(\mathbf{q}) = \sum_\delta e^{i\mathbf{q} \cdot \delta}, \quad (4.10)$$

where δ connects site i to all its nearest neighbors. One important fact to note of at once, is that $\omega_q \sim q^2$ for small q . For the phonon-case, with acoustical phonons, $\omega_q \sim q$. Thus ω_q for small q is much smaller for ferromagnetic magnons than acoustical phonons. We will return to this point. Consider next the electron-spin coupling:

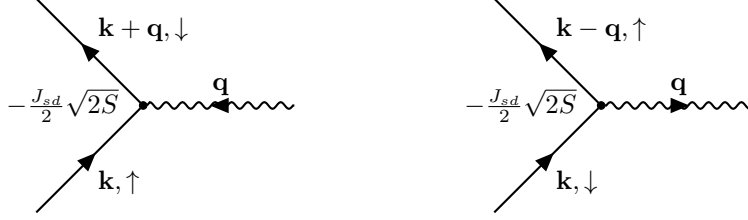
$$\mathcal{H}_{\text{el-spin}} = -J_{sd} \sum_i \mathbf{S}_i \cdot \mathbf{s}_i \quad (4.11)$$

$$= -J_{sd} \sum_i (S_{iz}s_{iz} + S_{ix}s_{ix} + S_{iy}s_{iy}) \quad (4.12)$$

$$= -J_{sd} \sum_i \left(S_{iz}s_{iz} + \frac{1}{2} (S_{i+}s_{i-} + S_{i-}s_{i+}) \right), \quad (4.13)$$

where $S_{i\pm} = S_{ix} \pm iS_{iy}$, $S_{iz} = S - a_i^\dagger a_i$, $S_{i+} = \sqrt{2S}a_i$, $S_{i-} = \sqrt{2S}a_i^\dagger$. $\mathbf{s}_i = \frac{1}{2}c_{i\alpha}^\dagger \vec{\sigma}_{\alpha\beta} c_{i\beta}$ with implicit summation over repeated indices α, β .

$$\Rightarrow s_{iz} = \frac{1}{2}(c_{i\uparrow}^\dagger c_{i\uparrow} - c_{i\downarrow}^\dagger c_{i\downarrow}) = \frac{1}{2} \sum_\sigma \sigma c_{i\sigma}^\dagger c_{i\sigma}$$



(a) Spin-1 magnon is dumped into electron, flipping $\downarrow \rightarrow \uparrow$ (b) Spin-1 magnon is excited, taking with it a spin-1, flipping $\uparrow \rightarrow \downarrow$

Figure 8: The two interaction vertices of interest

$$\begin{aligned} \sigma^x &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} & \sigma^y &= \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} & \sigma^z &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \\ \sigma^\pm &= \sigma^z \pm i\sigma^y & \sigma^+ &= \begin{pmatrix} 0 & 2 \\ 0 & 0 \end{pmatrix} & \sigma^- &= \begin{pmatrix} 0 & 0 \\ 2 & 0 \end{pmatrix} \end{aligned}$$

Thus, we have

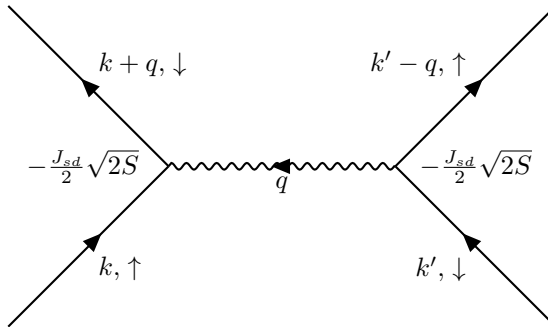
$$\begin{aligned} \mathcal{H}_{\text{el-spin}} &= -J_{sd}S \sum_{i,\sigma} \sigma c_{i\sigma}^\dagger c_{i\sigma} + J_{sd} \sum_{i,\sigma} \sigma a_i^\dagger a_i c_{i\sigma}^\dagger c_{i\sigma} \\ &\quad - \frac{J_{sd}\sqrt{2S}}{2} \sum_i \left(a_i c_{i\downarrow}^\dagger c_{i\uparrow} + a_i^\dagger c_{i\uparrow}^\dagger c_{i\downarrow} \right) \end{aligned} \quad (4.14)$$

For the remainder of the calculation, we focus on the linear coupling of magnons to electrons, and ignore the second term. Thus, we focus on el-el interaction mediated by the vertices in fig. 8.

The Hamiltonian is then

$$H = \sum_{k,\sigma} (\varepsilon_k - \mu - JS\sigma) c_{k\sigma}^\dagger c_{k\sigma} + \sum_q \omega_q a_q^\dagger a_q - \frac{J_{sd}}{2} \sqrt{2S} \sum_{k,q} \left(a_q c_{k+q,\downarrow}^\dagger c_{k\uparrow} + a_q^\dagger c_{k-q,\uparrow}^\dagger c_{k,\downarrow} \right).$$

The effective interaction mediated by this coupling, will be to second order in J_{sd} :



$$V_{eff}(q, \omega) = \left(-\frac{J_{sd}}{2} \sqrt{2S} \right)^2 D_0(q, \omega) \quad (4.15)$$

$D_0(q, \omega)$: Free magnon Green's function. Note that $\omega = \varepsilon_{k+q\downarrow} - \varepsilon_{k\uparrow} = \varepsilon_{k'\downarrow} - \varepsilon_{k'-q\uparrow}$, where $\varepsilon_{k\sigma} = \varepsilon_k - \mu - JS\sigma$. Thus

$$\omega = \varepsilon_{k+q} - \varepsilon_k + 2JS = \varepsilon_{k'} - \varepsilon_{k'-q} + 2JS. \quad (4.16)$$

$2JS$ acts like a magnetic field, $q \rightarrow 0 \rightarrow |\omega| \rightarrow 2JS$. This fact also suppresses attractive interactions, since it increases the denominator of V_{eff} .

$$\begin{aligned} D_0(q, \omega) &= -i \langle \varphi_0 | T[a_q(t) a_q^\dagger(t')] | \varphi_0 \rangle \\ a_q(t) &= e^{i\mathcal{H}_0 t} a_q e^{-i\mathcal{H}_0 t} \\ a_q^\dagger &= e^{i\mathcal{H}_0 t'} a_q^\dagger e^{-i\mathcal{H}_0 t'} \\ \mathcal{H}_0 &= \sum_q \omega_q a_q^\dagger a_q \end{aligned}$$

where time-evolution is expressed in the interaction picture. Formally, this is exactly the same as for the phonon Green's function, and hence

$$V_{eff}(q, \omega) = \left(-\frac{J_{sd}}{2} \sqrt{2S} \right)^2 \frac{2\omega_q^2}{\omega^2 - \omega_q^2}, \quad (4.17)$$

which is an attractive interaction if $|\omega| < |\omega_q|$.

Recall what we found with phonons: phonon-mediated el-el interactions was found to be

$$V_{eff}(q, \omega) = |g_q|^2 \frac{2\omega_q^2}{\omega^2 - \omega_q^2}. \quad (4.18)$$

There are a couple of notable differences between these two results:

- The coupling constant $-\frac{J_{sd}}{2} \sqrt{2S}$ for magnons is constant for $q \rightarrow 0$. The coupling constant g_q for phonons go to 0 as $q \rightarrow 0$. For optical phonons, it vanishes $\sim q$. For acoustical phonons it vanishes $\sim \sqrt{q}$. The acoustical phonons are thus more important for creating a phonon mediated el-el interaction.
- Acoustical phonons: $\omega_q \sim |q|$ ($\sim 1THz$)
 Magnons: $\omega_q \sim q^2$ ($\sim 1GHz$)
 Thus, for small q , $\omega_q^{mag} \ll \omega_q^{ph}$.

In total, we thus have

$$\begin{aligned} V_{eff}^{\text{mag}} &\sim \frac{q^4}{\omega^2 - c_1 q^4} && \text{Ferromagnetic magnons} \\ V_{eff}^{\text{ph}} &\sim \frac{q^3}{\omega^2 - c_2 q^4} && \text{Acoustic phonons} \end{aligned}$$

Thus, while ferromagnetic magnons will be able to create an attractive interaction between electrons, this attraction will be much weaker (due to smallness of the coupling constant and argument above) than the attraction created by phonons.

A good strategy for finding strong electron-electron attractions mediated by some boson, would be to look for bosons giving rise to a

$$V_{eff}(q, \omega) = |\lambda_q|^2 \frac{2\omega_q^2}{\omega^2 - \omega_q^2}, \quad (4.19)$$

with $\omega_q \sim |q|$ and $\lim_{q \rightarrow 0} \lambda_q = \lambda_0 \neq 0$. Candidate: Anti-ferromagnetic magnons!

Next, we will consider a very simple problem to illustrate the dramatic effect that an attractive interaction among electron has. The problem is so simple that it can be solved exactly. An important point to note, is that the solution to the problem will demonstrate that the answer could not have been found to any finite order in perturbation theory, no matter how weak the interaction is. Attractive interactions in the electron-system is a singular perturbation!

5 The Cooper problem

We consider a non-interacting Fermi-sea $|\Phi_0\rangle$, and two additional electrons. These two electrons do not interact with the Fermi-sea. They do however interact with each other. Let us now specify the way in which they interact. The initial states of the two electrons are taken to be $|k, \uparrow\rangle$ and $|-k, \downarrow\rangle$, such that a non-interacting two-particle state can be denoted by $|k, \uparrow; -k, \downarrow\rangle$. Short hand notation for this will be $|k, -k\rangle$, with the understanding that the electrons have opposite spins. While this choice of initial states may look a bit wierd, this is what we will work with, its justification will be made clear later. (Hint: go back and study the physical explanation for attractive phonon-mediated electron-electron interaction). The situation may be illustrated as in fig. 9.

The interaction among the electrons is now such that it scatters them into a new two-particle state $|k', -k'\rangle$, see illustration above. The interaction that causes such a scattering is denoted V . This interaction is assumed to be operative within a thin shell of width ω_0 around the Fermi-surface.

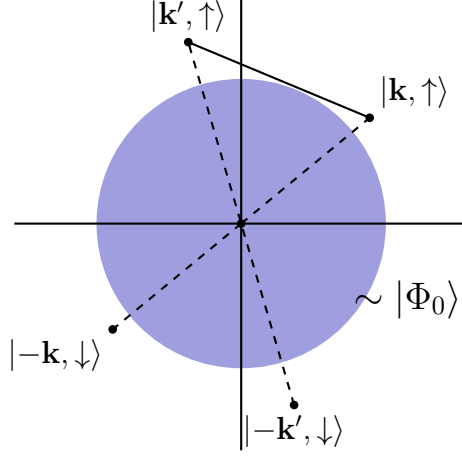


Figure 9: The scattering situation.

$$\mathcal{H}_0 |k, -k\rangle = \varepsilon_k |k, -k\rangle \quad (5.1)$$

ε_k : Kinetic energy of the two added electrons. \mathcal{H}_0 : Hamiltonian with no $V_{kk'}$.

Exact two-particle state with interactions: $|1, 2\rangle$.

$$|1, 2\rangle = \sum_{k'} a_{k'} |k', -k'\rangle, \quad (5.2)$$

where $a_{k'}$ must be determined.

$$(\mathcal{H}_0 + V_{eff}) |1, 2\rangle = E |1, 2\rangle \quad (5.3)$$

E : Exact two-particle energy for this problem.

$$(\mathcal{H}_0 + V_{eff}) \sum_{k'} a_{k'} |k', -k'\rangle = \sum_{k'} a_{k'} (\varepsilon_{k'} + V_{eff}) |k', -k'\rangle = \sum_{k'} a_{k'} E |k', -k'\rangle.$$

Multiplying with $\langle k, -k|$ and use orthonormality $\delta_{k,k'} = \langle k, -k | k', -k' \rangle$.

$$a_k \varepsilon_k + \sum_{k'} \langle k, -k | V_{eff} | k', -k' \rangle = a_k \varepsilon_k + \sum_{k'} V_{k,k'} = a_k E$$

$$V_{k,k'} = \begin{cases} -V & k, k' \in \Omega \\ 0 & k, k' \notin \Omega \end{cases}$$

where Ω denotes a region in k -space in the close vicinity of the Fermi-surface ("thin shell"). The Schroedinger equation now reads

$$a_k(\varepsilon_k - E) = - \sum_{k' \in \Omega} a_{k'} V_{k,k'} = \sum_{k' \in \Omega} V a_{k'}$$

where we have inserted the expression for $V_{k,k'}$ in the Ω -region in k -space. We make this summation explicit by including Heaviside step-functions.

$$a_k(\varepsilon_k - E) \Theta(2\omega_0 - |\varepsilon_k - 2\varepsilon_F|) = V \sum_{k'} a_{k'} \Theta(2\omega_0 - |\varepsilon'_k - 2\varepsilon_F|) \Theta(2\omega_0 - |\varepsilon_k - 2\varepsilon_F|).$$

The two step-functions on the r.h.s originate with the fact that both k and k' in $V_{k,k'}$ must be within this energy shell around the Fermi-surface. The step-functions that depend on k cancel on both sides of the equation. Thus, we have

$$\sum_{k'} a_{k'} \Theta(2\omega_0 - |\varepsilon'_k - 2\varepsilon_F|) = K_1,$$

constant and independent of k .

$$a_k = \frac{K_1}{\varepsilon_k - E}$$

a_k depends on k only via ε_k , so we can convert the k -sum into an energy sum:

$$\sum_{k'} f(\varepsilon_{k'}) = \sum_{k'} \int_{-\infty}^{\infty} d\varepsilon \delta(\varepsilon - \varepsilon_{k'}) f(\varepsilon) = \int d\varepsilon N(\varepsilon) f(\varepsilon)$$

NB: recall that ε is a two-particle kinetic energy.

$$a(\varepsilon)(\varepsilon - E) = V \int_{|\varepsilon' - 2\varepsilon_F| < 2\omega_0} d\varepsilon' a(\varepsilon') N(\varepsilon')$$

$$a(\varepsilon) = \frac{K_1}{\varepsilon - E} \implies K_1 = V \int_{|\varepsilon' - 2\varepsilon_F| < 2\omega_0} d\varepsilon' \frac{K_1}{\varepsilon' - E} N(\varepsilon')$$

Thus, the unknown factor K_1 drops out. Furthermore, the energy shell is thin, and we assume $N(\varepsilon)$ is a slowly varying function of ε around the , $\varepsilon \approx 2\varepsilon_F$.

$$1 \approx \overbrace{VN(\varepsilon_F)}^{\equiv \lambda} \int_{2\varepsilon_F}^{2\varepsilon_F + 2\omega_0} d\varepsilon' \frac{1}{\varepsilon' - E}$$

$\lambda > 0$, by definition.

$$\frac{1}{\lambda} = \ln \left| \frac{2\varepsilon_F + 2\omega_0 - E}{2\varepsilon_F - E} \right|$$

Now define the two particle binding-energy $\Delta \equiv 2\varepsilon_F - E$
Then,

$$\frac{1}{\lambda} = \ln \left(1 + \frac{2\omega_0}{\Delta} \right)$$

$\lambda > 0$: Solution requires that $\Delta > 0 \implies E < 2\varepsilon_F$!
Solve for Δ :

$$\begin{aligned} \frac{2\omega_0}{\Delta} &= e^{\frac{1}{\lambda}} - 1 \\ \Delta &= 2\omega_0 \frac{1}{e^{\frac{1}{\lambda}} - 1} \\ \lambda \ll 1 : \Delta &\approx 2\omega_0 e^{-\frac{1}{\lambda}}. \end{aligned}$$

Had we cept \hbar explicitly in the calculations, we would have found

$$\Delta = 2\hbar\omega_0 e^{-\frac{1}{\lambda}}. \quad (5.4)$$

We next comment on $E < 2\varepsilon_F$. At first glance, this would seem to violate the Pauli-principle, since it looks like we have the two added electrons now residing inside the Fermi-sea. In fact, there is no violation of the Pauli-principle, for the following reason. The bound state must be viewed as an entity, not as two individual electrons. We may think about this as a state created by a creation operator

$$b_k^\dagger = c_{k\uparrow}^\dagger c_{-k\downarrow} \quad (5.5)$$

and corresponding destruction operator

$$b_k = c_{-k\downarrow}^\dagger c_{k\uparrow}. \quad (5.6)$$

These operators do not obey fermionic anti-commutation relations. Therefore, this composite particle is not a fermion. Note that by forming this pair, called a Cooper-pair, the electrons have gotten rid of the severe limitations posed by the Pauli-principle, and this composite state is allowed to reside inside the Fermi-sea. A few remarks are in order:

- The bound state energy
 $\Delta = 2\hbar\omega_0 e^{-\frac{1}{\lambda}}$
This means that $\Delta > 0$ is a quantum effect, since it requires $\hbar \neq 0$.
- Δ is exponentially sensitive to $\lambda = VN(\varepsilon_F)$. Note that, in addition to V , we must have a non-zero density of states on the Fermi-surface. Thus, a Fermi-surface is required to get Cooper-pairs.
- These electron-pairs are bound states in momentum-space, not in real space!
- Note how Δ depends on λ . As $\lambda \rightarrow 0$, Δ features an essential singularity. Such a result could not have been obtained in perturbation theory to any finite order. An attractive electron-electron interaction is a singular perturbation.
- Thermal effects: It stands to reason that the bound state we have found will be dissociated at some temperature. This temperature will be $k_B T_0 \sim \Delta$. Above this temperature, no Cooper-pairs will exist.
- Note also the important fact that the binding of two electrons into a Cooper-pair (a composite non-fermionic entity) does not rely on a specific mechanism for producing an attractive electron-electron interaction. Thus, the concept is quite general in any fermionic system with a non-zero density of states on the Fermi-surface.
- Note also that we are careful in not saying that Cooper-pairs are bosons, they are in fact not! Elementary particles are either bosons or fermions, but Cooper-pairs is not an elementary particle, obviously.
- The problem just considered is admittedly quite artificially, only two electrons in a thin shell around the Fermi-surface interact. What if we include interactions also among all electrons within a thin shell around the Fermi-surface?

In that case, we would have a real many-body problem to solve, with an interaction that cannot be treated in perturbation theory (lesson from Cooper-problem). This is the problem we will next, and it leads to a microscopic theory of superconductivity, the phenomena that a metal loses all electrical resistance below a certain temperature. The binding energy Δ of a Cooper-pair turns into a gap in the excitation spectrum of electrons close to the Fermi-surface. This protects electrons from scattering, leading to zero resistivity. This happens at a temperature \sim gap at zero temperature.

6 The Bardeen-Cooper-Schiff theory of superconductivity

This is essentially the many-particle version of the Cooper-problem. Superconductivity: **TODO: Sett inn figur**

Note that a non analytic function like this usually suggests that there is some phase-transition in the system, so we are essentially looking at a phase transition of the electron gas. T_C : A sharply defined temperature

$$\rho(T) = \begin{cases} 0 & \text{if } T < T_C \\ \text{nonzero} & \text{if } T > T_C \end{cases} \quad (6.1)$$

T_C is denoted the critical temperature. Superconductivity was discovered experimentally in 1911 by Heike Kammerlingh Onnes in Leiden, measuring low- T $\rho(T)$ in ultra pure Mercury (Hg). This was 15 years before the discovery of quantum mechanics. It turns out that the phenomena is purely a quantum effect. So in 1911, there was no hope of giving a correct explanation for what is happening. It took 46 years to figure out what is going on. The most important reasons for this, is that apart from having to invent quantum mechanics first, completely novel and radical ideas had to be formulated in order to solve the problem¹. Historically, one important clue to figuring out what is happening, was the experimental observations that T_C varied with ion mass. (Isotope substitution on elemental superconductors). This indicated that lattice-vibrations somehow were involved in the early discovered superconductors. (Recall that electron-phonon-coupling $\sim \frac{1}{\sqrt{M}}$). This “isotope-effect” was announced in 1950 on elemental Mercury, and the measured shift in T_C was 0.01K, something that required very careful and precise measurements. We may guess what will happen with T_C by appealing to what we found in the Cooper-problem, where we surmised a Cooper-pair dissociation temperature $T^* \sim \Delta$ and

$$\Delta = 2\hbar\omega_0 e^{-\frac{1}{\lambda}} \quad (6.2)$$

ω_0 : A typical phonon-frequency, if we assume that the effective attractions originates with e-ph coupling. $\omega_0 \sim \frac{1}{\sqrt{M}} \rightarrow T^* \sim \frac{1}{\sqrt{M}}$. This means that $\sqrt{M}T_C = \text{constant!}$ This relation is validated very well in experiments on elemental superconductors such as Hg, Sn, and Tl. Previously, we have derived an effective e-e interaction, including Coulomb-interactions and e-ph-e interactions, \tilde{V}_{eff} .

$$\begin{aligned} \mathcal{H} = & \sum_{k,\sigma} (\varepsilon_k - \mu) c_{k\sigma}^\dagger c_{k\sigma} \\ & + \sum_{\substack{k,k',q \\ \sigma,\sigma'}} \tilde{V}_{\text{eff}} c_{k+q,\sigma}^\dagger c_{k'-q,\sigma'}^\dagger c_{k',\sigma'} c_{k,\sigma} \end{aligned} \quad (6.3)$$

Notice the global U(1)-symmetry of this Hamiltonian. This is on the standard form for a second-quantized electron-gas, now including the (potentially singu-

¹From in the lecture: illustration of the Meissner effect. The Higgs providing a mass to the em-field in the metal blob drawn is the expectation value of the Cooper pair operator. Superconductivity is that the photon acquires a mass through the Higgs field, which is a cooper pair. Lots of analogs to the standard model.

lar) effects of e-ph- coupling

$$\tilde{V}_{\text{eff}} = \frac{2|g_q|^2\omega_q}{\omega^2 - \omega_q^2} + V_{\text{Coulomb}}(q) \quad (6.4)$$

TODO: *Sett inn figure*

ω : Energy-transfer in scattering. $\omega = \varepsilon_{k+q} - \varepsilon_k$, $\varepsilon_{k'} = \varepsilon_{k'-q} + \omega$. The effect of the repulsive interaction can be calculated perturbatively. In any case, this repulsion is not a singular perturbation. We therefore set it aside for the moment, and consider

$$\tilde{V}_{\text{eff}} = \frac{2|g_q|^2\omega_q}{\omega^2 - \omega_q^2}. \quad (6.5)$$

This interaction as attractive (< 0) if

$$(\varepsilon_{k+q} - \varepsilon_k)^2 < \omega_q^2$$

or

$$(\varepsilon_{k'-q} - \varepsilon_{k'})^2 < \omega_q^2$$

We now focus on those scattering processes that give attraction between electrons. The processes giving repulsion do nothing more than what the Coulomb interaction does. We will include these effects later on. We now simplify this in a series of steps. The scattering caused by the weak e-ph-e coupling can only take place in a thin shell around the Fermi-surface. Thus $\varepsilon_k, \varepsilon_{k'}, \varepsilon_{k+q}, \varepsilon_{k'-q}$ must all lie within a thin shell around the Fermi surface. Let us take a look at the relevant kinematics seen in fig. 10. We see that in general, the state with momenta $k' - q$ will lie outside the shell, even if $\varepsilon_k, \varepsilon_{k'}, \varepsilon_{k+q}$ lie within the shell. There is an important special case where $\varepsilon_{k'-q}$ will always lie within shell if $\varepsilon_k, \varepsilon_{k'}, \varepsilon_{k+q}, \varepsilon_{k'-q}$ is within shell, namely the case when $k' = -k$. This choice will this maximize the scattering phase-space for attractive interactions. We will retain only such terms: $k' = -k$.

A second simplification: $\sigma' = -\sigma$. The spatial extent of attractive interaction is small. We may essentially think of it (in real space) as an attractive Hubbard-interaction. Thus, we end up with the following simplified Hamiltonian

$$\mathcal{H} = \sum_{k,\sigma} (\varepsilon_k - \mu) c_{k\sigma}^\dagger c_{k\sigma} + \sum_{k,q,\sigma} \tilde{V}_{\text{eff}} c_{k+q,\sigma}^\dagger c_{-(k+q),-\sigma}^\dagger c_{-k,-\sigma} c_{k\sigma}. \quad (6.6)$$

Now redefine variables $k \rightarrow k'$, $k + q \rightarrow k$, $\tilde{V}_{\text{eff}} \rightarrow V_{k,k'}/2$ (spin independent interaction). Thus we can write eq. (6.6) as

$$\mathcal{H} = \sum_{k,\sigma} (\varepsilon_k - \mu) c_{k\sigma}^\dagger c_{k\sigma} + \sum_{k,k'} V_{k,k'} c_{k,\uparrow}^\dagger c_{-k,\downarrow}^\dagger c_{-k',\downarrow} c_{k',\uparrow}, \quad (6.7)$$

with $V_{k,k'}$ being attractive if k, k' lie in a small vicinity of the Fermi-surface, and zero otherwise. eq. (6.7) is the so called BCS-model of superconductivity.

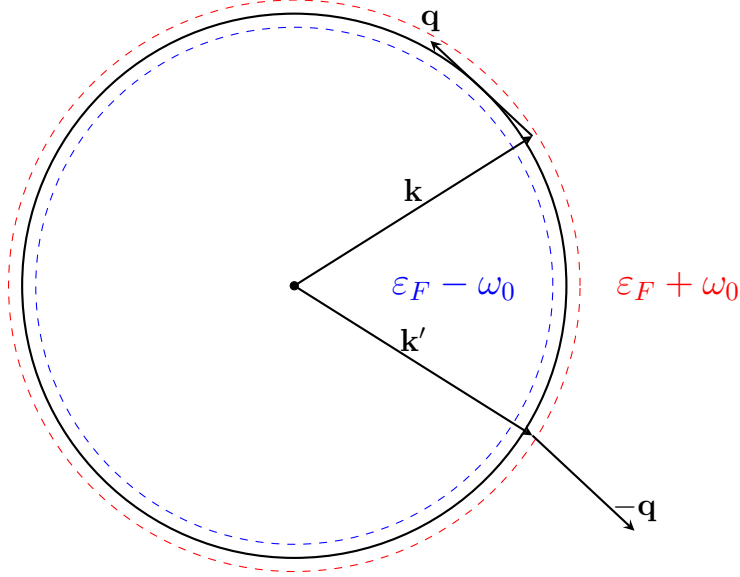


Figure 10: Thin shell around the Fermi surface.

Although it has been motivated by an attractive e-ph-e interaction, the above model is in fact more general than that, and can be applied to any system with an effective (somehow) attractive electron-electron interaction. This model in spirit is very much like the model we looked at for the Cooper-problem. The difference is that $V_{k,k'}$ in the BCS-model works between all electrons in a thin shell around the Fermi-surface, while the Cooper-problem only considered interactions between two such electrons. The Hamiltonian can not be treated exactly. Moreover, from the Cooper-problem, there is every reason to believe that in order to get correct eigenvalues, we cannot use perturbations theory. We must therefore treat \mathcal{H} both approximately and non-perturbatively. This is what we will do next. We will transform this many-body problem to a self-consistent one-particle problem. This is done very much like what we do when we perform a mean-field approximation on spin-systems:

$$\begin{aligned}
 c_{-k\downarrow}c_{k\uparrow} &= \underbrace{\langle c_{-k\downarrow}c_{k\uparrow} \rangle}_{\equiv b_k} + \underbrace{c_{-k\downarrow}c_{k\uparrow} - \langle c_{-k\downarrow}c_{k\uparrow} \rangle}_{\delta b_k} \\
 &= b_k + \delta b_k.
 \end{aligned} \tag{6.8}$$

Here, b_k is a statistical average ². Note that giving the b 's a finite expectation value breaks the U(1)-symmetry of the system. There is no way to gradually break this symmetry, it either happens or not. Note also that these expectations values are not on the usual $\langle c^\dagger c \rangle$ -form, and the question now is to answer whether such expectation values can exist or not. Now insert the definitions in

²with respect to the “correct” Hamiltonian.

eq. (6.8) and the Hermitian conjugate into eq. (6.7) and ignore terms $\mathcal{O}((\delta b)^2)$. Consider the interaction term:

$$\begin{aligned} \sum_{k,k'} V_{k,k'} c_{k,\uparrow}^\dagger c_{-k,\downarrow}^\dagger c_{-k',\downarrow} c_{k,\uparrow} &= \sum_{k,k'} V_{k,k'} \left(b_k^\dagger + \delta b_k^\dagger \right) \left(b_{k'} + \delta b_{k'} \right) \\ &= \sum_{k,k'} V_{k,k'} \left(b_k^\dagger b_{k'} + b_k^\dagger \delta b_{k'} + \delta b_k^\dagger b_{k'} \right) + \mathcal{O}((\delta b)^2) \\ &\simeq \sum_{k,k'} V_{k,k'} \left(b_k^\dagger b_{k'} + b_k^\dagger c_{-k',\downarrow} c_{k',\uparrow} + b_{k'} c_{k,\uparrow}^\dagger c_{-k,\downarrow}^\dagger - 2b_k^\dagger b_{k'} \right). \end{aligned}$$

Next, define

$$\Delta_k \equiv - \sum_{k'} V_{kk'} b_{k'} \quad (6.9a)$$

$$\Delta_k^\dagger \equiv - \sum_k V_{kk'} b_k^\dagger. \quad (6.9b)$$

Inserting these in definitions into the Hamiltonian gives

$$\begin{aligned} \mathcal{H} &= \sum_{k,\sigma} (\varepsilon_k - \mu) c_{k\sigma}^\dagger c_{k\sigma} - \sum_k \left[\Delta_k c_{k\uparrow}^\dagger c_{-k\downarrow}^\dagger + \Delta_k^\dagger c_{-k\downarrow} c_{k\uparrow} \right] \\ &\quad + \sum_k \Delta_k b_k^\dagger. \end{aligned} \quad (6.10)$$

This is the mean-field approximation to the BCS-model, where b_k (and hence Δ_k) must be determined self-consistently, by minimizing the free energy of the system. We return to that below, but first we must diagonalize the Hamiltonian in eq. (6.10). Note that we now have terms like $c^\dagger c$, $c^\dagger c^\dagger$, and cc in \mathcal{H} , reminiscent of what we had with boson-operators for the case of quantum antiferromagnets. We will now proceed along a similar route, but with the important difference that we are now considering fermions. Introduce new fermion-operators

$$\eta_k = u_k c_{k\uparrow} + v_k c_{-k\downarrow}^\dagger \quad (6.11a)$$

$$\gamma_k = u_k c_{-k\downarrow} - v_k c_{k\uparrow} \quad (6.11b)$$

These operators are fermionic quasi-particles as linear combinations of spin-up and spin-down particles. Thus spin is not a correct quantum number for the new fermions. Note the minus sign in eq. (6.11b). This transformation is required to preserve fermionic commutation relations, for instance

$$\left\{ \eta_k, \eta_{k'}^\dagger \right\} = \delta_{kk'}, \quad (6.12)$$

η_k, γ_k anticommute,

$$\left\{ \eta_k, \gamma_{k'}^\dagger \right\} = 0$$

$$u_k u_{k'} \delta_{kk'} + v_k v_{k'} \delta_{kk'} = \delta_{kk'},$$

with the +-sign originating in anti-commutation relations. Thus $u_k^2 + v_k^2 = 1$. We reach the same conclusion with $\{\gamma_k, \gamma_{k'}\} = \delta_{kk'}$. This relation is the reason for the minus sign in front of v_k in eq. (6.11b)!

$$\begin{pmatrix} \eta_k \\ \gamma_k \end{pmatrix} = \overbrace{\begin{pmatrix} u_k & v_k \\ -v_k & u_k \end{pmatrix}}^{\equiv M} \begin{pmatrix} c_{k\uparrow} \\ c_{-k\downarrow}^\dagger \end{pmatrix} \quad (6.13)$$

With these signs, $\det M = u_k^2 + v_k^2 = 1$

$$M = \begin{pmatrix} u_k & v_k \\ -v_k & u_k \end{pmatrix} \quad M^T = \begin{pmatrix} u_k & -v_k \\ v_k & u_k \end{pmatrix} \quad M^{-1} = \begin{pmatrix} u_k & -v_k \\ v_k & u_k \end{pmatrix} \quad (6.14)$$

Thus, M is a unitary transformation with the constraint $u_k^2 + v_k^2 = 1 \implies |u_k|, |v_k| \leq 1$. This is very different from the “squeezing” transformation we used in the quantum AFM-case. Going back to eq. (6.11), we have

$$\begin{pmatrix} \eta_k \\ \gamma_k \end{pmatrix} = \begin{pmatrix} u_k & v_k \\ -v_k & u_k \end{pmatrix} \begin{pmatrix} c_{k\uparrow} \\ c_{-k\downarrow}^\dagger \end{pmatrix} \quad (6.15a)$$

$$\begin{pmatrix} \eta_k^\dagger \\ \gamma_k^\dagger \end{pmatrix} = \begin{pmatrix} u_k & v_k \\ -v_k & u_k \end{pmatrix} \begin{pmatrix} c_{k\uparrow}^\dagger \\ c_{-k\downarrow} \end{pmatrix} \quad (6.15b)$$

$$\begin{pmatrix} c_{k\uparrow} \\ c_{-k\downarrow}^\dagger \end{pmatrix} = \begin{pmatrix} u_k & -v_k \\ v_k & u_k \end{pmatrix} \begin{pmatrix} \eta_k \\ \gamma_k \end{pmatrix} \quad (6.15c)$$

$$\begin{pmatrix} c_{k\uparrow}^\dagger \\ c_{-k\downarrow} \end{pmatrix} = \begin{pmatrix} u_k & -v_k \\ v_k & u_k \end{pmatrix} \begin{pmatrix} \eta_k^\dagger \\ \gamma_k^\dagger \end{pmatrix} \quad (6.15d)$$

Insert this into the Hamiltonian eq. (6.10),

$$\begin{aligned} \mathcal{H} = \sum_k \bigg\{ & (\varepsilon_k - \mu) \left(u_k \eta_k^\dagger - v_k \gamma_k^\dagger \right) \left(u_k \eta_k - v_k \gamma_k \right) \\ & + (\varepsilon_k - \mu) \left(v_k \eta_k + u_k \gamma_k \right) \left(v_k \gamma_k^\dagger + u_k \gamma_k^\dagger \right) \\ & - \Delta_k \left(u_k \eta_k^\dagger - v_k \gamma_k^\dagger \right) \left(v_k \eta_k + u_k \gamma_k \right) \\ & - \Delta_k^\dagger \left(u_k \eta_k^\dagger + u_k \gamma_k^\dagger \right) \left(u_k \eta_k - v_k \gamma_k \right) + \Delta_k b_k^\dagger \bigg\} \end{aligned} \quad (6.16)$$

As in the quantum antiferromagnet-case, we now collect terms of different types:

$$\eta_k^\dagger \eta_k : (\varepsilon_k - \mu) u_k^2 - u_k v_k (\Delta_k + \Delta_k^\dagger) \quad (6.17a)$$

$$\gamma_k^\dagger \gamma_k : (\varepsilon_k - \mu) v_k^2 + u_k v_k (\Delta_k + \Delta_k^\dagger) \quad (6.17b)$$

$$\eta_k \eta_k^\dagger : (\varepsilon_k - \mu) v_k^2 \quad (6.17c)$$

$$\gamma_k \gamma_k^\dagger : (\varepsilon_k - \mu) u_k^2 \quad (6.17d)$$

$$\gamma_k^\dagger \eta_k : -2(\varepsilon_k - \mu) u_k v_k + \Delta_k v_k^2 - \Delta_k^\dagger u_k^2 \quad (6.17e)$$

$$\eta_k^\dagger \gamma_k : -2(\varepsilon_k - \mu) u_k v_k - \Delta_k u_k^2 + v_k^2 \Delta_k^\dagger \quad (6.17f)$$

Using the anticommutation relations in eq. (6.12), and the corresponding for γ_k , we may express eqs. (6.17a) and (6.17b) as

$$\eta_k^\dagger \eta_k : (\varepsilon_k - \mu) (u_k^2 - v_k^2) - u_k v_k (\Delta_k + \Delta_k^\dagger) \quad (6.18a)$$

$$\gamma_k^\dagger \gamma_k : (\varepsilon_k - \mu) (v_k^2 - u_k^2) + u_k v_k (\Delta_k + \Delta_k^\dagger) \quad (6.18b)$$

These are the same, except opposite sign. Adjust u_k, v_k such that the coefficients in front of eqs. (6.17e) and (6.17f) are zero. Fortunately, these two equations are just complex conjugate of each other, so if one is fulfilled, so is the other. If we set these two to 0, we have

$$-2(\varepsilon_k - \mu) u_k v_k = u_k^2 \Delta_k - v_k^2 \Delta_k^\dagger \quad (6.19)$$

$$-2(\varepsilon_k - \mu) u_k v_k = u_k^2 \Delta_k^\dagger - v_k^2 \Delta_k. \quad (6.20)$$

By adding these two equations, we get

$$\begin{aligned} -4 \underbrace{(\varepsilon_k - \mu)}_{\equiv \tilde{\varepsilon}_k} u_k v_k &= (u_k^2 - v_k^2) (\Delta_k + \Delta_k^\dagger) \\ \Delta_k + \Delta_k^\dagger &= 2 \operatorname{Re}\{\Delta_k\} \equiv 2\tilde{\Delta}_k \\ -2\tilde{\varepsilon}_k u_k v_k &= (u_k^2 - v_k^2) \tilde{\Delta}_k \end{aligned}$$

Since we have $u_k^2 + v_k^2 = 1$, we may write

$$\begin{aligned} u_k &= \cos \theta \\ v_k &= \sin \theta \\ -\tilde{\varepsilon}_k \sin 2\theta &= \tilde{\Delta}_k \cos 2\theta \\ \tan 2\theta &= -\frac{\tilde{\Delta}_k}{\tilde{\varepsilon}_k} \end{aligned} \quad (6.21)$$

This is an equation for θ , and thus u_k, v_k , which gives coefficients of $\gamma_k^\dagger \eta_k, \eta_k^\dagger \gamma_k$

equal to zero. Choose $\tilde{\Delta}_k \geq 0$

$$\begin{aligned} \tan 2\theta < 0; \quad \tilde{\varepsilon} > 0 \\ \tan 2\theta > 0; \quad \tilde{\varepsilon} < 0 \\ \frac{\sin^2(2\theta)}{\cos^2(2\theta)} &= \left(\frac{\tilde{\Delta}_k}{\tilde{\varepsilon}_k} \right)^2 \equiv b^2 \\ \cos^2(2\theta) &= \frac{1}{1+b^2} \\ \cos(2\theta) &= \begin{cases} \frac{-1}{\sqrt{1+b^2}}; & \tilde{\varepsilon} > 0 \\ \frac{1}{\sqrt{1+b^2}}; & \tilde{\varepsilon} < 0 \end{cases} \end{aligned}$$

Coefficient in front of $\eta_k^\dagger \eta_k$:

$$\begin{aligned} \tilde{\varepsilon}_k \cos 2\theta - \tilde{\Delta}_k \sin 2\theta &= \cos(2\theta) \left(\tilde{\varepsilon}_k + \left(\frac{\tilde{\Delta}_k}{\tilde{\varepsilon}_k} \right)^2 \right) \\ &= -\frac{\text{sign} \tilde{\varepsilon}_k \left(\tilde{\varepsilon}_k^2 + \tilde{\Delta}_k^2 \right)}{\tilde{\varepsilon}_k (1+b^2)^{\frac{1}{2}}} \\ &= -\frac{\text{sign} \tilde{\varepsilon}_k}{\frac{\tilde{\varepsilon}_k}{|\tilde{\varepsilon}_k|}} \left(\tilde{\varepsilon}_k^2 + \tilde{\Delta}_k^2 \right)^{\frac{1}{2}} \\ &= -\left(\tilde{\varepsilon}_k^2 + \tilde{\Delta}_k^2 \right)^{\frac{1}{2}} \end{aligned}$$

Coefficient in front of $\gamma_k^\dagger \gamma_k$: $\left(\tilde{\varepsilon}_k^2 + \tilde{\Delta}_k^2 \right)^{\frac{1}{2}}$. Thus, we have finally diagonalized the Hamiltonian

$$\mathcal{H} = \sum_k \left[2(\varepsilon_k - \mu) + \Delta_k b_k^\dagger + E_k \left(\gamma_k^\dagger \gamma_k - \eta_k^\dagger \eta_k \right) \right], \quad (6.22)$$

where the summation over spins has been made, and with

$$E_k \equiv \left(\tilde{\varepsilon}_k^2 + \tilde{\Delta}_k^2 \right)^{\frac{1}{2}}. \quad (6.23)$$

b_k and $\tilde{\Delta}_k$ are as yet undetermined. They will have to be determined by minimizing the free energy of this system. The long-lived fermionic excitation are described by $(\eta_k, \eta_k^\dagger), (\gamma_k, \gamma_k^\dagger)$. **TODO: Sjekkk at fortegnene er riktige på eta/gamma**

$$\mathcal{H} = E_0 + \sum_k E_k \left(\gamma_k^\dagger \gamma_k - \eta_k^\dagger \eta_k \right) \quad (6.24)$$

$$E_0 = \sum_k \left[2(\varepsilon_k - \mu) + \Delta_k b_k^\dagger \right] \quad (6.25)$$

If we have a fermionic system with a Hamiltonian

$$\mathcal{H} = \sum_k (\varepsilon_k - \mu) c_k^\dagger c_k,$$

the grand canonical partition function is given by

$$\mathcal{Z}_g = \prod_k \left(1 + e^{-\beta(\varepsilon_k - \mu)} \right). \quad (6.26)$$

In the present case, this gives

$$\mathcal{Z}_g = e^{-\beta E_0} \prod_k (1 + e^{\beta E_k}) (1 + e^{-\beta E_k}). \quad (6.27)$$

In the limit of large number of particles, all ensembles are equivalent. To expedite the computations, we will consider \mathcal{Z}_g to be equal to $\mathcal{Z} = e^{-\beta F}$, where F is the Helmholtz free energy for a system.

$$F = E_0 - \frac{1}{\beta} \sum_k [\ln(1 + e^{-\beta E_k}) + \ln(1 + e^{\beta E_k})] \quad (6.28)$$

We now minimize with respect to Δ_k or b_k^\dagger for a particular value of k . It does not matter which one of these we use. We look for

$$\frac{\partial F}{\partial \Delta_k} = 0, \quad (6.29)$$

or

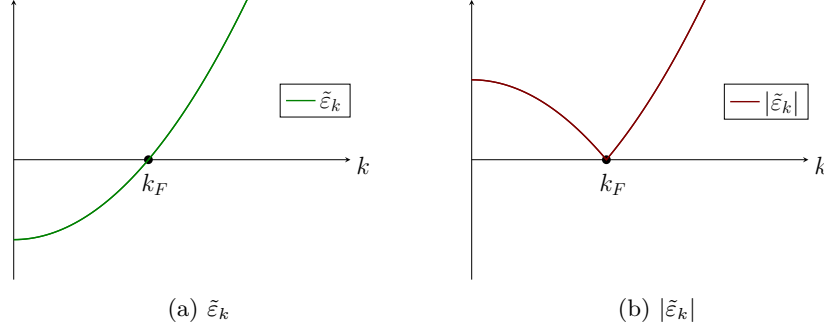
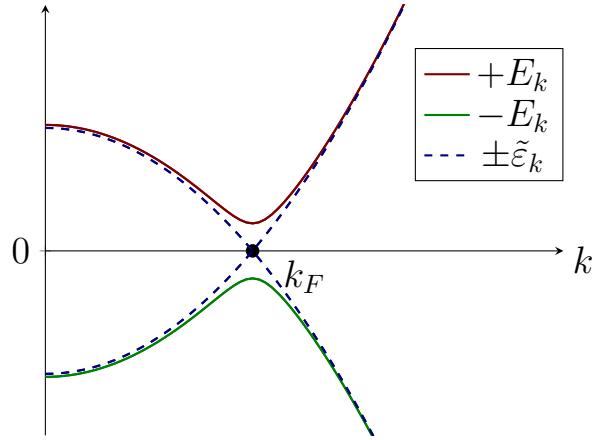
$$b_k^\dagger - \frac{1}{\beta} \left(\frac{1}{1 + e^{-\beta E_k}} (-\beta) \frac{\partial E_k}{\partial \Delta_k} e^{-\beta E_k} + \frac{1}{1 + e^{\beta E_k}} (\beta) \frac{\partial E_k}{\partial \Delta_k} e^{\beta E_k} \right) = 0$$

$$\begin{aligned} b_k^\dagger &= \frac{\partial E_k}{\partial \Delta_k} \left(\frac{e^x}{1 + e^x} - \frac{e^{-x}}{1 + e^{-x}} \right) \\ &= \frac{\partial E_k}{\partial \Delta_k} \cdot \tanh\left(\frac{x}{2}\right); \quad x = \beta E_k \\ \frac{\partial E_k}{\partial \Delta_k} &= \frac{\Delta_k}{\sqrt{\tilde{\varepsilon}_k^2 + \Delta_k^2}}, \end{aligned}$$

where we have set Δ_k to be real, such that $\tilde{\Delta}_k = \Delta_k$.

$$b_k^\dagger = \frac{\Delta_k}{\sqrt{\tilde{\varepsilon}_k^2 + \Delta_k^2}} \tanh\left(\frac{\beta E_k}{2}\right) \quad (6.30)$$

We close this to an equation for Δ_k by using the definitions in eq. (6.9) to obtain


 Figure 11: Typical excitation spectrum at $\Delta_k = 0$.

 Figure 12: $\Delta_k \neq 0$ represents a gap in the excitation spectrum at the Fermi surface, here greatly exaggerated. The difference in the minimum of $+E_k$ and the maximum of $-E_k$ is $2\Delta_k$. This gap always tracks the Fermi surface.

$$\Delta_k = - \sum_{k'} V_{kk'} \Delta_{k'} \chi_{k'} \quad (6.31)$$

$$\chi_k = \frac{1}{(\tilde{\epsilon}_k^2 + \Delta_k^2)^{\frac{1}{2}}} \tanh\left(\frac{\beta E_k}{2}\right) \quad (6.32)$$

This is the so-called BCS gap-equation. The reason for this name is that it is an equation for Δ_k , which represents a gap in the excitation-spectrum. To see this, we first consider the excitation spectrum at $\Delta_k = 0$, depicted in fig. 11. Note that on the Fermi-surface ($k = k_F$), there is zero gap in the excitation spectrum $\Delta_k = 0$. From fig. 12, we see that Δ_k represents a gap on the Fermi-surface in the excitation spectrum of the Bogoliubov fermions. We will now solve eq. (6.31)

for the same model for $V_{kk'}$ that we used in the Cooper problem, namely a constant attractive potential in a thin shell around the Fermi-surface. With the understanding that k, k' lie within this thin shell, we have

$$\Delta_k = V \sum_{k'} \Delta_{k'} \chi_{k'} \quad (6.33)$$

This means that Δ_k is independent of k , and we can divide by $\Delta = \Delta_k$ and get

$$1 = V \sum_{k'} \frac{1}{(\tilde{\varepsilon}_{k'}^2 + \Delta^2)^{\frac{1}{2}}} \tanh\left(\frac{\beta E_{k'}}{2}\right). \quad (6.34)$$

Now use

$$\sum_k g(\tilde{\varepsilon}_k) = \int_{-\infty}^{\infty} d\varepsilon \sum_k \delta(\varepsilon - \tilde{\varepsilon}_k) g(\tilde{\varepsilon}) = \int_{-\infty}^{\infty} d\varepsilon N(\varepsilon) g(\varepsilon), \quad (6.35)$$

$$1 = V \int_{-\omega_0}^{\omega_0} d\varepsilon \frac{N(\varepsilon)}{\sqrt{\varepsilon^2 + \Delta^2}} \tanh\left(\frac{\beta \sqrt{\varepsilon^2 + \Delta^2}}{2}\right) \quad (6.36)$$

Note: ε must lie within a thin energy-shell around the Fermi surface! We have denoted the width of this shell $2\omega_0$

$$-\omega_0 < \varepsilon < \omega_0$$

when energies ε are measured relative μ . Consider now $N(\varepsilon)$ a rather slowly varying function of ε in the thin shell around the Fermi-surface, such that $N(\varepsilon) \simeq N(\varepsilon_F) = N(\mu)$. Introduce $\lambda \equiv VN(\varepsilon_F)$, such that

$$1 = \lambda \int_{-\omega_0}^{\omega_0} d\varepsilon \frac{1}{\sqrt{\varepsilon^2 + \Delta^2}} \tanh\left(\frac{\beta \sqrt{\varepsilon^2 + \Delta^2}}{2}\right). \quad (6.37)$$

eq. (6.37) is difficult to solve, but we will look at two special cases, at $T = 0$ and $T = T_C$.

i) $T = 0$

At $T = 0$, $\tanh\left(\frac{\beta\sqrt{\varepsilon^2 + \Delta^2}}{2}\right) = 1$, such that ³

$$\begin{aligned}
 1 &= \lambda \int_0^{\omega_0} \frac{d\varepsilon}{\sqrt{\varepsilon^2 + \Delta^2}} \\
 &= \lambda \int_0^{\frac{\omega_0}{\Delta}} \frac{dx}{\sqrt{x^2 + 1}} \\
 &= \lambda \sinh^{-1}\left(\frac{\omega_0}{\Delta}\right) \\
 &= \lambda \ln\left(\frac{\omega_0}{\Delta} + \sqrt{\left(\frac{\omega_0}{\Delta}\right)^2 + 1}\right) \\
 \Rightarrow \frac{\omega_0}{\Delta} &= \sinh\left(\frac{1}{\lambda}\right) = \frac{1}{2} \left(e^{\frac{1}{\lambda}} - e^{-\frac{1}{\lambda}}\right)
 \end{aligned} \tag{6.38}$$

Now consider $\lambda \ll 1 \Rightarrow \frac{2\omega_0}{\Delta} \simeq e^{\frac{1}{\lambda}}$. Reinserting \hbar we obtain

$$\Delta = 2\hbar\omega_0 e^{-\frac{1}{\lambda}}. \tag{6.39}$$

Notice the similar expression in eqs. (5.4) and (6.39).

ii) The critical temperature

We see from the gap-equation that as T increases, the tanh-factor decreases. Thus, to obtain a solution to the gap-equation requires smaller Δ . As T increases, Δ decreases. Sooner or later, we will reach a temperature where $\Delta \rightarrow 0^+$. This will be the critical temperature, T_C , which is determined by the equation

$$1 = \lambda \int_0^{\omega_0} d\varepsilon \frac{\tanh\left(\frac{\beta\varepsilon}{2}\right)}{\varepsilon}. \tag{6.40}$$

Introducing $x = \frac{\beta\varepsilon}{2}$,

$$\begin{aligned}
 \frac{1}{\lambda} &= \int_0^{\frac{\beta\omega_0}{2}} \frac{dx}{x} \tanh(x) \\
 &= \ln(x) \tanh(x) \Big|_0^{\frac{\beta\omega_0}{2}} - \int_0^{\frac{\beta\omega_0}{2}} dx \frac{\ln(x)}{\cosh^2(x)}.
 \end{aligned}$$

Again, we consider $\lambda \ll 1 \Rightarrow \frac{\beta\omega_0}{2} \gg 1$. In the last term, we may replace the upper limit by ∞ .

$$\begin{aligned}
 \frac{1}{\lambda} &\simeq \ln\left(\frac{\beta\omega_0}{2}\right) - \underbrace{\int_0^{\infty} dx \frac{\ln(x)}{\cosh^2(x)}}_{=\ln\left(\frac{\pi}{4}e^{-\gamma}\right) \equiv \ln(C)},
 \end{aligned} \tag{6.41}$$

³The subsequent λ is now redefined by a factor 2, not any more considering per-spin density of states.

where $\gamma \simeq 0.5772156649$ is the Euler-Mascheroni constant.

$$\frac{1}{\lambda} = \ln\left(\frac{\beta\omega_0}{2C}\right) \quad (6.42)$$

$$\frac{\beta\omega_0}{2C} = e^{\frac{1}{\lambda}} \quad (6.43)$$

$$k_B T_C = \frac{2}{\pi} e^{\gamma} \omega_0 e^{-\frac{1}{\lambda}} \quad (6.44)$$

Note how extremely sensitive both Δ and $k_B T_C$ is to λ ! Note also that the depend on λ in the same way. So if we take their ratios, this dependence cancels, as does the prefactor.

$$\frac{2\Delta(T=0)}{k_B T_C} = \frac{4\omega_0 e^{-\frac{1}{\lambda}}}{\frac{2}{\pi} e^{\gamma} \omega_0 e^{-\frac{1}{\lambda}}} \quad (6.45)$$

$$= 2\pi e^{-\gamma} \simeq 3.53, \quad (6.46)$$

which is a universal number! This prediction of the theory turned out to be remarkably accurate for real superconductors where $\lambda \ll 1$. Examples are Hg, Al, Sn. For Pb, the ratio is somewhat larger, and this is attributed to the fact that λ is larger than in Hg, Al, Sn. The opening up of a gap on the Fermi-surface means that the electron many-body state is protected from scattering by this gap. As a result, the resistivity of the electron gas drops abruptly to 0 at $T = T_C$.

Superconductivity-onset is thus a phase-transition associated with the opening of a gap Δ_k on the Fermi-surface.

Often, this gap Δ_k is referred to as an order-parameter of the system. The original Hamiltonian is invariant under the transformation

$$c_{k\sigma} \rightarrow e^{i\theta} c_{k\sigma}, \quad (6.47)$$

where θ is a global phase factor. This is therefore a symmetry of the problem, a global $U(1)$ -symmetry as mentioned above. Δ_k is nonzero if and only if b_k is nonzero. The quantity

$$\langle b_k \rangle = \langle c_{-k\downarrow} c_{k\uparrow} \rangle \quad (6.48)$$

is, however, not invariant under this global $U(1)$ -transformation. Thus, in the superconducting state, the $U(1)$ -symmetry of \mathcal{H} is spontaneously broken.

7 The Meissner Effect

Another truly remarkable property of superconductors is its electromagnetic properties, which are radically different from those of metals. Inside a metal, we have $\mathbf{E} = 0$. However, an externally applied magnetic field \mathbf{B} will essentially penetrate a metal completely

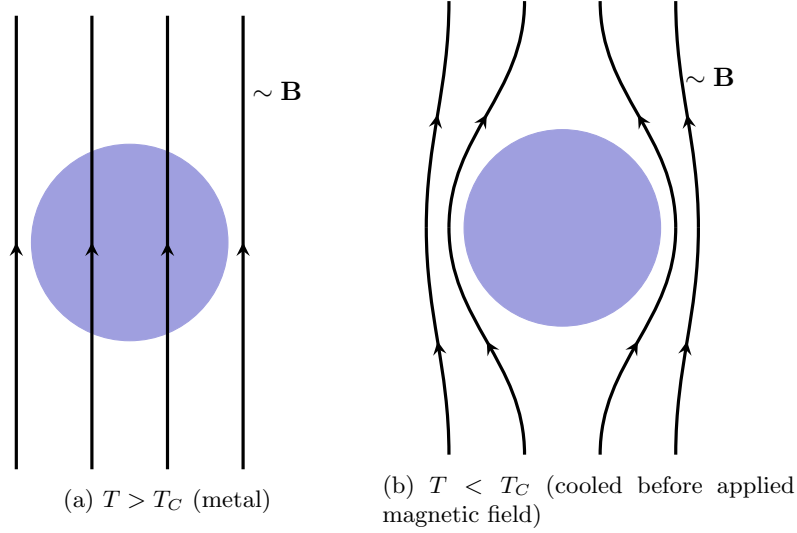


Figure 13: Meissner effect.

If there is any tendency for the system to resist admitting the external \mathbf{B} -field, then this is called diamagnetism. In a metal ($T > T_C$) this diamagnetism is very weak, see fig. 13a. In a superconductor ($T < T_C$) this is very different. If we take a metal and cool it down and then apply an external field, the magnetic field is excluded, as shown in fig. 13b.

Now, the magnetic field is entirely excluded from the superconductor. This is called the Meissner-effect. We will now relate the Meissner-effect to the onset of a gap Δ_k below T_C .

The Meissner-effect is the essential phenomenon characterizing a superconductor.

Start with the Maxwell-equations relating magnetic field to a current \mathbf{J} .

$$\nabla \cdot \mathbf{B} = 0 \implies \mathbf{B} = \nabla \times \mathbf{A} \quad (7.1)$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad (7.2)$$

Now, as always, we need a constitutive relation for the current \mathbf{J} . Obviously, the standard one, $\mathbf{J} = \sigma \mathbf{E}$, where σ is conductivity and \mathbf{E} is electric field, will not work, since it gives Ohmic resistance.

Supercurrent:

$$\mathbf{J}_s = e^* n_s \mathbf{v}_s. \quad (7.3)$$

e^* : An effective “quasiparticle” charge

n_s : density of superconducting charge-carriers (Bogoliubov quasiparticles)

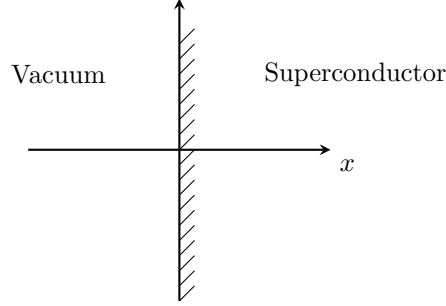


Figure 14: Semi-infinite superconductor

\mathbf{v}_s : velocity of such quasiparticles

$\mathbf{v} = \frac{\mathbf{p}}{m^*}$, m^* : Mass of quasiparticle.

In the presence of an electromagnetic field,

$$\mathbf{p} \rightarrow \mathbf{p} - e^* \mathbf{A} \quad (7.4)$$

$$\mathbf{J}_s = \frac{e^*}{m} n_s (-e^* \mathbf{A}) = -\frac{(e^*)^2}{m} \mathbf{A} \quad (7.5)$$

$$\nabla \times (\nabla \times \mathbf{A}) = \mu_0 \mathbf{J}_s = -\frac{\mu_0 (e^*)^2 n_s}{m} \mathbf{A} \quad (7.6)$$

$$\nabla \times (\nabla \times \mathbf{A}) = \nabla (\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A} \quad (7.7)$$

$$\implies -\nabla^2 \mathbf{A} + \frac{\mu_0 (e^*)^2 n_s}{m} \mathbf{A} = 0, \quad (7.8)$$

where we have restricted ourselves to the gauge where $\nabla \cdot \mathbf{A} = 0$ (Coulomb gauge). Define

$$\frac{1}{\lambda^2} \equiv \frac{\mu_0 (e^*)^2 n_s}{m}. \quad (7.9)$$

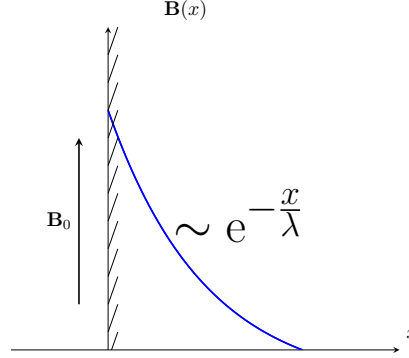
λ : A length (by dimensional analysis of equation for \mathbf{A}).

Consider for simplicity a semi-infinite superconductor as in fig. 14. Here, $\mathbf{A} = \mathbf{A}(x)$. At $x = 0$: $\mathbf{A}(x=0) = \mathbf{A}_0$.

$$\frac{d^2 \mathbf{A}}{dx^2} = \frac{1}{\lambda^2} \mathbf{A} \quad (7.10)$$

$$\implies \mathbf{A}(x) = \mathbf{A}_0(x) e^{-\frac{x}{\lambda}} \quad (7.11)$$

$$\mathbf{B}(x) = \nabla \times \mathbf{A} \quad (7.12)$$



$B_i = \varepsilon_{ijl} \partial_j A_l$. $j = x (= 1)$ since there is only x -dependence.

$$B_y = \varepsilon_{213} \partial_x A_z = -\partial_x A_z = \frac{1}{\lambda} A_{0z} e^{-\frac{x}{\lambda}}$$

$$B_z = \varepsilon_{312} \partial_x A_y = +\partial_x A_y = -\frac{1}{\lambda} A_{0y} e^{-\frac{x}{\lambda}}$$

Thus,

$$\mathbf{B}(x) = \mathbf{B}_0 e^{-\frac{x}{\lambda}}. \quad (7.13)$$

Now we see the physical meaning of λ : It is a characteristic length for how far a magnetic field penetrates a superconductor. It is referred to as the London penetration length. Thus, a magnetic field only exists within a layer of thickness λ from the surface of the superconductor. There is no magnetic field in the bulk of the superconductor. This is the Meissner-effect.

Meissner-effect : $\lambda^{-1} > 0$.

No Meissner-effect: $\lambda^{-1} = 0$.

The expression for λ is

$$\lambda = \left(\frac{m}{\mu_0 n_s (e^*)^2} \right)^{\frac{1}{2}}, \quad (7.14)$$

a magnetic penetration length. $\lambda^{-1} > 0$ if and only if $n_s > 0$. $\lambda^{-1} = 0$ otherwise. How does n_s relate to Δ_k^\dagger ? Δ_k^\dagger originates with $b_k^\dagger = \langle c_{-k\downarrow} c_{k\uparrow} \rangle^\dagger$ which is the expectation value of the creation operator of a Cooper pair. Fourier-transformed to real-space it is the wavefunction $\psi(\mathbf{r})$ of a Cooper-pair. $n_s \sim |\psi|^2$, thus $n_s \neq 0$ if and only if $\Delta_k \neq 0$.⁴ Thus the onset of Δ_k for $T < T_C$ also means the onset of the Meissner-effect.

⁴Says iff $\Delta_k = 0$ in the notes, which doesn't seem right.s

The onset of Δ_k at $T < T_C$ explains:

- i) loss of resistivity $\rho(T)$
- ii) onset of Meissner-effect