

Week 14 Worksheet

Time-Dependent Scattering

Jacob Erlikhman

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Exercise 1. General Theory.

- a) Consider the Schrödinger equation for time-dependent perturbation theory

$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = [H^0 + \lambda H'(t)] |\Psi(t)\rangle .$$

Suppose

$$|\Psi(t)\rangle = \sum_n c_n(t) e^{-iE_n t/\hbar} |n\rangle ,$$

where $|n\rangle$ are the eigenstates of H^0 . Derive the *exact* result

$$i\hbar \frac{dc_n(t)}{dt} = \lambda \sum_m \langle n | H'(t) | m \rangle e^{i\omega_{nm}t} c_m(t). \quad (1)$$

- b) Now, set

$$c_n(t) = \sum_{k=0}^{\infty} \lambda^k c_n^{(k)}(t),$$

and plug it into your result from (b) to obtain the first order, i.e. $\mathcal{O}(\lambda)$, differential equation.

- c) Obtain the second order equation.

Remark. Notice that your results for (b) and (c) are *exactly* the same as the two-level results when we begin in a single initial state!

Exercise 2. Sinusoidal Perturbations. In the case that

$$H' = K e^{-i\omega t} + K^\dagger e^{i\omega t}$$

is sinusoidal and acts up until time t , solve the first order perturbation theory differential equation from Exercise 1(b).

Exercise 3. Spin Resonance. Consider a spin-1/2 particle in a static magnetic field $B_0 \hat{z}$, so $H^0 = -\frac{1}{2} \hbar \gamma B_0 \sigma_z$. The perturbation is due to a magnetic field B_1 rotating in the (x, y) -plane with angular velocity ω :

$$H'(t) = -\frac{1}{2} \hbar \gamma B_1 [\sigma_x \cos(\omega t) + \sigma_y \sin(\omega t)].$$

- a) Writing the eigenvectors of σ_z as

$$|+\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad |-\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix},$$

rewrite H' in the form given in Exercise 2, using these eigenvectors as a basis.

- b) Suppose at $t = 0$ we have the initial state $|i\rangle = |+\rangle$. Find the first order probability for the spin to be down at time t . It is convenient to set $\omega_0 = \gamma B_0$ and $\omega_1 = \gamma B_1$.
- c) It turns out that the exact Equation 1 can be solved for such a hamiltonian. The exact answer for (b) is

$$P(t) = \sin^2(\alpha t/2) \left(\frac{\omega_1}{\alpha} \right)^2,$$

where $\alpha^2 = (\omega_0 + \omega)^2 + \omega_1^2$; $\alpha/2$ is called the **Rabi flopping frequency**. Using this answer, what is the range of validity of the perturbation theory result, assuming we are not near resonance?

- d) Suppose we are near resonance. What is the range of validity of the perturbation theory result? Give a physical explanation of your result.
- e) **Challenge.** Solve Equation 1, and derive the formula for $P(t)$.