

Absorption, Scattering, and Collisions - Chapter 4

Throughout the book, we have emphasized a "scattering" approach to absorption. That is, for a medium of atoms, the field intensity diminishes with distance in the sample but, in steady state, the atoms scatter radiation from the incident field mode to previously unoccupied fields of the vacuum field centered at the laser frequency (in an atom's rest frame). This interpretation is strictly valid only in the absence of collisions, since collisions can either provide or take away energy from center-of-mass energy of the colliding atoms. Thus, within the impact approximation, the collision can provide the energy necessary to make up the energy difference between the atomic transition energy $\hbar\omega_0$ and the laser "photon" energy $\hbar\omega$. As a consequence, while the radiation is scattered by the atoms, even in the presence of collisions, there is a component of the scattered radiation centered at the *atomic* transition frequency when collisions are present. This overall process is referred to as *radiation redistribution* [1].

Radiation redistribution can be viewed as resulting from collisional assisted radiative *absorption*. This interpretation is strengthened by considering pulsed excitation in the adiabatic limit. Following such a pulse, atoms in its ground states would remain return to their ground states; however, with collisions present (in the impact approximation where the collision duration is much smaller than the inverse collision duration), there would be some excited state population produced that is proportional to the collision rate. Another way to view this is that collisions result in some excited *dressed* state population that evolves into the excited bare state following the field. Thus, throughout the book, the scattering interpretation should be understood to apply only in the absence of collisions or other dephasing processes.

There are examples related to collisional redistribution given in Fig. 8.3 for three-level atoms, where there is an extra resonance associated with collisional redistribution, and in problem 7.3, where there is a collision-induced contribution to the probe absorption spectrum centered at the laser frequency. The most direct example of collisional redistribution is the scattering spectrum in weak fields. There it is possible to show that, for stationary atoms, the scattering spectrum is proportional to

$$I_k \sim \delta(\omega_k - \omega) + \frac{2\Gamma}{\pi\gamma\gamma_2} \frac{\gamma^2}{\gamma^2 + \delta^2};$$

that is, the frequency spectrum for scattered radiation having frequency ω_k has a delta function component centered at the laser frequency and a collision-induced

component centered at the atomic frequency. The collisional redistribution component can be connected with a dressed state population that is nonvanishing only when collisions are present, in the secular approximation. In other words, one component of the Mollow triplet, whose amplitude is normally proportional to the field intensity squared, has an amplitude that varies as the field intensity multiplied by Γ/γ_2 in the presence of dephasing collisions.

On the other hand, an equation such as Eq. (4.15) should still be correct, even in the presence of collisions. In each scattering process, with or without collisions or dephasing events, the field loses $\hbar\omega$ of energy. If collisions or dephasing events are absent, the energy appears totally in the scattered radiation. When such processes are present, the difference in energy between the incident field frequency and the atomic frequency is provided by the collisions or dephasing.

Note that when moving atoms are considered, there is also a change in momentum and energy of the atoms that scatter the radiation, even in the absence of collisions. As a result, the scattered radiation, while at the laser frequency in an atom's rest frame (neglecting recoil), will be at a Doppler shifted frequency in the laboratory frame. In other words, an atom that has momentum $\mathbf{p} = m\mathbf{v}$ (with $p \gg \hbar k$) that scatters radiation from the $\mathbf{k}$ to $\mathbf{k}'$ direction changes its energy to

$$\frac{p'^2}{2m} = \frac{|\mathbf{p} + \hbar(\mathbf{k} - \mathbf{k}')|^2}{2m} \approx \frac{p^2}{2m} + \frac{\hbar\mathbf{p} \cdot (\mathbf{k} - \mathbf{k}')}{m},$$

implying that the scattered radiation has frequency

$$\omega_s \approx \omega - (\mathbf{k} - \mathbf{k}') \cdot \mathbf{v}$$

in the laboratory frame.

References

- [1] See, for example, J. Cooper in *Spectral Line Shapes* (Walter de Gruyter & Co., Berlin, 1983), pps. 2737-753; R. J. Bieniek, Phys. Rev. A **35**, 3663 (1987), and references therein.