Plasma Physics and Engineering

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be derived taking into account the ion motion

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}\frac{1}{\left(1 \pm \frac{\omega_B}{\omega} - \frac{\omega_B\omega_{Bi}}{\omega^2}\right)}. \tag{6.6.42}$$

If the electromagnetic wave frequency exceeds ion-cyclotron frequency ($\omega \gg \omega_B$), influence of the term $\omega_B\omega_{Bi}/\omega^2$ in the denominator is negligible and the dispersion equation 6.6.42 coincides with Equation 6.6.39. Conversely, if the wave frequency is low ($\omega \ll \omega_B$), then the term $\omega_B\omega_{Bi}/\omega^2$ becomes dominant in the dispersion equation. In this case, the dispersion equation 6.6.42 can be rewritten as

$$\frac{c^2}{(\omega/k)^2} = 1 + \frac{\omega_p^2}{\omega_B\omega_{Bi}} = 1 + \frac{\mu_0\rho}{B^2} \approx \frac{c^2}{v_A^2}. \tag{6.6.43}$$

This introduces again the Alfven wave velocity v_A (Equation 6.5.17); here, $\rho = n_e M$ is the mass density in completely ionized plasma (see Ginsburg,1960; Ginsburg and Rukhadze, 1970).

6.7 Emission and Absorption of Radiation in Plasma, Continuous Spectrum

6.7.1 Classification of Radiation Transitions

Radiation occurs due to transitions between different energy levels of a quantum system: transition up corresponds to absorption of a quantum $E_f - E_i = \hbar\omega$, transition down the spectrum corresponds to emission $E_i - E_f = \hbar\omega$ (see Section 6.7.2). From the point of classical electrodynamics, radiation is related to the nonlinear change of dipole momentum, actually with the second derivative of dipole momentum. Neither emission nor absorption of radiation is possible for free electrons. Electron collisions are necessary in this case. It will be shown in Section 6.7.4 that electron interaction with a heavy particle, ion, or neutral is able to provide emission or absorption, but electron–electron interaction cannot. It is convenient to classify different types of radiation according to the different types of electron transition from one state to another. Electron energy levels in the field of an ion as well as transitions between the energy levels are illustrated in Figure 6.32. The case when both initial and final electron states are in continuum is called the free–free transition. A free electron in this transition loses part of its kinetic energy in the Coulomb field of a positive ion or in interaction with neutrals. The emitted energy in this case is a continuum, usually infrared and called bremsstrahlung (direct translation—

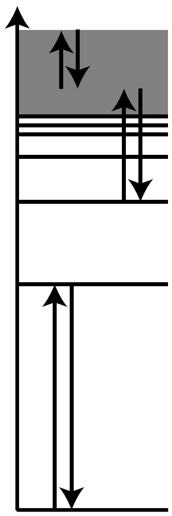

FIGURE 6.32
Energy levels and electron transitions induced by ion field.

Electron transition between a free state in continuum and a bound state in atom (see Figure 6.32) is usually referred to as the free–bound transition. The free–bound transitions correspond to processes of the radiative electron–ion recombination (see Section 2.3.5) and the reverse one of photoionization (see Section 2.2.6). Such kinds of transitions also could take place in electron-neutral collisions. In this case, these are related to photo-attachment and photo-detachment processes of formation and destruction of negative ions (see Section 2.4). The free-bound transitions correspond to continuum radiation. Finally, the bound–bound transitions mean transition between discrete atomic levels (see Figure 6.32) and result in emission and absorption of spectral lines. Molecular spectra are obviously much more complex than that of single atoms because of possible transitions between different vibrational and rotational levels.

6.7.2 Spontaneous and Stimulated Emission: Einstein Coefficients

Consider transitions between two states (upper "u" and ground "0") of an atom or molecule with emission and absorption of a photon $\hbar\omega$, which is illustrated in Figure 6.33. The probability of a photon absorption by an atom per unit time (and, hence, atom transition "0" → "u") can be expressed as

$$P(\text{“}0\text{”}, n_\omega \to \text{“}u\text{”}, n_\omega - 1) = An_\omega. \tag{6.7.1}$$

Here, n_ω is the number of photons; A is the Einstein coefficient, which

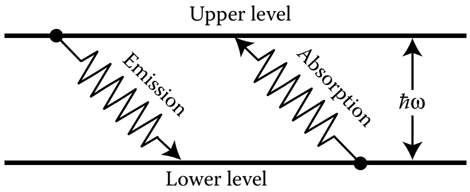

FIGURE 6.33
Radiative transition between two energy levels.

characteristics. Similarly, the probability of atomic transition with a photon emission is

$$P(\text{“}u\text{”},\, n_\omega \to \text{“}0\text{”},\, n_\omega + 1) = \frac{1}{\tau} + Bn_\omega. \qquad (6.7.2)$$

Here, $1/\tau$ is the frequency of spontaneous emission, which takes place without direct relation to external fields; Einstein coefficient B characterizes emission induced by an external electromagnetic field. The factors B and τ as well as A depend only on atomic parameters. If the first right-hand side term in Equation 6.7.2 corresponds to spontaneous emission, the second term is related to the stimulated emission. To find relations between the Einstein coefficients A, B and the spontaneous emission frequency $1/\tau$, analyze the thermodynamic equilibrium of radiation with the atomic system. In this case, the densities of atoms in lower and upper states (Figure 6.33) are related in accordance with the Boltzmann law (Equation 4.1.9) as

$$n_\mathrm{u} = \frac{g_\mathrm{u}}{g_0} n_0 \exp\left(-\frac{\hbar\omega}{T}\right), \qquad (6.7.3)$$

where $\hbar\omega$ is energy difference between the two states, g_u, g_0 are their statistical weights. According to the Planck distribution, the average number of photons $\bar{n}_\omega$ in one state can be determined as

$$\bar{n}_\omega = 1\bigg/\left(\exp\frac{\hbar\omega}{T} - 1\right). \qquad (6.7.4)$$

Taking into account, the balance of photon emission and absorption (see Figure 6.33)

$$n_0 P(\text{“}0\text{”},\, n_\omega \to \text{“}u\text{”},\, n_\omega - 1) = n_\mathrm{u} P(\text{“}u\text{”},\, n_\omega \to \text{“}0\text{”},\, n_\omega + 1), \qquad (6.7.5)$$

which can be rewritten based on Equations 6.7.1 and 6.7.2 as

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