Plasma Physics and Engineering

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$$\frac{c^2}{(\omega/k)^2} = 1 + \frac{\omega_p^2}{\omega_B \omega_{Bi}} = 1 + \frac{\mu_0 \rho}{B^2} \approx \frac{c^2}{v_A^2} \tag{6.214}$$

This introduces again the Alfven wave velocity v_A (Equation 6.139); here, $\rho = n_e M$ is the mass density in completely ionized plasma.

Only a few principal types of electromagnetic waves in magnetized plasma have been discussed. For example, numerous possible modes are related to electromagnetic wave propagation not along the magnetic field. Some of them are very important in plasma diagnostics and in high-frequency plasma heating. More details on the subject can be found in Ginsburg[215] and Ginsburg and Rukhadze.[216]

6.7 EMISSION AND ABSORPTION OF RADIATION IN PLASMA: CONTINUOUS SPECTRUM

6.7.1 Classification of Radiation Transitions

Because of its application in different lighting devices, radiation is probably the most commonly known plasma property. Radiation also plays an important role in plasma diagnostics, including plasma spectroscopy, in the propagation of some electric discharges, and sometimes even in plasma energy balance.

From a quantum mechanical point of view, 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 (see Section 6.7.4).

It should be mentioned that neither emission nor absorption of radiation is impossible for free electrons. As was shown in Section 6.6, 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 an 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) called **bremsstrahlung** (direct translation: stopping radiation). The reverse process is the bremsstrahlung absorption.

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**. These 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). These kinds

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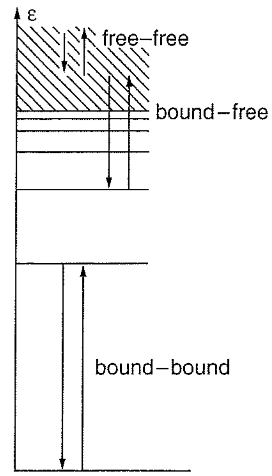

Figure 6.32 Energy levels and electron transitions induced by ion field

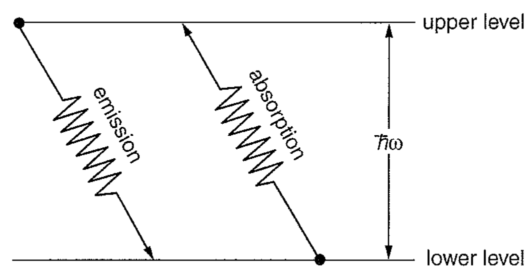

Figure 6.33 Radiative transition between two energy levels

of transitions can also take place in electron–neutral collisions. In such a case these are related to photoattachment and photodetachment 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 those of single atoms because of possible transitions between different vibrational and rotational levels (see Section 3.2).

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 thus atom transition "0" → "u") can be expressed as:

$$P(\text{"0"}, n_\omega \rightarrow \text{"}u\text{"}, n_\omega - 1) = An_\omega \tag{6.215}$$

Here, n_ω is the number of photons and A is **the Einstein coefficient**, which depends on atomic parameters and does not depend on electromagnetic wave characteristics. Similarly, the probability of atomic transition with a photon emission is:

$$P(\text{"}u\text{"}, n_\omega \rightarrow \text{"0"}, n_\omega + 1) = \frac{1}{\tau} + Bn_\omega \tag{6.216}$$

Here, $1/\tau$ is the frequency of **spontaneous emission** of an excited atom or molecule, which takes place without direct relation with external fields; another 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. Thus, if the first right-side term in Equation 6.216 corresponds to spontaneous emission, the second term is related to **stimulated emission.**

To find relations between the Einstein coefficients A and B and the spontaneous emission frequency $1/\tau$, analyze the thermodynamic equilibrium of radiation with the atomic system under consideration. 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:

$$n_u = \frac{g_u}{g_0} n_0 \exp\left(-\frac{\hbar\omega}{T}\right) \tag{6.217}$$

where $\hbar\omega$ is energy difference between the two states and g_u and g_0 are their statistical weights. According to the Planck distribution (see Section 4.1.5 and Equation 4.19), the averaged number of photons $\bar{n}_\omega$ in one state can be determined as:

$$\bar{n}_\omega = 1\bigg/\left(\exp\frac{\hbar\omega}{T} - 1\right) \tag{6.218}$$

Then, taking into account the detailed balance of photon emission and absorption for the system illustrated in Figure 6.33,

$$n_0 P(\text{"0"}, n_\omega \rightarrow \text{"}u\text{"}, n_\omega - 1) = n_u P(\text{"}u\text{"}, n_\omega \rightarrow \text{"0"}, n_\omega + 1) \tag{6.219}$$

which can be rewritten based on Equation 6.215 and Equation 6.216 as:

$$n_0 A \bar{n}_\omega = n_u\left(\frac{1}{\tau} + B\bar{n}_\omega\right) \tag{6.220}$$

The relations between the Einstein coefficients A and B and the spontaneous emission frequency $1/\tau$ can be expressed based on Equation 6.217, Equation 6.218, and Equation 6.220 as:

$$A = \frac{g_u}{g_0}\frac{1}{\tau}, \quad B = \frac{1}{\tau} \tag{6.221}$$

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