MANIFESTATION OF KIRCHHOFF' S LAW IN GAMMA SPECTROSCOPY

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Abstract

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MANIFESTATION OF KIRCHHOFF’S LAW IN GAMMA SPECTROSCOPY

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The exact coincidence of the spectral lines of absorption and emission, manifested in the optical region of the spectrum, is usually regarded as an experimental manifestation of Kirchhoff’ s law for the relation between absorption and radiation. In the region of γ radiation, the absorption and nuclear-fluorescence lines, as is known, are shifted relative to one another by a considerable spectral interval owing to the photon recoil effect, which is insignificant in the optical region. If one keeps in mind that spectral lines must be characterized by a certain frequency distribution of their intensity, and that the intensity of black-body radiation varies over the spectrum, then the fact that the absorption and emission lines do not coincide is not unexpected from the point of view of Kirchhoff’ s law ([1]). In this connection it is of interest to compare the requirements imposed by Kirchhoff’ s law on the relation between the contours of the absorption and emission lines with a calculation of these contours taking into account the mechanism that leads to their noncoincidence—the recoil effect. In ([1]) it was shown that, in the case when in a gas the line contour is formed by phenomena associated with the thermal motion of atoms, and if the velocity distribution of the emitting atoms is Maxwellian, Kirchhoff’ s law implies

$$\frac{I_\nu}{a_\nu} = CK_\nu = C\frac{2h\nu^3}{c^2}\exp\left(-\frac{h\nu}{kT}\right), \tag{1}$$

where I_ν is the fluorescence-line spectrum; a_ν is the spectral absorption coefficient; C is a coefficient independent of frequency; K_ν is the equilibrium-radiation spectrum represented in the form of Wien’ s formula.

In the case when the line shape is determined by the Doppler effect, a calculation taking simultaneous account, by means of the conservation laws for energy and momentum in the emission and absorption of a quantum, of line broadening and the recoil effect leads to the expressions ([1])

$$I_\nu = \frac{Ah\nu N_c^*}{4\pi\nu_0}\sqrt{\frac{M}{2\pi kT}}\exp\left[-\frac{(\nu_0 - R/h - \nu)^2 Mc^2}{2kT\nu_0^2}\right]; \tag{2}$$

$$a_\nu = \frac{ANc^3}{8\pi\nu^2\nu_0}\sqrt{\frac{M}{2\pi kT}}\exp\left[-\frac{(\nu_0 + R/h - \nu)^2 Mc^2}{2kT\nu_0^2}\right]. \tag{3}$$

Here A is the probability of a spontaneous transition; N and N^* are the numbers of atoms per unit volume, respectively in the ground and excited states; M is the mass of the atom; $h\nu_0 = E_0$ is the transition energy; R is the photon recoil energy, which determines the distance between the lines and is equal to

$$R \cong E_0^2/2Mc^2. \tag{4}$$

Substituting (2) and (3) into (1), it is not difficult to verify that relation (1) is satisfied. If the ratio N^*/N is taken to be the equilibrium one corresponding to temperature T, then I_ν will characterize thermal radiation. In this

case, upon substituting (2) and (3) into (1), the coefficient C becomes unity and (1) turns into Kirchhoff' s law. Thus, the spectra (2) and (3) correspond to relation (1) in the case of nonequilibrium emission and to Kirchhoff' s law in the transition to thermal emission. It is important that this correspondence holds only if the quantity R entering into (2) and (3) is defined by (4). Therefore, if one carries out a purely formal symmetric displacement along the frequency scale of initially coincident spectra of classical Doppler lines so that Kirchhoff' s law is satisfied, then the distance between their centers gives the correct expression for R, independently of knowledge of the mechanism leading to the mismatch of the lines.

Let us note that, although expressions (2) and (3) correspond strictly to (1), these expressions themselves were derived from the conditions of conservation of energy and momentum approximately, and these conditions were also taken in the approximate form (1). At the same time, both of these approximations are very accurate, and exact cumbersome calculations taking relativistic effects into account practically do not change the shapes of the spectra in comparison with (2) and (3). Therefore, although the obtained correspondence of the spectra (4) and (5) to relation (1) is not formally fully rigorous, it definitely indicates the existence of a physical connection between Kirchhoff' s law and the mechanism of emission and absorption of a quantum that takes its recoil into account.

Thus, photon recoil, manifested in γ-spectroscopy, is in the system considered a microscopic mechanism ensuring the fulfillment of Kirchhoff' s law and, consequently, the possibility of a state of thermodynamic equilibrium of radiation with matter, since Kirchhoff' s law follows from the most general consideration of the conditions for such equilibrium.

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CITED LITERATURE

[1] Yu. T. Mazurenko, DAN, 165, 790 (1965).

Note: Figure translations are in progress. See original paper for figures.