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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According to Kirchhoff' s law ([1]), the ratio of the spectral emission coefficient of an equilibrium medium ε_ν (by the spectral emission coefficient is meant the radiation power of a small volume, referred to unit volume, solid angle, and frequency) to the spectral absorption coefficient a_ν is equal to the spectral brightness of equilibrium radiation at the temperature of the medium K_ν:

$$\varepsilon_\nu / a_\nu = K_\nu. \tag{1}$$

Let us consider a gas consisting of atoms that have a discrete set of energy levels and, correspondingly, a line absorption and emission spectrum. Let the form of the absorption and emission lines be determined chiefly by broadening associated with the thermal motion of the atoms, i.e., by collisions of atoms in the process of absorption and emission, or by the Doppler effect. The natural width of the line is therefore regarded as negligibly small. Under conditions of thermal equilibrium the contours of the absorption and emission lines are mutually related by Kirchhoff' s law (1), from which it follows that, generally speaking, these contours do not coincide, i.e., the absorption and emission lines may be shifted with respect to one another (since the brightness of equilibrium radiation varies with frequency).

Under real experimental conditions, in measuring emission spectra, thermal equilibrium is usually sharply disturbed. Therefore the line contours of nonequilibrium emission and of thermal emission should, generally speaking, differ. In the case where forced emission may be neglected, which is valid in the region $h\nu \gg kT$, the spectra of thermal emission and nonequilibrium emission (fluorescence) are due only to spontaneous transitions between excited and unexcited states of the atoms. Suppose that the lifetime of the excited state for one of the lines is sufficiently long, so that the velocity distribution of the excited atoms by the moment of quantum emission, irrespective of the method of excitation, has practically enough time to become equilibrium as a result of atomic collisions. Then the fluorescence conditions differ from those of thermal emission only by the presence of a larger number of excited atoms, and therefore the spectra of the fluorescence lines and of thermal emission will differ only in intensity, retaining similar forms. Thus, if the conditions given above are satisfied, the following relation, following from (1), must hold:

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

Here I_ν is the fluorescence-line spectrum, defined analogously to the quantity ε_ν; C is a quantity independent of frequency. The spectrum of equilibrium radiation K_ν is represented in the form of Wien' s formula, valid in the region $h\nu \gg kT$. (We note that relation (2) is analogous to the relation obtained-

valuable for the electron-vibrational absorption and fluorescence spectra of solutions of complex molecules ([2]).)

Let us consider the case in which the line shape is determined by the Doppler effect. The classical description of Doppler broadening ([3]) leads to coincidence of the contours of the absorption and emission lines, which agrees with experiment in the optical frequency region. For γ-lines, together with the Doppler effect, it becomes essential to take into account the phenomenon of photon recoil ([4]), which, as is known, leads to a relative displacement of the absorption and fluorescence lines observed experimentally. The Doppler effect and the recoil effect can be taken into account simultaneously by means of the conditions of conservation of energy and momentum when a photon is emitted or absorbed by an atom. For the case of emission, this condition in the nonrelativistic approximation is written in the form ([4])

$$E_0 - E = \mathbf{p}^2/2M - \mathbf{p}\mathbf{P}/M, \tag{3}$$

where $E_0 = h\nu_0$ is the transition energy; $E = h\nu$ is the photon energy; $\mathbf{p}$ is the photon momentum; $\mathbf{P}$ is the atom momentum; M is the atom mass. An analogous relation can also be written for the case of photon absorption by an atom. The use of these relations together with the Maxwellian distribution of atoms over momenta makes it possible to obtain expressions for the contours of the absorption and emission lines. Within the assumption $\mathbf{p} \cong E_0/c$, justified by the fact that E_0 considerably exceeds the recoil energy and the line width ([4]), these expressions have the following form. For emission:

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

for absorption:

$$\alpha_\nu = \frac{Ac^3 N}{8\pi\nu^2\nu_0}\sqrt{\frac{M}{2\pi kT}}\exp\left[-\frac{(\nu_0 + R/h - \nu)^2 Mc^2}{2kT\nu_0^2}\right]. \tag{5}$$

Here A is the probability of a spontaneous transition (γ-decay); N and N^* are the numbers of atoms per unit volume, respectively in the ground and excited states; R is the photon recoil energy, equal to

$$R \cong E_0^2/2Mc^2. \tag{6}$$

Expressions (4) and (5) differ from the classical expressions for a Doppler line in that they include the quantity R, owing to which the emission and absorption line spectra are separated by the amount $2R/h$.

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CITED LITERATURE

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