ANISOTROPY OF GAMMA RADIATION IN THE MÖSSBAUER EFFECT

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Anisotropy of γ radiation in the Mössbauer effect is calculated for the case when the source is in a magnetic field (external magnetic field or field of ferromagnetic domains).

MÖSSBAUER[1,2] pointed out the possibility of direct observation of resonance scattering of γ rays in the case when the nucleus is sufficiently rigidly bound to the crystal lattice. Under this condition, the recoil momentum can be transferred not to the individual nucleus, but to the lattice as a whole; consequently, both the emission and the absorption of the γ quantum proceed without energy loss. Thus, realization of resonance scattering requires no additional Doppler shift of the photon energy, and the effective scattering cross section reaches thereupon a large value.

The sensitivity of the Mössbauer effect to minute energy changes has made it possible to observe heretofore undetected phenomena, such as the transverse Doppler effect or the Zeeman splitting of nuclear levels.[3,4] The Zeeman effect was investigated in the decay of Co^{57}, as was the polarization of γ radiation. The latter phenomenon was observed with a source and absorber placed in a magnetic field sufficiently strong to orient the ferromagnetic domains.

The positive results of these experiments indicate that the anisotropy of the emission of γ radiation in the Mössbauer effect can be observed when the source is in a magnetic field. Unlike ordinary experiments with oriented nuclei, such a phenomenon can be observed at high temperatures.

We assume that the source is situated in a magnetic field strong enough to cause a noticeable Zeeman splitting. This can be either an external field or the field of ferromagnetic domains oriented by means of a weak external field.[5]

Let us examine a nucleus situated in a magnetic field H, directed along the z axis, and let the nucleus emit a quantum on going from a state with spin J_1 into a ground state with spin J_0. When the magnetic field is applied, these two levels are split into $2J_1+1$ and $2J_0+1$ levels, respectively. Let 2^L be the multipolarity of the γ quantum. If we do not measure the polarization, we need not distinguish between magnetic and electric radiation.

The angular distribution of radiation of multipolarity 2^L with magnetic quantum number M is given by the expression

$$I_M^L(\theta) = \sum_k a_k (L, M) P_k (\cos\theta),$$

$$a_k = (2k+1)\left[1 - \frac{k(k+1)}{2L(L+1)}\right] C(kLL;\, 00) C(kLL;\, 0M),$$

where θ is the angle between the direction of radiation and the z axis, P_k a Legendre polynomial, k an even number, and C a Clebsch-Gordan coefficient.

The relative probability of radiation of an (LM) transition going to a level with magnetic quantum number m_0, is

$$g(m_0M) = |C(J_0LJ_1;\, m_0M)|^2 \Big/ \sum_{m_0M} |C(J_0LJ_1;\, m_0M)|^2,$$

where the summation is over all the Zeeman components; we note that

$$\sum_{m_0M} g(m_0M) = 1.$$

The intensity of the (LM) component in the θ direction is $I_M^L(\theta)\, g(m_0M)$, with

$$\sum \boldsymbol{I}_M^L(\theta) g(m_0M) = 1.$$

We assume that an absorber, in which resonance scattering can take place, is located in this direction. We shall assume that the absorber is not in an external magnetic field. Two cases are then possible:

a) The intensity of the magnetic field inside the absorber is zero, as for example in the case of $Na_4Fe(CN)_6 \cdot 10H_2O$.[6] In this case there is no Zeeman splitting and the resonant absorption takes place only for the transition $m_1 = 0 \rightarrow m_0 = 0$, if this is possible. In the opposite case, and in general for the observation of other components, it is necessary to compensate for the energy difference in the radiation and absorption with a Doppler shift.[2] In this case the intensity of the transmitted radiation will depend only on the function $I_M^L(\theta)$ for the given multipole.

b) Inside the absorber there is an unordered magnetic field, for example a ferromagnetic-domain field strong enough to produce a noticeable Zeeman effect. If the Zeeman splitting is sufficiently large, then the radiation (m_0M) can produce only a transition $J_0m_0 \rightarrow J_1m_1$, which is the inverse of the transition that takes place in the source nucleus. The quantization axis will coincide for each nucleus with the direction of the local magnetic field. The probability of absorption of the component (m_0M) by the unoriented nuclei of the absorber is proportional to the probability of radiation by the unoriented nuclei, i.e., it can be written in the form $p_R g(m_0M)$.

In experiments on the nuclear Zeeman effect it is also customary to use sources with unordered magnetic field. The share of the component (m_0M) in the radiation from such a source is $g(m_0M)$, and the observed summary probability of absorption is

$$\bar{p}_R = p_R \sum_{m_0M} g^2(m_0M) = p_R/\alpha, \qquad 1/\alpha = \sum g^2(m_0M).$$

We assume for the time being that all the absorption is resonant. The probability of passage of the radiation through the absorber is equal, for each individual component,

$$1-\alpha\,\bar{p}_R\,g(m_0M),$$

and the angular distribution of the transmitted radiation is given by

$$F(\theta) = 1 - p - \alpha\bar{p}_R \sum_{m_0M} I_M^L(\theta) g^2(m_0M),$$

where p is the probability of electron absorption. If the fraction of the resonant radiation is f, the sum in this formula should be multiplied by f.

In order to perform such an experiment it is necessary that the Zeeman splittings in the source and in the absorber be the same. If a source is used with domains oriented by an external field, it should be sufficiently weak so that its influence on the Zeeman splitting can be neglected. The work described in [5] was performed precisely under these conditions.

We shall consider briefly the case of a 14.4-kev transition in the decay of Co^{57}, between the levels $J_1 = 3/2$ and $J_0 = 1/2$ of the Fe^{57} nucleus. Because of the high intensity of the magnetic field of the domains ($\sim 10^5$ oe), the Zeeman splitting exceeds the width of the level. The angular distribution of M1 radiation has the form

$$F(\theta) = 1 - p - \frac{3}{28} f\bar{p}_R [9 + \cos^2\theta].$$

Thus, for an absorber 3 mg/cm² thick, containing 76% Fe^{57}, we have[5]

$$\bar{p}_R = 0.543, \qquad f \approx 0.9.$$

Under these conditions the anisotropy obtained is

$$[F(\pi/2) - F(\pi)]/F(\pi) \approx 0.018.$$

In conclusion, the author takes pleasure in thanking Prof. S. Titeica for a discussion of the results of this work.

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