Polarization of Gamma-Radiation Following Capture of Polarized Neutrons*

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(Received June 14, 1951)

IN an attempt to utilize polarized neutrons for purposes of nuclear spectroscopy we were led to a consideration of the anisotropy properties of the emitted gamma-rays.[1] It is well known that for the capture of s-neutrons the intensity is isotropic. Therefore, the question arises of obtaining information concerning angular momentum of compound states and/or multipolarity of the γ's by looking for anisotropy with polarization-sensitive detectors.

It can be shown that with ordinary Compton scattering, pair formation, or photoelectric processes as detection devices (all of which measure linear polarization) no anisotropy will occur. The probability that a neutron with polarization $\mathbf{P}_0$ will lead to the emission of a photon with propagation vector $\mathbf{k}$ and polarization vector $\mathbf{e}$ is

$$W(\mathbf{P}_0, \mathbf{k}, \mathbf{e}) \sim \Sigma_{m_0 m'} |\Sigma_m (A(\mathbf{P}_0, m_0)|H_c|B_m)(B_m|H_2(\mathbf{k}, \mathbf{e})|C_{m'})^*|^2 \quad (1)$$

with A, B, and C representing probability amplitudes of initial, intermediate, and final states, respectively; m_0, m, and m' the magnetic quantum numbers of target, compound, and final nuclear states. The angular momenta of these states are J_0, J, and J', respectively. H_c and $H_2 \sim \boldsymbol{\alpha} \cdot \mathbf{A}$ are the capture and γ-emission interaction operators; for the emission of plane polarized radiation the vector potential $\mathbf{A}$ is

$$\mathbf{A}(\mathbf{k}, \mathbf{e}) = \Sigma_{P=\pm 1} e^{-iP\tau} \mathbf{A}(\mathbf{k}, P), \quad (2)$$

where $\mathbf{e}$ makes an angle τ with respect to a fixed direction in the plane normal to $\mathbf{k}$ and $\mathbf{A}(\mathbf{k}, P)$ corresponds to right ($P=1$) and left ($P=-1$) circularly polarized radiation.[2] The result for the intensity, in the linearly polarized case, for emission of a general multipole mixture is

$$W(\mathbf{P}_0, \mathbf{k}, \mathbf{e}) \sim \Sigma_L [(2J'+1)/(2L+1)] |a(JJ'L)|^2 \pm \frac{2|P_0|}{2J_0+1} \sin 2\tau \, \Sigma_{L<L'} \Sigma_M \operatorname{Im}[a(JJ'L) a^*(JJ'L')] \times \Sigma_P P^{L-L'+1} D_{MP}^{(L)}(0\vartheta 0) D_{M,-P}^{(L')}(0\vartheta 0) \times \Sigma_m C_{J'mM}^{JL} C_{J'mM}^{JL'} \quad (3)$$

where the polarization-dependent part arises from the interference between different multipoles (order 2^L and $2^{L'}$). In (3) the $\pm$ corresponds to $J = J_0 \pm \frac{1}{2}$, the a coefficients are reduced matrix elements[3] (independent of magnetic quantum numbers but dependent on parity), the $D^{(L)}$ factors are the rotation matrices of order L, ϑ is the angle between $\mathbf{k}$ and $\mathbf{P}_0$, and the C's are vector addition coefficients.[4] Since the imaginary part of the matrix-element product vanishes,[5] the potentially anisotropic term in (3) disappears.

The detector processes referred to do not distinguish between right and left circular polarization or between these and unpolarized radiation. What is needed is a "nuclear quarter-wave plate." One obtains the desired circular polarization detector by using magnetized iron as a Compton scatterer.[6] Then an azimuthal anisotropy in the Compton scattered intensity will arise because the intensities of the right and left circularly polarized components of the radiation are different. In fact, these intensities for unmixed 2^L-pole radiation are

$$W(\mathbf{P}_0, \mathbf{k}, P) \sim 1 \pm |P_0| P \frac{J'(J'+1) - L(L+1) - J(J+1)}{L(L+1)(2J_0+1)} \cos\vartheta, \quad (4)$$

where $(P = \pm 1)$.

The only essential factor limiting the magnitude of the anisotropy is the relative number of electrons contributing to the magnetization in iron (~ 0.1). As an example of the application of our result we may consider the neutron capture leading to an even-even compound nucleus and a transition leading to the ground state. Such a transition may be identified by using energy-sensitive detectors. Then, since the anisotropy is determined by the coefficient of P in (4) a determination of this sign selects one of the two possibilities $J = J_0 \pm \frac{1}{2}$ and, since $J = L$, the sign measurement determines the multipole order of the radiation as well. It should be noted that there are certain exceptional cases where the anisotropy vanishes. The only cases of interest are $J = 2 \to J' = 3$ with the emission of quadrupole radiation ($L=2$) and, considerably less likely, $J = 5 \to J' = 6$ with octupole radiation ($L=3$). Of course, $J=0$ corresponds to isotropy. So far as dependence on angular momenta is concerned, the anisotropy is maximum when $J'(J'+1) - J(J+1) = \pm L(L+1)(2J_0+1 \pm 1)$. This occurs when $J_0 = 0$, $J = J' = \frac{1}{2}$ and when $J_0 = \frac{1}{2}$, $J' = 0$; in both cases $W \sim 1 \mp |P_0| P \cos\vartheta$ and for these particular cases dipole radiation is expected. Thus, for complete neutron polarization[7] only right, left circular polarization is obtained at $\vartheta = \pi$, $0 (J = J_0 + \frac{1}{2})$ and at $\vartheta = 0, \pi (J = J_0 - \frac{1}{2})$.

A special case of the foregoing considerations was discussed by Halpern.[8]

* This paper is based on work performed for the AEC at the Oak Ridge National Laboratory.

[1] Biedenharn, Rose, and Arfken, AEC Report, ORNL 986 (March 26, 1951).
[2] G. Goertzel, Phys. Rev. **70**, 897 (1946).
[3] E. U. Condon and G. H. Shortley, *Theory of Atomic Spectra* (Cambridge University Press, London, 1935), Chapter III.
[4] E. P. Wigner, *Gruppentheorie* (J. W. Edwards, Ann Arbor, Michigan, 1944), reprint. See also reference 3, pp. 76–77.
[5] S. P. Lloyd, Phys. Rev. **81**, 161 (1951). In obtaining (3) the direction of $\mathbf{P}_0$ was chosen as the axis of quantization. Choosing the latter along $\mathbf{k}$ we obtain only the first term of (3), which is, of course, isotropic. Since none of the factors in the second term of (3) other than $\operatorname{Im}[a(JJ'L)a^*(JJ'L')]$ can vanish identically, we obtain an alternative demonstration of Lloyd's result on relative phases of nuclear matrix elements.
[6] See U. Fano, J. Opt. Soc. Am. **39**, 859 (1949), where this result is implicitly contained.
[7] C. G. Shull, Phys. Rev. **81**, 626 (1951).
[8] O. Halpern, Phys. Rev. **82**, 753 (1951).

Domain Wall Relaxation in Nickel

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(Received June 11, 1951)

RECENT measurements[1] of the decrement δ and the difference between the magnetically saturated and the demagnetized elastic constants (the ΔE effect) of nickel have shown that these effects are much smaller at 10 megacycles than they are in the low frequency range. Complete decrement-frequency and ΔE-frequency curves have been measured on a well-annealed polycrystalline rod with the results shown by Fig. 1. The decrement has reached a maximum value at about 150,000 cycles, while the $\Delta E/E_D$ ratio is decreasing continuously with frequency. It is the purpose of this note to show that this effect is due to a relaxation in the domain wall motion caused by the fact that the wall cannot follow the applied stress at high frequencies, on account of the induced micro-eddy-currents.

The simplest model that will demonstrate the ΔE effect is the 90° wall model shown by Fig. 2. This model applies to iron, since the directions of easy magnetization lie along cube axes. The equation of motion for such a domain wall for a sinusoidally applied magnetic field H, is

$$M'(d^2x/dt^2) + R'(dx/dt) + K'x = HI_s e^{j\omega t}, \quad (1)$$

where M', R', and K' are the effective mass, resistance, and stiffness constants of the wall and I_s is the saturation magnetic intensity. At the low frequencies considered here, M' can be neglected, K' can be evaluated from the initial susceptibility, and R' from power losses.

Taking account of the fact that the domains are distributed in all directions, the average displacement for a field H is

$$\bar{x} = HI_s/3K'. \quad (2)$$