POLARIZATION OF GAMMA RAYS FROM THE REACTION $Si^{30}(p, \gamma)P^{31}$

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Photographic emulsions impregnated with heavy water are used to measure the plane polarization of γ rays from the $Si^{30}(p,\gamma)P^{31}$ reaction. A study of transitions from resonance levels to the ground level of the $P^{31}(3/2^+ \to 1/2^+)$ nucleus is made for energies $E_p = 773$, 939, and 975.5 keV. The mixture coefficients δ for different types of transitions came to -2.3, -0.15, and -1.6, respectively. The transition to the first excited level 1.26 MeV $(3/2^+)$ at $E_p = 1393$ keV is studied. Spin and parity of the resonance level turn out to be $5/2^+$, and $\delta = 0.02$.

1. INTRODUCTION

MEASUREMENTS of the angular distributions of gamma rays in proton capture reactions yield information on the level spins and multipolarities of the radiations. In case of mixed transitions, however (for example M1 + E2), the experimentally obtained angular distribution correspond almost always to two radiation mixtures. This duality applies in many cases also to the spins of the levels. Thus, in transitions to a level with known spin and parity, the angular distribution may sometimes correspond to two values of the upper-level spins.

To determine the true values of the multipole mixtures and the level spins, it is very useful to measure the plane polarization of gamma rays. Endt, Suffert, and Hoogenboom [1] measured with the aid of a Compton polarimeter the polarization of gamma rays from the reactions $Mg^{24}(p,\gamma)Al^{25}$, $Si^{30}(p,\gamma)P^{31}$, and $S^{32}(p,\gamma)Cl^{33}$ and compared the results obtained with those expected from the angular distributions. The comparisons have shown that if the gamma-ray angular distributions and polarizations are measured with sufficient accuracy, it is possible to determine both the radiation mixture coefficient and the level spins uniquely.

In the present investigation we measured the polarization of gamma rays from the reaction $Si^{30}(p,\gamma)P^{31}$ for the resonances at $E_p = 773$, 939, 979.5, and 1393 keV in order to determine the multipolarities of the transitions and the spin of the 8.64-MeV level ($E_p = 1393$ keV).

2. THEORETICAL PART

The theory of correlation measurements of two successive radiations was completely developed in [2].

The direction correlation can be represented in general form by

$$W(\theta) = \sum_{\nu} A_\nu(1) A_\nu(2) P_\nu(\cos\theta), \quad (1)$$

where θ is the angle between the directions of the primary and secondary radiations and $P_\nu(\cos\theta)$ is the Legendre polynomial.

If the intermediate state is characterized by a definite spin and parity, and the primary radiation corresponds to a material particle (for example, a proton incident on a target), then the values of A_ν will be

$$A_\nu(1) = \frac{2l_p(l_p+1)}{2l_p(l_p+1) - \nu(\nu+1)} F_\nu(l_p J_s J), \quad (2)$$

$$A_\nu(2) = F_\nu(LLJJ') + 2\delta F_\nu(LL'JJ') + \delta^2 F_\nu(L'L'JJ'), \quad (3)$$

where l_p is the orbital momentum of the incident proton, J_s the spin of the input channel ($J_s = I \pm 1/2$, where I is the spin of the target nucleus), J the spin of the resonant level, J′ the spin of the level to which the transition takes place, L and $L' = L + 1$ the multipolarity of the gamma radiation, δ the radiation mixture coefficient, ν even integers, and F_ν a coefficient.

The angular distribution (1) has its simplest form when the target nucleus spin is $I = 0$. In this case there is neither a mixture of orbital momenta

l_p nor a mixture of input channels J_S present. The angular distribution is then determined only by the mixture of multipolarities L and L′ and by the spins J and J′. Equation (2) is written out for the case when I = 0. Equation (1) is so normalized that $A_0(2) = 1 + \delta^2$.

The correlation of the linear polarization and of the radiation directions are in this case [3]

$$W(\theta, \varphi) = W(\theta) \pm \cos 2\varphi \cdot \sum A_\nu(1)\, a_\nu(2)\, P_\nu^{(2)}(\cos\theta), \quad (4)$$

$$a_\nu(2) = -k_\nu(LL)\, F_\nu(LLJJ') + 2\delta k_\nu(LL')F_\nu(LL'JJ') + \delta^2 k_\nu(L'L')\, F_\nu(L'L'JJ'), \quad (5)$$

where φ is the angle between the polarization vector and the plane of the (p, γ) reaction, $P_\nu^{(2)}(\cos\theta)$ is the associated Legendre function, and k_ν is a coefficient that depends on ν, L, and L′. The plus sign is taken for the M1 + E2 mixture, and the minus sign for the E1 + M2 mixture.

If the intensity of the gamma rays is measured at angles φ equal to 0 and 90°, we have for the M1 + E2 mixture

$$\frac{W(\theta, 0^\circ)}{W(\theta, 90^\circ)} = \frac{W(\theta) + \sum_\nu A_\nu(1)\, a_\nu(2)\, P_\nu^{(2)}(\cos\theta)}{W(\theta) - \sum_\nu A_\nu(1)\, a_\nu(2)\, P_\nu^{(2)}(\cos\theta)} = R. \quad (6)$$

3. EXPERIMENTAL PARTS AND MEASUREMENT RESULTS

The experimental procedure was described earlier [4]. A beam of H_2^+ ions, accelerated by the electrostatic generator of the Physico-technical Institute of the Ukrainian Academy of Sciences was aimed at a thin target of the isotope Si^{30} (I = 0). The gamma quanta emitted at an angle $\theta = 90°$ were normally incident on photographic plates impregnated with heavy water. The directions and lengths of the photoproton tracks were measured with a microscope.

The gamma-ray polarization was measured by the deuteron photodisintegration method, described in detail in the literature [3,5,6].

At gamma-ray energies between 4 and 12 MeV, the disintegration is almost completely due to the E1 type of absorption. The differential absorption cross section is given by

$$d\sigma_\alpha \sim \cos^2\alpha \sin^2\beta\, d\Omega, \quad (7)$$

where α is the angle between the polarization vector and the plane of the d(γ, p)n reaction, and β is the photoproton emission angle relative to the direction of the gamma beam.

In measurements of the directions of the photoproton tracks, the angle α is reckoned in the emulsion plane from the direction of the beam of accelerated H_2^+ particles. The photoproton tracks picked out for the measurement had a dip angle (90° − β) not larger than 30°.

In the case of partially polarized radiation, the angular distribution of the photoprotons can be represented in the form

$$W(\alpha) = 1 + (R - 1)\cos^2\alpha. \quad (8)$$

where R is given by (6).

It has already been demonstrated [7,8] that the transitions from the 8.04-, 8.20-, and 8.24-MeV levels (resonances E_p = 773, 939, and 979.5 keV, respectively) to the ground level of the P^{31} nucleus are $3/2^+ \to 1/2^+$ transitions. For each of these there are two possible M1 + E2 mixtures.

Figure 1 shows the dependence of the gamma-ray intensity on the mixture coefficient δ for the $3/2 \to 1/2$ transitions and $\theta = 0°$, calculated from the formula

$$W_{12}(\theta) = 1 - \frac{0.75 - 0.75\delta^2 - 2.60\delta}{1.25 + 0.75\delta^2 - 0.87\delta}\cos^2\theta. \quad (9)$$

This formula was obtained from expressions (1)–(3). The F_ν tables of [9] were used in the calculation.

The measured numbers of photoproton tracks were grouped in three angle intervals α = 0–30°, 31–60°, and 61–90° [4]. For comparison with the measured number of tracks in the intervals 0–30° and 61–90°, formulas (4)–(6) and (8) were used to calculate the ratio

$$K = \frac{W(\alpha = 15°)}{W(\alpha = 75°)} = \frac{1 + (R-1)\cos 15°}{1 + (R-1)\cos 75°}. \quad (10)$$

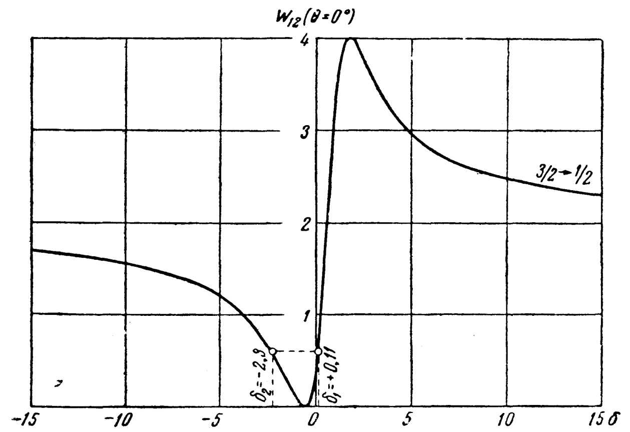

FIG. 1. Dependence of the gamma-ray intensity on the mixture coefficient δ for the $3/2 \to 1/2$ transition ($\theta = 0$, M1 + E2 mixture). Both values of δ correspond to an angular distribution $1 - 0.40\cos^2\theta$ [8] of the gamma rays from the reaction $Si^{30}(p, \gamma)P^{31}$ for the transition of the resonant 8.04-MeV level to the ground level of the P^{31} nucleus (E_p = 773 keV).

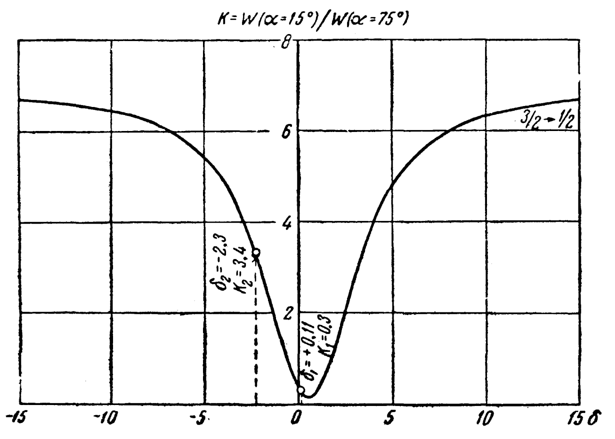

FIG. 2. Dependence of the ratio K of the number of photoprotons for the angles α equal to 15° and 75° on the mixture coefficient δ (3/2 → 1/2 transition, M1 + E2 mixture). The points on the curve designate the values of K corresponding to two different δ for the $Si^{30}(p, \gamma)P^{31}$ reaction (E_p = 773 keV, 8.04 → 0 MeV transition). The cross denotes the value K_{exp} = 3.2.

The dependence of this ratio on the coefficient δ is plotted in Fig. 2. The numerical values of k, listed in Table 2 of [3], were used in the calculations.

The 773-keV resonance. The gamma-ray angular distribution for a transition from the 8.04-MeV resonant level to the ground level of the P^{31} nucleus was measured by several authors [1,7,8]. The measurements of Broude, Green, and Willmott [8] give a value $W(\theta) = 1 - (0.31 \pm 0.01) P_2(\cos\theta)$, i.e., $W(\theta) = 1 - 0.40 \cos^2\theta$, which leads to coefficients $\delta_1 = +0.11$ and $\delta_2 = -2.3$. Hoogenboom et al [1] obtained $W(\theta) = 1 - (0.37 \pm 0.03) P_2(\cos\theta)$ $[W(\theta) = 1 - 0.47 \cos^2\theta]$, hence $\delta_1 = 0.06 \pm 0.06$ and $\delta_2 = -2.2 \pm 0.5$. The measurements of [7] are less accurate. All the measurements point to a $3/2^+ \to 1/2^+$ transition.

Endt, Suffert, and Hoogenboom [1] measured the polarization of these gamma rays with the aid of a Compton polarimeter. Their measurements point to the existence of a coefficient $\delta = \delta_2$.

The ratios K_1 and K_2 calculated by means of formula (10) for $\delta_1 = 0.11$ and $\delta_2 = -2.3$ are equal to 0.3 to 3.4, respectively. The measured ratio of the number of tracks in the angle intervals α = 0—30° and α = 61—90° is K_{exp} = 109:34 = 3.2. Thus, as in [1], it corresponds to $\delta_2 = -2.3$, i.e., to a mixture with preferred emission of E2 electric quadrupole radiation.

The 939-keV resonance. The gamma-ray angular distribution for the transition from the 8.20-MeV resonant level to the ground level was measured twice [7,8]. More accurate measurements [8] yield a value $W(\theta) = 1 - (0.72 \pm 0.02) P_2(\cos\theta)$ $[W(\theta) = 1 - 0.80 \cos^2\theta]$, corresponding to $\delta_1 = 0.15$ and $\delta_2 = -1.25$. The values $K_1 = 0.51$ and $K_2 = 1.94$ were calculated for these values of δ. The measured ratio K_{exp} = 124:228 = 0.54. Consequently, in this case we have a magnetic dipole radiation of the M1 type with a small addition of E2 radiation.

The 979.5-keV resonance. The gamma-ray angular distribution for the transition from the 8.24-MeV resonance level to the P^{31} ground level has the form $1 - (0.55 \pm 0.03) P_2$ $[W(\theta) = 1 - 0.64 \cos^2\theta]$ [8]. It corresponds to the values $\delta_1 = -0.03$ and $\delta_2 = -1.6$ and to the two values $K_1 = 0.40$ and $K_2 = 2.44$; K_{exp} = 173:73 = 2.37. Thus, this radiation can be regarded essentially as a type E2 radiation with M1 added.

The measured angular distribution differs very little from the angular distribution for pure dipole radiation, $1 - 0.60 \cos^2\theta$ ($3/2 \to 1/2$ transition). The value of K calculated from (10) for the E1 radiation is 2.63. It is almost equal to K_2 and K_{exp}; consequently, we cannot identify the transition in this case. It may be either E2 with M1 added or E1.

The gamma-ray angular distribution for the transition from the resonant level to the 3.13-MeV level ($J' = 3/2^+$), which has the form [8] $1 - (0.27 \pm 0.02)P_2$, indicates even parity for the 8.24-MeV level. Thus, the transition to the ground level of the P^{31} nucleus should be regarded not as

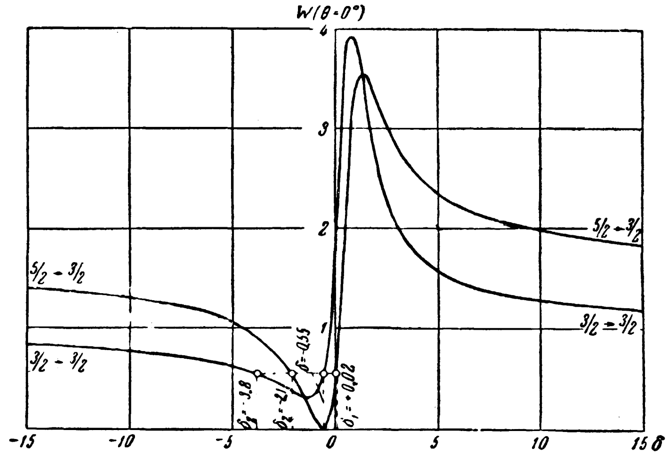

FIG. 3. Dependence of the intensity of gamma rays on the mixture coefficient δ for 3/2 → 3/2 and 5/2 → 3/2 transitions (θ = 0, M1 + E2 mixture). All four values of δ correspond to an angular distribution of the form $1 - 0.45 \cos^2\theta$ [10] of the gamma rays from the $Si^{30}(p, \gamma)P^{31}$ reaction for a transition from the 8.64-MeV resonant level to the first excited level 1.26-MeV ($J' = 3/2^+$) of the P^{31} nucleus (E_p = 1393 keV).

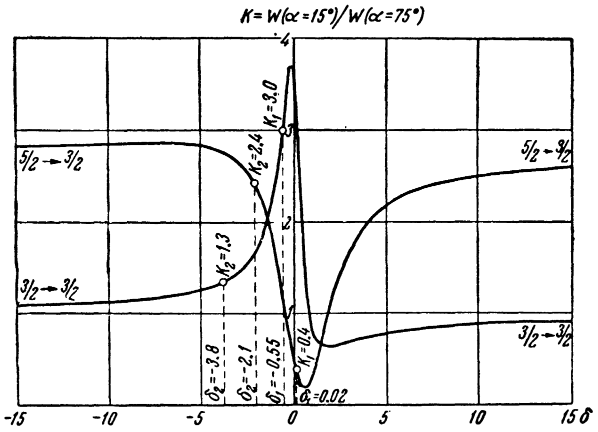

FIG. 4. Dependence of the ratio of the number of photoprotons K for $\alpha = 15°$ and 75°, on the mixture coefficient δ ($3/2 \to 3/2$ and $5/2 \to 3/2$ transitions, M1 + E2 mixture). The points on the curves designate the values of K_1 and K_2 corresponding to δ_1 and δ_2 for the reaction $Si^{30}(p, \gamma)P^{31}$ (E_p = 1393 keV, 8.64 → 1.26 MeV transition). The cross marks $K_{exp} = 0.24$.

an almost pure M1 transition ($\delta_1 = -0.03$), but as a preferred E2 transition with M1 added ($\delta_2 = -1.6$).

The 1393-keV resonance. The gamma-ray angular distribution for the transition from the 8.64-MeV resonant level to the first excited 1.26-MeV level ($J' = 3/2^+$) has the form $1 - 0.45 \cos^2 \theta$ [10]. As can be seen from Fig. 3, which shows the calculated dependence of the gamma-ray intensity $W(\theta = 0)$ on the mixture coefficient δ, this distribution corresponds to the transitions $3/2^+ \to 3/2^+$ ($\delta_1 = -0.55$ and $\delta_2 = -3.8$) and $5/2^+ \to 3/2$ ($\delta_1 = 0.02$ and $\delta_2 = -2.1$). Figure 4 shows the dependence of K [formula (10)] on δ. It is seen from this figure that the $3/2^+ \to 3/2^+$ transition corresponds to values $K_1 = 3.0$ and $K_2 = 1.3$, while $5/2^+ \to 3/2^+$ corresponds to $K_1 = 0.4$ and $K_2 = 2.4$; $K_{exp} = 26{:}109 = 0.24$. The resonant level has thus a spin $5/2^+$, and the transition to the 1.26-MeV level will be of the type M1 ($\delta_1 = 0.02$).

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