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1.39 Analyzing Power of Medium Energy Gamma Rays Following Radiative Capture of Polarized Protons on Light Nuclei

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This work reports first extensive measurements of medium energy gamma rays following radiative capture of polarized protons on light nuclei.

Medium energy gamma rays following radiative capture reactions of 40-80 MeV polarized protons on ^{11}B and ^{12}C were studied. The analyzing powers are found to be classified into two types. Those for the final states with $j_> = \ell + 1/2$, namely the orbital angular momentum parallel to the spin, decrease as the angle increases, while those for the $j_< = \ell - 1/2$ increase as the angle increases.

The differential cross-section for the radiative capture gamma ray is expressed in terms of the Legendre polynomials P_k and P_k^1 as follows.

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{\sigma_0}{4\pi}\left[1 + \Sigma a_k P_k(\cos\theta) + \vec{P}\vec{n}\Sigma b_k P_k^1(\cos\theta)\right], \tag{1}$$

where $\vec{p}$ is the polarization vector of the incident proton and $\vec{n} = (\vec{k}_p \times \vec{k}_\gamma)/|k_p \times k_\gamma|$. the coefficients a_k and b_k are derived from the observed angular distributions and the analyzing powers as shown in Fig. 1. The b_2 coefficients are indeed classified into two groups, one is positive for $j_< = \ell - 1/2$ final orbits and another is negative for $j_> = \ell - 1/2$.

For simplicity we consider the stretched E1 and E2 gamma rays following direct radiative capture reactions. The major components of the radiative capture into the final orbit of the $\psi_f(j,\ell)$ are the stretched E1 radiations of $A_1(\ell+1\to\ell)$ and $A_1^1(\ell-1\to\ell)$ and the stretched E2 radiation of $A_2(\ell+2\to\ell)$. The analyzing power coefficient b_2 arises from the interference of the two E1 radiation with different angular momenta, A_1 and A_1^1.

$$b_2(j\ell) = Nd_2(j\ell)R_1^1R_1(-\sin(\delta_1-\delta_1^1)), \tag{2}$$

where N is the normalization factor given by $N = 1/[a_0(A_1)+a_0(A_1^1)+a_0(A_2)]$. The R_1, R_1^1 and R_2 are the radial matrix elements for the A_1, A_1^1 and A_2 radiations, respectively, and δ_1, δ_1^1 and δ_2 are corresponding phases.

The b_2 coefficient for the analyzing power is written as

$$\begin{aligned} b_2 &= Nd_2(j\ell)\, R_1^1R_1\sin(\delta_{\ell+1} - \delta_{\ell-1}) \\ &= Nd_2(j\ell)R_1^1R_1\sin\frac{\partial\delta_\ell}{\partial V^{cf}}V^{cf}\cdot(4\ell+2)\pm\frac{\partial\delta_\ell}{V_{so}}\cdot 2V_{so}\,. \end{aligned} \tag{3}$$

The coefficient $d(j\ell)$ is positive for $j_> = \ell + 1/2$ and negative for $j_> = \ell + 1/2$. The ± signs of the V_{so} term is the same as in Eq. (1), namely + for $j_<$ and - for $j_>$. Noting that the V^{cf} term plays a major role in the $\delta_{\ell+1} - \delta_{\ell-1}$ phase difference and $R_1^1R_1>0$, one gets a positive b_2 value for $j_<$ and a negative b_2 value for $j_>$. These signs are just in good agreement with the observed values. The calculated b_2 values are shown in Fig. 2. They reproduce the general feature of the observed values. The absolute b_2 values for the $j_<$ and $j_>$ decreases as the proton (γ-ray) energy increases. This is considered to be partly due to the increase of the E2 admixture as derived from the a_1 coefficients of the angular distribution and partly due to the decrease of the absolute value of the phase difference $(\delta_{\ell+1} - \delta_{\ell-1})$(Fig. 3).

Since the electric gamma transition does not flip spin, initial protons with $j_>^i = \ell_i + 1/2$ contributes to the radiative capture into the final orbit of $j_> = \ell + 1/2$, and protons with $j_<^i = \ell_i - 1/2$ to the capture into the $j_< = \ell - 1/2$ orbit. Thus the incident spin-up proton captured into the $j_> = \ell + 1/2$ final orbit must interact with the right-hand side of the nucleus because the orbital angular momentum is oriented upwards. On the other hand the incident spin-down proton must interact with the left-hand side to have downward orbital angular momentum. In case of the $j_< = \ell - 1/2$, the right-left relation is just reversed. These are schematically illustrated in Fig. 4. The analyzing power, which is the difference between the spin-up cross-section and the spin-down one, is thus given by $A_R - A_L$ for $j_>$, while it is given by $A_L' - A_R'$ for $j_<$. The b_2 coefficient, which arises from the interference between the proton waves of $\ell+1$ and $\ell-1$, changes the sign for the change from the $j_>$ state to $j_<$ state provided that $A_R \sim A_R'$ and $A_L \sim A_L'$, provided that the effect of the spin orbit interaction is much smaller than the effect of the centrifugal potential. With the increasing proton energy, both the impact parameter and the phase shift difference between the $\ell+1$ and $\ell-1$ waves become small, resulting in reduction of the difference between the b_2 values for the $j_<$ and $j_>$ final states.

References

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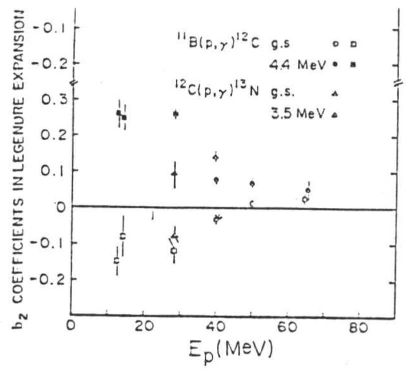

Fig. 1. Legendre expansion coefficients of the analyzing powers for the $^{11}B(p,\gamma)$ and $^{12}C(p,\gamma)$ reactions. Squares are taken from ref. 2.

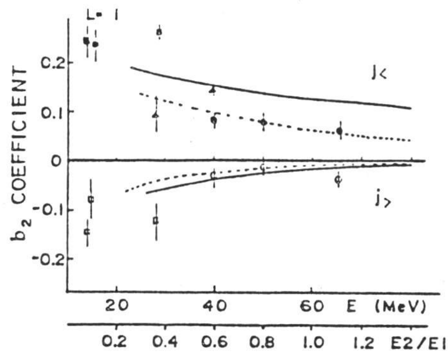

Fig. 2. b_2 coefficients for $P_{1/2}$ ($j_<$) and $P_{3/2}$ final orbits. Solid lines are calculated values. Dotted lines are calculated by including $E2/E1=k^2$ as derived from the angular distributions.

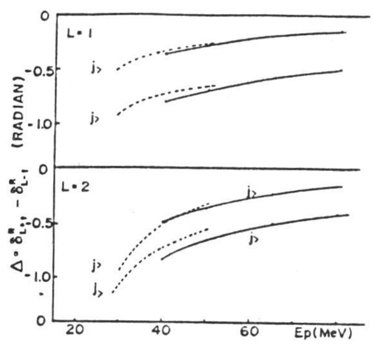

Fig. 3. Phase difference as a function of the proton energy. Solid lines: parameters by Beccketti-Greenless. Dotted lines: those by Fannon et al..

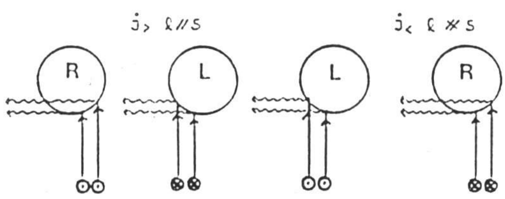

Fig. 4. Schematic diagrams of the analyzing power for the E1 radiative capture process. R (L) indicates the case of interaction of the incident protons with the right (left) hand side of the nucleus. Asymmetry for the $j_>$ is R-L, while it is L-R for the $j_<$.