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Magnetic Hyperfine Rotation of a Gamma Ray Angular Distribution Due to Target Tilting*

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Abstract

A spin rotation type modification of a gamma angular distribution pattern has been observed in gamma rays emitted from ^{16}O nuclei recoiling from a target tilted to the direction of recoil (which is also the beam direction and the symmetry axis). The spin rotation is ascribed to the effect of hyperfine interactions with ionic states that are polarized when the ions emerge from the tilted foil.

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In some recent measurements the circular polarization of light emitted in beam-foil experiments has been studied[1-5]. A large polarization was found for ions emerging from "tilted" foils (i.e. not normal to the beam), with the direction of the observed light normal to the beam and lying in the plane of the foil. This circular polarization of the emitted light is associated with a polarization of the ions themselves and this is generally considered to be a polarization of the ionic orbital angular momentum introduced at the tilted exit surface of the foil. It has been speculated that this polarization may also effect the ionic nuclei via hyperfine interactions resulting in a modification of the angular distribution of subsequent gamma rays. In one particular case the response of the nuclei to such polarized ions can be computed rather easily: if for all hyperfine frequencies ω involved the characteristic angles $\omega\tau$ (τ is the nuclear mean life) are very small, then the ionic polarization will not change in first order and can be considered constant. The interaction Hamiltonian can then be written[6]

$$H_t = aI_x\langle J_x\rangle + aI_y\langle J_y\rangle + aI_z\langle J_z\rangle$$

$$\text{with} \quad a = \mu_N g \frac{H(o)}{J}$$

where g is the nuclear g-factor, $H(o)$ - the hyperfine field acting on the nucleus and I, J - the angular momenta of the nucleus and the electrons in the ion respectively. Taking the z axis along the axis of ionic polarization we have $\langle J_x\rangle = \langle J_y\rangle = 0$, and therefore:

$$H_t = \mu_N g \ H(o) \ \frac{\langle J_z\rangle}{J} I_z$$

This Hamiltonian has the same form as the interaction Hamiltonian for the motion of the nucleus in an applied external field H_z : $H_z = H(o)\langle J_z\rangle/J$. Under the conditions assumed above the angular distribution in the presence of the polarized ions is given by:

$$W_R(\theta) = W(\theta-\Delta\phi) \;;\quad \Delta\phi = (\mu_N g\, H(o)\tau/\hbar)\;(\langle J_z\rangle/J) \qquad (1)$$

More generally, for an ionic ensemble in a variety of states we have:

$$\Delta\phi = (\mu_N g\tau/\hbar)\;\sum_i \alpha_i\; H(o)_i\; \langle J_z\rangle_i/J_i \qquad \Sigma_i\alpha_i = 1 \qquad (2)$$

where α_i is the fractional population of the ionic level i.

The condition for the validity of (2) is:

$$(\mu_N g\tau/\hbar)\; H(o)_i \ll 1 \qquad \text{for all } i \qquad (2a)$$

We present here the results of a measurement of the angular distribution pattern of gamma rays emitted from ^{16}O nuclei in the 3^- (τ = 26.6 ps) state, emerging from a carbon foil at a velocity: $v = 0.011c$.

The excited nuclei were produced in the $^{19}F(p,\alpha)^{16}O\;[3^-]$ reaction at the resonance of E_p = 1.375 MeV.

The experimental arrangement is shown in fig. 1. The targets were made of LiF evaporated on carbon. The target thickness was adjusted to the tilt angle ψ so that the thickness of both the LiF layer and the carbon layer travelled by the beam was always the same: 50μg/cm^2 of LiF - corresponding to the resonance width, and 20μg/cm^2 of carbon. The target was alternated between the "right" and "left" positions by a motor-driven device after the accumulation of a preset number of particle counts, usually at intervals of about 3 minutes. The axis of rotation of the target was aligned to pass through the beam axis within ~.5 mm. The particle counter was a surface barrier detector. Four 5 in. dia. x 5 in. long NaI(Tl) γ ray detectors were positioned at symmetric angles about the beam direction and at corresponding forward and backward angles. The measurements were carried out at two angles θ : $\theta = 25^{\circ}$ and $\theta = 73^{\circ}$. The collimators in front of the particle counter and the gamma counters served to sharpen the angular distribution and also to avoid shadows cast by the target frame on either the particle or the gamma counters. Coincidence counts of γ's and α's were recorded for all four gamma counters and the double ratios

$$\rho_{14} = \sqrt{\frac{N_1(\text{right})}{N_4(\text{right})} \cdot \frac{N_4(\text{left})}{N_1(\text{left})}} \; ; \quad \rho_{32} = \sqrt{\frac{N_3(\text{right})}{N_2(\text{right})} \cdot \frac{N_2(\text{left})}{N_3(\text{left})}}$$

were formed. The two ratios ρ_{14} , ρ_{32} were generally found to be consistent and so, finally, the average double ratio ρ was evaluated as :

$$\rho = \sqrt{\rho_{14} \cdot \rho_{32}}$$

The average double ratio effectively cancels out all right-left asymmetry effects due to misalignment of the beam spot with respect to the axis of rotation of the target.

For reference we quote here a value of ρ for one of the measurements at $\psi = 75^{\circ}$ $\theta = 25^{\circ}$: $\rho = 0.984$ (3) .

ρ is related to the angle $\Delta\phi$ in (2) as

$$\rho = 1 - 2 \frac{1}{W(\theta)} \frac{dW(\theta)}{d\theta} \Delta\phi \qquad (3)$$

The logarithmic derivatives of the angular distributions were determined for both recoil into vacuum $W_p(\theta)$, and recoil into carbon $W_o(\theta)$, in angular distribution measurements carried out at seven angles between 0^o and 90^o:

$$\frac{1}{W_o} \frac{dW_o}{d\theta} = -3.61(17)\,\mathrm{rad}^{-1} \; ; \quad \frac{1}{W_p} \frac{dW_p}{d\theta} = -3.03(14)\,\mathrm{rad}^{-1} \quad \theta = 25^o$$

$$\frac{1}{W_o} \frac{dW_o}{d\theta} = -3.62(19)\,\mathrm{rad}^{-1} \; ; \quad \frac{1}{W_p} \frac{dW_p}{d\theta} = -3.26(17)\,\mathrm{rad}^{-1} \quad \theta = 73^o$$

These values are consistent with evaluations based on the known theoretical distribution and the known perturbation in vacuum[7].

The angles $\Delta\phi$, derived from the measurements through (3), are shown in fig. 2 for various tilt angles.

Also shown in fig. 2 are results of control measurements carried out with thick carbon backings in which the recoils are completely stopped, thus eliminating any possibility of effects due to the exit surface of the foil. We quote here again the value of ρ for a control experiment, at $\psi = 75^o$, $\theta = 25^o$: $\rho = 0.998(3)$.

It is evident from fig. 2 that there is a definite and observable rotation of the symmetry axis of the angular distribution of the gamma-rays over a large range of tilt angles. The measurement at $\psi = 85^o$ is somewhat less reliable than the others partly because it was carried out under slightly less favourable conditions (e.g. no collimators for the gamma counters) and partly because at such a large angle various geometrical artifacts may appear. The fact that this measurement is consistent with all the others indicates that all such geometrical effects must be very small and are certainly negligibly small for the smaller tilt angles.

The g factor of the 3^- state in ^{16}O is positive[8], and we conclude from the measurement that the vector J points out of the plane in the "right" configuration of fig. 1.

The hyperfine interactions relevant to this measurement have been studied quite extensively[7] and can be described adequately as static interactions of ions with principal quantum number n = 2 and which are otherwise randomly distributed among the possible configurations. The polarization is assumed to be due to p electrons and the hyperfine fields associated with these electrons are therefore also taken into account, even though they are much smaller than the contact fields of unpaired s electrons. The quantities α_i, $H(o)_i$ were computed in this way. The polarization of the orbital angular momentum is transformed into J polarization via L-S coupling and for $\frac{\langle L_z \rangle}{L} = 1$ we get: $\Delta\phi_{max} \approx 60$ mrad. Comparing this figure with the measurement, we see that the average polarization of the electrons interacting with the ^{16}O nuclei is approximately .05 at $\psi = 75^o$, $\theta = 25^o$.

The polarization observed in well defined ionic states varies between 0 and .25 [3-5], and can occasionally also be of the opposite sign. The average polarization evident in the hyperfine interaction is consistent both in direction and in magnitude with this range of values.

In the model computations it was also established that the condition (2a) is fulfilled quite well for all relevant configurations.

Results similar to those presented here have been obtained elsewhere for ^{18}O nuclei in the 2^+ state[9] where an effect of opposite sign was observed, consistent with a negative value of the nuclear g-factor[10].

It is apparent that the effect observed here may provide a means for determining the sign of g-factors of short lived nuclear states under favorable conditions. This effect should also be taken into account in angular distribution measurements of high precision, for example particle-gamma reorientation measurements following Coulomb excitation.

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Figure Captions

1. Schematic drawing of the experimental arrangement. Gamma rays were recorded in coincidence with back scattered alphas. All counters have slot-like collimators. The measurements were carried out at two angles θ ; $\theta = 25^{\circ}$ and 73° for various tilt angles ψ .

2. Measured rotation angles $\Delta\phi$ of the gamma ray angular distribution pattern as a function of the tilt angle of the target. Also shown are the results of control measurements with thick carbon backings. $\Delta\phi$ is defined as pusitive in the same sense as θ and ψ . The error bars are one standard deviation and represent the combined effect of the errors in ρ and in $\frac{1}{w}\frac{dw}{d\theta}$.

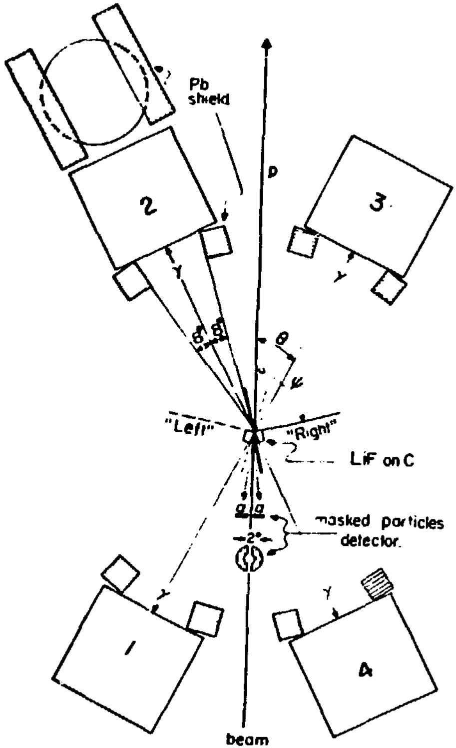
Pb
shield
2
3
p
γ
δ δ
θ
ψ
"Left"
"Right"
LiF on C
α α
2°
masked particles
detector
1
4
beam

Fig. 1

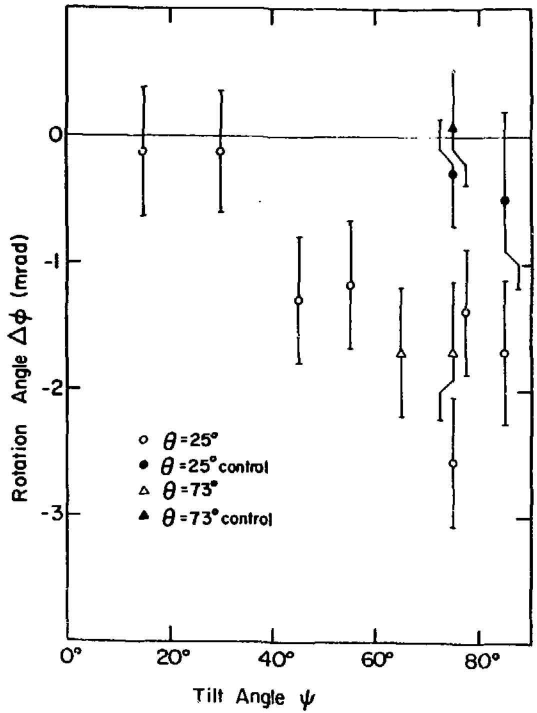
0
-1
-2
-3
0°
20°
40°
60°
80°
Rotation Angle Δφ (mrad)
Tilt Angle ψ
○ θ=25°
● θ=25° control
△ θ=73°
▲ θ=73° control

Fig. 2