for many stimulating discussions.

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[16]For example, preferential population of $m_1 = +1$ ($m_j = +\frac{1}{2}$ and $+\frac{3}{2}$) for the $2p$ configuration will lead to the preferential population of $m_j = +\frac{1}{2}$ for the $1s$ ground state.

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

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A spin-rotation–type modification of a γ-ray angular-distribution pattern has been observed in γ 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.

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 affect the ionic nuclei via hyperfine interactions, resulting in a modification of the angular distribution of subsequent γ 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 $\omega\tau$ (where 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]

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

with $a = \mu_N gH(0)/J$, where g is the nuclear g factor, $H(0)$ is the hyperfine field acting on the nucleus, and I and J are the angular momenta of the nucleus and the electrons in the ion, respectively. By taking the z axis along the axis of ion-

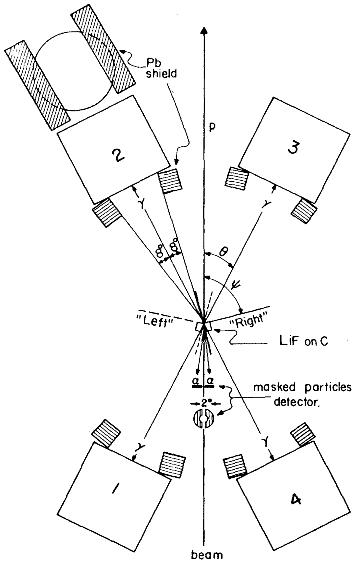

FIG. 1. Schematic drawing of the experimental arrangement. γ rays were recorded in coincidence with backscattered α's. All counters have slotlike collimators. The measurements were carried out at angles $\theta = 25°$ and 73° for various tilt angles ψ.

ic polarization, we have $\langle J_x\rangle = \langle J_y\rangle = 0$, and therefore

$$H_t = \mu_N g H(0) J^{-1}\langle J_z\rangle I_z .$$

This Hamiltonian has the same form as the interaction Hamiltonian for the motion of the nucleus in an applied external field H_z: $H_z = H(0)\langle J_z\rangle/J$. Under the conditions assumed above, the angular distribution in the presence of the polarized ions is given by

$$W_R(\theta) = W(\theta - \Delta\varphi); \qquad \Delta\varphi = [\mu_N g H(0)\tau/\hbar](\langle J_z\rangle/J). \tag{1}$$

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

$$\Delta\varphi = (\mu_N g\tau/\hbar)\textstyle\sum_i \alpha_i H_i(0)\langle J_z\rangle_i/J_i, \tag{2}$$

where α_i is the fractional population of the ionic level i and $\sum_i \alpha_i = 1$.

The condition for the validity of (2) is

$$(\mu_N g\tau/\hbar)[H_i(0)\langle J_z\rangle_i/J_i] \ll 1 \tag{2a}$$

for all i.

We present here the results of a measurement of the angular-distribution pattern of γ rays emitted from ^{16}O nuclei in the 3^- ($\tau = 26.6$ ps) state, emerging from a carbon foil with a velocity $v = 0.011c$. The excited nuclei were produced in the reaction $^{19}F(p,\alpha)^{16}O[3^-]$ 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 traveled by the beam was always the same: 50 $\mu g/cm^2$ of LiF, corresponding to the resonance width, and 20 $\mu g/cm^2$ 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 ~0.5 mm. The particle counter was a surface-barrier detector. Four 5-in.-diam × 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 angles $\theta = 25°$ and $\theta = 73°$. The collimators in front of the particle counter and the γ counters served to sharpen the angular distribution and also to avoid shadows cast by the target frame on either the particle or the γ counters. Coincidence counts of γ's and α's were recorded for all four γ counters and the double ratios

$$\rho_{14} = \left(\frac{N_1^{\text{right}}}{N_4^{\text{right}}}\right)^{1/2}\left(\frac{N_4^{\text{left}}}{N_1^{\text{left}}}\right)^{1/2},$$

$$\rho_{32} = \left(\frac{N_3^{\text{right}}}{N_2^{\text{right}}}\right)^{1/2}\left(\frac{N_2^{\text{left}}}{N_3^{\text{left}}}\right)^{1/2},$$

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

$$\rho = (\rho_{14}\rho_{32})^{1/2}.$$

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 $\psi = 75°$ and $\theta = 25°$: $\rho = 0.984(3)$. ρ is related to the angle $\Delta\varphi$ in (2) by

$$\rho = 1 - 2\,\frac{1}{W(\theta)}\,\frac{dW(\theta)}{d\theta}\,\Delta\varphi . \tag{3}$$

The logarithmic derivatives of the angular distributions were determined for both recoil into vacuum $W_p(\theta)$, and recoil into carbon $W_0(\theta)$, in angular-distribution measurements carried out at

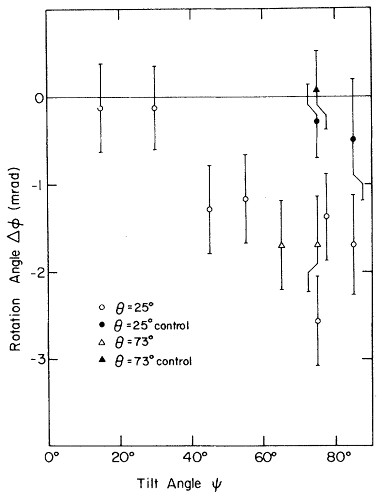

FIG. 2. Measured rotation angles $\Delta\varphi$ of the γ-ray angular-distribution pattern as a function of the tilt angle of the target. Also shown are the results of control measurements with thick carbon backings. $\Delta\varphi$ is defined as positive in the same sense as θ and ψ. The error bars are 1 standard deviation and represent the combined effect of the errors in ρ and in $W^{-1}dW/d\theta$.

seven angles between 0° and 90° so that we get

$$\left(\frac{1}{W_0}\frac{dW_0}{d\theta}\right)_{\theta=25^\circ} = -3.61(17)\ \mathrm{rad}^{-1},$$

$$\left(\frac{1}{W_p}\frac{dW_p}{d\theta}\right)_{\theta=25^\circ} = -3.03(14)\ \mathrm{rad}^{-1},$$

$$\left(\frac{1}{W_0}\frac{dW_0}{d\theta}\right)_{\theta=73^\circ} = -3.62(19)\ \mathrm{rad}^{-1},$$

$$\left(\frac{1}{W_p}\frac{dW_p}{d\theta}\right)_{\theta=73^\circ} = -3.26(17)\ \mathrm{rad}^{-1}.$$

These values are consistent with evaluations based on the known theoretical distribution and the known perturbation in vacuum.[7] The angles $\Delta\varphi$, 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 $\psi = 75°$ and $\theta = 25°$: $\rho = 0.998(3)$.

It is evident from Fig. 2 that there is a definite and observable rotation of the symmetry axis of the angular distribution of the γ rays over a large range of tilt angles. The measurement at $\psi = 85°$ is somewhat less reliable than the others partly because it was carried out under slightly less favorable conditions (e.g., no collimators for the γ 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 $\vec{J}$ 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 and $H_i(0)$ were computed in this way. The polarization of the orbital angular momentum is transformed into J polarization via L-S coupling and for $\langle L_z\rangle/L = 1$ we get $\Delta\varphi_{\max} \approx 60$ mrad. Comparing this figure with the measurement, we see that the average polarization of the electrons interacting with the ^{16}O nuclei is approximately 0.05 at $\psi = 75°$ and $\theta = 25°$.

The polarization observed in well-defined ionic states varies between 0 and 0.25,[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-γ ray reorientation measurements following Coulomb excitation.

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Simple Model for Asymptotic Level Clusters in SF_6 Rotational Spectra*

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We construct a simple model to explain the qualitative features of level clusters in the asymptotic regions or limbs of centrifugally split J levels in SF_6, as observed in diode spectroscopy and computer experiments. Parametric formulas for cluster splittings are derived by use of methods which may be useful for analysis of other molecular and solid-state resonance effects.

The spectrum of SF_6 has received considerable attention recently in connection with problems involving laser isotope separation and self-induced transparency. The first clearly identifiable rotational lines were recently observed[1] with use of a diode laser and analyzed through computer reductions of certain approximate molecular Hamiltonians.[2,3] In the process Fox *et al.*[4] noticed a curious cycle pattern for clusters of levels belonging to octahedral-group (O) irreducible representations (IR's) that appeared in the splitting of each J manifold. A cycle of four sixfold, nearly degenerate clusters (A_1, E, T_1), (T_1, T_2), (A_2, E, T_2), and (T_1, T_2) may be repeated several times in the upper limb until it abruptly splits and forms a similar cycle of eightfold clusters (E, T_1, T_2), (A_1, A_2, T_1, T_2), and (E, T_1, T_2). A similar clustering was noticed earlier by Dorney and Watson[5] in their XY_4 model calculations. They explained the degeneracies of 6 and 8 from a classical point of view in which the rotation axis is localized on a fourfold or threefold symmetry axis, respectively.

We describe here a quantum model which, in its simplest form, indicates the exact composition of the clusters, and parametrizes the form of the splitting within them. The model has recently been extended to give accurate approximate formulas for the spectrum of cubic 2^k-pole operators ($k=4$ and 6) as we will report in longer follow-up publications.

We introduce state vectors $|1\rangle_3$, $|2\rangle_3$, ..., $|8\rangle_3$ to describe the eight equivalent states of rotation about each of the eight threefold symmetry axes perpendicular to faces of the SF_6 octahedron. For high rotational momentum J, we may imagine that these states are nearly degenerate; i.e., we picture a molecule "stuck" in rotation on any one of the threefold axes, and hardly able to "tunnel" over to other equivalent choices since it has become centrifugally flattened. Since the radial bonds of SF_6 are much stronger than the bending ones, we expect the eight threefold axes to be "soft" and to correspond to lower centrifugal energy. On the other hand, the six fourfold axes will be "hard" axes, and we introduce six "hard" state vectors $|1\rangle_4$, $|2\rangle_4$, ..., $|6\rangle_4$ to describe rotation around the fourfold axes at the vertices