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Evidence for Surface-Interaction Effects via a Nuclear Hyperfine-Interaction Experiment

M. Hass,* J. M. Brennan, H. T. King, and T. K. Saylor
Department of Physics, Rutgers University, New Brunswick, New Jersey 08903†

and

R. Kalish‡
Rutgers University, New Brunswick, New Jersey 08903, and Bell Laboratories, Murray Hill, New Jersey 07974

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A rotation of the perturbed angular correlation of de-excitation γ rays from ^{18}O nuclei recoiling into vacuum at high velocity has been observed in a tilted-foil geometry. This rotation is due to the polarization of electronic configurations which interact strongly with the nuclear state via the hyperfine interaction. This experiment provides the first experimental evidence for polarization by surface interactions of deeply bound electrons in highly stripped oxygen ions.

Much theoretical and experimental effort has recently been focused on beam-foil measurements in which the normal to the foil surface does not lie along the beam axis.[1-4] Circularly polarized light, characteristic of electronic configurations polarized perpendicular to the plane defined by the beam axis and the normal to the foil surface, has been observed for various ionic configurations which decay be visible light. Circular-polarization measurements on shorter-wavelength radiation emitted by more deeply bound configurations are, however, exceedingly difficult.[5] There is thus no previous experimental information regarding the orientation of inner-shell electronic configurations by surface interactions in beam–tilted-foil experiments.

Here we report on a method that can provide this information by utilizing the strong magnetic hyperfine interaction (HFI) between inner electronic configurations and an excited nuclear level. The very strong HFI with unpaired 1*s* electrons can cause a significant attenuation of the angular correlation for de-excitation γ rays from the nuclear level; this interaction provides an experimental tool for measuring magnetic moments of short-lived states in light nuclei and for studying relative populations of electronic configurations on a picosecond time scale.[6-10] Moreover, if the electronic configurations participating in the HFI are polarized, a net *rotation* of the angular correlations results. Observation of this rotation is a clear signature of polarized electrons in the atomic ensemble and is the subject of the present experiment. The 2^+, 1.98-MeV ($\tau = 3.6$ ps, $g = -0.3$) level of ^{18}O is well suited for such a measurement since the value of $\omega\tau$ (where ω is the Larmor frequency due to the HFI and τ is the nuclear mean life) is close to unity. The condition $\omega\tau = 1$ is the condition for maximum sensitivity in this method.[11]

A 19.7-MeV ^{4}He beam from the Rutgers University–Bell Laboratory tandem accelerator impinged on a 100-μg/cm^2 Si^{18}O self-supporting target. Backscattered ^{4}He particles were detected

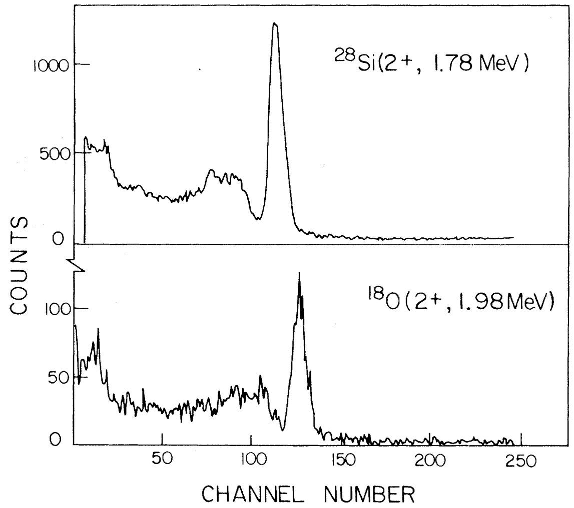

FIG. 1. Typical coincident γ spectra for the $2_1^+ \rightarrow 0$ transitions in ^{28}Si and ^{18}O.

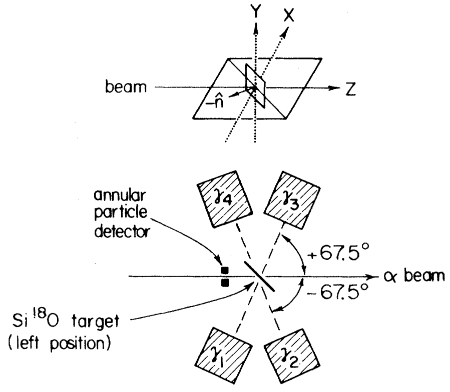

FIG. 2. Schematics of the experimental arrangement. The normal $\hat{n}$ to the target surface is at ± 45° to the z axis; the electronic polarization is along the y axis.

in a 100-μm-thick annular surface-barrier detector. Decay γ rays in coincidence with the inelastic ^{4}He groups populating the first 2^+ levels in ^{28}Si and ^{18}O were measured in four movable 7.5 cm × 7.5 cm NaI(Tl) scintillators. Typical coincidence γ-ray spectra are shown in Fig. 1, demonstrating the quality of the spectra and the reliability of peak summation. The angular correlations of the $2_1^+ \rightarrow 0^+$ decays of ^{28}Si and ^{18}O were measured with the target perpendicular to the beam axis and were found to be

$$\begin{aligned} W_{^{28}\mathrm{Si}}(\theta) &= 1 + (0.58 \pm 0.03)P_2(\cos\theta) \\ &\quad - (1.2 \pm 0.03)P_4(\cos\theta), \\ W_{^{18}\mathrm{O}}(\theta) &= 1 + (0.56 \pm 0.05)P_2(\cos\theta) \\ &\quad - (1.04 \pm 0.05)P_4(\cos\theta). \end{aligned} \tag{1}$$

The four scintillators were then placed at $\theta = \pm 67.5^\circ$ and $\theta = \pm 112.5^\circ$, where the sensitivity to rotation of the correlation is large. Coincidence γ rays were measured for two target-tilt angles, ± 45° to the beam (Fig. 2). Extreme care was taken to insure that the center of rotation of the target lies on the beam axis as to eliminate systematic errors associated with target rotation. The target was rotated under computer control approximately every 3 minutes and the accumulated counts for the ^{18}O$(2^+ \rightarrow 0^+)$ and ^{28}Si$(2^+ \rightarrow 0^+)$ transitions were stored separately for each target position. Random coincidences were found to be negligible. Seventeen separate runs were carried out, resulting in a total of 25 000 counts and 250 000 counts for the ^{18}O and ^{28}Si transitions, respectively, for each NaI(Tl) crystal and each target position. Peak areas were computed after background subtraction and were formed into double ratios defined by

$$\rho_{ij} = (N_i^L/N_i^R)^{1/2}(N_j^L/N_j^R)^{1/2}, \tag{2}$$

where, for example, N_i^R represents the peak area for the ith detector with the target rotated to the right (i.e., clockwise as viewed from the top). The indices 1, 2, 3, and 4 correspond to detectors at -112.5°, -67.5°, 67.5°, and 112.5°, respectively. The parameter $\epsilon \equiv (\rho - 1)/(\rho + 1)$, with $\rho = (\rho_{14}/\rho_{23})^{1/2}$, is a measure of the rotation of the correlation and is proportional to the electronic polarization.

Table I summarizes the double ratios for the ^{18}O and ^{28}Si transitions. In the absence of systematic errors, the symmetric-angle ratios ρ_{14} and

TABLE I. Summary of the experimental double ratios ρ_{ij} for the ^{28}Si and ^{18}O transitions.

	ρ_{14}	ρ_{23}	ρ_{13}	ρ_{24}	$\rho = (\rho_{14}/\rho_{23})^{1/2}$	$\epsilon = (\rho - 1)/(\rho + 1)$ ($\times 10^{-3}$)
^{18}O	1.005(6)	0.987(6)	0.995(7)	1.001(6)	1.009	4.5 ± 2.1
^{28}Si	1.000(2)	1.002(2)	1.001(2)	1.001(2)	0.999	-0.5 ± 0.7

ρ_{23} should show the same effect ($\rho_{14}=1/\rho_{23}$) while the ratios ρ_{13} and ρ_{24} should show no effect ($\rho_{13}=\rho_{24}=1$).

The presence of a polarized electronic configuration in this experiment is manifested through its HFI with the excited nuclear level. For very small HFI ($\omega\tau \ll 1$), the nuclear level couples very weakly to the electrons and *no* attenuation and hence *no* rotation of the angular correlation will be observed. This is the case for the ^{28}Si($2^+ \rightarrow 0^+$) transition. As the dominant charge states of Si ions at the recoil energy of this experiment (~ 5 MeV) are 6^+ and 7^+,[12] the hyperfine magnetic fields result mainly from unpaired 3*s* electrons and are much too weak to influence the nucleus within the mean life $\tau = 0.7$ ps of the 2^+ level. The measured angular correlation for ^{28}Si is indeed consistent with a $2 \rightarrow 0$ ($\Delta m=0$) transition after correction for the finite solid angles of the particle and γ-ray detectors.

In contrast, strong perturbations of the angular correlation have been observed for ^{18}O ions[6,7] as well as for ^{16}O and ^{20}O ions[8,9] at velocities comparable to the recoil velocity of the present experiment. These perturbations arise from unpaired 1*s* electrons in hydrogenlike and heliumlike charge states which are predominant at these recoil energies ($\varphi_7 \approx 0.2$, $\varphi_6 \approx 0.4$, for this experiment). The present result of $\epsilon = (4.5 \pm 2.1)\times 10^{-3}$ supports the hypothesis that the deeply bound electronic configurations contributing to the perturbations studies in Refs. 6–9 are partially polarized in the tilted-foil geometry. The sense of rotation of the angular correlation is consistent with the phenomenological picture of the surface interaction[4] and the negative *g* factor of the ^{18}O 2^+ state.[13] Results comparable to those presented here were recently obtained for ^{16}O nuclei in the 3^- state at a lower recoil velocity.[14] An effect of opposite sign was observed, consistent with a positive value of the nuclear *g* factor for the 3^- state of ^{16}O.[15]

In searching for such a small rotation in the ^{18}O angular correlation it was crucial to establish that the observed effect was not due to systematic errors. Besides the quality of the spectra and the precautions taken with the centering of the target, the simultaneous collection of data for the ^{28}Si($2_1^+ \rightarrow 0$) transition was extremely important in this regard: Table I shows that, to very high precision, no false asymmetries exist for the ^{28}Si transition. Equally crucial is the absence of asymmetries between detectors 1 and 3 and between detectors 2 and 4 for the ^{18}O transition itself. The error assigned above to the asymmetry ϵ is therefore statistical only.

The interpretation of the optical tilted-foil spectroscopy experiments suggests that it is the orbital angular momentum of the electronic configuration which is polarized by the surface interaction. For hydrogenlike oxygen ions, the 1*s* ground-state configuration will therefore not be polarized if it is formed directly upon the ion's exit from the foil. However, polarized 1*s* configurations may ensue in the decay of polarized 2*p* electrons,[16] since the 0.4-ps lifetime of the 2*p*-1*s* transition is very short compared to the ^{18}O(2_1^+) nuclear lifetime. For heliumlike ions, the $(1s^2)^1S_0$ ground state has no hyperfine interaction, and it is terms like $(1s2p)^3P_J$ that contribute the measured strong hyperfine fields.[6,10] The lifetime of the $^3P_2$ term is about 1 ns—much longer than the nuclear lifetime. These examples illustrate that polarization of the electron orbital angular momentum can yield a net polarization of the hyperfine magnetic field at the nucleus.

In contrast to optical spectroscopy, beam-foil measurements which probe a specific atomic level, a measured effect in a nuclear hyperfine-interaction experiment can be produced by any of several electronic configurations. In the present case of oxygen ions recoiling out of a foil at 10 MeV, it is mostly the polarization of electronic *P* states that is responsible for the measured effect. In order to estimate the magnitude of such polarization, it is necessary to determine the absolute population of relevant atomic levels within a few picoseconds of the ions' exit from the foil. While this information is unavailable from beam-foil measurements, nuclear HFI experiments can shed some light on the problem (see, for example, the review article by Goldring[10]). With use of the estimates of Ref. 10, the rotation in the ^{18}O angular correlation measured in the present work corresponds to an intrinsic 2*p* electron polarization of 5%–20%. The quoted uncertainty reflects the experimental error and uncertainties in the absolute population of atomic levels.

In conclusion, the observed rotation of the angular correlation of de-excitation γ rays from ^{18}O ions recoiling rapidly from a tilted foil demonstrates for the first time that the polarization of electronic configurations observed in optical experiments for outer-shell electrons exists also for deeply bound electrons in highly stripped ions.

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‡Present address: The Technion, Technion City, Haifa, Israel.

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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[*]

G. Goldring, Y. Niv, Y. Wolfson, and A. Zemel
The Weizmann Institute of Science, Department of Nuclear Physics, Rehovot, Israel

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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-