Nuclear Polarization and Sign of the Quadrupole Moment of the ^{54}Fe(10$^+$) Isomer

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A novel approach to the determination of *signs* of quadrupole deformations of high-spin isomers is presented. Recoiling ^{54}Fe(10$^+$) isomers, populated by the reaction ^{45}Sc(^{12}C, $p2n$), are polarized by passage through an array of tilted carbon foils and stop in a Cd single crystal. The observation of a quadrupole precession serves to measure both the induced nuclear polarization and the sign of the quadrupole moment. A positive sign of $Q(^{54}$Fe(10$^+$)) has been deduced.

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One of the more intriguing questions in current nuclear physics is the possible transition from a prolate or spherical shape at low spins to an oblate shape at high spins. The prevailing view is that the transition results from the alignment of angular momenta of valence nucleons along the symmetry axis, which polarizes the core and produces the oblate shape. Such behavior is presumed to take place in several recently studied nuclei (^{152}Dy, ^{154}Er, ^{147}Gd,[1-4] and others). The absolute value of the quadrupole moment of the $(\frac{49}{2})^+$ level in ^{147}Gd was measured[3] to be $|Q| = 3.14(17)$ b and an oblate deformation was inferred.[4] However, direct confirmation of the oblate nature can be obtained only by determining the *sign* of the quadrupole moment (positive for prolate and negative for oblate). A sign determination can also be of great interest for high-spin isomers of a shell-model structure and provide information on the nature of relevant quasiparticle configurations.

Quadrupole moments of isomeric levels are studied usually by measuring the electric quadrupole coupling constant, $\nu_Q = e^2qQ/h$, in a noncubic crystal with a known electric field gradient (EFG). High-spin isomers are best populated by fusion evaporation (HI,xn) reactions, yielding nuclear alignment. Under these conditions, the magnitude of ν_Q can be determined in a time-differential perturbed-angular-distribution (TDPAD) experiment, but not the sign of the coupling constant; sign measurements of ν_Q via TDPAD experiments require the initial nuclear ensemble to be polarized. Various techniques have been employed to determine the sign of ν_Q at low spins,[5] none of which is technically suitable for high-spin isomers.

The present experiment employs a novel tilted-foil technique to polarize a high-spin isomer. Recoil products from a conventional (HI,xn) reaction, excited to a high-spin isomeric level, traverse an array of tilted carbon foils before being implanted in a noncubic single crystal. Ionic polarization has been clearly demonstrated in numerous beam-foil experiments[6] in which the excited ions pass through a thin foil which is not perpendicular to the beam direction (tilted-foil geometry). The polarized hyperfine fields of the tilted-foil geometry have been utilized in a number of measurements of nuclear magnetic moments of short-lived (picosecond) levels.[7] Improved sensitivity has been achieved by the introduction of several polarizing foils in the tilted-multifoil geometry.[8,9] For the purpose of nuclear magnetic-moment measurements, the flight time t between foils is kept short so that $\omega_L t \ll 1$, where ω_L is the Larmor precession frequency of the nucleus in the hyperfine field, and the nuclear spin experiences consecutive small precessions which together approximate a classical precession in an external magnetic field.[8] In order to enable the ionic polarization to be transferred to the nucleus via the hyperfine interaction, t must be increased so that $\omega_L t \gg 1$ and the ion-nucleus system reaches its equilibrium state after each foil.

For the first application of this method we have chosen the 10$^+$ isomer in ^{54}Fe. The isomer was made to recoil through a multifoil assembly at a velocity of $v/c = 0.013$. The polarization terms in the nuclear density matrix have been evaluated in model calculations.[8,9] The average ionic spin was assumed to be $J = \frac{5}{2}$ and the initial average ionic polarization for the Fe ions ($Z = 26$) was estimated to be

$$p_J = \langle J_z \rangle / [J(J+1)]^{1/2} = 0.08,$$

on the basis of experiments with Ca ($Z = 20$) and Sr ions ($Z = 38$) at similar velocities.[7,9] We find that a large number of polarizing foils is required to produce a sizable polarization for the $I = 10$

spin of the ^{54}Fe isomer. The calculations indicate that for $\omega_L t \gg 1$ and seventeen foils the nuclear polarization $p_I = \langle I_z \rangle / [I(I+1)]^{1/2}$ reaches a value of 0.17. The model calculation shows that the initial *alignment* from the fusion evaporation reaction is virtually destroyed by the interaction with the multifoil array. The loss of the nuclear alignment is understood as a repeated reduction to a lower hard-core value after each foil. These results serve only as an estimate of the polarization; the sign determination does not depend on the calculation and the actual nuclear polarization and alignment are determined directly in the experiment.

The experimental arrangement is shown in Fig. 1. A 40-MeV pulsed ^{12}C beam with a pulse width of ≈ 2 ns full width at half maximum and a repetition time of 2.4 μs from the Koffler 14UD Pelletron accelerator at Rehovot impinged on a 350-μg/cm^2 ^{45}Sc target, tilted with the normal $\hat{n}$ at 60° to the beam. The ^{54}Fe(10$^+$) isomer [$E_x = 6.526$ MeV, $T_{1/2} = 357(4)$ ns (Ref. 10), $g = 0.728(1)$ (Ref. 11)] was populated by the reaction ^{45}Sc(^{12}C, $p2n$). The isomers recoiled through the multifoil array described below, and stopped in a metallic stopper. The assemblies consisted of twelve to seventeen carbon foils, 3–4 μg/cm^2 thick, stretched at interfoil spacings of 0.15 mm and placed parallel to the target. A complete account of the various measurements will be given in an extended publication[12]; here we discuss in detail the results for a Cd single-crystal stopper with the symmetry axis $\hat{c}$ along the direction of $\hat{n}$.

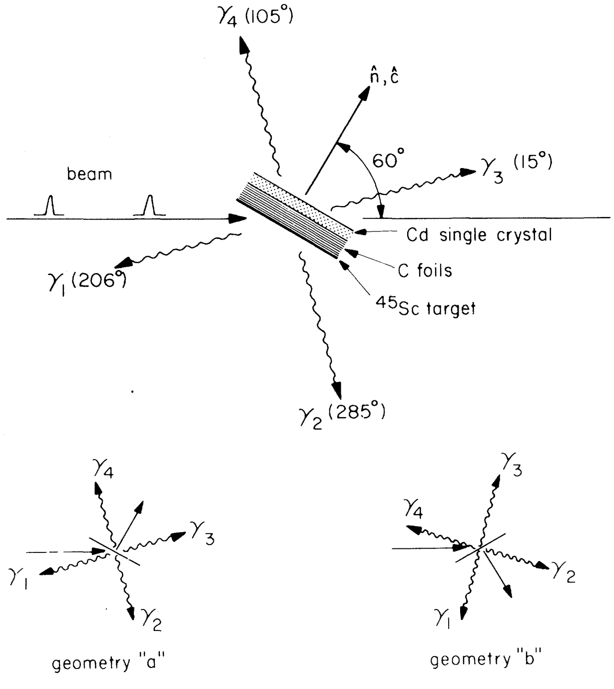

FIG. 1. Schematic view of the experimental arrangement.

Gamma rays from the decay of the ^{54}Fe(10$^+$) isomer were detected by four NaI counters 15 cm long × 12.5 cm diam placed in the plane perpendicular to the tilt axis at ± 45° and ± 135° to the $\hat{c}$ (and $\hat{n}$) axis (Fig. 1). Time spectra of γ radiation from the $10^+ \rightarrow 0^+$ $E2$ stretched cascade were collected by the standard slow-fast technique. Measurements were performed in the geometries "a" and "b" (Fig. 1), with and without polarizing carbon foils. In order to extract the time-dependent angular distributions of the decay γ rays, ratio functions were generated, where

$$R_j(t) = \frac{Y_1(t) - Y_2(t) + Y_3(t) - Y_4(t)}{Y_1(t) + Y_2(t) + Y_3(t) + Y_4(t)}$$

at the geometry j ($j = a, b$). $Y_i(t)$ is the time-dependent yield of detector i ($i = 1$–4) after summation over the cascading γ lines, background subtraction, and normalization. The various ratio functions have been fitted separately by theoretical expressions (see below), yielding overall consistent results. For demonstration purposes and for final fits with improved statistics we have generated combined ratio functions $R(t) = [R_a(t) - R_b(t)]/2$ which are shown in Fig. 2.

The ratio function without polarizing foils was fitted with use of the standard formalism of perturbed angular distribution of aligned nuclei.[13] The data are consistent with the assumption that (60 ± 8)% of the recoiling iron nuclei came to rest in substitutional sites in the cadmium host, and were subjected to an electric quadrupole interaction with a unique EFG. The rest of the recoils appear to have stopped in other sites, possibly interstitial or associated with radiation damage, and display a slow damping of the nuclear alignment due to different perturbations. The same situation was found[12] when the Fe isomer was implanted into another Cd single crystal, having a different orientation, and into a polycrystalline Cd foil. From the fit in the upper part of Fig. 2, a value of

$$|\omega_0| = 3e^2qQ/4I(2I-1)\hbar = 1.124(22) \text{ Mrad/s}$$

was found for the fraction with the well-defined EFG, corresponding to a quadrupole coupling-constant value of $|\nu_Q| = 45.3(9)$ MHz for the ^{54}Fe(10$^+$) isomer in Cd at room temperature.

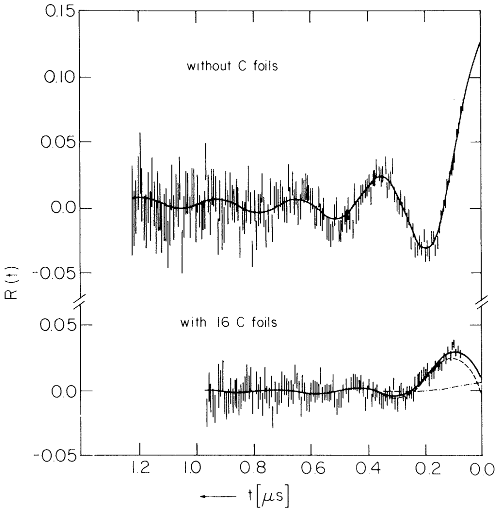

FIG. 2. Ratio functions for the quadrupole precession of the ^{54}Fe(10^+) level in Cd single crystal with (bottom) and without (top) C foils. The fitting procedures are described in the text and are represented by the solid lines. The dashed line in the lower part is from a fit by a polarization term only; the effects of residual alignment are shown by the dash-dotted line.

The combined data from runs with sixteen C foils (seventeen polarizing surfaces, including the target itself) are shown in the lower part of Fig. 2 together with the best fit. The introduction of C foils into the assembly resulted in an increased energy loss of the recoils as well as angular dispersion due to multiple scattering. After the runs, the ^{52}Mn radioactivity ($T_{1/2} = 5.59$ d) from the competing (^{12}C, $n\alpha$) reaction was measured in the various parts of the target assembly. On the assumption that the stopping profiles of the ^{52}Mn and ^{54}Fe recoils are similar, it was determined that only (62 ± 10)% of the recoils reached the Cd host. In a control experiment with seventeen carbon foils and a polycrystalline cadmium stopper (where no polarization effects can be seen), we observed[12] small effects of alignment damping. The alignment attenuation factor for the $I = 10^+$ level following recoil in vacuum under the present experimental conditions (for a single foil interaction) was measured[12] to be $G_2 = 0.80(4)$. Therefore only $(G_2)^{17} = 0.02(2)$ of the initial alignment is preserved for recoils which stop in Cd after traversing 16 foils. The residual alignment effects are probably due to recoils stopped before traversing many C foils.

In the present geometries, the time-dependent angular distribution of decay γ rays from polarized nuclei in the presence of an oriented axially symmetric EFG (with neglect of terms with $k \geqslant 3$) is given by

$$4\pi W(t) \approx 1 \pm \tfrac{3}{2} P_I F_2 \sum_n S_{n1}{}^{12}(n\omega_0 t).$$

The positive or negative sign depends on the orientations of the polarization axis and the detector with respect to the interaction axis (i.e., the $\hat{c}$ axis of the single crystal). P_I is the nuclear polarization, F_2 is the γ-ray angular distribution coefficient,[14] and the coefficients $S_{n1}{}^{11}(t)$ are defined in Ref. 13.

The dashed line in the lower part of Fig. 2 is from a fit by that equation. The fit also includes a term of residual alignment (dash-dotted line) of the type found in the polycrystalline host. The free parameters in that fit are the sign of ω_0 and the magnitudes of the polarization and alignment terms. From the fit we deduce a positive sign of ω_0 and a value of effective polarization $|P_I|_{\mathrm{eff}} = 0.069(8)$. The alignment term is indeed determined to be small and the results for the polarization are not sensitive to the assumed nature of the small residual alignment damping. The leading term due to the quadrupole interaction of *polarized* nuclei with the well-defined EFG in Cd is essential to obtaining an acceptable fit. The presence of nuclear polarization is thereby unambiguously confirmed by the present results.

The sign of the EFG for Fe in Cd is known to be positive,[15] and we conclude that the sign of the quadrupole moment is also positive. This is the first direct measurement of the sign of a quadrupole deformation of a high-spin level. Our results, together with the known value of ν_Q for the ^{57}Fe($\frac{3}{2}^-$) Mössbauer isomer in Cd,[15] yield the ratio

$$Q(^{54}\mathrm{Fe}(10^+))/Q(^{57}\mathrm{Fe}(\tfrac{3}{2}^-)) = 3.62(22),$$

in excellent agreement with the ratio from measurements in a Zn host[16] but with improved accuracy. Using the recently corrected value of

$$Q(^{57}\mathrm{Fe}(\tfrac{3}{2}^-)) = 8.2(8)\ e\cdot\mathrm{fm}^2$$

(Ref. 17) we arrive at the value

$$Q(^{54}\mathrm{Fe}(10^+)) = +29.7(4)\ e\cdot\mathrm{fm}^2.$$

The calculated value of the quadrupole moment for the predominant nuclear configuration of the ^{54}Fe(10^+) isomer lies in the range $Q = +(24\text{–}29)$ $e\cdot$fm^2,[18] in agreement with the present results.

The experimental value of $|P_I|_{\mathrm{eff}}$ must be corrected for the 38(10)% of the recoils which did not reach the Cd host and for the 40(8)% of those implanted into Cd but not subjected to the oriented

EFG. The nuclear polarization for recoils which have traversed the stack is therefore $P_I = 0.18(5)$.

Nuclear polarization has been previously demonstrated following grazing-angle atomic collision[19] and in a single tilted-foil experiment[20] with stable light ions. The polarization of high-spin nuclear levels, however, requires the interaction with an array of many foils. The multifoil technique has been shown here to induce a sizable post-reaction polarization of high-spin nuclear isomers populated by a conventional (HI,*xn*) reaction.

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