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Signs of the quadrupole moments of the 8^+ isomers in ^{88,90}Zr

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The signs of the quadrupole moments and the induced nuclear polarization of the 8^+ isomers in ^{88,90}Zr have been measured by the tilted multifoil technique. The isomers were populated by pulsed ^{16,18}O beams and polarized by the tilted multifoil interaction. The recoil nuclei were implanted into a single crystal of Zr and the quadrupole precession was observed. The sign of the Q moments was measured to be positive for ^{88}Zr and negative for ^{90}Zr, in accordance with shell model predictions.

Within the last few years a number of experiments have shown that it is possible to measure the *sign* (in addition to the magnitude, which could be measured previously) of the nuclear deformation at high angular momentum using the tilted multifoil (TMF) interaction. In this technique, details of which are described in Refs. 1–3, high spin isomers are produced in a thin target via fusion evaporation reactions and recoil through a stack of tilted carbon foils into a noncubic single crystal. The TMF interaction polarizes the nuclear spin which then precesses due to the static nuclear quadrupole interaction with the electric field gradient (EFG) inside the crystal.

Previously, this technique was applied to the medium light-f-shell region[1] (Fe) and to the medium heavy transition region[2–4] (Gd,Ce,Sm). With the advent of improved shell model calculations utilizing a greatly expanded model space, there has been renewed interest in the structure of nuclei around $A=90$. Recently, high spin spectroscopy studies[5] in this mass region and quadrupole moment measurements[6] on the 8^+ isomers in ^{88,90}Zr have been performed. Determination of the signs of the quadrupole moments of these states can provide additional evidence for the role of particles and holes in their structure and their interpretation in the shell model.

Isomers in ^{88,90}Zr were populated by the ^{76}Ge(^{16,18}O,4n) reactions, respectively, using pulsed beams from the 14UD Pelletron at Rehovot and 700 μg/cm^2 ^{76}Ge targets. The reaction products recoiled from the target through an array of carbon foils tilted at an angle of $\psi=60°$; due to the interaction of the recoiling ions at the exit surfaces of the carbon foils, an electronic polarization is induced in a direction perpendicular to the beam and normal to the foils. The electronic polarization is transferred to the nuclei via the hyperfine interaction (HFI) during the flight time between foils. A fuller account of the TMF technique can be found elsewhere.[1,2,7] We would like to note here that in order to achieve maximum polarization transfer, a sufficiently long interaction time (i.e., large interfoil spacing) and a sufficient number of carbon foils are required.[8]

As in previous measurements, the recoiling nuclei were implanted into a single crystal (Zr in the present experiment) with the ĉ axis oriented along the beam direction. In this geometry the quadrupole interaction due to nuclear alignment vanishes and only polarization effects are observed. The decay gamma rays were detected by four hyperpure large-volume P-type Ge detectors located at ±45° and ±135° in the horizontal plane. The time spectra were accumulated after routing by windows set on the γ-ray energies in each detector. The ratio function $R(t)$, defined in Refs. 1 and 2, was fitted to the expression

$$R(t) = -\tfrac{3}{2} P_I^{\rm eff} F_2 \sum_n S_{n1}^{12} \sin(n\omega_0 t) \ , \tag{1}$$

where $P_I^{\rm eff}$ is the effective nuclear polarization, F_2 the gamma radiation angular distribution coefficient,[9] S_{n1}^{12} are geometrical coefficients,[10] and $\omega_0 = e^2qQ/160\hbar$ is the quadrupole frequency for $I=8$. The value of $|\omega_0|$ determined in the present work is consistent with previous measurements[6] and was kept as a fixed parameter in the fits. However, leaving $|\omega_0|$ as a free parameter did not affect the results significantly.

Ratio functions for the summed $E2$ transitions of 671, 1083, and 1052 keV in ^{88}Zr, for the $E2$ transition of 141 keV and the $E1$ transition of 1129 keV in ^{90}Zr (Fig. 1) are shown in the top, middle, and bottom of Fig. 2, respectively. Ratio functions were also evaluated for individual detectors and for different directions of polarization. All the results are consistent with those displayed in Fig. 2. Furthermore, analysis of the 511 keV line yielded a null effect, as expected. From Figs. 2(a) and 2(b) one can see that the signs of the quadrupole moments of ^{88}Zr and ^{90}Zr are opposite. In order to determine the absolute sign of Q we need to know the sign of the EFG of Zr$\underline{\rm Zr}$. From impurity-host systematics there are strong arguments for a positive sign for the EFG (Zr$\underline{\rm Zr}$).

(i) For a given metallic host, including IV-B elements, impurities isoelectric to the host (same column in the periodic table) were shown to have the same EFG as the pure system, except for a trivial scaling by the impurity's Sternheimer antishielding factor.[11] The Zr$\underline{\rm Zr}$ system is expected, therefore, to have the same sign of the EFG as Hf$\underline{\rm Zr}$, which is positive.[12]

(ii) It was recently demonstrated that the sign of the EFG in transition metals is determined uniquely by the properties of the host.[13] For Cd and Hf impurities in Zr the EFG is positive[12] and it should be the same for other probe nuclei.

(iii) The modified "universal correlation" model of Ernst, Hagen, and Zech[14] predicts a positive sign of Q for IV-B hexagonal crystals of metals, including Zr.

The S_{n1}^{12} coefficients are negative and so are the F_2 for $E2$ transitions, therefore the analysis yields a positive quadrupole moment for ^{88}Zr and negative for ^{90}Zr.

The effective polarization $P_I^{\rm eff}$ in Eq. (1) is smaller than the polarization P_I induced by the TMF array,

$$P_I^{\rm eff} = \alpha P_I \ , \tag{2}$$

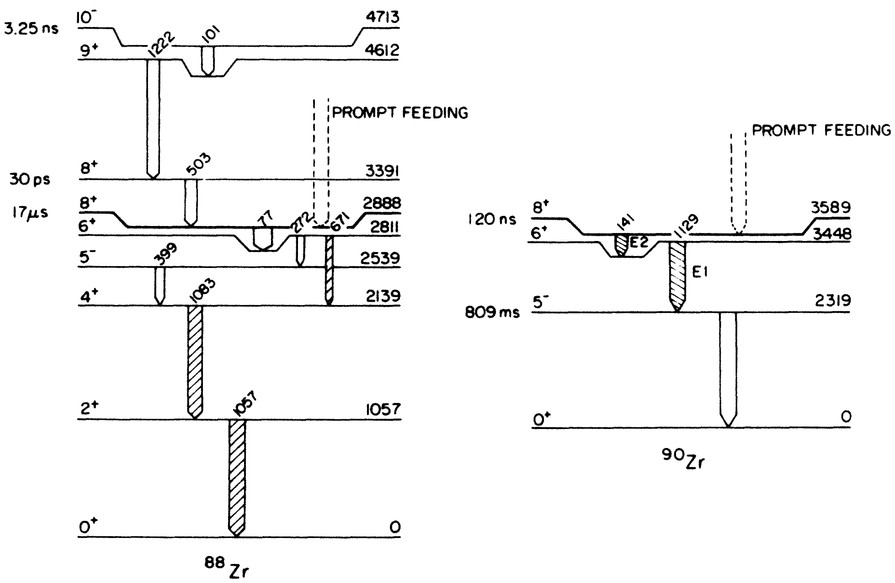

FIG. 1. Partial level scheme of ^{88}Zr and ^{90}Zr (Ref. 5). The γ rays observed in the present experiment are indicated.

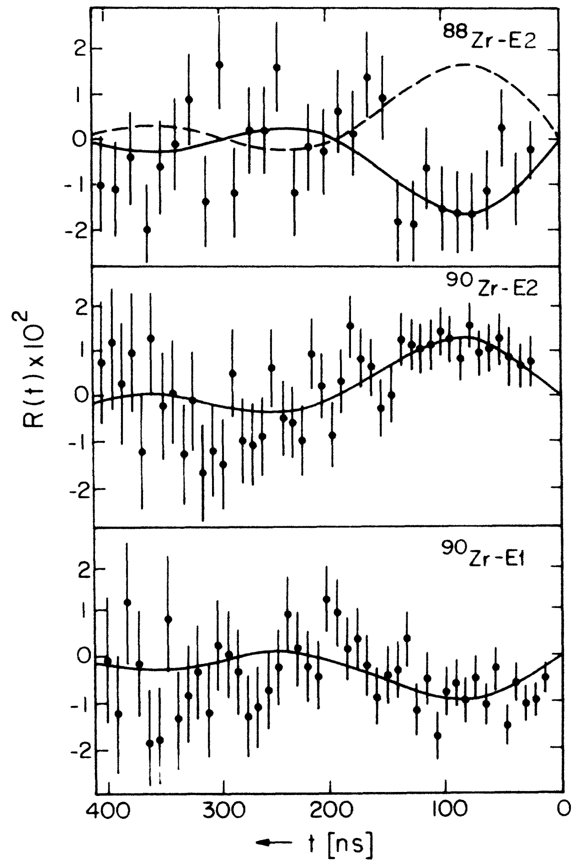

FIG. 2. The ratio functions $R(t)$ constructed for the ^{88,90}Zr(8^+) isomers: Top shows $R(t)$ for the sum of $E2$ transitions in ^{88}Zr; middle shows $R(t)$ for the 141 keV, $E2$ transition in ^{90}Zr; bottom shows $R(t)$ for the 1129 keV, $E1$ transition in ^{90}Zr. The opposite signs of the quadrupole moments of the 8^+ levels in ^{88}Zr and ^{90}Zr are immediately apparent. With a positive EFG for Zr$\underline{\text{Zr}}$ (see text) these ratio functions correspond to $Q[^{88}Zr(8^+)] > 0$ and $Q[^{90}\text{Zr}(8^+)] < 0$. The dashed line presents for the sake of illustration the results of calculations with $Q[^{88}\text{Zr}(8^+)] < 0$.

where α is the fraction of the recoils stopped in the Zr crystal. The fraction α was determined by a radioactivity survey of the various components of the target assembly and was typically found to be $\alpha \approx 0.75$.

From least-squares fit of Eq. (1) and from Eq. (2) we obtain a nuclear polarization $P_l = 5.8(1.5)\%$ for ^{88}Zr and 4.5(1.1)% for ^{90}Zr isotopes.

Maximum nuclear polarization is obtained under the condition of long interaction time $\omega_{\text{HF}} t >> 1$, where ω_{HF} is the average HF frequency and t is the interfoil flighttime. Measurements of the attenuation of nuclear alignment in vacuum conducted at our laboratory suggest that this condition is fulfilled for interfoil distances of about 2 mm and that the average electronic spin is $\langle J \rangle = 4.0(5)$. According to model calculations,[8] 12 carbon foils are required for $I = 8$ and $J = 4$ to obtain 90% of the maximum polarization. The actual stacks employed consisted of 25 foils at an interdistance $d = 0.4$ mm and 8 foils at $d = 1.6$ mm and the value of P_l quoted above is an average of results for the two stacks. For the purpose of the determination of the signs of Q moments, this deviation from the ideal configuration does not affect the present conclusions, but we note that the *measured* polarization P_l differs from the *induced* polarization due to loss of polarization in unobserved gamma transitions (expected to be small for a rank 1 tensor). Also, the 8^+ isomer of ^{88}Zr is fed by prompt decays and by the delayed $10^- \rightarrow 9^+ \rightarrow 8^+$ transition.[5] Since the 10^- state is also an isomer with half-life $T_{1/2} = 3.25$ ns, the observed polarization of the 8^+ isomer originates in two different initial nuclear ensembles, the 10^- isomer (with an unknown g factor) and the 8^+ isomer itself. Therefore, direct comparison with model calculations is not straightforward.

The 8^+ level in ^{88}Zr is described as two protons and two neutron holes outside of the ^{88}Sr core. The small negative g factor of the 8^+ state reveals the neutron character of this level and indicates a small proton contribution to the wave function. Shell model calculation[6] of the $|\pi(p_{1/2})^2 \nu g_{9/2}^{-2}\rangle$ configuration of the 8^+ isomeric level yields $Q = +51.6$ $e$fm^2. The 8^+ state of ^{90}Zr is described as two protons in the $g_{9/2}$ shell outside of the ^{88}Sr core which yields[6]

$Q=-50.4$ $e\text{fm}^2$. The magnitudes of both quadrupole moments were measured[6] and found to be identical, $|Q|_{\text{exp}}=51(3)$ $e\text{fm}^2$, indicating similar effective charges for protons and neutron holes. With the present measurement of positive Q for the 8^+ in ^{88}Zr and negative Q for the 8^+ in ^{90}Zr, the shell model picture of particles and holes for these nuclei receives further and direct confirmation.

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