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g factor of the $3/2^+$ 121.8-keV level in ^{99}Zr

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The magnetic moment of the first excited, $3/2^+$ state of ^{99}Zr was measured using the integral perturbed angular correlation method, in an external magnetic field of 6.25 T. The result, $g(3/2^+) = +0.28(4)$, is discussed in relation to theoretical calculations for spherical nuclei and also compared to predictions of the core-excitation model.

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I. INTRODUCTION

The $A = 100$ region of the periodic table is of special interest for nuclear structure studies. The reason for this is that in a relatively narrow range of nuclei, a sharp transition from spherical to deformed nuclear shapes takes place. This onset of deformation is particularly evident in the Sr, Y, and Zr isotopic chains, for which the isotopes with $50 \leq N \leq 58$ have spherical shape, while those with $N \geq 60$ are strongly deformed. The $N = 59$ isotones, located at the transition point, are expected to exhibit shape coexistence. Indeed, experimental evidence has been found [1–3] for the coexistence of spherical and deformed structure in the neutron-rich ${}^{97}_{38}\mathrm{Sr}_{59}$, ${}^{98}_{39}\mathrm{Y}_{59}$, and ${}^{90}_{40}\mathrm{Zr}_{59}$ isotones. A common feature of these $N = 59$ isotones is that their ground state and low-lying states have spherical shape, while deformed structure is observed at excitation energies above 500 keV. Until now, a number of $E2$ and $M1$ transition rates have been measured for the above isotones, and have provided important information on the structure of the states involved in the transitions. However, no information exists to date about magnetic moments of excited states for these nuclei. Since g factors are known to be good probes of both spherical and deformed states, an experiment was undertaken to measure the magnetic moment of the first excited, $E = 121.8$ keV, $3/2^+$, level of ^{99}Zr. In this work we present the result of this measurement and compare it with calculations for spherical nuclei, with the predictions of the simple core excitation model, and with systematics of $N = 53$ isotones.

II. EXPERIMENTAL TECHNIQUE

The experiment presented here is part of a program of g-factor measurements for excited states in odd-N, even-Z neutron-rich isotopes in the $A = 100$ region, at the TRISTAN fission product separator [4], which operates on-line with the High Flux Beam Reactor at Brookhaven National Laboratory. Previous measurements include the g factors of the $E = 1264$ keV, $7/2^+$ state in ^{97}Zr [5] and of the $E = 93.6$ keV, $3/2^+$ state in ^{91}Sr [6].

A detailed description of TRISTAN is given elsewhere [4]. In the present experiment, a plasma ion source assembly containing a 5 g, 93% enriched ^{235}U target placed in a thermal neutron flux of about 2×10^{10} $n/\mathrm{cm}^2\,\mathrm{s}$ produced a beam of separated, singly ionized, $A = 99$ fission products, containing the short-lived ($T_{1/2} = 1.5$ s) ^{99}Y isotope which decays to ^{99}Zr. The intensity of the ^{99}Y beam was about 5000 ions/s. The fission products are deposited on an aluminized tape, and transported periodically to the center of a superconducting magnet.

The half-life of the $3/2^+$, 121.8-keV first excited state is $T_{1/2} = 1.07(3)$ ns [7], and therefore the integral perturbed angular correlation method (IPAC) was used. We used the usual setup [8] of four HPGe detectors placed concentrically around the magnet at 9.5 cm from its center. The angles between the detectors were 90° (1), 120° (2), 150° (3), where the numbers in parentheses indicate the number of pairs at the given angle. The experimental setup is shown schematically in Fig. 1.

The data were accumulated in event mode using a PDP 11/34 computer, and sorted off-line using a micro-VAX computer. In a ten-day run, about 10^7 coincidence events

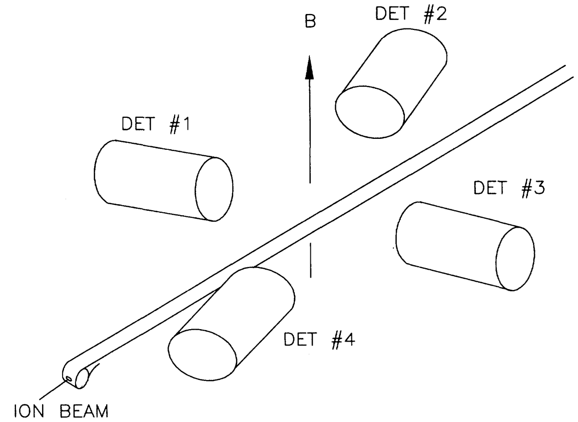

FIG. 1. Schematic description of the four-detector system, with the tape collector and ion beam. The magnetic field is schematically depicted by the arrow.

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were recorded for each field direction. In a separate experiment, nonperturbed angular correlations were measured using the same HPGe detectors, in order to determine the anisotropies of the $\gamma\gamma$ correlations.

III. RESULTS

The strongest cascade involving the 121.8-keV level is 453.6–121.8 keV. The unperturbed correlation for this cascade is shown in Fig. 2. The solid angle correction coefficients for the correlation were calculated from the table of Camp and Van Lehn [9], and found to be $Q_{22} = 0.90$, $Q_{44} = 0.62$, so the corrected values of the angular correlation coefficients are $A_{22} = -0.491(24)$, $A_{44} = 0.065(81)$. The spin of the 575.4-keV level cannot be unambiguously determined from the correlation. Both 3/2 and 5/2 assignments are possible, depending on the mixing ratios of the transitions. However, for magnetic moment measurements it suffices to know the coefficients A_{22}, A_{44}, of the Legendre polynomials. The anisotropy of the correlation is quite large, indicating that for g factors of about $|g| = 0.1$–0.5 reasonably large effects of about 10% – 30% are expected for magnetic fields of a few tesla. For the parameters of this experiment ($T_{1/2} = 1.07$ ns, unperturbed correlation (Fig. 2) and $|g|$ between 0.1 and 0.5), the maximum IPAC effect is expected for magnetic field values larger than the full field of our magnet. We therefore used the full field of 6.25 T. Extranuclear perturbations in the aluminized tape collector, if present, can significantly affect the results of the IPAC measurement. These perturbations can be estimated theoretically and experimentally. Knight shift and diamagnetic corrections are estimated [10] in this case to be less than a few percent. A good experimental test for the existence of extranuclear perturbations is from time-differential measurements. The amplitude of the time-dependent intensity oscillations from these measurements gives directly the angular correlation coefficients. In the absence of extranuclear perturbations, these coefficients should be equal to those obtained when no magnetic field is applied. Time-dependent experiments at TRISTAN have clearly shown [5,6] that extranuclear perturbations on Rb and Y ions implanted in the aluminized tape collector are indeed negligible. About the same number of events was recorded for both fields up and down. The data were analyzed off-line by setting energy gates on the gamma lines of interest. Background was subtracted by setting appropriate gates in the vicinity of the respective peaks. For the data analysis, we define the double ratio $R(B,\vartheta)$ in the usual way:

$$R(B,\vartheta) = \left(\frac{I(B,\vartheta)/I(-B,\vartheta)}{I(B,-\vartheta)/I(-B,-\vartheta)}\right)^{1/2} \tag{1}$$

where B is the value of the magnetic field, and $I(B,\vartheta)$ is the net number of coincidence events for the $\gamma\gamma$ cascade at angle ϑ, and the sign of the angle for a given direction of the field is determined by the usual convention [11]. $I(B,\vartheta)$ can be calculated from the known IPAC formula [12]:

$$\begin{aligned} I(B,\vartheta) \propto 1 &+ \frac{b_2}{[1+(2\omega\tau)^2]^{1/2}}\cos 2(\vartheta - \triangle\vartheta) \\ &+ \frac{b_4}{[1+(4\omega\tau)^2]^{1/2}}\cos 4(\vartheta - \triangle\vartheta)\ , \end{aligned} \tag{2}$$

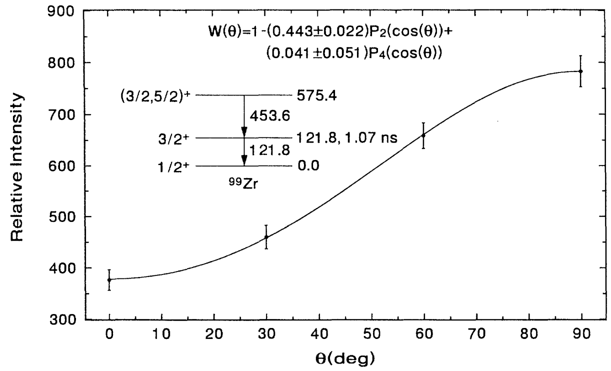

FIG. 2. Angular correlation results for the 453.6–121.8 keV cascade of ^{99}Zr. The solid line is a best fit to a sum of Legendre polynomials.

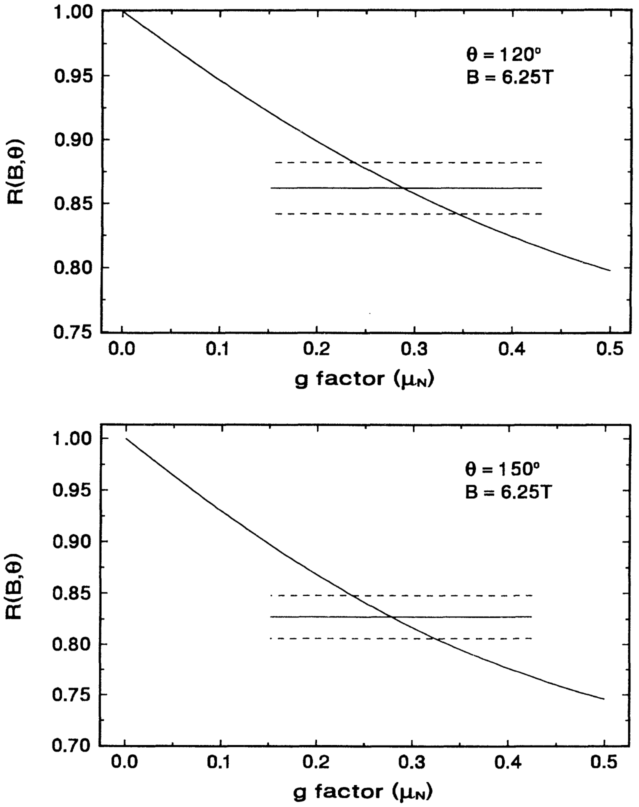

FIG. 3. $R(B,\vartheta)$ vs the g factor of the 121.8-keV state for two angles: $\vartheta = 120°$ and $\vartheta = 150°$. The horizontal solid and dotted lines represent the experimental values of $R(B,\vartheta)$ with the respective error bars, from Table I. See Eq. (1) for the definition of $R(B,\vartheta)$.

TABLE I. Values of the double ratio $R(B,\vartheta)$ at 90°, 120°, 150° and the deduced g factor.

ϑ(deg)	$R(B,\vartheta)$	$g(\mu_N)$
90	0.99(5)	...
120	0.862(23)	+0.293(45)
150	0.827(21)	+0.278(48)

where b_2, b_4 are simple functions of the A_{22}, A_{44} angular correlation coefficients, the precession angle $\triangle\vartheta$ is given by the relation tan $(N\triangle\vartheta) = N\omega\tau$ $(N = 2, 4)$ and ω is the Larmor frequency $\omega = -g\mu_N B/\hbar$. The above definition of R has the advantage that it eliminates possible systematic errors related to normalization and different relative efficiencies of the detectors. For angular correlations of the type considered here (Fig. 2), $R(B,\vartheta)$ has a maximum (minimum) at about 35° (145°). This is the reason we chose the angles between the detectors so that three of them were 30° (150°). The expected effect at 60° (120°) is about 10% smaller than the maximum, so the data at these angles could also be used to deduce the g factor. Thus, in the present setup, five angles were used to determine the magnetic moment. $R(B,90°)$ is always 1.00 as can be easily seen from Eqs. (1) and (2) and was used as a consistency check. In Fig. 3 we present the sensitivity of $R(B,120°)$ and $R(B,150°)$ to the value of g$(3/2^+)$. For positive g factors, both values are smaller than 1.

The experimental values of $R(B,\vartheta)$ for $\vartheta = 90°$, 120°, 150° are given in Table I, together with the deduced g factors. The value at 90° is indeed consistent within experimental error with 1.00. Also, the effects at 120° and 150° are both in the same direction, and considerably smaller than 1.00. The experimental g factor is therefore unambiguously determined to be positive; its value is obtained by averaging the results in Table I:

$$g_{\rm exp}(3/2^+,\ ^{99}{\rm Zr}) = +0.28(4)\ . \qquad (3)$$

The error bar here includes the uncertainties of the angular correlation coefficients and the lifetime of the excited state.

IV. DISCUSSION

The structure of the low-lying states of ^{97}Sr and ^{99}Zr is quite similar. The ground state of both isotopes is most probably associated with the $(g_{7/2})^2 s_{1/2}$ neutron configuration, while the $3/2^+$ first excited state has a strong neutron $d_{3/2}$ character with considerable $g_{7/2}$ admixture [1]. The Schmidt value of the g factor for a pure $d_{3/2}$ neutron single particle state is +0.767. A more realistic calculation [13] for spherical nuclei yields for an almost pure (97%) $d_{3/2}$ single neutron quasiparticle state for the single magic ^{117}Sn nucleus:

$$g_{\rm theor}(3/2^+,\ ^{117}{\rm Sn}) = \begin{array}{ll} +0.45 & \text{for } g_R = 0\ , \\ +0.51 & \text{for } g_R = Z/A\ . \end{array} \qquad (4)$$

The same calculation [13] yields for the $d_{3/2}$ quasiparticle state of the $N = 59$ isotone ^{107}Cd:

$$g_{\rm theor}(3/2^+,\ ^{107}{\rm Cd}) = \begin{array}{ll} +0.19 & \text{for } g_R = 0\ , \\ +0.25 & \text{for } g_R = Z/A\ . \end{array} \qquad (5)$$

No detailed calculations are available for the other $N = 59$ isotones. We note that the value for $g_R = Z/A$ in Eq. (5) is in reasonable agreement with the experimental value of Eq. (3).

Another possible interpretation of the present experimental result is in terms of the core excitation model of deShalit [14]. In a previous work [6] we have shown that this model provides a good description of the systematics of g factors of $3/2^+$ states in $N = 53$ isotones. According to this model, the low-lying excited states in odd-even nuclei can be interpreted as a coupling between the odd particle and the 2_1^+ state of the even-even core. In the present case, the odd $s_{1/2}$ neutron of the g.s. of ^{99}Zr coupled to the 2_1^+ state of ^{98}Zr produces the low-lying excited states in ^{99}Zr. Since these states are expected to be of spherical nature, it is of interest to apply the core excitation (CE) model to the transitional ^{99}Zr nucleus. By applying the basic formulas of the model [14] to calculate $g(3/2^+)$ in our case, we obtain

$$g_{\rm CE}(3/2^+, N = 59) = -0.20g(1/2^+) + 1.20g(2_1^+)\ , \qquad (6)$$

where $g(1/2^+)$, $g(2_1^+)$ are the g factors of the g.s. of ^{99}Zr and the 2_1^+ state of ^{98}Zr, respectively. Unfortunately, neither of these g factors is known. However, due to the structure similarity of the $N = 59$ isotones ^{97}Sr and ^{99}Zr, we use for $g(1/2^+)$ the known [15] value for ^{97}Sr, i.e., $g(1/2^+) = -1.000(2)$. For $g(2_1^+)$ we can use the average of the experimental $g(2_1^+)$ for ^{98}Sr (0.38(7)), and ^{100}Zr (0.22(5)) [15], i.e., 0.30(8), incorporating within the error bar both experimentally known g factors. We also note that the value 0.30 is about what we expect for the g factor of a 2_1^+ state in a collective even-even nucleus, when we consider the deviation from Z/A due to the different pairings of protons and neutrons. With these assumptions, we obtain the estimate of $g(3/2^+)$ for ^{99}Zr in the core excitation model:

$$g_{\rm CE}(3/2^+,\ ^{99}{\rm Zr}) = +0.56(10)\ . \qquad (7)$$

This value is considerably larger than the experimental value of 0.28(4), indicating that unlike the case of the $N = 53$ isotones, for the ^{99}Zr transitional nucleus the core excitation model does not provide a good quantitative estimate of the g factor, although the sign is correctly predicted. Another possible reason for the large deviation between the CE model prediction and the experimental value may be related to the fact that neither $g(1/2^+)$ or $g(2_1^+)$ is known, and we had to use estimates from systematics. We also note that while in the quasiparticle model of Kisslinger and Sorensen [13] the positive value of $g(3/2^+)$ is due to the positive g factor of a $d_{3/2}$ neutron, in the core excitation model the positive sign is due to the second term in Eq. (6), and the fact that a $s_{1/2}$ neutron has a negative g factor [i.e., $g(1/2^+) < 0$ in Eq. (6)]. It is interesting to mention that the CE model prediction for the g factor of the $3/2^+$, first excited state of the $N = 53$ isotones ^{91}Sr, ^{93}Zr, ^{95}Mo is [6]

$$g_{\mathrm{CE}}(3/2^+, N = 53) = 0.867g(5/2^+) + 0.133g(2_1^+) \; . \quad (8)$$

Since for these isotones the $5/2^+$ ground state has a predominantly $d_{5/2}$ character, its g factor is negative, and therefore Eq. (8) predicts a negative g factor for the first excited $3/2^+$ state. Therefore, although the abovementioned $N = 53$ isotones and the $N = 59$ isotone ^{97}Sr have negative g factors for their g.s., the sign of the moment for the excited $3/2^+$ state is different. This fact is simply understood in the CE model, as it is easy to see by comparing Eqs. (6) and (8).

In conclusion, the experimental value of the magnetic moment of the first excited, $3/2^+$ state of the transitional ^{99}Zr nucleus reported in this work is in good agreement with the prediction of the Kisslinger – Sorensen model [13] for the $N = 59$ isotone ^{107}Cd. Since this model is essentially intended for spherical nuclei, we conclude that the present experimental value is consistent with the assumption that the low-lying states of ^{99}Zr have spherical nature. The estimate based on the CE model is not in agreement with the experimental value. However, this simple model predicts correctly the change in sign of the g factors of the first excited $3/2^+$ states in the $N = 53$, 59 isotones. We expect that comparison of the experimental value reported in this work with more detailed theoretical calculations will provide specific information on the nuclear structure of the $3/2^+$ state, and thus will further our understanding of this transitional nucleus.

Note added. V. Paar and S. Brandt have recently performed a theoretical calculation of $g(3/2^+)$ for ^{99}Zr, within the Interacting Boson–Fermion model, and obtained +0.34, in good agreement with the experimental result presented in this work. Details of their calculation will be presented in a forthcoming publication.

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