PHYSICAL REVIEW C VOLUME 48, NUMBER 2 AUGUST 1993

# $g$ factor of the $\frac{3}{2}^+$ 93.6 keV level in $^{91}$Sr

A. Wolf,[1-3] R. L. Gill,[1] D. S. Brenner,[2] Z. Berant,[3] R. B. Schuhmann,[1,2,*] and N. V. Zamfir[1,2,4]
[1]*Brookhaven National Laboratory, Upton, New York 11973*
[2]*Clark University, Worcester, Massachusetts 01610*
[3]*Nuclear Research Center Negev, Beer-Sheva 84190, Israel*
[4]*Institute of Atomic Physics, Magurele, Bucharest, Romania*

(Received 30 April 1993)

The $g$ factor of the first excited, $\frac{3}{2}^+$, 93.6 keV level of $^{91}$Sr was measured using a beam of separated fission products and the time-differential perturbed angular correlation method. The result, $g(\frac{3}{2}^+)=-0.231(11)$, is discussed in the context of the systematics of $g$ factors of $N=53-57$ isotones, and found to be in good agreement with the prediction of the core-excitation model.

PACS number(s): 21.10.Ky, 27.60.+j

## I. INTRODUCTION

The study of odd-$A$ spherical nuclei can provide useful information for understanding the mechanism of single-particle excitations and the interaction between the single particle and the even-even core. In general, quite different modes of excitation can lead to the low-lying levels of an odd-$A$ nucleus: simple single-particle transitions to higher-lying orbits, coupling of the odd particle with the core, interactions among several particles outside a closed shell, etc. These different modes of excitation are usually characterized by different values of some observables such as level energies, electromagnetic transition rates, or static moments. The experimental measurement of these observables can help distinguish among the different excitation modes.

In this work we have measured the $g$ factor of the first excited state, $E=93.6$ keV, $\frac{3}{2}^+$, in the $N=53$ isotone $^{91}$Sr. This nucleus has three neutrons outside the closed shell $N=50$, and is an important multiparticle odd-$A$ system in this region, in which $Z=38$ (and 40) act as significant shell gaps. The relatively long (88.8 nsec) half-life of its first excited state makes it a good candidate for a perturbed angular correlation measurement. The result will be analyzed in the context of systematics of $N=53-57$ isotones, and the predictions of calculations using several different models for these nuclei will be discussed.

## II. EXPERIMENTAL TECHNIQUE

The experiment was performed at the TRISTAN fission product separator [1], which operates on-line with the High Flux Beam Reactor at Brookhaven National Laboratory. An integrated ion source assembly containing a 5 g, 93% enriched $^{235}$U target placed in a thermal neutron flux of about $2.010^{10}$ n/cm$^2$ sec provides beams of singly ionized fission products which are subsequently electromagnetically separated and directed to various experimental beam ports. The beam intensity is strongly dependent on the mass of the fission product, in general following the fission fragment yield distribution, and is modulated by the ionization mechanism in the source. Different types of ion sources have been developed and investigated, in order to provide the highest possible intensity for each element. A detailed description of TRISTAN and of the ion sources is given elsewhere [1]. In the present experiment a plasma ion source was used, and a very high intensity beam containing $^{91}$Rb was produced. In fact, we had to reduce the power of the ion source in order to maintain a reasonable rate in the counting system. A superconducting magnet (maximum field 6.3 T) is installed on one of the beam ports. The fission products are deposited on an aluminized tape, and transported periodically to the center of the magnet. This setup was used in the past [2,3] for integral and time-differential perturbed angular correlation measurements (IPAC and TDPAC). These measurements have shown that no significant attenuation of the correlation occurs in the aluminized tape.

The half-life of the 93.6 keV level in $^{91}$Sr is known to be $88.8\pm1.7$ nsec [4]. For such long-lived nuclear states, it is well known [5] that the TDPAC technique can be used to provide quite accurate $g$-factor measurements. Since such an experiment requires good electronic timing, our usual HPGe setup for $g$-factor measurements was not suitable and a new system exploiting the excellent timing characteristics of BaF$_2$ detectors was designed, constructed, and tested [6]. The BaF$_2$ crystals were coupled to fast XP-2020Q photomultipliers, yielding a time resolution better than 1 nsec FWHM for the dynamic range of interest (90–400 keV). The energy resolution was about 25% at 100 keV. This relatively poor energy resolution was nevertheless found to be sufficient to resolve the most important lines in the spectrum. The detectors were placed concentrically around the magnet, at about 12 cm from its center. The angles between the detectors were +135°, −135°, and 90°. The angle signs in the external magnetic field were determined using the usual conven-

---

[*] Present address: American Physical Society, Ridge, NY 11961.

tion [7]. Special magnetic shielding (Philips base assembly S-5632) was used around the photomultipliers, which enabled proper operation of the detectors using a field of up to about 4 T at the center of the magnet. The average fringe field at the position of the detectors was about 0.1 T.

The data were accumulated in event mode using a PDP 11/34 computer, and sorted off-line using a micro-VAX computer. In a seven-day run, a total of about $1.5\times10^8$ coincidence events were recorded.

In a separate experiment, nonperturbed angular correlations were measured using four high-resolution HPGe detectors at fixed positions around the source, in order to determine the anisotropies of the gamma-gamma correlations.

## III. RESULTS

The strongest cascade involving the 93.6 keV level is 345.5-93.6 keV. The measured angular correlation for this cascade is presented in Fig. 1. The anisotropy is quite large, indicating that a TDPAC measurement is certainly feasible.

Since the TDPAC setup had both $+135°$ and $-135°$ angles, and for each pair of detectors we could set analysis gates on either radiation of the cascade, only one field direction was required. The expected absolute value of the $g$ factor was in the range 0.1–0.7, and since the time resolution was quite good, we could use a large magnetic field. We chose 3.85 T, mainly because of limitations in the use of the photomultipliers in the fringe field at higher field strengths. The resulting time spectra for the 345.5-93.6 keV cascade were summed for both pairs of detectors, and the following function was calculated:

$$R(135°,t)=\frac{I(135°,t)-I(-135°,t)}{I(135°,t)+I(-135°,t)} . \tag{1}$$

For cases such as ours, where the coefficient $A_{44}$ of the unperturbed correlation is zero, this function is known [5] to have the simple analytic form:

$$R(135°,t)=\tfrac{3}{4}A_{22}\sin 2\omega_L t , \tag{2}$$

where the Larmor frequency of precession $\omega_L$ is given by

$$\omega_L=-gB\mu_N/\hbar . \tag{3}$$

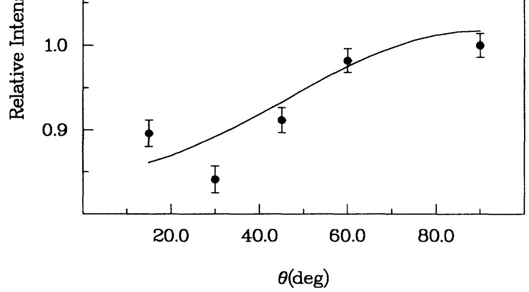

FIG. 1. The unperturbed gamma-gamma correlation of the 345.5-93.6 keV cascade. The solid line is a fit by a sum of Legendre polynomials.

The experimental function $R(135°,t)$ is presented in Fig. 2. The total intensity from both pairs, $I(135°,t)+I(-135°,t)$, is also shown in Fig. 2, and gives a half-life of $T_{1/2}=94\pm5$ nsec, in good agreement with the known half-life. A nonlinear least-squares fit of the experimental $R(135°,t)$ by Eq. (2) yields

$$\omega_L=(42\pm2)\text{ MHz} ,$$

from which we deduce

$$g_{\text{exp}}(\tfrac{3}{2}^+)=-(0.231\pm0.011) .$$

We also note that the fit in Fig. 2(b) is consistent with an angular correlation coefficient of $A_{22}=-0.13$, as found in the unperturbed angular correlation measurement (Fig. 1). This is an important consistency check of the experiment, and shows that no significant attenuation takes place in the aluminized tape. Knight shift and diamagnetic corrections in this case are estimated [8] to be less than 2%, and were not included in the experimental result quoted above.

## IV. DISCUSSION

We will now discuss the result of this work within the broader context of magnetic moments of the g.s. and first excited $\frac{3}{2}^+$ states in $N=53-57$ isotones. It is a common feature of many of these isotones that their g.s. is $\frac{5}{2}^+$, while the first excited state is $\frac{3}{2}^+$, occurs at relatively low excitation energy, and has a rather long half-life. Some of these nuclei have been the subject of several detailed nuclear structure calculations. Choudhury and Clemens [9] have studied the $^{93-97}$Mo isotopes using an intermediate coupling approach, in which one or several single-particle states are coupled to the vibrations of an even-even core. Their result for the $g$ factor of the $\frac{3}{2}^+$ state of $^{95}$Mo, $g(\frac{3}{2}^+)=-0.38$, is in disagreement with the experimental value [10] of $-0.261(8)$. Bhattacharya and Basu [11] have applied the quasiparticle-phonon coupling model for several odd-$A$ Ru isotopes. However, their calculations predict only higher-lying (above 400 keV) $\frac{3}{2}^+$ states in $^{101,103,105}$Ru, with a positive magnetic moment. These states are most probably related to a neutron $d_{3/2}$ excitation, and are not relevant to the present study, since our experimental result for the magnetic moment is negative, indicating that it is probably due to a $d_{5/2}$ neutron configuration. In a different approach, Paar [12] showed that the low-lying levels of $^{95}$Mo can be reasonably well described by a cluster-vibrational field coupling model. However, within this model the value $-0.17$ obtained for $g(\frac{3}{2}^+)$ of $^{95}$Mo is again quite far from the experimental value.

Although all the above calculations do provide quite good agreement with experimental level energies and at least with some experimental electromagnetic transition rates, they all fail to reproduce the magnetic moment of the low-lying $\frac{3}{2}^+$ state. On the other hand, the simple core-excitation model of deShalit [13] was found [14] to

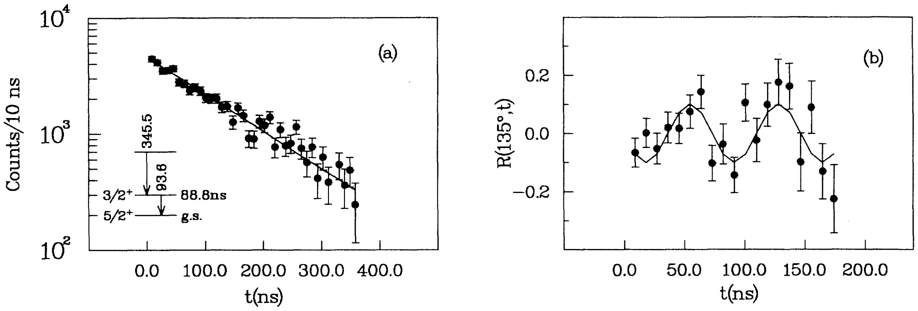

FIG. 2. (a) Sum of time spectra for the 93.6 keV transition in the 345.5 keV gate. The solid line is a fit with a lifetime plus background function, yielding $T_{1/2}=94(5)$ nsec. (b) The function $R(135°,t)$ [Eq. (1)] for the 345.5-93.6 keV cascade. The solid line is a fit by Eq. (2).

reproduce reasonably well the experimental $g$ factors of the $\frac{3}{2}^+$ states in $^{95}$Mo and $^{101}$Ru. We will therefore attempt to apply the same model to $^{91}$Sr.

The basic assumption of the core-excitation model is that the low-lying states of an odd-even nucleus are formed by coupling the odd particle in the g.s. configuration of the odd nucleus to the $2_1^+$ excitation of the even-even core. In our case, the $d_{5/2}$ neutron configuration of $^{91}$Sr coupled to the $2_1^+$ state of $^{90}$Sr produces the low-lying spectrum of $^{91}$Sr. It is important to note that this model does not provide a direct calculation of $g(\frac{3}{2}^+)$ from the diagonalization of a certain Hamiltonian, but, rather, gives a relation between the magnetic moments of several closely related states. In this sense the core-excitation model is different from the models mentioned above. On the other hand, its simplicity makes it very suitable for the interpretation of systematics of experimental data, and it can help identify common features of neighboring nuclei. Within this model, $g(\frac{3}{2}^+)$ of $^{91}$Sr is given by the relation [14]

$$g_{\rm calc}(\tfrac{3}{2}^+)=0.867g(\tfrac{5}{2}^+)+0.133g(2_1^+)\ , \tag{4}$$

where $g(\frac{5}{2}^+)$, $g(2_1^+)$ are the $g$ factors of the g.s. of $^{91}$Sr, and the $2_1^+$ state of $^{90}$Sr, respectively. The numerical coefficients in Eq. (4) depend only on the spins of the respective states. The experimental value of $g(\frac{5}{2}^+)$ for $^{91}$Sr is $-0.355(1)$ [10]. The value of $g(2_1^+)$ for $^{90}$Sr is not known. However, most $2_1^+$ states in this region have $g$ factors close to $Z/A$ [10]. Moreover, inspection of Eq. (4) above shows that $g(\frac{3}{2}^+)$ is not very sensitive to $g(2_1^+)$. We therefore use $g(2_1^+)=0.42(10)$, incorporating in the error bar any reasonable deviation from $Z/A$. With this assumption we obtain

$$g_{\rm calc}(\tfrac{3}{2}^+)=-0.252(13)\ ,$$

in agreement with the experimental value. The negative sign of the measured $g$ factor is simply explained in this model as being due to the $d_{5/2}$ neutrons in the ground state.

We performed similar calculations for $^{95}$Mo, $^{99}$Ru, and $^{101}$Ru. These are the only $N=53-57$ isotones for which $g(\frac{3}{2}^+)$ is known [10]. No such data are available for $N=51$ isotones. The calculated and experimental values of the $g$ factors are shown in Fig. 3, together with the value for $^{91}$Sr reported in the present work. We see that in general there is quite good agreement between the experimental and calculated values. Also shown in Fig. 3 are experimental $g(\frac{5}{2}^+)$ values for $N=51-57$ isotones. A comparison of the experimental values in the two panels of Fig. 3 shows that $g(\frac{5}{2}^+)$ and $g(\frac{3}{2}^+)$ have a quite similar $N$ dependence. A trend is clearly observed, namely, the absolute value of the $g$ factor tends to decrease as more neutrons are added to the nucleus. This trend may be due to effects related to particle-hole excitations, which are known [15] to considerably affect the magnetic moments, and become less effective as the shell fills because of the Pauli principle. However, detailed calculations are needed to substantiate this hypothesis. In Fig. 3(b) we also observe a clear $Z$ dependence of $g(\frac{5}{2}^+)$, for each value of $N$. For $N=51$, the isotopes with larger $Z$ have a larger absolute value of the $g$ factor. In fact, the value for $^{91}$Zr is quite close to the Schmidt limit of $-0.765$ for a $d_{5/2}$ neutron. The $Z$ dependence for the other isotone chains is less clear, but shows the effect of the even number of protons on the magnetic moment. A detailed interpretation of the $Z$ dependence of the data in Fig. 3(b) will certainly provide interesting information about the proton-neutron interaction, but it is beyond the scope of the present work.

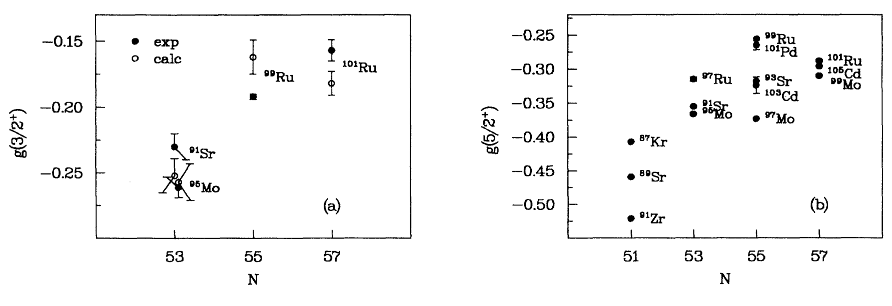

FIG. 3. (a) Experimental and calculated $g$ factors for $\frac{3}{2}^+$ states in $N=53-57$ isotones. Data from this work ($^{91}$Sr) and Ref. [10] ($^{95}$Mo, $^{99,101}$Ru). (b) Experimental $g$ factors of $\frac{5}{2}^+$ states in $N=51-57$ isotones. Data from Ref. [10].

In conclusion, the experimental $g$ factor of the $\frac{3}{2}^+$ state in $^{91}$Sr reported in this work is in good agreement with the systematics of $\frac{3}{2}^+$ states in $N=53-57$ isotones. The agreement between the systematics and the calculations shows that the simple core-excitation model provides a good description of magnetic moments of low-lying states in these nuclei.

## ACKNOWLEDGMENTS

We thank Dr. R F. Casten for helpful comments and discussions. Thanks are also due to Dr. J. A. Winger for help in the unperturbed angular correlation experiment. This work was supported by the U.S. DOE under Contracts DE-AC02-76CH00016 and DE-FG02-88ER40417.

---

[1] R. L. Gill and A. Piotrowski, Nucl. Instrum. Methods **A234**, 213 (1985).

[2] A. Wolf, Z. Berant, D. D. Warner, R. L. Gill, M. Shmid, R. E. Chrien, G. Peaslee, H. Yamamoto, J. C. Hill, F. K. Wohn, C. Chung, and W. B. Walters, Phys. Lett. **123B**, 165 (1983).

[3] Z. Berant, R. L. Gill, M. H. Rafailovich, R. E. Chrien, J. C. Hill, F. K. Wohn, R. F. Petry, C. Chung, G. Peaslee, and M. Mohsen, Phys. Lett. **156B**, 159 (1985); B. Fogelberg, C. Stone, R. L. Gill, H. Mach, D. D. Warner, A. Aprahamian, and D. Rehfield, Nucl. Phys. **A451**, 104 (1986).

[4] H. W. Müller, Nucl. Data Sheets **31**, 181 (1980).

[5] H. Frauenfelder and R. M. Steffen, in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), p. 997.

[6] A. Wolf *et al.* (unpublished).

[7] O. Dorum and B. Selsmark, Nucl. Instrum. Methods **97**, 243 (1971).

[8] L. E. Drain, Met. Rev. **12**, 195 (1967); F. D. Feiock and W. R. Johnson, Phys. Rev. Lett. **21**, 785 (1968).

[9] D. C. Choudhury and J. T. Clemens, Nucl. Phys. **A125**, 140 (1969).

[10] P. Raghavan, At. Data Nucl. Data Tables **42**, 189 (1989).

[11] S. Bhattacharya and S. K. Basu, Phys. Rev. C **18**, 2765 (1978).

[12] V. Paar, Z. Phys. **271**, 11 (1974).

[13] A. deShalit, Phys. Rev. **122**, 1530 (1961).

[14] A. Alzner, E. Bodenstedt, G. Gemünden, C. Herrmann, H. Münning, H. Reif, H. J. Rudolf, R. Vianden, and U. Wrede, Z. Phys. A **317**, 107 (1984).

[15] A. Arima and H. Horie, Prog. Theor. Phys. **12**, 623 (1954).