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# Magnetic moment of the first excited state of $^{43}$Sc†

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We have measured the $g$ factor of the $3/2^+$ hole state in $^{43}$Sc. This state, which has an excitation energy of 152 keV and a mean life of 632 μs, has $g = +0.232 \pm 0.004$. The result is consistent with an earlier measurement for a similar state in $^{47}$Sc and requires modification of a model earlier developed to explain the large inhibition in the decay of these states.

[NUCLEAR MOMENTS $^{40}$Ca($\alpha$,$p$), $E_\alpha$=20 MeV, pulsed beam, measured $I_\gamma(\theta, B, t)$ for $E_\gamma$=152 keV, spin rotation; deduced $g$, relaxation time.]

## I. INTRODUCTION

One expects the low-lying states for the odd Sc nuclei to be formed from the coupling of the $f_{7/2}$ valence nucleons to form negative-parity states. However, it has been known[1-5] for several years that in $^{43,45,47}$Sc the first excited states are $\frac{3}{2}^+$ states which are presumably formed by promoting a nucleon from the closed $d_{3/2}$ shell to the $f_{7/2}$ valence shell. Figure 1 gives the level diagrams for these Sc isotopes (the information on spins, parities, energies, and lifetimes was taken from the literature).[6-12]

Evidence of the nature of these states comes from a variety of experiments. Pickup (and stripping) reactions probe the configuration mixing in the state; lifetime measurements place restrictions on configuration mixing; and, finally, measurements of magnetic moments also contribute to limiting the admixtures present in these states. This paper presents the results of a measurement in the latter category, namely on the magnetic moment of the $d_{3/2}$ state in $^{43}$Sc. It is consistent with an earlier measurement in $^{47}$Sc by Fossan and Poletti.[12]

Lawson and Macfarlane[13] and Bansal and French[14] have examined the lifetime evidence on these states in order to determine the configuration mixing. A model with some configuration mixing is required since the lifetimes observed are two orders of magnitude longer than the single-particle estimates expected with no configuration mixing. Lawson and Macfarlane found that these inhibited transitions could be explained if one took as the wave function

$$|^{43}\mathrm{Sc}_{3/2^+}\rangle = \alpha\,|\pi d_{3/2}{}^{-1}\otimes{}^{44}\mathrm{Ti}(0^+)\rangle + \beta\,|\pi d_{3/2}{}^{-1}\otimes{}^{44}\mathrm{Ti}(2^+)\rangle\,, \qquad (1)$$

where $\alpha^2+\beta^2=1$ and $\beta^2\approx 0.4$. Similiar wave functions were required for the other Sc isotopes. Some question was raised about this model by a measurement of Fossan and Poletti,[12] who found that the $d_{3/2}$ hole state in $^{47}$Sc had a magnetic moment of $(+0.35\pm0.05)\mu_N$. This is close to the magnetic moment of the corresponding state (the ground state) in $^{39}$K, which has a magnetic moment of $0.39\mu_N$. Our result for $^{43}$Sc gives a magnetic moment of $(+0.348\pm0.006)\mu_N$. These results for $^{43}$Sc and $^{47}$Sc require $\beta^2\approx 0$, contradicting the model sketched above.

Recently Lawson and Müller-Arnke[15] have reexamined these calculations and find that if the

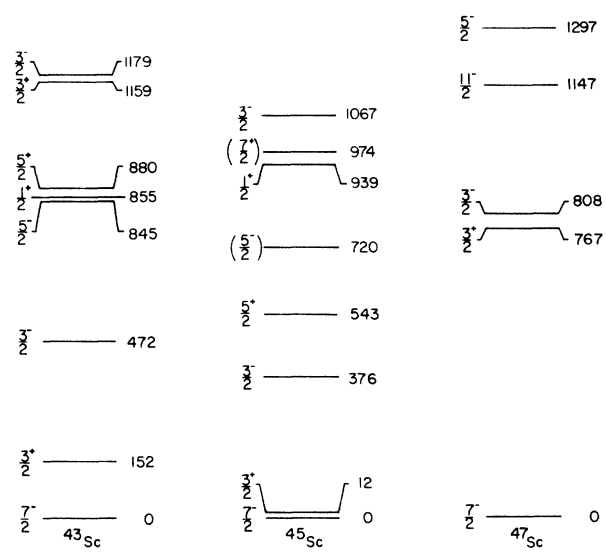


FIG. 1. Low-lying energy levels in $^{43,45,47}$Sc. Energy of levels is in keV. The mean lives of the first $\frac{3}{2}^+$ states are $632\pm8$ μs in $^{43}$Sc, $0.470\pm0.006$ s in $^{45}$Sc, and $0.39\pm0.01$ μs in $^{47}$Sc.

model is modified to include possible excitation of $s_{1/2}$ nucleons, then the lifetime measurements and magnetic moment measurements can be reconciled. We will consider this problem again in Sec. V. In Secs. II through IV we discuss the measurement of the $g$ factor for $^{43}$Sc.

## II. EXPERIMENT

The time differential perturbed angular distribution method of measuring $g$ factors was used in this work. After population of the state of interest, the decay $\gamma$ rays were observed for a time of about three mean lives of the state. This decay takes place in an external magnetic field which interacts with the magnetic moment of the state and causes the nucleus to precess. The precession can be observed as a rotation of the anisotropic angular distribution of the decay $\gamma$ rays with the classical Larmor frequency. The decaying distribution function takes the form[16]

$$N(\theta, B, t) = N_0 e^{-t/\tau}[1 + A\cos 2(\theta - \omega_L t) + \cdots] \tag{2}$$

where $\tau$ is the mean life and $\theta$ is the detector angle. Higher order terms are very small and will be neglected. The $g$ factor is related to the Larmor frequency $\omega_L$ by

$$g = \frac{\hbar \omega_L}{\mu_N B}, \tag{3}$$

where

$\hbar \equiv$ Planck's constant$/2\pi$,

$\mu_N \equiv$ nuclear magneton,

$B \equiv$ magnetic field at the nucleus.

Thus a measurement of the frequency of oscillation in the decay curve will give the $g$ factor. If data is taken at two angles separated by 90°, then the following ratio[16] determines $\omega_L$:

$$R(\theta, B, t) = \frac{N(\theta, B, t) - N(\theta + 90°, B, t)}{N(\theta, B, t) - N(\theta + 90°, B, t)} \tag{4}$$

$$= C\cos 2(\theta - \omega_L t). \tag{5}$$

This procedure removes the exponential factor and leaves the oscillatory function. A search[17] for minimum $\chi^2$ then can be used to determine $C$, $\theta$, and $\omega_L$.

The 152-keV state was populated by the $^{40}$Ca$(\alpha, p)^{43}$Sc reaction using 20 MeV $\alpha$ particles from the Argonne tandem Van de Graaff accelerator. The beam was pulsed on for 12.8 $\mu$s every 1.64 ms. A system based on a crystal controlled oscillator with a frequency of 40 MHz was used to do the beam pulsing and the time measurement.[18] The low anistropy (about 2%) observed in this reaction required that a large number of counts be obtained to determine $\omega_L$ and the $g$ factor. Fortunately, the 152-keV $\gamma$ ray was much more intense than any other in the region of interest, which allowed us to use NaI detectors with their lower resolution but higher detection efficiency. Two NaI crystals each $3.81 \times 2.54$ cm were placed at 45° and 135° with respect to the beam axis. The data were stored simultaneously in a two-dimensional array 64 energy channels × 512 time channels for each detector. Data were taken at three magnetic field values, $37 \pm 1$, $55 \pm 3$, and $79.0 \pm 0.5$ G. The magnetic field was generated with an iron-core magnet and the field measured with a rotating coil gaussmeter[19] which was calibrated with proton nuclear magnetic resonance. At the 37 G setting an intermediate angle was measured in order to find the direction of rotation of the angular distribution, which correspond to a positive $g$ factor. The experimental arrangement is schematically illustrated in Fig. 2.

## III. TARGET PREPARATION

In order to minimize the relaxation effects which quickly destroy the $\gamma$-ray angular distribution, we used a liquid target. Although pure Ca melts at an easily manageable temperature of 842°C, its evaporation rate is high even at 500°C[20]; hence it cannot be used in pure form. It was found that a mixture of 75 at% Sn and 25 at% Ca gave an alloy with a melting point of about 625°C with no significant evaporation of Ca.

Ca metal is very active chemically, but we were able to produce targets by using the following procedure. Filings from a large block of Ca metal were made just before use. The filings were quickly weighed and mixed with the correct amount of Sn powder which had been reduced in an $H_2$ atmosphere. This mixture was pressed into a pellet 3 mm in diameter and placed in a water cooled

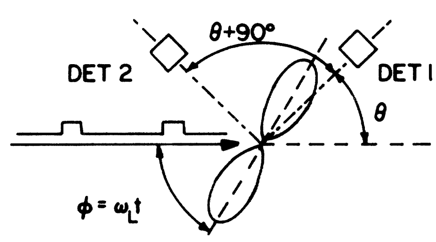


FIG. 2. Schematic of experimental procedure. The pulse train identifies the beam and the figure eight represents the rotating $\gamma$-ray angular distribution at some time $t$ with its maximum at an angle $\phi$ with respect to the beam. The direction of the magnetic field is out of the page.

copper crucible in a vacuum chamber which was then evacuated to $10^{-6}$ Torr. The crucible was raised to a potential of +2000 V and the Ca-Sn pellet was bombarded with electrons from a hot Ta filament. Great care was needed to avoid raising the temperature of the pellet too quickly or it would explode.[21] As soon as the Ca melted the alloy was formed. After cooling, the alloy pellet, weighing approximately 100 mg, was transferred to a dimple in a Ta strip and melted, wetting the Ta strip. This target was mounted in a special liquid target holder which has been described elsewhere,[22] and heated to the melting point with current through the Ta strip. This heating current was pulsed and data were taken during the time it was off in order to avoid the additional field associated with the heating current.

## IV. RESULTS

Figure 3 presents the data for $B = 37$ G in the form of the ratio $R(\theta, B, t)$. The solid line is a least squares fit using the function

$$R(t) = A \exp(-t/\tau_{\mathrm{rel}}) \cos[2(\theta - \omega_L t)] + \Delta . \qquad (6)$$

The parameter $\tau_{\mathrm{rel}}$ is the relaxation time associated with the magnetic dipole and electric quadrupole interactions in the liquid.[23] The fits to the data give $\tau_{\mathrm{rel}} \approx 350$ $\mu$s. Any error in normalization of the data at $\theta$ and $\theta + 90°$ will not affect the value of $\omega_L$ extracted but will displace $R(t)$ from the normal position of centering about zero. This effect is taken into account by the offset parameter $\Delta$.

The data fitting was started late in time because of a large dead-time problem which occurred immediately after the beam pulse. This problem was due to the high count rates needed to obtain sufficient data in a reasonable amount of time.

As can be seen from Fig. 3, the anisotropy of the $\gamma$-ray angular distribution is very small. For this reason and because the fields needed were very small, we made measurements at three magnetic field settings as discussed in Sec. II. The values obtained for the $g$ factors at each of these field settings were consistent within the errors of the measurements. The average value obtained was $g = +0.232 \pm 0.004$. This value should be corrected for effects due to the Knight shift and diamagnetism, since both phenomena change the value of the magnet field at the nucleus. The Knight shift is not known for Sc in a liquid Ca-Sn alloy, but it should be similar to the value for Sc in Sc which is +0.27%[24]; the diamagnetic correction is −0.2%.[25] Since the corrections cancel approximately, no adjustment for them was made to the experimental value. The quoted error is already large enough to cover any possible uncertainty. The magnetic moment is found from $\mu = gJ$, where $J = \frac{3}{2}$ for this state, hence $\mu = (+0.348 \pm 0.006)\mu_N$.

One comment concerning the accuracy of the $g$ factor measurement should be made. Any higher excited states which decay through the $\frac{3}{2}^+$ state of interest will add their precessions to that of the $\frac{3}{2}^+$ decay and thus alter the observed angular precession associated with the $\frac{3}{2}^+$ state. However, in $^{43}$Sc all known higher lying levels with the exception of the $\frac{19}{2}^-$ state at 3.122 MeV have lifetimes of a few hundred picoseconds or less and present no problems with the interpretation of the present data.[6] The 3.122-MeV state has a mean life of 650 ns which is still too short to be of consequence in comparison to the 632 $\mu$s mean life of the state of interest.

## V. DISCUSSION

Pickup reactions[1-4] leading to the $\frac{3}{2}^+$ states in the Sc isotopes indicate that these states may be rela-

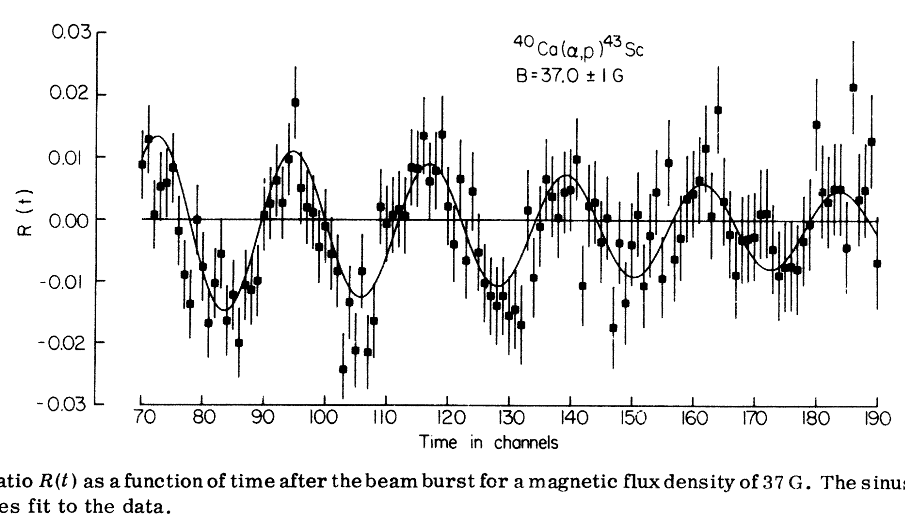


FIG. 3. The ratio $R(t)$ as a function of time after the beam burst for a magnetic flux density of 37 G. The sinusoidal curve is a least squares fit to the data.

tively pure $d_{3/2}$ hole states. Referring to Eq. (1) this situation implies $\alpha^2 \approx 0.9$. Since it is very hard to obtain highly accurate spectroscopic information from this kind of reaction, additional information is needed to establish the amounts of configuration mixing which may be present in the given state. As discussed in the introduction, the lifetime measurements on these states lead to the conclusion that there is an appreciable amount of core excitation present in these states. However, the previous $g$ factor measurement[12] in $^{47}$Sc and the present one in $^{43}$Sc imply a large value of $\alpha^2$ and a small, almost zero, value of $\beta^2$ if the two-term wave function of Eq. (1) is used to calculate the $g$ factor of these states.

Recently, Lawson and Müller-Arnke[15] have shown that the lifetime and magnetic moment of this state can be accounted for simultaneously by extending the model to include a term which couples an $s_{1/2}$ proton hole to the excited state of the $^{44}$Ti core. The wave function becomes

$$|^{43}\mathrm{Sc}_{3/2^+}\rangle = \alpha\,|\pi d_{3/2}{}^{-1} \otimes {}^{44}\mathrm{Ti}(0^+)\rangle + \beta\,|\pi d_{3/2}{}^{-1} \otimes {}^{44}\mathrm{Ti}(2^+)\rangle + \gamma\,|\pi s_{1/2}{}^{-1} \otimes {}^{44}\mathrm{Ti}(2^+)\rangle\,, \qquad (7)$$

with $\alpha^2+\beta^2+\gamma^2=1$. The above empirical wave function is used to fit the $M2$ decay and magnetic moment data in order to determine the values of the coefficients. Using Lawson's model, the values which reproduce the data are $\alpha^2=0.656$, $\beta^2=0.229$, and $\gamma^2=0.114$.

As pointed out in the introduction, $g$ factor measurements can provide information on the amount of configuration mixing present in a nuclear state. Here we see that the determination of the $g$ factor is necessary to reveal the presence of the 11% additional admixture in the wave function using the above model assumptions.

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