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Magnetic Moment Measurements of First (2^+) and Second (4^+) States of Even Nd and Sm Nuclei[†]

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Abstract: The ion implantation perturbed angular correlation technique was used to measure γ -ray angular distributions from the decay of the first (2^+) and second (4^+) states of even Nd and Sm nuclei recoiled into polarized iron. These data and the results of previous measurements give values of $H_0 = 2.4 \pm 0.3$ MOe for H (NdFe), $H_0 = 2.3 \pm 0.2$ MOe for H(SmFe) and $H_{t\tau t} = 10.8 \pm 8.9$ MOe-ps for the transient effect for Sm and Nd nuclei recoil implanted into polarized iron (300°K). The

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Abstract (cont'd) g-factor results for the first (2^+) states of $^{144,146,148}\text{Nd}$ and $^{148,150}\text{Sm}$ and for the second (4^+) states of ^{150}Nd and $^{152,154}\text{Sm}$ show a rather strong decreasing trend with decreasing neutron number.

NUCLEAR REACTIONS $^{144,146,148,150}\text{Nd}(^{16}\text{O}, ^{16}\text{O}'\gamma)$
 $^{148,150,152,154}\text{Sm}(^{16}\text{O}, ^{16}\text{O}'\gamma)$, $E = 35 \text{ MeV}$.

E NUCLEAR MOMENTS deduced g for first (2^+) states of $^{144,146,148}\text{Nd}$, and $^{148,150}\text{Sm}$ and second (4^+) states of ^{150}Nd , and $^{152,154}\text{Sm}$.

1. Introduction

The Sm and Nd nuclei exhibit abrupt changes in the properties of their low lying states, from spherical and vibration like near the closed neutron shell at $N = 82$ to deformed and rotation like as neutrons are added. These characteristics have motivated extensive theoretical and experimental studies of the static and transition electric and magnetic moments.

In particular, several of the g-factors of the first 2^+ states of nuclei in this transition region, have been measured using either Mössbauer or perturbed angular correlation techniques. The values obtained, however, exhibit wide fluctuations probably as a result of the different assumptions and corrections used with the various techniques.

This work reports g-factor measurements of the first (2^+) states of $^{144,146,148}\text{Nd}$ and ^{150}Sm , and the second (4^+) states of ^{150}Nd and $^{152,154}\text{Sm}$ using the ion implantation (into Fe) perturbed angular correlation (IMPAC) technique. While this technique is also subject to assumptions and corrections, considerable effort was expended to maximize the accuracy of the relative g-factors so that the systematic trends of the magnetic moments were clear.

The present results for the g-factors are in agreement with a previous systematic study of the even Nd isotopes implanted in iron¹⁾ and recent results for the Nd and Sm isotopes recoiled into gas²⁾. In general the g-factors increase markedly with the neutron number as the nuclei become more deformed.

2. Experimental

The experimental geometry has been described previously³⁾.

In the present measurements, a 35 MeV $^{16}\text{O } 5^+$ beam entered a target chamber through an annular surface barrier particle detector to Coulomb excite nuclei in 100-400 $\mu\text{g}/\text{cm}^2$, vacuum evaporated, enriched Nd and Sm targets. The Coulomb excited nuclei were recoiled into thick iron backing foils polarized by a reversible 1400 Oe magnetic field. Several different targets on 0.0013 cm and 0.0025 cm backing foils were used for each measurement. The backscattered ^{16}O particle detector counting rate was $< 10^4$ particles/sec with a beam spot size of < 2 mm in diameter. Gamma-ray angular correlations were measured for opposite applied field directions with four moveable 7.6 cm $\times$ 7.6 cm NaI(Tl) detectors (at 10 cm) in coincidence (FWHM $\approx$ 5 nsec) with backscattered ^{16}O particles. Chance coincidence events were accumulated simultaneously with true plus chance events and were subtracted after each run.

In order to make sure that the dominant interaction of the nuclei while in their excited state is the magnetic one, Coulomb excited Nd and Sm nuclei were recoil implanted into Cu and the gamma ray angular distribution in coincidence with backscattered particles was measured. The angular correlation coefficients determined from these measurements were always in agreement (to within the experimental uncertainty of $\lesssim 10\%$) with those calculated according to the spins of the initial and final states⁴⁾. This is in agreement with previous work^{5,6)} that has shown that there is only a very small misalignment of excited nuclei with nuclear lifetimes relevant to this work ($\tau < 250$ psec) when implanted into Cu. The electric quadrupole interactions on nuclei in Fe are assumed to be similar to those measured for the same nuclei in Cu and can thus be neglected in the analysis of the magnetic precession data.

The time integral gamma ray angular correlation observed for nuclei precessing in a static magnetic field, applied perpendicular to the beam axis and the plane defined by the detector geometry, is given by

$$W(\underline{\theta} \uparrow \downarrow) = b_0 + \sum_k \frac{b_k}{[1 + (k\underline{\omega\tau})^2]^{1/2}} \cos k(\underline{\theta} \pm \Delta\underline{\theta}) \quad (1)$$

where $b_0 = 1 + (1/4)A_2^{\text{exp}} + (9/64)A_4^{\text{exp}}$, $b_2 = (3/4)A_2^{\text{exp}} + (5/16)A_4^{\text{exp}}$, $b_4 = (35/64)A_4^{\text{exp}}$ and $A_k^{\text{exp}} = G_k Q_k A_k$; $k\Delta\theta = \arctan(k\underline{\omega\tau})$, ($k = 2, 4$); the arrows refer to the applied field direction. The A_k coefficients are determined by the spins of the initial and final states⁴⁾; Q_k are the geometric attenuation factors due to the finite solid angles of the particle and γ -ray detectors⁷⁾ and G_k are attenuation factors due to small randomly oriented perturbations. The assumptions and corrections necessary for the application of eq. (1) will be discussed later.

Two different experimental methods were used to measure the precession angles ($\underline{\omega\tau}$):

(a) Small precession angles ($\underline{\omega\tau} \lesssim 40$ mrad), expected for the very short lived states (the 2^+ states of ^{144}Nd and ^{148}Sm), were determined from the relative change in counting rates associated with changes in the polarizing field directions observed in the γ counters set at angles of maximum slope of the $0^+ \rightarrow 2^+ \rightarrow 0^+$ angular correlation ($\pm 22.5^\circ$, $\pm 112.5^\circ$).

The $\underline{\omega\tau}$ values were calculated from the ratio

$$R = \frac{W(\underline{\theta} \uparrow) - W(\underline{\theta} \downarrow)}{W(\underline{\theta} \uparrow) + W(\underline{\theta} \downarrow)} \quad (2)$$

where $W(\underline{\theta} \uparrow \downarrow)$ is defined according to eq. (1) with calculated values for A_k^{exp} .

(b) The precession angles for the longer lived states, the first (2^+) states of $^{146,148}\text{Nd}$ and ^{150}Sm and the second (4^+) states of ^{150}Nd and $^{152,154}\text{Sm}$ were obtained from measurements of the full angular correlations

at twelve or more angles and the least squares fitting of eq. (1) to the data by varying ω_T . The measured angular correlations and the results of the least squares fitting procedure are shown in Figures 1 and 2. The experimental angular correlation data were also least square fit to eq. (1) by varying both A_k^{exp} and ω_T . In addition, as a check, some data were fit to eq. (1) by varying ω_T and G_k where G_k is given by the Abragam and Pound model⁸⁾ for paramagnetic relaxation in the presence of a static magnetic field. The precession angles obtained using these different procedures were always within the quoted experimental uncertainties. As a check on the large precession angles and possible dependence on target conditions, precession of the second (4^+) state of ^{154}Sm ($\omega_T = -0.889 \pm 0.044$) was measured using five different targets with isotope thicknesses ranging from ≈ 100 to $400 \mu\text{g}/\text{cm}^2$ on 0.0013 and 0.0025 cm iron foils at different backscattered particle counting rates. Since the presence of unaccounted for attenuation tends to increase the ω_T value obtained from the least squares fitting procedure, in the case of large precession angles where the denominators in eq. (1) play an important role, the results obtained for the iron host were checked by recoiling ^{154}Sm into cobalt and nickel hosts. Previous work⁹⁾ has shown that the observed precession angles for the first (2^+) state of ^{150}Sm implanted in iron, cobalt and nickel hosts are proportional to the respective host magnetic moments. The cobalt and nickel backing foils were 0.0025 cm thick and the external polarizing fields were 1400 and 2000 Oe respectively.

3. Results and Discussion

The mean precession angles deduced from the data corrected for the effect of beam bending in the stray magnetic fields, (which increases the

true precession angles by ≈ 0.002 radians) are given in tables 1 and 2 for the Sm and Nd isotopes respectively. Also listed in the tables are relevant nuclear properties of the levels studied.

The results of the precession experiments in which ^{154}Sm nuclei were recoil implanted into polarized Fe, Co and Ni are given together with similar data⁹⁾ for ^{150}Sm in table 3 and in fig. 3. The proportionality of the measured $\omega\tau$ values to the host magnetic moments, which holds even for large $\omega\tau$ values, indicate that no systematic errors were introduced in the analysis of the large precession angles obtained for ^{154}Sm in Fe.

Magnetic moments can only be derived from precession data when the magnetic field acting on the nucleus and the lifetime of the excited state are known. While determination of lifetimes from B(E2) measurements is straightforward, the determination of the actual fields is more complicated.

Two different kinds of magnetic fields contribute to the measured precession angle in an IMPAC experiment of the kind described here; the transient field which acts on the nuclei while in flight, and the static hyperfine field which causes the precession of the stationary nucleus. A description of these phenomena and their inclusion in data analysis for IMPAC experiments has been published^{10,11,12)}.

The impulse nature of the transient interaction and the short stopping times (< 0.8 psec) allow the measured precession angle $(\omega\tau)_{\text{exp}}$ to be expressed as the sum of the net transient precession $(\omega_t\tau_t)$ and the static Larmor precession $(\omega_0\tau)$ i.e.

$$(\omega\tau)_{\text{exp}} = \omega_t\tau_t + \omega_0\tau \quad (3a)$$

or

$$\frac{(\omega\tau)_{\text{exp}}}{g} = \frac{-\mu_N}{\hbar} [(H_{\tau\tau}) + (H_0\tau)] \quad (3b)$$

where $H_{\tau\tau}$ is the integrated transient interaction and H_0 is the static field.

The values of H_0 and $H_{\tau\tau}$ for the case of Sm ions recoil implanted in Fe were extracted from a least squares fit to eq. (3b) of the lifetimes and the respective measured precession angles divided by the appropriate g factors. The 4^+ and the 6^+ states of ^{154}Sm and the 4^+ state of ^{152}Sm were included in the least square fit using the $(\omega\tau)_{\text{exp}}$ results of the present work (for the 4^+ states) together with the previously reported results¹³⁾ for the precession of the third(6^+) rotational state of ^{154}Sm . Previous measurements¹⁴⁾ of first excited (2^+) state precession angles were not included in the analysis because of difficulties introduced by the relaxation processes which effect longer lived (≈ 1 nsec) states as discussed above. The averages of all previously reported g-factor measurements for the first (2^+) states of ^{152}Sm and ^{154}Sm , respectively, were used for the 4^+ and 6^+ levels under the assumption that there is negligible variation in the collective g-factors for low lying members of the ground state rotational band. The data used in the least squares fit are summarized in table 4. Figure 4 illustrates the spread in previous g-factor measurements for the first (2^+) states of ^{152}Sm and ^{154}Sm . The unweighted averages were used in the least squares fit.

The mean lifetime of the 4^+ and 6^+ states were calculated using the rotational model¹⁵⁾ $[B(E2:6\rightarrow4)/B(E2:2\rightarrow0)] = 1.573$ and $[B(E2:4\rightarrow2)/B(E2:2\rightarrow0)] = 1.429$ and the weighted mean of all $B(E2:0\rightarrow2)$ measurements for the first (2^+) states (see tables 1 and 2). This procedure is justified by recent measurements¹⁶⁾ of Coulomb excitation probabilities for rotational states ($I^\pi < 10^+$)

in the ground state ($K = 0$) band of ^{154}Sm which are found to be in agreement with the predictions of the adiabatic rotational model. Similar measurements^{17,18)} for other rare earth deformed nuclei indicate the constancy of the intrinsic quadrupole moment for rotational states ($I < 6^+$) of the ground state ($K = 0$) band, to within an experimental uncertainty of $\approx 10\%$. A previous measurement¹⁹⁾ of $B(E2:2 \rightarrow 4)$ for the second (4^+) state has a 20% experimental uncertainty. The mean lifetime derived from this measurement is in agreement with the value calculated using the rotational model $[B(E2:4 \rightarrow 2)/B(E2:2 \rightarrow 0)] = 1.429$ and the weighted mean of all $B(E2:0 \rightarrow 2)$ measurements for the first (2^+) state. The calculated mean lifetime for the second (4^+) state was used in the least squares fit.

This data, shown in fig. 5, was analyzed assuming, as described above, the constancy[†] of the collective g-factor for the low lying members of the ^{154}Sm ground state ($K = 0$) rotational band. The smooth fit (solid line in fig. 5) is an indication of the validity of this approach.

The values of H_0 and H_{τ_t} obtained from the least squares fit are $H_0 = +2.3 \pm 0.2$ MOe and $H_{\tau_t} = +10.8 \pm 8.9$ MOe-psec (300°K). The present value for H_0 is consistent with the large positive magnetic hyperfine fields at rare earth nuclei having less than half filled atomic 4f shells but is in disagreement with the previously reported value¹⁴⁾. H_{τ_t} fits into the systematics of slowly increasing transient field intensities¹¹⁾ from $Z = 26$ (3.4 MOe-psec) to $Z = 78$ (17.3 MOe-psec).

The distribution of equilibrium sites for ions recoil implanted in Cu and Fe is still under investigation although a variety of studies

[†] For further discussion of this point refer to ref. 13.

indicate that for some species of ions the predominant final site distribution may be substitutional. There is also evidence that some ionic species come to equilibrium in magnetically equivalent sites²⁰⁾ while others exhibit a wide distribution of hyperfine magnetic fields²¹⁾. The distribution of equilibrium sites for a given species appears to be related to the solid solubility of the system²¹⁾. The angular correlations measured in the present work do not exhibit unaccounted for attenuations (within the given experimental uncertainties) which is taken as evidence for a predominance of magnetically equivalent sites.

The ionic solid solubility may also partially determine the amount of lattice distortion in the vicinity of a given site. Recent work^{22,23)} suggests that a small lattice distortion may occur in the vicinity of the impurity ion which alters the direction of magnetization at the impurity nucleus so that it is no longer parallel to the applied field direction. As noted above, eq. (1) describes the angular distribution observed for the case of nuclei precessing in a static magnetic field which is perpendicular to the beam axis and to the plane defined by the detector geometry. The results of preliminary experiments²²⁾ for Nd and W nuclei implanted in iron and nickel foils (with an external field of about 1000 Oe) indicate that the actual g-factors and effective magnetic hyperfine fields may be 10 to 20% greater than values obtained from the application of eq. (1). Calculations²³⁾ suggest that the angle between the applied field direction (H_{ext}) and the direction of magnetization at the nucleus is approximately proportional to the inverse of the applied field strength and should therefore approach zero or at least decrease as H_{ext} becomes large. However, recent precession measurements²⁴⁾ for the first (2^+) state of ^{150}Sm implanted

into iron with applied field strengths from 1000 to 8000 Oe give an $\omega\tau$, as determined by eq. (1), which is constant to within a 5% experimental uncertainty. Hence, the detailed magnetic structure of the ionic equilibrium site requires further clarification and may effect the accuracy of the present absolute g-factor determinations. Nevertheless, it should not effect the general trend of the observed g-factors.

Recent studies^{6,25,26)} have shown that rare earth nuclei implanted in copper and ferromagnetic hosts exhibit the perturbing effects of ionic relaxation processes. These interactions have a predominant magnetic character and cause the nuclear alignment to decay (with time) at an almost simple exponential rate. The integral angular correlation for nuclei interacting with a time dependent perturbation of the form $G_K(t) \approx \exp(-\lambda_K t)$ in the presence of a static magnetic field is given by eq. (4).

$$\begin{aligned}
 W(\theta) = & 1 + \frac{1}{4} A_2 G_2 \left(\frac{1 + 3 \cos 2(\theta - \Delta\theta_{22})}{(1 + (2\omega\tau G_2)^2)^{1/2}} \right) \\
 & + \frac{1}{64} A_4 G_4 \left(9 + \frac{20 \cos 2(\theta - \Delta\theta_{24})}{(1 + (2\omega\tau G_4)^2)^{1/2}} \right. \\
 & \left. + \frac{35 \cos 4(\theta - \Delta\theta_{44})}{(1 + (4\omega\tau G_4)^2)^{1/2}} \right)
 \end{aligned} \tag{4}$$

where

$$n\Delta\theta_{nk} = \arctan (n\omega\tau G_k)$$

$$G_k = (1 + \lambda_K \tau)^{-1}$$

$$(n = 2, 4; k = 2, 4) \text{ with } n \leq k.$$

As $G_k \rightarrow 1$, eq. (4) reduces to eq. (1). G_k differs from 1 for nuclear lifetimes on the order of ≈ 1 nsec and must be known accurately in order to obtain the true precession angle $(\omega\tau)$. Computer simulation studies, performed in the present work using realistic parameters, indicate that the presence of such attenuations has a negligible effect on the precession angles as obtained using eq. (1) for the states discussed in this paper.

The intensity of the average effective magnetic hyperfine field at Nd nuclei implanted in iron was calibrated using the previously measured g-factors for the first (2^+) states of ^{148}Nd and ^{150}Nd , the average of the precession angles (assuming $g_{2+} = g_{4+}$ for ^{150}Nd), and the mean lifetimes given in table 2. The intensity of the transient field interaction has not been measured for Nd nuclei recoiled into polarized iron. The measured precession angles are, within the present experimental uncertainties, insensitive to the value of H_{t-t} . However, an interpolated value of $H_{t-t} \approx 10$ MOe-psec can be determined from the available experimental trend¹¹⁾ of H_{t-t} vs Z. Rewriting eq. (3b) gives:

$$H_0 = \frac{(\omega\tau)_{\text{exp}}}{\frac{-\mu_N}{\hbar} \tau g} - \frac{H_{t-t}}{\tau g}$$

or since the second term is small

$$H_0 \approx \frac{(\omega\tau)_{\text{exp}}}{\frac{-\mu_N}{\hbar} \tau g} \quad (5)$$

A weighted average of H_0 using the two previously reported g-factors gives $H_0 = 2.4 \pm 0.3$ MOe which is in agreement with the previous measurement²¹⁾

$H_0 = 2.400 \pm 0.260$ MOe determined using the conical field model

($\theta = 24 \pm 6$ deg).

The relative g-factors are a function of only the measured precession angles and lifetimes for those states for which the equilibrium magnetic hyperfine interaction is large compared to the transient field interaction. The g-factor ratios for the Sm and Nd isotopes studied in the present work are given in tables 4 and 5 respectively. An additional relative g-factor determination was obtained for the first (2^+) state of ^{150}Sm and the second (4^+) state of ^{154}Sm using both the present and previously⁹⁾ measured precession angles for the respective states implanted in iron, cobalt and nickel hosts. Using the observed proportionality^{3,11)} of the transient and equilibrium magnetic hyperfine interactions to the host magnetic moment, eq. (3) can be written

$$(\omega\tau)_{\underline{\mu}} = \frac{-\underline{\mu}_N}{\hbar} g[k_t + k_0\tau]\underline{\mu}$$

where

$$k_t = \frac{H_t\tau_t}{\underline{\mu}} \text{ and } k_0 = \frac{H_0}{\underline{\mu}}.$$

Hence, the slopes of the least square fitted straight lines shown in fig. 3 are equal to $(-\underline{\mu}_N/\hbar)g(k_t + k_0\tau)$, where $(\text{slope})_{150} = -0.1007 \pm 0.0019$ radians/n.m. and $(\text{slope})_{154} = -0.401 \pm 0.014$ radians/n.m. Using these values one obtains

$$\frac{g_{152}}{g_{154}} = \frac{(\text{slope})_{150}}{(\text{slope})_{154}} \frac{\tau_{154}}{\tau_{150}} = 0.864 \pm 0.046$$

where $k_t \ll k_0\tau_{154}$ since $H_t\tau_t \ll H_0\tau_{154}$. The above value and the ratios

given in tables 4 and 5 for the respective states of the Sm and Nd isotopes are to first order (with the exception of ^{144}Nd and ^{148}Sm) independent of detailed knowledge of the intensities of the transient and equilibrium magnetic hyperfine interactions. The present measured relative g-factors are in agreement with the relative g-factors measured previously using the recoil implantation into gas technique²⁾ (see table 4).

The absolute g-factors were determined using eq. (3) and the values for $H_{\text{t}\tau_{\text{t}}}$ and H_0 given above. The results are given in column six of tables 4 and 5 together with previous results from gas implantation studies²⁾. It should be noted however, that both sets of measurements use the same previously measured g-factors for calibration. Hence the relative trends are of more significance than differences in absolute values. The present measured g-factors are shown in fig. 6 together with the predictions of several theoretical calculations²⁷⁻³⁰⁾.

The present results confirm an increasing g-factor trend and a large variation with neutron number as Nd and Sm nuclei become rotational above the closed neutron shell at $N = 82$. The calculations of Lombard³⁰⁾ seem to best reproduce the observed trend for $^{144,146,148}\text{Nd}$ and $^{148,150}\text{Sm}$. This model gives a microscopic description of the first 2^+ states of even-even spherical nuclei with the residual interaction between nucleons represented by a pairing plus multipole force. The short range neutron-proton interactions are neglected while the long range part of the force is taken as acting equivalently between all pairs of nucleons. This procedure allows a study of the influence of ground state correlations which are found to contribute significantly to the E2 transition rate but have little effect on the magnetic moment. Contributions to the magnetic moment arise primarily from the configuration mixing of single particle states near the

Fermi surface.

The uncertainties in the present results may be reduced when improved knowledge of the transient field is gained, thus revealing further details of the trend of magnetic moments in the vicinity of the closed neutron shell at $N = 82$.

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References

- 1) I. Ben-Zvi, P. Gilad, G. Goldring, R. Herber, and R. Kalish, Nucl. Phys. A96 (1967) 138
- 2) I. Ben-Zvi, P. Gilad, M.B. Goldberg, G. Goldring, K.H. Speidel and A. Sprinzak, Nucl. Phys. A151 (1970) 401
- 3) G.M. Heestand, R.R. Borchers, B. Herskind, L. Grodzins, R. Kalish and D.E. Murnick, Nucl. Phys. A133 (1969) 310
- 4) R.M. Steffen and H. Frauenfelder, in Alpha-beta-and gamma-ray spectroscopy, ed. Kai Siegbahn (North-Holland, Amsterdam, 1966) p. 997
- 5) R. Kalish, L. Grodzins, R.R. Borchers, J.D. Bronson, and B. Herskind, Phys. Rev. 161 (1967) 1196
- 6) J.C. Waddington, K.A. Hagemann, S. Ogaza, D. Kiss, and B. Herskind, Proc. Int. Conf. on Nuclear reactions induced by heavy ions, Heidelberg, eds. R. Bock and W.R. Hering (North Holland, Amsterdam 1970) p. 438
- 7) M.J.L. Yates, see ref.⁴⁾ p. 1691
- 8) A. Abragam and R.V. Pound, Phys. Rev. 92 (1953) 943
- 9) D.E. Murnick, L. Grodzins, J.D. Bronson, B. Herskind, and R.R. Borchers, Phys. Rev. 163 (1967) 254
- 10) R.R. Borchers, B. Herskind, J.D. Bronson, L. Grodzins, R. Kalish, and D.E. Murnick, Phys. Rev. Lett. 20 (1968) 424
- 11) R.R. Borchers, G.M. Heestand, H.W. Kugel, and R. Kalish, see. ref.⁶⁾ p. 415
- 12) J. Lindhard, Proc. Roy. Soc. A311 (1969) 11
- 13) H.W. Kugel, Rafael Kalish and R.R. Borchers, Nucl. Phys. A167 (1971) 193

References (Cont'd)

- 14) F. Boehm, G.B. Hagemann and A. Winther, Phys. Lett. 21 (1966) 217
- 15) A. Bohr and B.R. Mottelson, Mat. Fys. Medd. Dan. Vid. Selsk. 27, No. 16 (1953)
- 16) I.A. Fraser, J.S. Greenberg, S.H. Sie, R.G. Stokstad and D.A. Bromley, Phys. Rev. Lett. 23 (1969) 1051
- 17) R.M. Diamond, F.S. Stephens, W.H. Kelly, and D. Ward, Phys. Rev. Lett. 22 (1969) 546
- 18) R.D. Sayer, P.H. Stelson, F.K. McGowan, W.T. Milner, and R.L. Robinson, Phys. Rev. to be published
- 19) D.G. Alkhazev et al., Bull. Acad. Sci. USSR (Phys. Ser.) 28 (1964) 146
- 20) L. Grodzins, R.R. Borchers and G.B. Hagemann, Phys. Lett. 21 (1966) 214, and references therein
- 21) H. de Waard, P. Schurer, P. Inia, L. Niesen, and Y.K. Agarwal, Hyperfine Interactions in excited nuclei, eds. G. Goldring and R. Kalish (Gordon and Breach, New York, 1971) p. 89
- 22) I. Ben-Zvi, P. Gilad, G. Goldring, P. Hillman, A. Scharzschild, and Z. Vager, Phys. Rev. Lett. 19 (1967) 373
- 23) Amikam Aharoni, Phys. Rev. Lett. 22 (1969) 856; Phys. Rev., to be published; also refer to ref.²¹⁾ p. 75; Proc. int. conf. on magnetism, Grenoble, France, 1970, to be published
- 24) F.J. Woyach, University of Wisconsin, private communication 1970
- 25) B.I. Deutch, K. Bonde Nielsen, and H. Bernas, Phys. Lett. 27B (1968) 209
- 26) P. Ryge, H.W. Kugel and R.R. Borchers, see ref.²¹⁾, p. 1043
- 27) O. Prior, F. Boehm and S.G. Nilsson, Nucl. Phys. A110 (1968) 257

References (Cont'd)

- 28) K. Kumar and M. Baranger, Nucl. Phys. A110 (1968) 529
- 29) W. Greiner, Nucl. Phys. 80 (1966) 417
- 30) R.J. Lombard, Nucl. Phys. A114 (1968) 449
- 31) L.A. Sliv and I.M. Band, Tables of internal conversion coefficients given in ref.⁴⁾, p. 1639
- 32) D. Eccleshall, M.J.L. Yates, and J.J. Simpson, Nucl. Phys. 78 (1966) 481
- 33) G.A. Burginyon, J.S. Greenberg, R.F. Caster and D.A. Bromley, Proc. int. conf. on nuclear structure, ed., J. Sanada, Tokyo, Japan, 1967, p. 657
- 34) F.W. Richter, J. Schutt and D. Wiegandt, Z. Phys. 213 (1968) 202
- 35) J. Bjerregard, B. Elbek, O. Hansen, and P. Salling, Nucl. Phys. 44 (1963) 280
- 36) M. Birk, G. Goldring, Y. Wolfson, Phys. Rev. 116 (1959) 730
- 37) J.D. Kurfess and R.P. Scharenberg, Phys. Rev. 161 (1967) 1185
- 38) I. Lindgren, Table of nuclear spins and moments, see. ref.⁴⁾, p. 1621
- 39) P.J. Wolfe and R.P. Scharenberg, Phys. Rev. 160 (1967) 866
- 40) R.W. Bauer and M. Deutsch, Phys. Rev. 128 (1962) 751
- 41) P. Debrunner and W. Kündig, Helv. Phys. Acta 33 (1960) 395, with correction by I. Lindgren (see. ref.³⁸⁾)
- 42) G. Goldring and R.P. Scharenberg, Phys. Rev. 110 (1958) 701, with correction by I. Lindgren (see ref.³⁸⁾)
- 43) G. Manning and J.D. Rogers, Nucl. Phys. 19 (1960) 675, with correction by I. Lindgren (see ref.³⁸⁾)
- 44) U. Atzmony, E.R. Bauminger, D. Froindlich, and S. Ofer, Phys. Lett. 26B (1967) 81

References (Cont'd)

- 45) R.M. Wheeler, U. Atzmony, and J.C. Walker, Phys. Rev. 186 (1969) 1280
- 46) J.J. Simpson, D. Eccleshall, M.J.L. Yates, N.J. Freeman, Nucl. Phys. A94 (1967) 177
- 47) E. Veje, B. Elbek, B. Herskind, and M.C. Olesen, Nucl. Phys. A109 (1968) 489
- 48) R.M. Diamond, F.S. Stephens, K. Nakai, and R. Nordhagen, UCRL-19517, Lawrence Radiation Laboratory, Berkeley, Calif. (1969)
- 49) B. Elbek, M.C. Olesen, O. Skilbreid, Nucl. Phys. 19 (1960) 523
- 50) H.S. Gertzman, D. Cline, H.E. Gove, P.M.S. Lesser, J.J. Schwartz, Bull. Amer. Phys. Soc. 13 (1968) 1471
- 51) G. Goldring and Z. Vager, Nucl. Phys. 26 (1961) 250
- 52) R.D. Sharp and W.W. Buechner, Phys. Rev. 109 (1958) 1698
- 53) R. Graetzer and E.M. Bernstein, Phys. Rev. 129 (1963) 1772
- 54) B.W. Hootan, Nucl. Phys. 59 (1964) 332
- 55) P.A. Crowley, J.R. Kerns and J.X. Saladin, Phys. Rev. C3 (1971) 2049

Figure Captions

Fig. 1 Typical measured angular distributions for (A) the first (2^+) state of ^{148}Sm , (B) the first (2^+) state of ^{150}Sm , (C) the second (4^+) state of ^{152}Sm and (D) the second (4^+) state of ^{154}Sm for opposite ($\uparrow, \downarrow$) applied field directions. The solid lines represent the least squares fit of eq. (1) to the data.

Fig. 2 Typical measured angular distributions for (A) the second (4^+) state of ^{150}Nd , (B) the first (2^+) state of ^{148}Nd , and (C) the first (2^+) state of ^{146}Nd for opposite ($\uparrow, \downarrow$) applied field directions. The solid lines represent the least square fit of eq. (1) to the data.

Fig. 3 The measured precession angles for the first (2^+) state of ^{150}Sm and the second (4^+) state of ^{154}Sm plotted versus the atomic magnetic moment of the host material for iron, cobalt and nickel. The ω_T values for ^{150}Sm are taken from ref. 9). The ω_T 's for nickel are increased 4% from the measured values for this graph to correct for the Curie temperature for nickel $T_C = 631^\circ\text{K}$. The solid lines represent least squares fits to straight lines.

Fig. 4 The spread in previous g-factor measurements for the first (2^+) states of ^{152}Sm and ^{154}Sm . The solid lines represent the values of the unweighted averages; the dashed lines represent the values of the weighted averages. $g(g)$ and $g(h)$ were determined using the Mössbauer effect; the other values were determined using various perturbed angular correlation techniques.

Figure Captions (Cont'd)

- Fig. 5 The reduced precession angle ($\omega\tau/g$) versus mean lifetime (τ).
The solid line represents the least squares fit of the data to eq. (3b).
- Fig. 6 The present absolute g-factor measurements for the first (2^+) states of $^{144,146,148}\text{Nd}$ and $^{148,150}\text{Sm}$ and the second (4^+) states of ^{150}Nd and $^{152,154}\text{Sm}$ versus A (refer to text for explanation). The results of various theoretical predictions are included for comparison.

Table 1

Summary of the Present Measured Precession Angles and Previous $B(E2)^\dagger$
Measurements for the First (2^+) and Second (4^+) States of Even Sm Isotopes

Nucleus	E_γ (keV)	I^π	$B(E2)^\dagger_{\text{exp.}}$	$B(E2)^\dagger_{\text{ave.}}$	α_T	τ (psec)	$\omega\tau_{\text{exp.}}$ (rad)
^{148}Sm 62 86	551	2^+	0.70(7) ^a 0.79(8) ^b 0.65(5) ^c 0.79(5) ^d 0.89(10) ^e 0.753(7) ^f	0.75(1)	0.010	10.6(2)	-0.030(2)
^{150}Sm 62 88	334	2^+	1.37(15) ^a 1.44(15) ^b 1.29(7) ^c 1.32(6) ^e 1.41(5) ^d	1.36(3)	0.041	69.1(1.5)	-0.0226(11)
^{152}Sm 62 90	366	4^+	1.94(12) ^g 1.82(6) ^d	1.84(5)	0.109	81.7(2.2)	-0.313(10)
^{154}Sm 62 92	81.9	2^+	4.61(20) ^e 4.1(4) ^h 3.45(40) ⁱ 4.2(1) ^j 4.4(3) ^k 5.1(4) ^l	4.28(8)	5.008		
	267	4^+			0.282	238(7) ^m	-0.889(44)
	549	6^+			0.071	33.9(6) ^m	-0.141(10)

a) ref. 32)
b) ref. 46)
c) ref. 47)
d) ref. 48)
e) ref. 49)

f) ref. 50)
g) ref. 17)
h) ref. 51)
i) ref. 52)
j) ref. 39)

k) ref. 53)
l) ref. 54)
m) ref. 13)

Table 2

Summary of the Present Measured Precession Angles and Previous B(E2) $\uparrow$
Measurements for the 2 $^+$ and 4 $^+$ States of Even Nd Isotopes

Nucleus	E_{γ} (keV)	I^{π}	B(E2) $\uparrow$ _{exp.}	B(E2) $\uparrow$ _{ave.}	α_T	τ (psec)	$\omega\tau$ _{exp.} (rad)
$^{144}_{60}\text{Nd}_{84}$	695	2 $^+$	0.44(5) ^a 0.48(7) ^b 0.51(2) ^c	0.50(2)	0.005	4.9(2)	-0.011(2) ^h -0.016(4) ⁱ
$^{146}_{60}\text{Nd}_{86}$	453	2 $^+$	0.65(7) ^a 0.68(10) ^b 0.76(2) ^c	0.75(2)	0.015	28.0(8)	-0.083 ^h -0.078 ⁱ
$^{148}_{60}\text{Nd}_{88}$	300	2 $^+$	0.96(7) ^a 1.05(16) ^b 1.36(3) ^c	1.29(3)	0.052	123.2(2.9)	-0.38(4) ^h -0.36(3) ⁱ
$^{150}_{60}\text{Nd}_{90}$	132	2 $^+$	2.65(10) ^d 2.67(10) ^e 2.46(11) ^f 2.493(39) ^g	2.53(3)	0.857	2183(30)	
	397	4 $^+$			0.081	80.6(4.2)	-0.31(3) ^h

a) ref. 32)
b) ref. 33)
c) ref. 55)

d) ref. 34)
e) ref. 35)
f) ref. 36)

g) ref. 37)
h) Precession angles as detected in the present
experiment (corrected for the beam bending
effect)
i) ref. 2)

Table 3

Summary of the Present Measurements for the Second (4^+) State of ^{154}Sm .

Recoiled Into Fe, Ni and Co Hosts and Previous Results for the

First (2^+) State of ^{150}Sm

Host	$^{154}\text{Sm}(4^+)$		$^{150}\text{Sm}(2^+)$		$\frac{\mu_{\text{Host}}}{\mu_{\text{Fe}}}$	H(Sm-Host) (Me)
	$\omega\tau(\text{rad})$	$\frac{\omega\tau_{\text{Host}}}{\omega\tau_{\text{Fe}}}$	$\omega\tau(\text{rad})^{\text{a)}$	$\frac{\omega\tau_{\text{Host}}}{\omega\tau_{\text{Fe}}}$		
Fe	-0.889(44)	1.000	-0.219(4)	1.000	1.000	2.3(2)
Co	-0.745(55)	0.838(68)	-0.175(10)	0.802(40)	0.773	1.9(2)
Ni	-0.250(12)	0.281(16)	-0.057(2)	0.263(10)	0.273	0.61(6)

a) Ref.⁹⁾

Table 4

Summary of the Present and Previous g factor measurements for the
Low Lying States of Even Sm Isotopes

Nucleus	E_{γ} (keV)	I^{π}	Present work		Recoil into gas ^{a)}		Other Experiments
			g/g_{154}	g	g/g_{152}	g	g
$^{148}_{62}\text{Sm}$ 86	551	2^{+}	0.752(88)	0.171(46)			
$^{150}_{62}\text{Sm}$ 88	334	2^{+}	0.903(98)	0.273(31)	0.936(60)	0.318(17)	
$^{152}_{62}\text{Sm}$ 90	122	2^{+}			1.000	0.339(12) 0.346(13)	0.277(28) ^b 0.35(3) ^c 0.33(6) ^d 0.31(6) ^e 0.27(7) ^f 0.416(25) ^g 0.326(20) ⁱ 0.346(15) ^j
$^{154}_{62}\text{Sm}$ 92	366	4^{+}	1.000	0.306(37)			
	82	2^{+}			0.917(88)	0.317(28)	0.288(29) ^b 0.31(6) ^e 0.389(18) ^h 0.329(23) ⁱ 0.358(15) ^j
$^{154}_{62}\text{Sm}$ 92	366	4^{+}	1.000	0.306(37)			
	82	2^{+}			0.917(88)	0.317(28)	0.288(29) ^b 0.31(6) ^e 0.389(18) ^h 0.329(23) ⁱ 0.358(15) ^j
	267	4^{+}	1.07(12)	0.337(36)			
	549	6^{+}	1.12(13)	0.317(46)			

Table 4 (Cont'd)

Summary of the Present and Previous g factor measurements for the
Low Lying States of Even Sm Isotopes

- a) ref.²⁾
- b) ref.³⁹⁾
- c) ref.⁴⁰⁾
- d) ref.⁴¹⁾
- e) ref.⁴²⁾
- f) ref.⁴³⁾
- g) ref.⁴⁴⁾
- h) ref.⁴⁵⁾
- i) Unweighted average
- j) Weighted average

Table 5
Summary of the Present and Previous g factor measurements
for the low lying states of even Nd isotopes

Nucleus	E_Y (keV)	I^π	Present Work		Recoil into gas ²⁾		Other Experiments
			g/g_{150}	g	g/g_{150}	g	g
$^{144}_{60}\text{Nd}$	695	2^+	0.40(10)	0.13(2)			
$^{146}_{60}\text{Nd}$	453	2^+	0.69(14)	0.22(3)			
$^{148}_{60}\text{Nd}$	300	2^+	0.80(18)	0.25(4)	0.638(52)	0.206(16)	0.24(5) ^{a)}
$^{150}_{60}\text{Nd}$	132	2^+			1.00	0.322(9) 0.339(50)	0.310(21) ^{b)}
	397	4^+	1.00	0.32(5)			

a) ref.¹⁾

b) ref.³⁷⁾

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5