action suggests that the charge exchange and stripping processes are modulated in a complex fashion by the p-p final-state interaction.[76–78]

The analysis of the deuteron breakup processes was reasonably successful and encouraging. There is a clear indication that these processes in the energy region between 30 to 100 MeV and even better between 100–200 MeV [79] are the most promising candidates to extract precise information regarding the neutron-neutron interaction.

In this paper the comparison procedure has been applied exclusively to the analysis of incomplete experiments. The comparison procedure should be applied also to complete experiments. At present, the available data are still quite scarce. Only the reaction $D(p,2p)n$ has been studied extensively[80] and even there much more remains to be done. A few attempts have been made to analyze the data obtained in complete experiments.[81,82] The agreement between the data and the calculated spectra based on either the Watson-Migdal model[44,45] or the Phillips, Griffy, and Biedenharn model,[46] or the Frank and Gammel approach[71] is only qualitative. In none of these complete experiments has the neutron-neutron interaction been investigated. There has been reported[83] only one study of the process $D(n,2n)p$. The data obtained so far are not good enough to encourage any analysis.

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Nuclear g Factors of the First Excited 2^+ States in Samarium-152 and -154 and Gadolinium-156, -158, and -160*

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The nuclear g factors of the Coulomb-excited 2^+ rotational states in samarium-152 and -154 and gadolinium-156, -158, and -160 have been measured using the pulsed-beam technique. The precession of the excited nuclei in an external magnetic field was detected by observing the angular distribution of the de-excitation γ radiation as a function of time. The measured g factors and mean lives τ were $g=0.277\pm0.028$ and $\tau=2.12\pm0.07$ nsec for the 122-keV state in ^{152}Sm, $g=0.288\pm0.029$ and $\tau=4.37\pm0.07$ nsec for the 82-keV state in ^{154}Sm, $g=0.296\pm0.018$ and $\tau=3.29\pm0.08$ nsec for the 89-keV state in ^{156}Gd, $g=0.315\pm0.025$ and $\tau=3.69\pm0.08$ nsec for the 79-keV state in ^{158}Gd, and $g=0.303\pm0.026$ and $\tau=3.92\pm0.08$ nsec for the 75-keV state in ^{160}Gd. For ^{152}Sm the precession was measured as a function of target temperature in order to understand better the internal field at the nucleus. It was found that the internal field did not have the theoretically expected temperature dependence above room temperature. The samarium results were obtained by using samarium metal targets, which were noticeably perturbed by electric quadrupole interactions. The gadolinium experiments utilized liquid-metal targets, and no perturbations were observed.

I. INTRODUCTION

THE determination of the nuclear g factors of rotational states is of interest because it gives information about the nature of the collective motion of the nucleus. In particular the g factor relates the relative contributions of the neutron and proton collective flow.[1,2]

In these experiments the 2^+ states at 122 keV in ^{152}Sm, 82 keV in ^{154}Sm, 89 keV in ^{156}Gd, 79 keV in ^{158}Gd, and 75 keV in ^{160}Gd were Coulomb excited by the nanosecond-pulsed beam from the Case Institute of Technology Van de Graaff accelerator. The precession of the excited nuclei in an external magnetic field was detected by observing the de-excitation γ radiation as a function of time. This technique has been described in earlier papers.[3–5] This differential γ-ray angular dis-

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† Present address: Wright State Campus, Dayton, Ohio.
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[1] O. Nathan and S. G. Nilsson, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965).
[2] S. G. Nilsson and O. Prior, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **32**, No. 16, (1960).
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tribution also gave information about the spin coupling between the excited target nucleus and the target environment. Consequently, it was possible to set a limit on the effect of randomly oriented electric or magnetic fields on the observed rotation of the angular distribution.

Samarium and gadolinium have paramagnetic ions. In an external magnetic field these ions produce an additional magnetic field at the nucleus.[6] The effective g factor measured must be corrected for the field due to the ion if the true g factor is to be obtained.

II. THEORY OF THE EXPERIMENT

By proper choice of the Coulomb-excitation conditions the γ-ray angular distribution of the excited 2^+ nuclei in a magnetic field perpendicular to the beam-counter plane can be written as[3,7,8]

$$W(\theta,H,t)=\alpha_1 e^{-\lambda t}+\alpha_2 e^{-\lambda t}P_2[\cos(\theta-\omega_L t)], \quad (1)$$

where α_1 and α_2 are coefficients which are determined by the Coulomb-excitation process and the spin and multipole orders involved in the excitation and de-excitation process, λ is the decay constant of the nuclear state, ω_L is the Larmor precession angular velocity, and P_2 is the second Legendre polynomial. The Larmor precession angular velocity is given by $\omega_L=g\mu_N H/\hbar$, where g is the g factor of the excited nuclear state, μ_N is the nuclear magneton, and H is the external magnetic field. If, in addition to the magnetic spin coupling, there are interactions with randomly oriented internal fields, such as coupling between a static electric field gradient of the target environment and the nuclear quadrupole moment, then Eq. (1) becomes[3]

$$W(\theta,H,t)=\alpha_1 e^{-\lambda t}+\alpha_2 G_2(t)e^{-\lambda t}P_2(\cos[\theta-\Delta\theta(t)]), \quad (2)$$

where $G_2(t)$ represents the time dependence of the magnitude of the correlation and $\Delta\theta(t)$ represents the resultant precession of the correlation. It is convenient to rewrite Eq. (2) in a slightly different form:

$$W(\theta,H,t)=\mathcal{A}_1(t)+\mathcal{A}_2(t)\cos 2\theta+\mathcal{A}_3(t)\sin 2\theta. \quad (3)$$

The simultaneous determination of the three parameters, $\mathcal{A}_1$, $\mathcal{A}_2$, and $\mathcal{A}_3$, as functions of time permits the determination of the time-dependent magnitude of the angular distribution, $|A|(t)$. The anisotropy factor of the angular distribution is defined by

$$|A|(t)=\frac{[\mathcal{A}_2^2(t)+\mathcal{A}_3^2(t)]^{1/2}}{\mathcal{A}_1(t)}$$

and the resultant precession is

$$\Delta\theta(t)=\tfrac{1}{2}\arctan[\mathcal{A}_3(t)/\mathcal{A}_2(t)]$$

when the angular distribution function is written

$$W(\theta,H,t)=e^{-\lambda t}\{1+|A|(t)\cos 2[\theta-\Delta\theta(t)]\}.$$

If the static magnetic interaction is sufficiently strong compared with other possible randomly oriented internal fields, then $\Delta\theta(t)$ is just $\omega_L t$. The function $|A|(t)$ can be used to check if this is justified.[9]

The decay constant of the nuclear state can be determined from the quantity[3]

$$\alpha_1(t)=\alpha_1 e^{-\lambda t}=\mathcal{A}_1(t)-\tfrac{1}{3}[\mathcal{A}_2^2(t)+\mathcal{A}_3^2(t)]^{1/2}, \quad (4)$$

which should exhibit a pure exponential decay with the nuclear decay constant λ. The fact that the experimental values of $\alpha_1(t)$ fall on a pure exponential decay can be used to determine when the data are free from background, particularly prompt background from the beam.

III. EXPERIMENTAL PROCEDURE

The experiment used a proton beam from the Case Van de Graaff accelerator with pulses of about 1 nsec duration. Time spectra of both the target γ rays and K x rays were taken at 10 angular positions relative to the beam. The zero of time was determined by means of a beam pickup just ahead of the target (see Fig. 1).

The x rays served as a beam current, target efficiency, and counting rate normalization. The centroid of the x-ray time spectrum also served as a time reference which was necessary to achieve the time stability required in these experiments.[3]

A typical experiment consisted of observing simultaneously the γ- and x-ray time distributions at 10 angular positions. In each of these spectra, about 10^5 counts were accumulated. The angular range consisted of 10° steps from 10° to 110°, with respect to the direction of the incident beam on the target. The time spectra runs were preceded and followed by time-calibration measurements. The time calibration was determined using a Ta target and suitable delay cables.

The electrical lengths of delay cables were measured using a new technique.[10] This technique made use of the

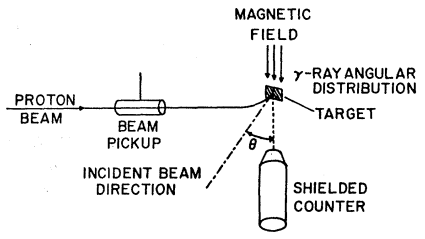

FIG. 1. Beam-counter diagram.

[6] C. Günther and I. Lindgren, in *Perturbed Angular Correlations*, edited by E. Karlsson, E. Matthias, and K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1964), p. 357.

[7] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. 28, 432 (1956).

[8] H. Frauenfelder and R. M. Steffen, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965) p. 1112.

[9] K. Alder, E. Matthias, W. Schneider, and R. Steffen, Phys. Rev. 129, 1199 (1963).

[10] J. W. Tippie, Ph.D. thesis, Case Institute of Technology, 1965 (unpublished).

known velocity of the pulsed beam. By using a movable target the distance between the beam pickup (see Fig. 1) and the target was varied. This, in effect, made it possible to measure the difference in delay between cables by measuring the distance through which it was necessary to move the target (along the beam axis) in order to obtain the same delay between pulses from the beam pickup and a γ-ray detector a fixed distance from the target. This method had the advantage of using the same cables in the same place in the equipment with essentially the same pulses as in the time calibration in the experiment. Using this technique the electrical lengths of the delay cables were measured to ± 0.11 nsec.

IV. RESULTS FOR SAMARIUM

The experiments on the samarium isotopes were performed with isotopically enriched metal targets. The metal was prepared by vacuum reduction of samarium oxide with lanthanum metal powder.[11] The oxide was obtained from the Oak Ridge National Laboratory and was greater than 95% isotopically pure. The Coulomb-excitation experiments were performed as a function of temperature to check the temperature dependence of the internal field correction. Fifteen experiments were performed on ^{152}Sm. Six were done near room temperature, six near 160°K, one at 500°K, and two at 660°K. The seven ^{154}Sm experiments were all performed at room temperature. Typical results for $\alpha_1(t)$, $|A|(t)$, and $\Delta\theta(t)$ are shown in Figs. 2, 3, and 4. Figure 2 of $\alpha_1(t)$ shows the exponential decay of the excited state. The early-time side of the peak is an indication of the time resolution. Figure 3 shows the magnitude of the angular distribution. It can be seen that there was a significant falloff in $|A|(t)$ after it reached its highest value. The peak of $|A|(t)$ occurred at approximately the time when $\alpha_1(t)$ started the exponential decay. This falloff indicated that significant perturbations acted on the excited nuclei. For experiments with liquid environments [12–14] it has been found that there was no significant attenuation of the angular correlation. It is, therefore, reasonable to assume that the principle cause of the decline of $|A|(t)$ in the present experiments with solid targets was due to randomly oriented static interactions between the electric quadrupole moments of the nuclei and the crystalline electric field gradients. This interaction is expected to be significant since the lattice sites have a mixture of cubic and hexagonal symmetry.

Alder *et al.* have calculated the effects of combined static magnetic and randomly oriented electric quadrupole interactions on $|A|(t)$ and $\Delta\theta(t)$.[9] Their results

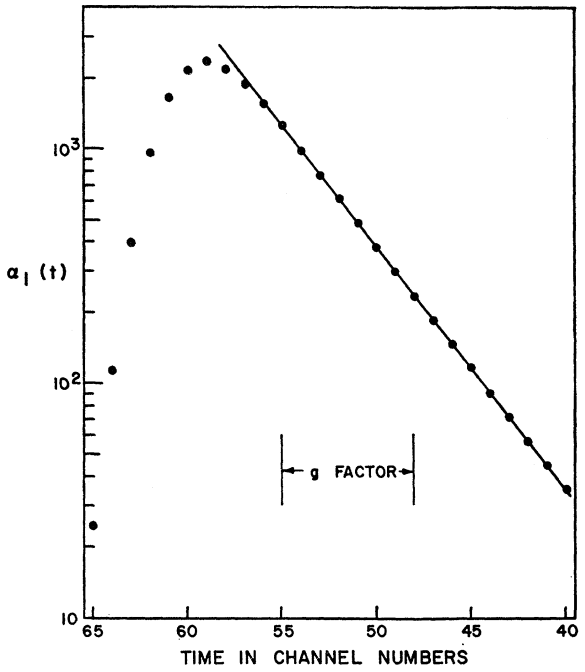

FIG. 2. The parameter $\alpha_1(t)$ for ^{152}Sm.

for $|A|(t)$ were used to approximately determine the strength of the quadrupole interactions. They found that $\Delta\theta(t)$ followed the Larmor precession for a time, which was dependent on the strength of the quadrupole interactions, and then started to deviate substantially. The point at which the deviation became significant was determined from the time dependence of $|A|(t)$. It was found that $\Delta\theta(t)$ was close to the Larmor precession until $|A|(t)$ fell to about 0.6 times the unperturbed value. The unperturbed value was calculable because no unknown multipole mixing ratios are present. The fit of $\Delta\theta(t)$ to determine the Larmor frequency ω_L was done between the channels where $\alpha_1(t)$ started on the exponential decay and where $|A|(t)$ reached 60% of the unperturbed value. For these experiments the electric quadrupole interaction strength was $\omega_E \approx 13\times 10^6$ sec^{-1}, where ω_E is the basic quadrupole frequency as defined by Alder *et al.*[9]

Since there are a variety of local symmetries at the lattice sites in samarium metal, it was expected that there would be a range in electric quadrupole interaction strengths. An attempt was made to fit $|A|(t)$ using various distributions of strengths. It was found possible to fit $|A|(t)$ equally well with several distributions and that the distributions had significantly different effects on $\Delta\theta(t)$. For this reason an additional independent error of 6% was included in the final samarium g-factor results.

Since the samarium ion is paramagnetic, the magnetic field at the nucleus includes a contribution from the ion. The correction β for the internal field was first

[11] F. H. Spedding and A. H. Daane, *The Rare Earths* (John Wiley & Sons, Inc., New York, 1961), p. 193.
[12] G. Goldring and R. P. Scharenberg, Phys. Rev. **110**, 701 (1958).
[13] G Manning and J. Rogers, Nucl. Phys. **19**, 675 (1960).
[14] R. W. Bauer and M. Deutsch, Phys. Rev. **128**, 751 (1962).

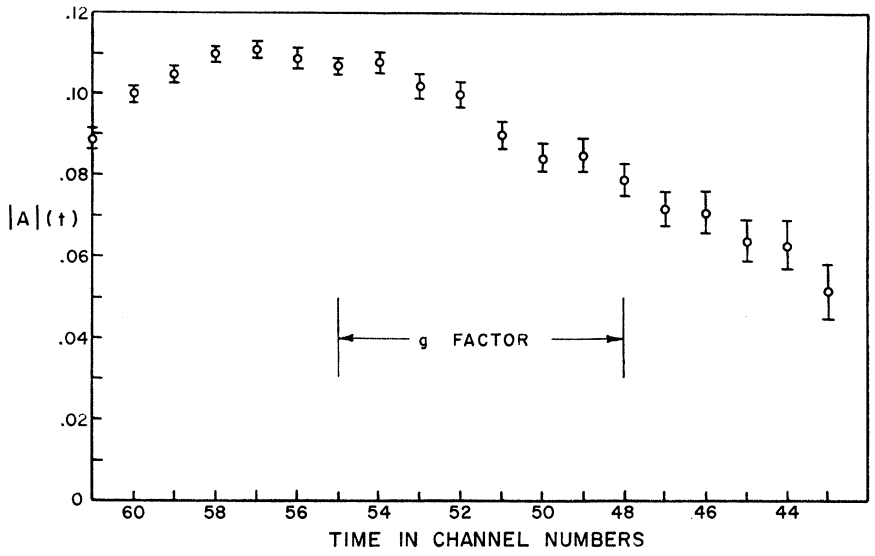

FIG. 3. The magnitude of the γ-ray angular distribution $|A|(t)$ for ^{152}Sm.

correctly calculated by Kanamori and Sugimoto[15] using the Van Vleck theory of paramagnetism.[16] Günther and Lindgren have refined the calculation with more recent atomic data.[6] The experiments actually measured an effective g factor which was equal to βg. The room temperature g value for ^{152}Sm was calculated using g_{eff} and the theoretical value for β. At all of the other temperatures g_{eff} was divided by this g to give β at each temperature. The resulting $\beta(T)$ values are plotted in Fig. 5 along with the calculations of Günther and Lindgren. It can be seen that the high-temperature points are in substantial disagreement with the experimental values. The low-temperature value of β is in approximate, though not good, agreement.

The Van Vleck theory for the magnetic susceptibility χ_M gives correct values at room temperature and below. Arajs and Colvin have measured χ_M for samarium metal above toom temperature.[17] They found that the susceptibility rises significantly above room temperature while the theory predicts only a slight increase. They also found that the susceptibility does not exhibit any discontinuity at the 1190°K phase transformation or at the melting point. They interpreted this continuity as demonstrating that the samarium ions do not interact with each other significantly. Tsang[18] has measured the susceptibility of SmAg up to 870°K and found a temperature depen-

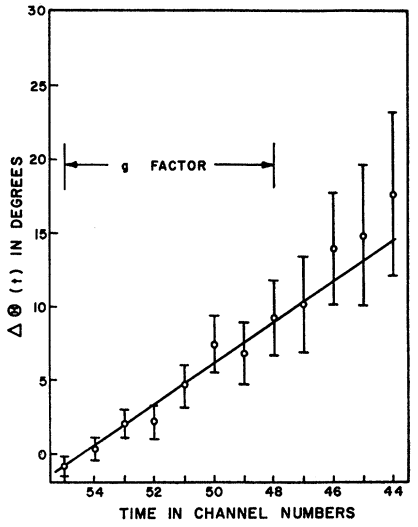

FIG. 4. The resultant precession of the γ-ray angular distribution $\Delta\theta(t)$ for ^{152}Sm.

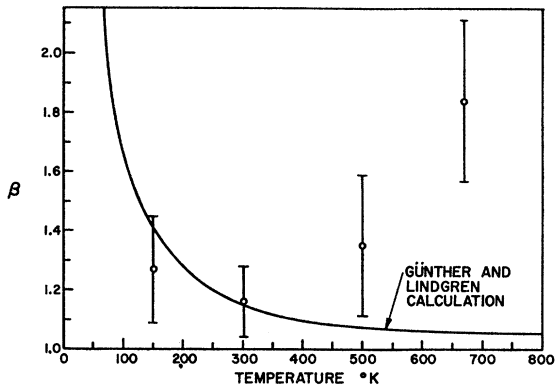

FIG. 5. The internal magnetic field correction β for samarium metal.

[15] J. Kanamori and K. Sugimoto, J. Phys. Soc. Japan 13, 754 (1958).

[16] J. H. Van Vleck, *Theory of Electric and Magnetic Susceptibilities* (Oxford University Press, London, 1932), p. 239.

[17] S. Arajs and R. V. Colvin, in *Rare Earth Research*, edited by E. V. Klever (The McMillan Company, New York, 1961), p. 178.

[18] E. Y. Tsang, Senior Physics Project, Case Institute of Technology, 1965 (unpublished).

TABLE I. Summary of experimental results.

Isotope	g	τ (nsec)	$g\tau$ (nsec)	Ref.
^{152}Sm	0.277±0.028	2.12±0.07	0.589±0.059	a
	0.31 +0.06	2.02±0.14	0.626±0.12	b
	0.28 ±0.07	2.0	0.56 ±0.14	c
	0.33 ±0.06	2.0	0.66 ±0.12	d
	0.350±0.030	2.05±0.06	0.717±0.062	e
^{154}Sm	0.288±0.029	4.37±0.07	1.255±0.120	a
	0.31 ±0.06	3.8	1.18 ±0.22	b
^{156}Gd	0.296±0.018	3.29±0.08	0.974±0.063	a
	0.32 ±0.03	3.20±0.08	1.024±0.095	e
^{158}Gd	0.315±0.025	3.69±0.08	1.161±0.095	a
^{160}Gd	0.303±0.026	3.92±0.08	1.189±0.105	a

[a] Present work.
[b] Reference 12 with correction by Ref. 6.
[c] Reference 13.
[d] Reference 19 with correction by Ref. 6 to room-temperature value.
[e] Reference 14.

dence in good agreement with the results of Arajs and Colvin.

Since β does not follow the theoretically predicted curve and since the susceptibility predictions are in agreement with experiment at room temperature, only the room temperature g_{eff} was used in determining the true g factor. Another reason for using the room-temperature value was that the internal-field correction is smallest in that region. The low-temperature point required a large and uncertain correction and the data were poor for this temperature since they were harder to obtain. The correction used at $T=330°$K was $\beta=1.135$. An error of ±5% was attached which corresponded to ±40% uncertainty in the ion contribution to the field.

The g factor for the 122-keV state in ^{152}Sm applying the internal-field correction was found to be $g=0.277$ ±0.028. The mean life τ was 2.12±0.07 nsec where most of the error was from the cable calibration. The quantity $g\tau$, which was independent of the time calibration, was 0.589±0.059 nsec. This quantity is of particular value for comparing with the results of other experimenters since the time calibration can be a major source of error in experiments of this type.

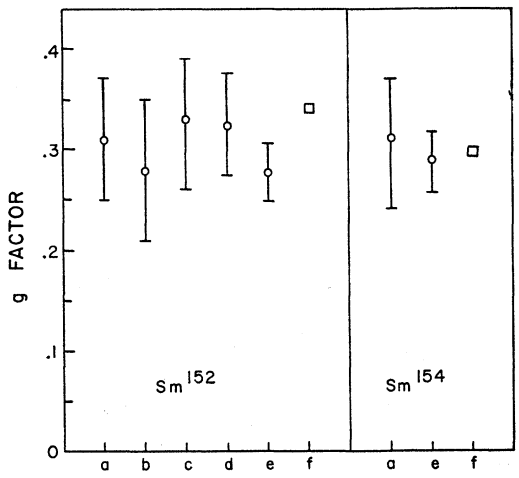

FIG. 6. The samarium g-factor results of various experimenters at room temperature with the internal field corrections of Günther and Lindgren. (a) Reference 12; (b) Ref. 13; (c) Ref. 19; (d) Ref. 14; (e) present work; (f) calculations from Ref. 2.

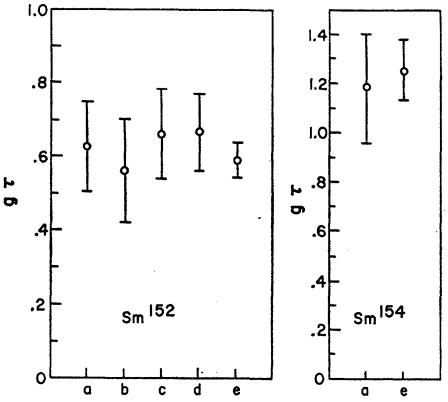

FIG. 7. The samarium $g\tau$ results of various experimenters at room temperature with the internal field corrections of Günther and Lindgren. (a) Reference 12; (b) Ref. 13; (c) Ref. 19; (d) Ref. 14; (e) present work.

The g factor for the 82-keV state of ^{154}Sm was found to be 0.288±0.029. The mean life was 4.37±0.07 nsec. The value of $g\tau$ was found to be 1.255±0.120 nsec. These results are tabulated in Table I.

Goldring and Scharenberg used the method of time-integrated angular correlation following Coulomb excitation.[12] They obtained a value $g=0.21\pm0.04$ for ^{152}Sm, but used an incorrect internal-field correction. Using the internal-field correction at room temperature of Günther and Lindgren gave $g=0.31\pm0.06$. The mean life used to calculate g was $\tau=2.02\pm0.14$ nsec. This gave $g\tau=0.626\pm0.12$ nsec. For ^{154}Sm they obtained a value which corrected by Günther and Lindgren gave $g=0.31\pm0.06$. For ^{154}Sm they used $\tau=3.80$ nsec. The value for $g\tau$ was 1.18±0.22 nsec.

Manning and Rogers measured the g factor of ^{152}Sm using the method of time-integral γ-γ angular correlation.[13] They obtained $g=0.28\pm0.07$ using $\tau=2.0$ nsec. The corresponding value of $g\tau$ was 0.56±0.14 nsec.

Debrunner and Kündig have also measured the ^{152}Sm g factor by time-integral γ-γ angular correlation.[19] Using a mean life $\tau=2.0$ nsec they obtained $g\beta=0.325$ ±0.045 for Sm_2O_3 sources at 300°K and $g\beta=0.188$ ±0.060 at 1200°K, where β is the internal-field correction factor. They assumed that the internal-field correction had a $1/T$ dependence and from this found $g=0.115$ ±0.075. Since it is believed that this is not the correct temperature dependence for β, Günther and Lindgren have recalculated g applying their correction to the 300°K data. The result of the recalculation was $g=0.33$ ±0.06. The value for $g\tau$ was then 0.66±0.12 nsec.

Bauer and Deutsch used the method of time-integral

[19] P. Debrunner and W. Kündig, Helv. Phys. Acta **33**, 395 (1960).

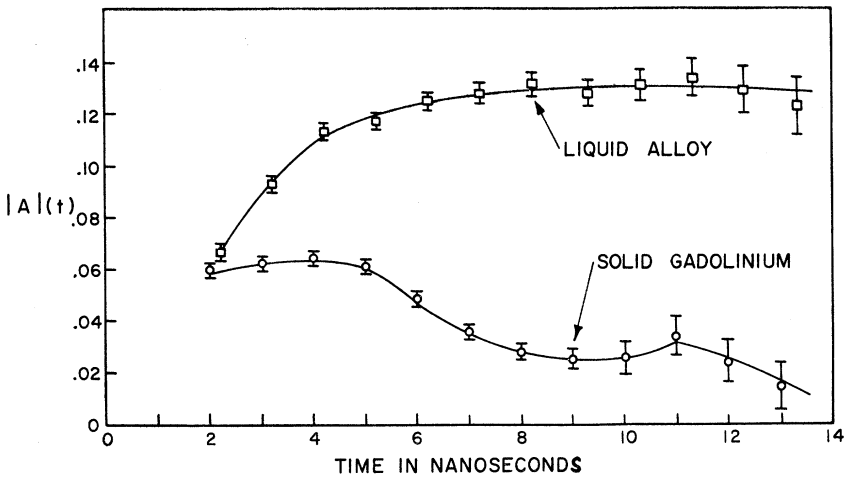

FIG. 8. A comparison of $|A|(t)$ for liquid and solid gadolinium targets.

γ-γ correlation to determine the ^{152}Sm g factor.[14] These authors measured the time dependence of the magnitude of the angular correlation to obtain a correction for the time-integral angular distribution used in determining the g factor. They obtained an attenuation time τ_2 for the angular correlation of greater then 70 nsec in molten $SmCl_3$ at 1300°K and in aqueous solutions of $SmCl_3$ at 300°K. By applying the corrections of Kanamori and Sugimoto[15] of $\beta=1.15$ at 300°K and 1.04 between 1000°K and 1500°K Bauer and Deutsch found $g=0.350\pm0.030$. This included their measured value for the mean life $\tau=2.05\pm0.06$ nsec. The value of $g\tau$ was 0.717 ± 0.062 nsec. If only the room-temperature measurements were used and the correction $\beta=1.15$ was applied, the g factor would have been about 0.326 ± 0.050 and $g\tau$ would have been 0.668 ± 0.105 nsec.

From our measurements of the precession at elevated temperatures it would seem that one must be very careful about applying theoretical corrections to samarium.

Figures 6 and 7 show the various values for g and $g\tau$ found at room temperature by each group of experimenters. The corrections of Günther and Lindgren have been applied. The values calculated by Nilsson and Prior using the collective model with pair correlations were $g=0.341$ for ^{152}Sm and $g=0.295$ for ^{154}Sm.

The experimental values as corrected all agree within errors. The agreement of $g\tau$ is quite good. For ^{154}Sm our experimental determination of g is in agreement with the calculation of Nilsson and Prior. For ^{152}Sm the calculated prediction is somewhat higher than our measured value.

V. RESULTS FOR GADOLINIUM

The g factors of the first 2^+ excited states of gadolinium-156, -158, and -160 were measured using liquid-metal targets at approximately 1100°K. It has been found by other groups that room temperature aqueous solutions of gadolinium salts are too perturbed to use for g-factor measurements.[12,20] Figure 8 compares $|A|(t)$ for a solid gadolinium metal target at room temperature and for a molten-metal target at 1130°K. For the liquid target $|A|(t)$ is almost flat after reaching a full value which is in agreement with the theoretically expected value. For the solid target $|A|(t)$ falls off very rapidly and never gets to the expected value.

We found that gadolinium and copper form a eutectic alloy for about 12% copper by weight. The eutectic point is approximately 710°C. This alloy was used for the target at between 850 and 950°C. In this range the metal presented a clear surface to the proton beam but did not vaporize significantly.

The gadolinium targets were produced by reducing isotopically enriched Gd_2O_3 with zirconium in an electron bombardment furnace. Gadolinium oxide, which had greater than 90% isotopic purity, was obtained from the Oak Ridge National Laboratory. The gadolinium metal and the copper were evaporated together onto a molybdenum ribbon which was used directly in the target holder. The temperature of the molten metal was measured with an optical pyrometer.

The results for the g factors and mean lives of the first excited states for the gadolinium isotopes are given in Table I. Three experiments were performed to obtain the ^{156}Gd results, four for the ^{158}Gd results, and four for the ^{160}Gd results.

The field at the nucleus of a gadolinium ion was not equal to the external magnetic field because of a contribution due to the ion. This correction was relatively small compared to the other rare-earth ions because gadolinium has a half-filled $4f$ shell and consequently to lowest approximation no orbital angular momentum. One of the mechanisms that has been suggested is that the observed hyperfine field was caused by the polari-

[20] R. Stiening and M. Deutsch, Phys. Rev. **121**, 1484 (1961).

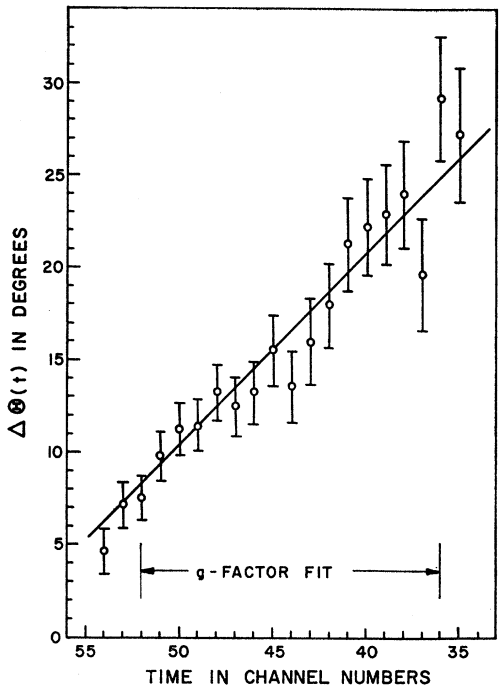

FIG. 9. The resultant precession of the γ-ray angular distribution $\Delta\theta(t)$ for ^{158}Gd.

zation of the inner s electrons by the unfilled $4f$ electron shell resulting in a net spin density at the nucleus.[21]

The internal-field correction for free gadolinium ions calculated by Günther and Lindgren was $\beta=1+69.6/T$, where T was the absolute temperature. Since gadolinium metal has a ferromagnetic transition, it was expected by the experimenters that the β correction, like the magnetic susceptibility, would be more accurately represented by $\beta=1+69.6/(T-T_c)$, where T_c is the paramagnetic Curie temperature. Using $T_c=310$°K found by Arajs and Colvin[17] gave $\beta=1.086$ at 1120°K. Assuming an error of 10% on the numerical factor, which included the atomic-field quantities, and errors of 50° for T and 100° for T_c gave an error on β of 1.4%. The large error on T_c was included because of incomplete knowledge of the effects of melting and alloying on the magnetic interactions of the ions.

Figures 9 through 11 show $\Delta\theta(t)$, $|A|(t)$, and $\alpha_1(t)$ as functions of time for a typical experiment on gadolinium-158. The range over which the precession was fit to determine the g factor is indicated on each figure. The early time limit for the channels used in finding the g factor was chosen by requiring that $\alpha_1(t)$ was decaying exponentially and that $|A|(t)$ had nearly reached its full value. These conditions assured that there was no significant amount of bremsstrahlung, which was emitted at time zero, in these channels. The late time limit for the g-factor fit was chosen to be when the error on $\alpha_1(t)$ became approximately 1%.

It can be seen from Fig. 10 that $|A|(t)$ showed no falloff after reaching its maximum value. The expected value for $|A|(t)$ was 0.125. The observed and expected values were in good agreement. The absence of any falloff in $|A|(t)$ indicated that there were no detectable electric or magnetic perturbations acting on the nuclei other than those set up by the applied magnetic field. The combination of high-temperature and liquid-metal environment produced very rapid relaxation of the ions and their spins.

The g factor was calculated from the average of the individual g-factor measurements weighted by their errors. The errors on the final g-factor results included a 1.4% error on the internal field correction factor and a 0.06 nsec error on the delay-cable calibration, in addition to the statistical errors on the experiments.

Independent errors of 3, 5, and 4% were included in the g-factor errors for gadolinium-156, -158, and -160, respectively. These errors were associated with uncertainties in the effect of the angular distribution in

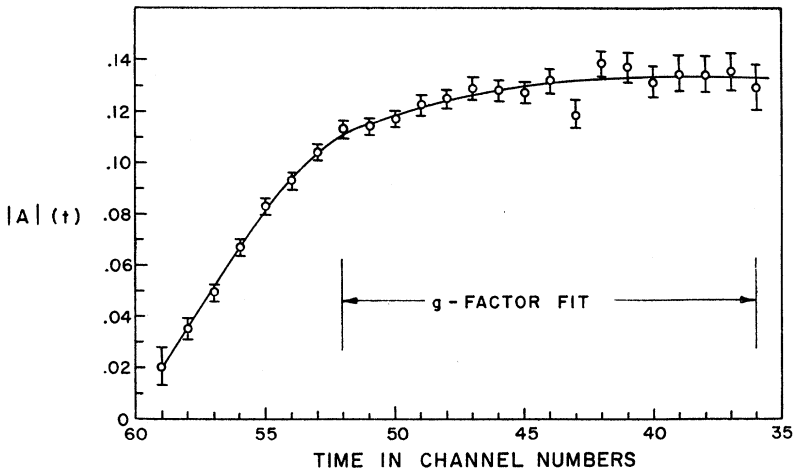

FIG. 10. The magnitude of the γ-ray angular distribution $|A|(t)$ for ^{158}Gd.

[21] R. E. Watson and A. J. Freeman, Phys. Rev. 123, 2027 (1961).

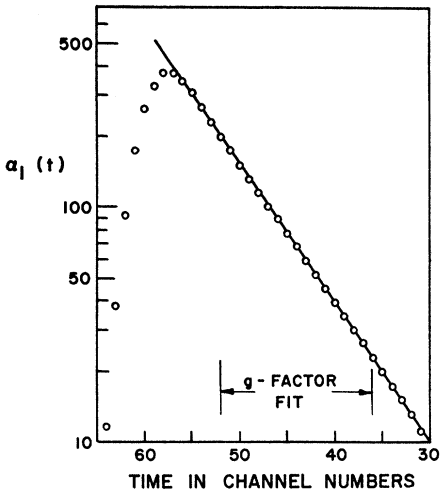

FIG. 11. The parameter $a_1(t)$ for ^{158}Gd.

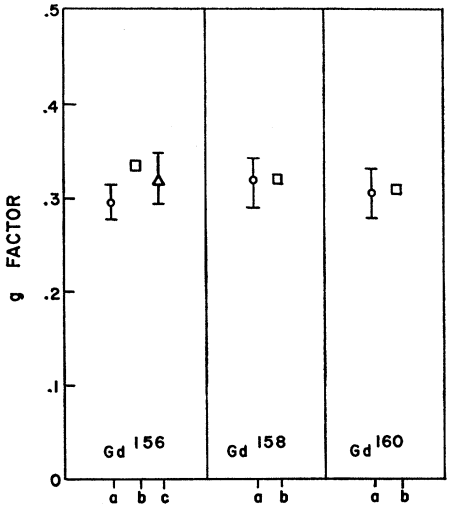

FIG. 12. The gadolinium g-factor results. (a) Present work; (b) calculations from Ref. 2; (c) Ref. 14.

the x-ray window on the precession. This angular distribution was produced by the existence of an admixture of γ rays and bremsstrahlung in the x-ray window. The errors used were consistent with the deviation of the observed from the expected $|A|(t)$ and with the possible correction calculated for ω_L. The correction was not made because of the uncertainty of its accuracy.

The g factor for the 89-keV state of ^{156}Gd was found to be 0.296 ± 0.018 and the mean life was 3.29 ± 0.08 nsec. For the 79.5-keV state of ^{158}Gd the g factor was 0.315 ± 0.025 and the mean life was 3.69 ± 0.08 nsec. The g factor for the 75.3-keV state of ^{160}Gd was 0.303 ± 0.026 and the mean life was 3.92 ± 0.08 nsec. The g-factor results are shown in Fig. 12.

The g factor for ^{156}Gd has been measured by Bauer and Deutsch using the method of time-integral γ-γ angular correlation with molten gadolinium chloride sources.[14] They obtained $g=0.32\pm0.03$ and a mean life $\tau=3.20\pm0.08$ nsec. Since they actually measured $g\tau$ in their angular-correlation experiment we can better compare results for $g\tau$. The value of $g\tau$ calculated from the results of Bauer and Deutsch is 1.024 ± 0.095 nsec. The present experiment found $g\tau=0.974\pm0.063$ nsec for ^{156}Gd. These values exhibit excellent agreement.

The values that Nilsson and Prior have calculated for the g factors using the collective model[2] are $g=0.333$ for ^{156}Gd, $g=0.319$ for ^{158}Gd, and $g=0.307$ for ^{160}Gd. These values have been indicated in Fig. 12 for comparison. The present measured value for ^{156}Gd is slightly lower than Nilsson and Prior's predicted values. The other values are in agreement with their calculations.

VI. SUMMARY

The measurement of excited state g factors by time-differential angular correlation following Coulomb excitation is very effective because it combines simple spectra, high counting rates, and an excellent signal to noise ratio. The method has a wide range of applicability. Another important advantage of this method is the ability to obtain information on extraneous perturbations acting on the excited nuclei with the same data from which the g factor is being determined.

The general method of perturbed angular correlations can be seen from Figs. 7 and 12 to give consistent results among various laboratories when they are all calculated on the same time calibration and internal field correction basis.

The results of these experiments are in general agreement with the calculations of Nilsson and Prior, although the ^{152}Sm and ^{156}Gd results are slightly lower.

The fact that the high-temperature liquid-metal targets used for the gadolinium experiments showed no perturbation of the angular correlation over the time of observations may simplify the interpretation of results in similar targets for other metals.