Spin and Magnetic Moment of the 1.094-MeV State in ^{168}Er

B. T. Kim, W. K. Chu, and J. C. Glass
Department of Physics, North Dakota State University, Fargo, North Dakota 58102
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The time-differential directional-correlation function of the 448-198-keV γ-γ cascade has been measured and the half-life of the 1.094-MeV state in ^{168}Er is found to be 107.3 ± 2.2 nsec. The time-differential behavior of $A_{22}(t)$ shows a possible time-dependent interaction with a decay constant $\lambda_2 = (1.0 \pm 0.5) \times 10^7$ nsec^{-1}. Extrapolation of $A_{22}(t)$ to zero time-delay gives $A_{22}(0) = 0.007 \pm 0.004$, which is compatible with spin 4 for the 1.094-MeV state and multipolarity $M1 + <8\% E2$ for the 448-keV transition. The g-factor of the 1.094-MeV state has been measured, by use of the constant-angle-differential-delay method, and is found to be $g = +0.45 \pm 0.02$. The time-dependent perturbation is interpreted in terms of rapidly fluctuating $4f$ electron magnetic hyperfine fields with a time-averaged value of 0.9 MG in Er^{3+} at room temperature.

[NUCLEAR MOMENTS ^{168}Er level; measured $\gamma\gamma$ coin., deduced J, $T_{1/2}$, γ mixing. Measured $\gamma\gamma(\theta, H)$, D. D. C. A. method, deduced g, Er^{3+} hyperfine field.]

I. INTRODUCTION

The decay scheme of ^{168}Er has been studied extensively by many workers, yet the spin and magnetic moment of the 1.094-MeV state have not yet been measured directly. From consideration of ^{168}Er as formed from the compound nuclide (^{167}Er $+ n^0$), a spin of 2, 3, or 4 for the 1.094-MeV state would be reasonable.[1] Early rotational-band calculations indicated a spin of 3 or 4 for the 1.094-MeV level.[2] The spin-parity of 3− was postulated on the basis of the assignment of $E1$ multipolarity to the 273-keV transitions, from the measured K/L conversion-electron ratio. The electron-capture branching ratios and the logft values supported this also.[3] Logft values, however, admitted the possibility of spin 4. Recent thermal-neutron-capture experiments[4,5] have studied the deexcitation mechanism of ^{168}Er and give a good indication that the 1.094-MeV level is the band head of a $K\pi = 4-$ rotational band. This is supported by recent average-resonance neutron capture,[6] the (d, p) reaction[7] on ^{167}Er, and angular correlation studies.[8,9] So at present it appears that a spin-parity of 4− is favored for the 1.094-MeV level, with 3− also possible.

The 1.094-MeV level serves as the intermediate level for a rather strong 448-198-keV γ-γ cascade. The intermediate-level lifetime makes this cascade an ideal candidate for use in perturbed angular-correlation work, yet its magnetic dipole and electric quadrupole moments have never been measured. Early time-integrated correlation measurements[3] gave zero anisotropy for the 448-198-keV cascade. The large hyperfine fields[10] of Er^{3+}, however, suggest that the observed anisotropy has a strong time dependence. Because of the potential of the 1.094-MeV level for use in perturbed γ-γ directional correlations, it was decided to examine the time dependence of the anisotropy for the 448-198-keV cascade decay of ^{168}Er and to measure the magnetic dipole moment of the 1.094-MeV level by using the constant-angle-differential-delay technique.

II. EXPERIMENTAL MEASUREMENTS

A 20-μCi source of 87-day ^{168}Tm was obtained commercially in 6 N HCl and housed in a 3-mm-diam glass capillary. Source-to-detector distance was 5.0 cm and NaI crystals were used, with dimensions of 3.8×3.8 cm for the 448-keV γ ray and 3.8×1.2 cm for the 198-keV transition. Coincidence data were taken with a time-differential coincidence system utilizing crossover pickoff timing and nominal time-to-pulse-height converter spans of 1 and 2 μsec. Time resolution for the energy windows used was 18 nsec. Energy windows were set at 160 keV $\leq E \leq$ 220 keV and 330 keV $\leq E \leq$ 600 keV for the 198- and 448-keV transitions, respectively. All coincidence measurements were corrected for accidentals and the channel-by-channel anisotropies obtained were corrected for finite solid angle of the detectors.

The constant-angle-differential-delay method[11] was used for the measurement of magnetic moment of the 1.094-MeV level in ^{168}Er. The magnet used was a Ealing large research electromagnet with in-house-constructed pole pieces having diameters of 2.6 cm. The gap spacing used was 3.25 cm, and a constant magnetic field with

magnitude 3750 ± 50 G was maintained between the pole tips throughout the time period while the data were being taken. The paramagnetic correction factor[12] of Er^{3+} at 300 K is known to be 6.83. Therefore, the effective field at the nuclear site of Er^{3+} was 25 600 ± 400 G throughout this experiment.

The two detectors were separated by 135° and the distance between the detectors and the source was 12.5 cm at 0° and 20 cm at 135°. Double-layer magnetic shielding was used, with an inner layer of iron sheet and an outer layer of fine-mesh iron screen. Shifts in detector gain due to the magnetic field applied to the source were negligible.

Coincidence rates with applied magnetic fields directed upwards and downwards were taken and used to calculate the time-differential behavior of the ratio $C(t)$, defined[13] from

$$C(t,\theta_0)=2\,\frac{W(\theta_0,B\uparrow,t)-W(\theta_0,B\downarrow,t)}{W(\theta_0,B\uparrow,t)+W(\theta_0,B\downarrow,t)}\,. \tag{1}$$

For $\theta_0=135°$ in our experiment, and assuming that $A_{22}(0)\gg A_{44}(0)$, $C(t)$ becomes

$$C(t,\tfrac{3}{4}\pi)=\frac{12A_{22}(0)\sin 2\omega_B t}{8+2A_{22}(0)}\,. \tag{2}$$

The time-differential behavior of $C(t,\frac{3}{4}\pi)$ was obtained by averaging over 112 runs of 10 000-sec duration for each magnetic-field configuration.

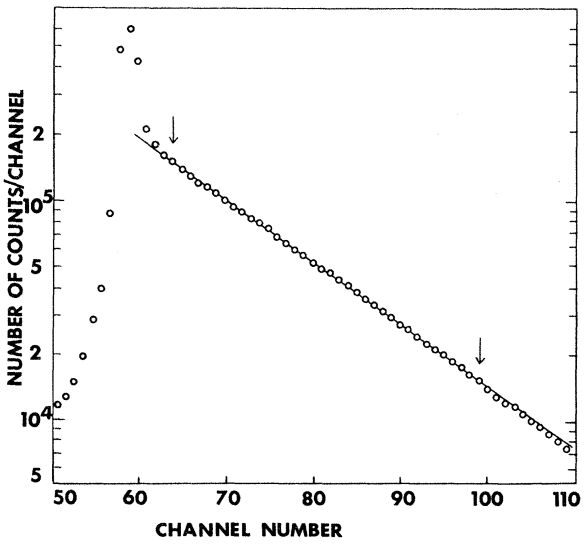

FIG. 1. Time-to-pulse-height converter spectrum of 448-198-keV cascade. Arrows indicate region over which the lifetime of the 1.094-MeV state in ^{168}Er was evaluated.

III. RESULTS

The time-to-pulse-height spectrum for the 448-198-keV cascade is shown in Fig. 1. The sharp spike in the coincidence spectrum indicates the presence of a competing γ-γ cascade involving a nuclear level lifetime small compared to the 18-nsec time resolution of the coincidence system. From inspection of the decay scheme of ^{168}Er, this seems likely due to the 448-831-184-keV cascade, with the 831-keV transition not observed. A least-squares fit of the data beyond 40-nsec delay gives $t_{1/2}=107.3\pm2.2$ nsec, which is in fair agreement with previously published results.[8,14]

The time dependence of the 448-198-keV anisotropy is shown in Fig. 2. The first data point at 5-nsec delay we again attribute to the 448-831-184-keV cascade. Beyond this, there is some indication that the anisotropy is decreasing with time. Theoretical calculations of A_{44} for spin sequences of 3-2-3, 3-3-3, 3-4-3 all give A_{44} values ranging from 10^{-4} to 10^{-6}, so A_{44} will be neglected here. The coefficient $A_{22}(t)$ was calculated from the anisotropy $A(t)$, corrected for finite solid angle of the detectors, and a weighted least-squares fit was done for an attenuation coefficient of the form

$$G_{22}(t)=e^{-\lambda_2 t}\,.$$

The best fit was obtained for

$$\lambda_2=(1.0\pm0.5)\times10^7\ \text{nsec}^{-1}\,.$$

Use of this attenuation coefficient to extrapolate the data back to $t=0$ gives $A_{22}(0)=+0.007\pm0.004$ for the 448-198-keV cascade. Our results for $A_{22}(0)$ and $\lambda_2(t)$ agree quite well with very recent[15] work done with solid-state detectors, in which effects of the 448-831-184-keV cascade were not present.

The multipolarity of the 198-keV transition has

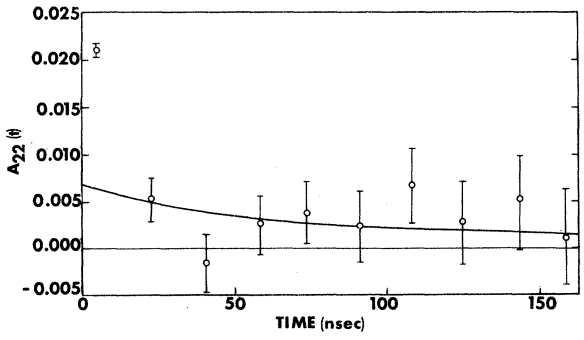

FIG. 2. Time-differential behavior of A_{22} for the 448-198-keV cascade decay of ^{168}Er 6 N HCl at room temperature. Solid curve is for a perturbation factor $G_{22}=e^{-\lambda_2 t}$, with $\lambda_2=(1.0\pm0.5)\times10^7$ nsec^{-1}.

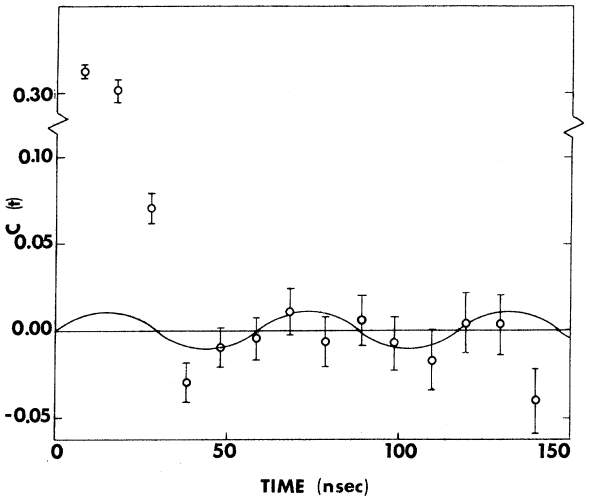

FIG. 3. Time-differential behavior of the ratio $C(t)$ for a relative detector angle of 135° and an effective applied magnetic field of 25 600 ± 400 G. The solid curve is calculated, using $g = +0.45$ for the 1.094-MeV level in ^{168}Er.

been reported[9] previously to be $E1 + <1\% M2$. Using these limits we have compared our experimental $A_{22}(0)$ with the theoretical $A_{22}(0)$ for spin sequences 3-2-3, 3-3-3, and 3-4-3. Spin 3 for the 1.094-MeV level may be ruled out unless one assumes $\delta_{448} = -0.4$, which means a 16% $E2$ admixture for the 448-keV transition, which should then be strongly hindered. Our data do allow $I = 2$ if $\delta_{198} = \delta_{448} = 0$, but this spin is ruled out by many other experiments. For $I = 4$, we obtain $0.1 \leq \delta_{448} \leq 0.17$ if we assume $-0.01 \leq \delta_{198} \leq 0.1$. The 448-keV transition is thus $M1 + <3\% E2$ admixture and our data strongly favor spin $I = 4$ for the 1.094-MeV level.

The channel-by-channel $C(t, \frac{3}{4}\pi)$ is shown in Fig. 3. Because of the competing cascade, the first four data points were ignored in obtaining the g factor. Beyond that, it is very obvious that $C(t, \frac{3}{4}\pi)$ is a periodic function of time. The theoretical $C(t)$, with $A_{44} \ll A_{22}$ and $A_{22} = 0.007 \pm 0.004$, is

$$C(t) = 0.011 \sin 2\omega_B t ,$$

where ω_B is the Larmor presession frequency. A best fit of the experimental data to theory was found for a period $T = 58.4 \pm 1.4$ nsec, which gives, with $B_{\text{eff}} = 25\,600 \pm 400$ G, $g = +0.45 \pm 0.02$ for the 1.094-MeV level in ^{168}Er. Using the spin of 4 for the 1.094-MeV level, the magnetic moment is then $\mu = (2.01 \pm 0.09)\mu_N$.

IV. DISCUSSION

The attenuation coefficient $\lambda_2(t)$ may be the result of aftereffects or due to fluctuating fields caused by molecular collisions and Er^{3+} $4f$ electrons. We feel that aftereffects may be ruled out since the environment is 6 N HCl and the hole caused by the electron-capture decay of ^{168}Tm should propagate out of the atom within a time of 10^{-10} to 10^{-11} sec. Fluctuating electric and magnetic hyperfine fields due to $4f$ electrons, however, must be considered seriously.

In the region of ^{168}Er, excited-state quadrupole moments may be as high as 3 b. If we use this value and assume a correlation time of 10^{-12} sec, then the time-averaged field gradient necessary to explain the observed value of λ_2 is found to be on the order of 5×10^{22} V/m^2, which is much higher than ionic fields expected for a normal liquid. The contribution of Er^{3+} $4f$ electrons to the electric field gradient at the nuclear site must then be considered. This has been calculated[10] to be -2.7×10^{22} V/m^2 at zero temperature, but falls off rapidly with increasing temperature and is expected to be negligible at room temperature.

To examine a possible time-dependent magnetic interaction, using our experimental g factor for the 1.094-MeV level and again assuming a correlation time of 10^{-12} sec, the time-averaged magnetic hyperfine field of Er^{3+} necessary to explain our value of $\lambda_2(t)$ found at room temperature is 0.93 MG. This appears to be quite reasonable, since Er^{3+} is known[10] to have a magnetic hyperfine field of 7.5 MG at zero temperature and this averaged field decreases much more slowly with increasing temperature. We thus conclude that the time dependence of the observed anisotropy is due to rapidly fluctuating magnetic hyperfine fields in Er^{3+}.

An examination of highly deformed nuclides[16] in the mass region of ^{168}Er shows that measured g factors of those states with negative parity lie between 0.4 and 0.7. Therefore, the value of the g factor of a 4− rotational state, as obtained here, seems reasonable. A direct comparison with theory cannot be made, however, since rotational-model calculations of g factors have not been made for the quasiparticle states of ^{168}Er.

[1] R. Fenstermacher, P. Draper, and J. Bockelman, Nucl. Phys. 10, 386 (1959).
[2] K. P. Jacob and J. W. Mihelich, Phys. Rev. 117, 1102 (1960).
[3] J. J. Reidy, E. G. Funk, and J. W. Mihelich, Phys. Rev. 113, B556 (1964).
[4] H. R. Koch, Z. Phys. 192, 142 (1966).
[5] W. Michaelis, H. Ottmar, and F. Weller, Nucl. Phys.

150, 161 (1970).
[6]L. M. Bollinger and G. E. Thomas, Phys. Rev. C 2, 1951 (1970).
[7]R. A. Harlan and R. K. Sheline, Phys. Rev. 160, 1005 (1967).
[8]C. Gunther and D. R. Parsignault, Phys. Rev. 153, 1297 (1967).
[9]L. Hasselgren, H. S. Sahota, J. E. Thun, and F. Falk, Phys. Scr. 3, 119 (1971).
[10]E. Karlsson, M. M. Bajaj, and L. Böstrom, Phys. Scr. 2, 60 (1970).
[11]E. Bozek, A. Z. Hrynkiewiez, and I. Styczen, Phys. Lett. 1, 126 (1962).
[12]C. Günther and I. Lindgren, in *Perturbed Angular Correlations*, edited by E. Karlsson, E. Matthias, and K. Siegbahn (North-Holland, Amsterdam, 1964), p. 367.
[13]E. Matthias, L. Böstrom, A. Maciel, M. Solomon, and T. Lindqvist, Nucl. Phys. 40, 656 (1963).
[14]E. Bodenstedt, Z. Phys. 170, 355 (1962).
[15]Z. W. Grabowski, private communication.
[16]I. Lindgren, in *Perturbed Angular Correlations* (see Ref. 12), p. 379.