Gyromagnetic Ratio of the 4^+ State of Ce^{140}†

M. SCHMORAK, H. WILSON, P. GATTI, AND L. GRODZINS
Laboratory for Nuclear Science and Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts
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The gyromagnetic ratio g of the 2083-keV 4^+ state in Ce^{140} was measured by precessing the γ–γ angular correlation through this state in a magnetic field. The value obtained for the g factor was 0.95 ± 0.10. This result indicates that the 4^+ state is essentially a 2-proton $g_{7/2}$, $d_{5/2}$ configuration. The angular correlation results are consistent with the accepted decay scheme. The ionic state of Ce following the β decay of La is discussed.

I. INTRODUCTION

RECENTLY, Currie[1] reported a measurement of the lifetime of the 2083-keV 4^+ state in $_{58}Ce_{82}^{140}$. He found the mean life to be 4.97 ± 0.09 nsec. Gyromagnetic ratios of nuclear states in this lifetime range are convenient to measure by the method of precession of a gamma-gamma angular correlation (see Sec. IV). Ce^{140} having a "magic" number (82) of neutrons is especially interesting to study, as the excited states are expected to be relatively simple proton states.

Following completion of our measurements, it came to our attention that other groups[2–4] also measured the gyromagnetic ratio of the same state. The results will be compared and discussed in Sec. V.

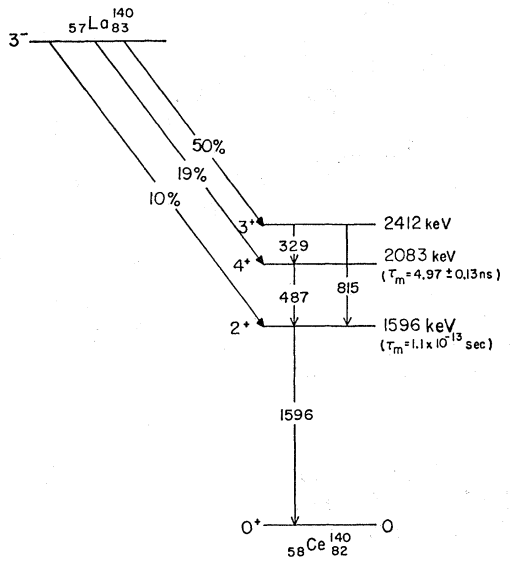

FIG. 1. Relevant features of the decay scheme of La^{140}. The data are from Refs. 1 and 8.

II. LIFETIME MEASUREMENT

The lifetime of the 2083-keV level was measured by the method of delayed coincidences. The equipment used in these measurements consisted of a 3-in.×3-in. NaI(Tl) crystal mounted on an RCA-7046 photomultiplier, a 2-in.×2-in. NaI(Tl) crystal mounted on an RCA-7265 photomultiplier and a conventional fast-slow coincidence circuit with the energies selected by single-channel analyzers. A transistorized time to pulse-height converter based on the design of Bell and Graham[5] was employed. A multichannel analyzer displayed the output of the time to pulse-height converter. The equipment was stabilized by a method similar to that described by deWaard[6] except that the feedback was applied to the preamplifier gain rather than to the photomultiplier high voltage in order to avoid changes in the electron-transit time.

The measurements were performed by accumulating the coincidences as a function of time of the 329-keV–487-keV gamma-ray cascade (see Fig. 1). The results are shown in Fig. 2.

A considerable error can arise in the lifetime determination if the measurements are performed at one angle between the detectors when the angular correlation is large and its attenuation per mean life is significant. This error was negligible in our case because the attenuation of the angular correlation was small (see Sec. III) and the detectors were placed close enough to the source to effectively smear out the angular correlation.

A least-squares fit to the data of Fig. 2 yields a mean life of 4.97 ± 0.13 nsec in agreement with the result of Currie.[1]

III. ANGULAR CORRELATION

As a preliminary step to the measurement of the gyromagnetic ratio of the 2083-keV state, the 329- to 487-keV angular correlation was measured as a function of time. In addition, the angular correlation of the 487-keV–1596-keV cascade was measured with the resolving time much greater than the mean life, as a further check on the multipolarities of the transitions involved.

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[1] W. M. Currie, Nucl. Phys. **32**, 574 (1962).

[2] R. M. Levy and D. A. Shirley, Phys. Letters **3**, 46 (1962); **3**, 256 (1962).

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[4] H. J. Körner, E. Gerdau, C. Günther, K. Auerbach, G. Mielken, G. Strube, and E. Bodenstedt, Z. Physik **172**, 203 (1963).

[5] R. E. Bell, R. L. Graham, and H. E. Petch, Can. J. Phys. **30**, 35 (1952).

[6] H. de Waard, Nucleonics **13**, 36 (1955).

The equipment used in this measurement was the same as that described in Sec. II. Counting was performed at angles of 90, 135, and 180 deg between the detectors. The position of the 3-in.×3-in. detector was changed every 10 min to average out any drifts in the electronic equipment. The detectors were shielded with hollow lead cones which masked the edges of the NaI(Tl) crystals reducing edge effects to the point where a geometric correction due to the finite solid angle could be obtained by the method of Rose.[7] The lead cones also reduced considerably the background of Compton-scattered gamma rays reaching the detectors.

Studies of the gamma-ray spectra in coincidence with gamma energies of 329, 487, and 1596 keV were performed. The results are shown in Fig. 3.

The sources used in these measurements consisted of lanthanum chloride which had been irradiated in the MIT Reactor, then dissolved in a solution of dilute HCl and allowed to dry on a small Mylar foil.

The angular correlation results for the 329- to 487-keV γ-ray cascade were analyzed in the form

$$W(\theta,t)=e^{-\lambda t}[1+A_2G_2(t)P_2(\cos\theta)+A_4G_4(t)P_4(\cos\theta)],$$

which is the correlation as a function of time. λ is the reciprocal mean life of the state. The equation

$$W(\theta)=1+A_2G_2P_2(\cos\theta)+A_4G_4P_4(\cos\theta)$$

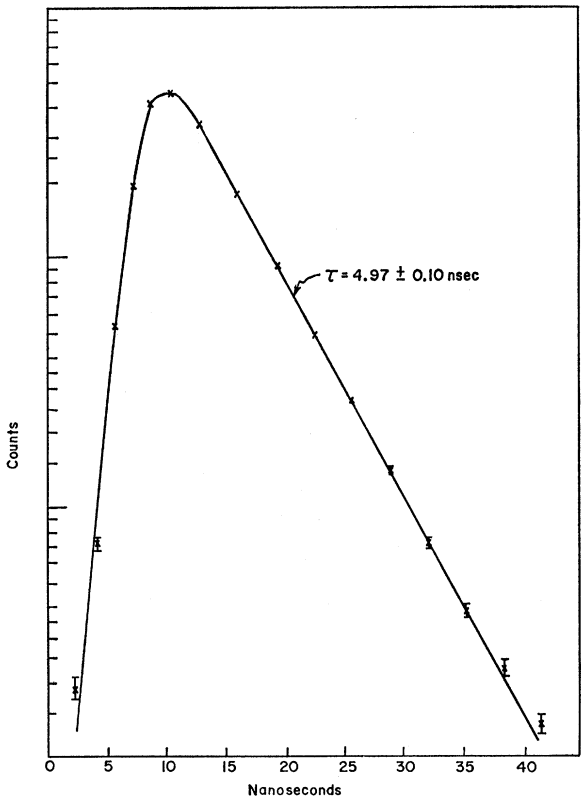

FIG. 2. Decay curve of the 2084-keV state.

[7] M. E. Rose, Phys. Rev. 91, 610 (1953).

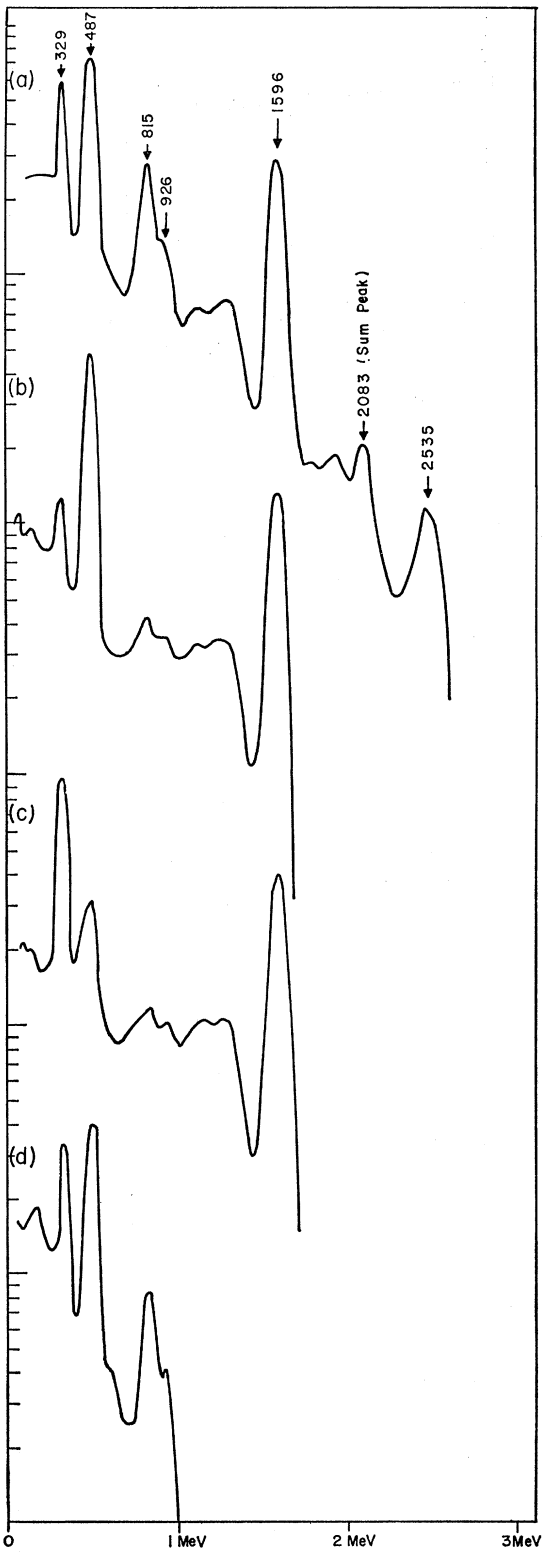

FIG. 3. Gamma-ray spectra: (a) singles, (b) coincidence with 329-keV gamma, (c) coincidence with 487-keV gamma, (d) coincidence with 1596-keV gamma.

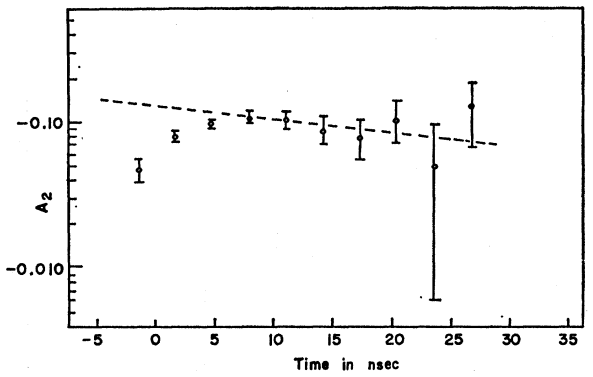

FIG. 4. Angular correlation of the 329- to 487-keV gamma-ray cascade versus time. The dashed line is a least-squares fit to the data omitting the first three points as they are affected by prompt coincidences.

gives the correlation for all gamma rays regardless of delay. Assuming the attenuation of the correlation is of an exponential form $G_n(t)=e^{-\lambda_n t}$, then $G_n=\lambda/(\lambda+\lambda_n)$. Figure 4 shows $G_2(t)A_2$ as a function of time for this cascade. The correction for the finite solid angle of the detectors has been included in this plot and in all subsequent data in this section. In the case of a decay scheme with a large gamma spectrum above the energies of interest, the angular correlation in the region corresponding to prompt decays will be strongly affected by the scattering of the higher energy gamma rays. For this reason the first three points in Fig. 4 were not used in the analysis of the data. A least-squares fit was made (the dashed line in Fig. 4) yielding

$$\lambda_2=0.022\pm0.01\ 10^9\ \text{sec}^{-1},$$
$$G_2=0.90\pm0.05,$$
$$A_2=-0.125\pm0.015.$$

The A_4 term in the angular correlation of the cascade was too small (0.004) to yield data on its attenuation. Thus for the 329- to 487-keV gamma-ray cascade the correlation at zero time is

$$W(\theta,0)=1-0.125P_2(\cos\theta).$$

The 1596-keV state has a mean life of 1.1×10^{-13} sec,[8] requiring that the angular correlation of the 487- to 1596-keV gamma-ray cascade be measured with the resolving time much greater than the mean life of the intermediate state. The results were

$$W(\theta)=1+(0.103\pm0.006)P_2(\cos\theta)+(0.012\pm0.007)P_4(\cos\theta).$$

A comparison of these results with those of previously cited papers[2-4] for the 329- to 487-keV gamma-ray cascade is shown in Table I. Our results are consistent with the assignment of multipolarities of $M1$ to the 329-keV transition and $E2$ to the 487- and 1596-keV transitions, with admixtures of higher order multipoles being less than 0.5%.

[8] S. Ofer and A. Schwarzschild, Phys. Rev. 116, 725 (1959).

TABLE I. Comparison of results of angular correlation parameters and g values.

	A_2	A_4	G_2	g
Present work	-0.125 ± 0.015	0.004 ± 0.007	0.90 ± 0.05	0.95 ± 0.10
Ref. 2	$-0.10\ \pm0.03$	Small		1.08 ± 0.10
Ref. 3	-0.097 ± 0.004	0.001 ± 0.004	>0.96	1.15 ± 0.08
Ref. 4	-0.105 ± 0.003		0.96	1.11 ± 0.04
Theory for 3(D)4(Q)2	-0.140	0		

IV. MEASUREMENT OF THE GYROMAGNETIC RATIO

The determination of the g factor of an excited state by measuring the Larmor precession frequency of an angular correlation through the state is well known. Two techniques, the integral and differential methods, are used. In both methods the two counters are usually set at an angle corresponding to the maximum slope point of the correlation. In the integral method the integrated coincidence rate is determined as a function of the value of the magnetic field. For this method to be successful both the lifetime of the state and the attenuation factors of the correlation have to be known precisely. Moreover, the subtraction of prompt coincidences introduces a further uncertainty which may be large in a complicated decay scheme. In the differential method the coincidence rate is measured as a function of the delay time between the radiations. This method is particularly suited to states whose mean life is longer than, or of the order of, the instrumental resolving time (the case here) since the prompt coincidences can be avoided, and the exact knowledge of the mean life and the attenuation factor are less important.

In our experiment, the differential method was used. The 329- to 487-keV cascade was investigated. The detectors were: a 1-in.×1-in. NaI(Tl) mounted on a light pipe leading to a 56-AVP photomultiplier and a 2-in.×2-in. NaI(Tl) connected through a light pipe to a RCA-7625 photomultiplier. The photomultipliers were shielded magnetically by concentric iron and mu metal shields. The angle between the detectors was fixed at 135°. The NaI scintillators were shielded from scattered gamma rays by means of hollow truncated lead cones.

The magnetic field was at right angles to the plane of the detectors. The direction of the field was reversed every 10 min in order to reduce the effect of instrumental drifts. Field strengths of 16.5, 20, and 24.5 kG were used. The field strength and homogeneity at the source position were determined by a rotating coil gaussmeter and should be accurate to 3%.

The electronic equipment was the same as that described in Sec. III. The time to pulse-height converter output was analyzed and stored in a 400-channel analyzer. The coincidences corresponding to the two magnetic field directions were accumulated in different parts of the analyzer memory. The punched paper tape output

of the analyzer was used for analyzing the data on a LGP-30 computer. First, the function $[N^+(t)-N^-(t)]/[N^+(t)+N^-(t)-2C]$ was calculated. N^+ being the number of coincidences accumulated for one direction of the magnetic field and N^- for the other direction. C is the number of accidental coincidences determined in a separate experiment.

The analyzer channel corresponding to the zero of time was determined by measuring the prompt coincidences of annihilation radiation, the energy channels remaining at 329 and 487 keV.

Figure 5 shows one run at 24.5 kG. A_4 being essentially zero the data can be analyzed approximately by the expression $B_2e^{-\lambda_2 t}\sin 2\omega t$, where λ_2 is the attenuation of the angular correlation and ω the Larmor precession frequency of the nucleus in the 2083-keV state. This damped sine formula has to be corrected for the effects of the finite resolving time of the apparatus.[9] In our case the resolving time was $2t_0=5.5$ nsec, this has the effect of shifting the first crossing point by approximately 6%.

The average effective g factor from numerous runs like those shown on Fig. 5 was $g_{\text{eff}}=0.95\pm0.1$. To obtain the magnetic moment of the nucleus the effective magnetic field at the nucleus has to be known.

The influence of paramagnetism in rare-earth ions on g-factor measurements have been investigated by several authors.[10] The effect can be described by a parameter β defined by

$$H_{\text{eff}}=\beta H_{\text{applied}}.$$

If the electronic configuration is known this factor can be calculated. In our experiment La is in the 3^+ ionic state, immediately after β decay Ce^{4+} is formed.

Ce(3+) has a $4f^1 5s^2 5p^6$ electronic configuration and is paramagnetic. β is estimated to be about 1.4. La(3+) and Ce(4+) are diamagnetic because the f shell is empty, and therefore one expects to see paramagnetic effects in our experiment only if the time of reorganization of the ions is not very long compared to the mean life time (5 nsec) of the state. Burgus and Davies,[11] in their study of chemistry of atoms following beta decay, have investigated the oxidation state of 33-h Ce^{143} that results from the beta decay of La^{143}. They found that at least 60% of Ce was in 4+ state for a period of minutes.

We used a carrier-free source of Ba^{140}—La^{140} obtained from Oak Ridge. Lanthanum was precipitated as lanthanum hydroxide using barium and lanthanum carriers and adding sodium hydroxide. Ceric sulfate $[Ce(HSO_4)_4]$ was added to produce an oxidizing environment which is expected to favor the stability of the 4^+ ion. For some runs the lanthanum hydroxide precipitate was dissolved in hydrazine instead of ceric sulfate. Thus, in our experiments we assume $\beta=1$, and $g=g_{\text{eff}}$. The small attenuation factor λ_2 obtained in the angular correlation experiment also supports the conclusion that Ce is not paramagnetic in the first few nanoseconds after its formation.[4]

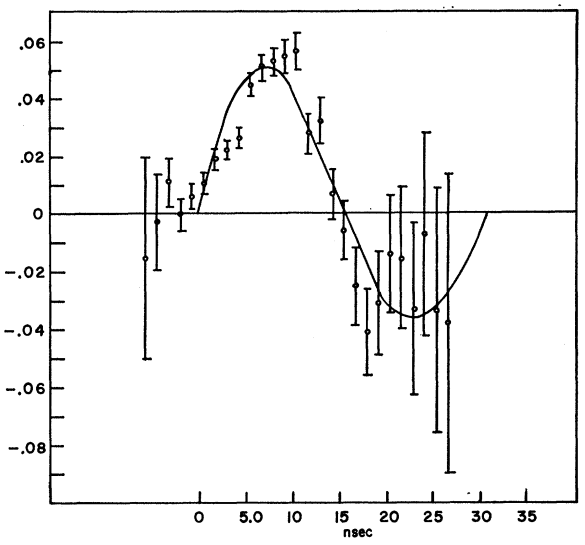

FIG. 5. Precession of the 329- to 487-keV angular correlation versus time. The solid line is a computer fit of an exponentially attenuated sine wave to the data. $B_2e^{-\lambda_2 t}\sin 2\omega t$.

V. CONCLUSIONS

Our value for g is in fair agreement with the recent values reported by other investigators (see Table I). This result is consistent with the assumption that the 2083-keV 4^+ state in Ce^{140} is essentially a 2-proton state $(g_{7/2},d_{5/2})$ the Schmidt value for this configuration is $g=0.95$, for $(g_{7/2},f_{7/2})g=0.49$ and for $(d_{5/2},d_{5/2})g=1.91$.

If, instead of the Schmidt values, we take the average empirical g factors, we obtain $g=0.90$ for $(g_{7/2},d_{5/2})$, $g=1.4$ for $(d_{5/2},d_{5/2})$, and $g=0.70$ for $(g_{7/2},g_{7/2})$; thus the $(g_{7/2},d_{5/2})$ configuration is still the most probable.

This interpretation is also consistent with the lifetimes of this 4^+ and the first 2^+ states. The $2^+\rightarrow 0^+$ transition is 7 times faster than single-proton estimate, while the $4^+\rightarrow 2^+$ is retarded by a factor of 17;[1] thus the 2^+ state is essentially collective while the 4^+ state is a two-proton state.

ACKNOWLEDGMENT

Some of the equipment for this study was built by M. Deutsch. We would like to thank him for its use and express our appreciation for his continued interest in this work.

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[10] J. Kanamori and K. Sugimoto, J. Phys. Soc. Japan **13**, 754 (1958); W. Kundig, Helv. Phys. Acta **34**, 125 (1961); G. Goldring and R. P. Scharenberg, Phys. Rev. **110**, 701 (1958); G. Manning and J. D. Rogers, Nucl. Phys. **15**, 166 (1960); R. Steining and M. Deutsch, Phys. Rev. **121**, 1484 (1961).

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