Influence of l Forbiddenness on the 82-kev Transition in Cs^{133}†*

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The gamma-gamma directional correlation of the 356–82-kev cascade in Cs^{133} was measured. The directional correlation coefficients were $A_2/A_0=0.031\pm0.006$ and $A_4/A_0=-0.006\pm0.010$. This is consistent with a spin assignment $\frac{1}{2}(Q)\frac{5}{2}(D+Q)\frac{7}{2}$. The ratio of the $E2$ to $M1$ matrix elements for the 82-kev transition is $\delta=-0.139\pm0.007$. The $M1$ transition is retarded by a factor of ~700 and the $E2$ transition is enhanced by a factor of ~20, compared to single particle transitions. The retardation of the $M1$ transition is consistent with the assignment $d\frac{5}{2}$ for the 82-kev state and $g\frac{7}{2}$ for the ground state which would make the $M1$ transition l forbidden. The enhancement of the $E2$ transition indicates there is a cooperative phenomenon present.

INTRODUCTION

THE first excited state of Cs^{133} decays to the ground state by the emission of an 82-kev gamma ray. According to shell model predictions, this transition occurs between a $d\frac{5}{2}(+)$ orbit and a $g\frac{7}{2}(+)$ orbit. With a spin change $\Delta I=1$ and no parity change, one would expect the radiation to be magnetic dipole. However, since the change in orbital angular momentum is $\Delta l=2$, this is a so-called l-forbidden transition, and the matrix element would be strictly zero if it were not for configuration mixing and higher order terms involving spin. One then expects that electric quadrupole radiation may compete favorably with the magnetic dipole radiation.

An accurate measurement of the conversion coefficient might possibly give an indication of the amount of $E2$ admixture. However, the conversion coefficients in retarded, transitions depend (maybe as much as 20%) on the nuclear matrix elements[1]; and since the nuclear matrix elements are not accurately known, the multipolarity of a gamma ray cannot accurately be determined in this manner.

In order to make any comparisons between observed values of the lifetime and conversion coefficients and the predicted values, the ratio of the intensities of the $E2$ radiation to the $M1$ radiation must be determined. In the decay of Ba^{133} if one assumes that the spin sequence for the 356–82-kev cascade is $\frac{1}{2}-\frac{5}{2}-\frac{7}{2}$,[2] then the $E2$ admixture in the 82-kev transition can be uniquely determined by means of a directional correlation measurement.

DIRECTIONAL CORRELATION OF THE 356-KEV–82-KEV CASCADE

The 356-kev transition most likely occurs between an $s\frac{1}{2}(+)$ state and a $d\frac{5}{2}(+)$ state,[2] and hence, is pure $E2$ radiation. The 82-kev transition occurs between the $d\frac{5}{2}(+)$ state and a $g\frac{7}{2}(+)$ state and can be considered as an unknown mixture of $E2$ and $M1$ radiation. A directional correlation measurement between these two gamma rays can be expressed as

$$w(\theta)=1+(A_2/A_0)P_2(\cos\theta)+(A_4/A_0)P_4(\cos\theta),$$

where $P_\nu(\cos\theta)$ is the Legendre polynomial of order ν, and A_ν/A_0 is a coefficient which can be experimentally determined. These coefficients may be calculated in terms of δ, which is the ratio of the $E2$ to $M1$ matrix elements for the 82-kev gamma ray, the spins of the three nuclear levels involved, and the multipolarity of the 356-kev gamma ray. The only quantity that is not already known is δ.

The source material, in the form of unenriched $BaCl_2$, was placed in a hollow cylinder made of 0.001-inch Mylar. The cylinder was 1 inch long and 0.036 inch in diameter. The probability for scattering of the 82-kev gamma ray in the source itself was estimated to be only 3–4%, and thus the correlation would not be appreciably attenuated due to scattering. The absorption of the 82-kev gamma ray due to the photoelectric effect would be greater than this, but for these events the gamma ray is completely absorbed and cannot be scattered.

The measured coefficients, after correcting for finite solid angle according to the method of Rose,[3] were $A_2/A_0=+0.031\pm0.006$ and $A_4/A_0=-0.006\pm0.010$. The results of this measurement are shown in Fig. 1. The asymmetry of the correlation, i.e., $A=w(\pi)/w(\pi/2)$, was also measured with the source in an aqueous solution. This was done to insure that the nuclei were not being re-oriented while in the intermediate nuclear state due to an electric quadrupole interaction and consequently causing the measured asymmetry to be lowered. For this measurement the source was placed in a thin glass tube about 1 inch long and 0.040 inch in diameter. The measured asymmetry, not correcting for geometry, was $A_{\text{liquid}}=1.053\pm0.010$. This value is to be compared with the measured asymmetry using the solid source and the same geom-

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* A preliminary report of this work was presented at the May, 1958 American Physical Society meeting in Washington, D. C. [Bull. Am. Phys. Soc. 3, 208 (1958)].
[1] G. Church and J. Weneser, Phys. Rev. **104**, 1382 (1956); M. E. Rose and T. A. Green, Phys. Rev. **110**, 105 (1958); L. S. Kisslinger, Phys. Rev. **114**, 292 (1959).
[2] M. G. Stewart and D. C. Lu, preceding paper [Phys. Rev. **117**, 1044 (1960)].
[3] M. E. Rose, Phys. Rev. **91**, 610 (1953).

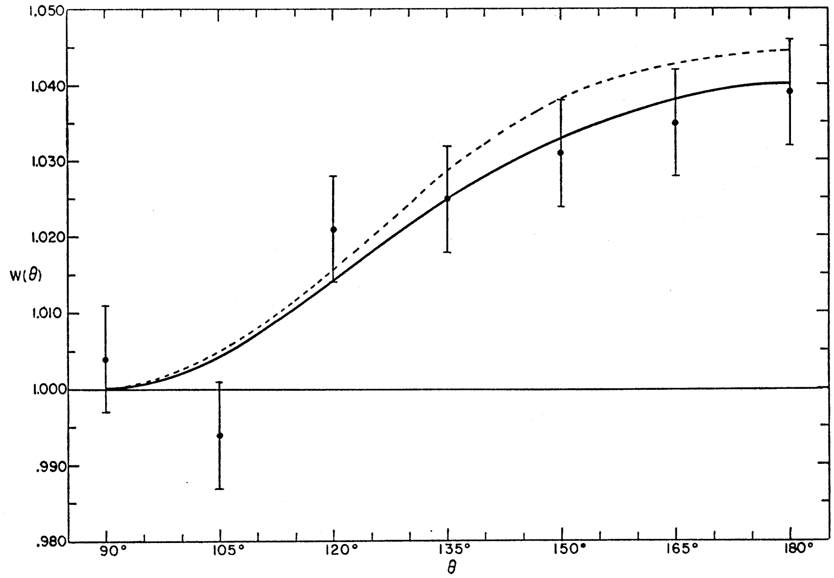

FIG. 1. Directional correlation of the 356–82-kev cascade. The solid curve is a least squares fit to the experimental points. The dashed curve has been corrected for the finite geometry.

etry. For this case, $A_{\text{solid}} = 1.040 \pm 0.010$. Although the asymmetry using the solid source is somewhat lower, the two measurements agree within statistics, and thus one can conclude that there are no serious perturbations during the time the nucleus is in the intermediate state. Even though the half-life of this state is fairly long, namely 6.0×10^{-9} second,[4] this result is reasonable since it is known that the quadrupole moment of the ground state of Cs^{133} is extremely small. It has been measured by Buck *et al.*[5] to have a value of $-(0.33 \pm 0.39) \times 10^{-26}$ cm^2, and it might be expected that the quadrupole moment of the 82-kev state is also small.

If the 82-kev gamma ray were entirely $M1$ radiation, the directional correlation coefficients would be $A_2/A_0 = -0.0714$ and $A_4/A_0 = 0.0$. Since the measured value of A_2/A_0 is $+0.031 \pm 0.006$, the 82-kev transition must be a mixture of $M1$ and $E2$ radiation. In Fig. 2 the coefficients A_2/A_0 and A_4/A_0 are plotted as a function of δ, the ratio of the $E2$ to $M1$ matrix elements. There are two curves for A_2/A_0; one for positive values of δ and one for negative values of δ. A_4/A_0 depends only upon δ^2 so there is only one curve for this coefficient. It is seen that there are two values of δ which are consistent with the measured value of A_2/A_0. These

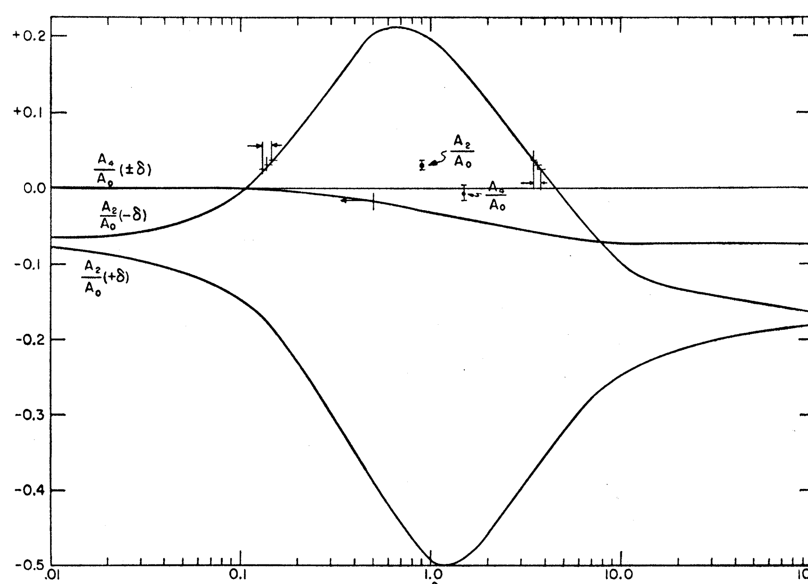

FIG. 2. The angular distribution coefficients for the 356–82-kev cascade plotted as a function of δ, the ratio of the $E2$ to $M1$ matrix elements for the 82-kev transition.

[4] R. L. Graham and R. E. Bell, Can. J. Phys. **31**, 377 (1953); P. Lehman and J. Miller, Compt. rend. **240**, 1525 (1955). A similar measurement in this laboratory gave the same result.
[5] P. Buck, I. I. Rabi, and B. Senitzky, Phys. Rev. **104**, 553 (1956).

TABLE I. Conversion coefficients for the 82-kev transition in Cs^{133}.

α_K	$\frac{\alpha_K}{\alpha_L+\alpha_M}$	Source used	Reference
1.51±0.15	4.90±0.15	Xe^{133}	a
1.47±0.05		Xe^{133}	b
1.77±0.15	6.0 ±?	Xe^{133}	c
1.3 ±0.5	7.5 ±0.5	Ba^{133}	d
1.40	5.7 ±0.5	Theoretical	e, g
1.39	5.1 ±0.5	Theoretical	f, g

[a] I. Bergström, footnote 6.
[b] I. Bergström *et al.*, footnote 7.
[c] R. L. Graham and R. E. Bell, footnote 4.
[d] B. Crasemann, J. G. Pengra, and I. E. Lindstrom, footnote 8.
[e] M. E. Rose, *Internal Conversion Coefficients* (Interscience Publishers, Inc., New York, 1958). The M-conversion coefficient does not include finite nuclear size effects. An estimate of the effect of screening for α_M was taken into account by reducing the calculated α_M by 25%. The large error in the theoretical $K/(L+M)$ ratio is due to the uncertainty of α_M.
[f] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57ICCK1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)]; Leningrad Physico-Technical Institute Report, 1958 [translation: Report 58ICCL1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].
[g] Calculated for a 98.1% $M1+1.9\%$ $E2$ transition.

are $\delta=-0.139\pm0.007$ and $\delta=-0.65\pm0.15$, representing mixtures of 98.1% $M1+1.9\%$ $E2$, and 7% $M1+93\%$ $E2$, respectively. The A_4/A_0 coefficient can be used to determine the correct value of δ. It is seen from Fig. 2 that the highest value of $|\delta|$ consistent with the experimental A_4/A_0 is 0.4. Thus δ is uniquely determined and is -0.139.

CONVERSION COEFFICIENTS

Since the multipolarity of this gamma ray is now known, it is of interest to calculate the conversion coefficients for this transition and compare them to the measured values. Table I is a summary of the more recent measured values of the conversion coefficients for the 82-kev transition. The theoretical conversion coefficients for a 98.1% $M1+1.9\%$ $E2$, 82-kev transition for $Z=55$ are also listed. The measured values of Bergström *et al.*[6,7] are in agreement with the theoretical values. The K-conversion coefficient as measured by Bell and Graham,[4] and the $K/L+M$ ratio as measured by Crasemann *et al.*[8] are high with respect to the theoretical values.

TRANSITION PROBABILITIES

The estimate of the transition probability of a single proton has been given by Moszkowski.[9] The experimental half-life $\tau_{\frac{1}{2}}$ is related to the gamma-ray transition probability for pure multipole emission by

$$T_\gamma=0.693[\tau_{\frac{1}{2}}(1+\alpha)]^{-1},$$

where α is the total conversion coefficient. Since the total transition probability is the sum of the transition probabilities for each multipole order, we have for a mixed $M1+E2$ transition

$$T_\gamma(E2)=T_\gamma\cdot\delta^2(1+\delta^2)^{-1},$$

and

$$T_\gamma(M1)=T_\gamma\cdot(1+\delta^2)^{-1},$$

where δ is the ratio of the $E2$ to $M1$ matrix elements. The half-life of the 82-kev state in Cs^{133} is $6.0\pm0.4\times10^{-9}$ sec, and the total conversion coefficient is 1.77 ± 0.05. Thus $T_\gamma(E2)=(7.8\pm0.7)\times10^5$ sec^{-1} and $T_\gamma(M1)=(4.1\pm0.3)\times10^7$ sec^{-1}. In terms of the reduced transition probability[10] these become

$$B(E2)=(1.6\pm0.1)\times10^{-50}\ e^2\ \mathrm{cm}^4,$$

and

$$B(M1)=(3.2\pm0.2)\times10^{-28}\ e^2\ \mathrm{cm}^2.$$

From work on the Coulomb excitation of Cs^{133}, Fagg[11] gives a value for $B(E2)$ in terms of the total conversion coefficient for the 82-kev transition. By using the value $\alpha_{\mathrm{total}}=1.77$ and multiplying by a factor of 0.75, which is a statistical factor that takes into account the different directions for the excitation and decay of the 82-kev state, his value for the reduced transition probability becomes $B(E2)=(1.8\pm0.4)\times10^{-50}\ e^2\ \mathrm{cm}^4$, which is in agreement with our value.

Compared to the estimates for the single-particle transitions, we have

$$\frac{B(E2)_{\mathrm{s.p.}}}{B(E2)_{\mathrm{observed}}}=\frac{1}{21},$$

and

$$\frac{B(M1)_{\mathrm{s.p.}}}{B(M1)_{\mathrm{observed}}}=711.$$

The $M1$ portion of this transition is retarded by a factor of ~700 from single-particle estimates which is in agreement with the interpretation that the orbital angular momentum changes by two units. The $E2$ portion is enhanced by a factor of ~20 compared to a single-particle transition. Thus some cooperative phenomenon is exhibited. This is about three times the enhancement that is observed, for example, in the 197-kev $E2$ transition in F^{19}.

SUMMARY AND CONCLUSIONS

From the directional correlation measurement of the 356–82-kev cascade in Cs^{133}, the 82-kev gamma ray is found to be an admixture of 98.1% $M1+1.9\%$ $E2$ radiation assuming a spin sequence of $\frac{1}{2}-\frac{5}{2}-\frac{7}{2}$.

With a knowledge of the half-life and the total

[6] I. Bergström, Arkiv Fysik **5**, 191 (1952).
[7] I. Bergström, S. Thulin, A. H. Wapstra, and B. Åström, Arkiv Fysik **7**, 255 (1954).
[8] B. Crasemann, J. G. Pengra, and I. E. Lindstrom, Phys. Rev. **108**, 1500 (1957).
[9] S. A. Moszkowski in *Beta- and Gamma-Ray Spectroscopy* edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. XIII.
[10] Defined in footnote 9, p. 394.
[11] L. W. Fagg, Phys. Rev. **109**, 100 (1958).

conversion coefficient of the 82-kev transition, the $M1$ and $E2$ transition probabilities may be calculated. Compared to single-particle estimates, the $M1$ transition is retarded by a factor of $\sim$700 and the $E2$ transition is enhanced by a factor of $\sim$20. This is in agreement with the assignment of $d\frac{5}{2}$ to the 82-kev state and $g\frac{7}{2}$ to the ground state which would make an $M1$ transition l forbidden. The fact that the $E2$ transition is enhanced suggests that there is some cooperative phenomenon present in spite of the fact that Cs^{133} has an extremely small electric quadrupole moment. It is interesting to note that the enhanced $E2$ transitions are usually associated with nuclei which have large quadrupole moments, such as in the rare earth region where the quadrupole moments may be as much as a thousand times larger than the quadrupole moment of Cs^{133}.

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Total Neutron Cross Section for C^{12} from 500 kev to 1350 kev*

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The total neutron cross section of C^{12} has been measured in an effort to observe resonances corresponding to states recently reported in the $B^{11}(He^3,p)C^{13}$ reactions. No resonances were observed within the 5% accuracy of the measurement. Upper limits are set on the possible widths of the states.

THE results of recent measurements[1] of the proton energy spectrum from the reaction $B^{11}(He^3,p)C^{13}$ clearly indicate two weak proton groups that cannot be accounted for by known states in C^{13}. Although the possibility that the two proton groups may arise from the reaction $B^{11}(He^3,pn)C^{12}$ cannot be excluded, the data can be interpreted as indicating the existence of two previously undetected levels in C^{13} at excitation energies of 5.51 Mev and 6.10 Mev. Since these levels have not been observed in the total neutron cross-section measurements of C^{12}, it must be concluded that, if they exist, they are narrow states. The reported energy spread[2] in the earlier cross-section measurements was approximately 12–20 kev in the energy region of interest. To provide additional information concerning the existence of these states or to set upper limits on their widths, it was decided to repeat the measurements of the total neutron cross section of C^{12} with better energy resolution and with the greater sensitivity provided by the self-indication technique.[3]

Transmission measurements were made over a range of neutron energies that comfortably span the resonant energies suggested by $B^{11}(He^3,p)$ results. Neutrons were produced by the $Li(p,n)$ reaction. A fresh target was evaporated each day, and threshold curves were taken at the beginning and end of each day. The threshold curves indicate that the neutron energy spread was less than 5 kev over most of the range of neutron energies covered.[4] Transmission measurements were made at 1-kev intervals over each of two ranges of about 200 kev centered about the two expected resonant energies, and at 2-kev intervals elsewhere.

A single transmission sample was used throughout the experiment. It consisted of a cylinder of pile-grade graphite 1.5 in. in diameter and 0.9 in. thick. The detector sample was a flat plate of pile-grade graphite 3 in.$\times$7 in.$\times\frac{1}{2}$ in. thick.

Figure 1 shows the results of the total cross-section measurements. If they are observable, resonances should be found at neutron energies in the vicinity of 610 kev and 1250 kev. No resonance was detected with a peak height greater than 0.3 barn (5% transmission) above the smooth trend observed for the measured cross section. If one assumes a flat energy resolution

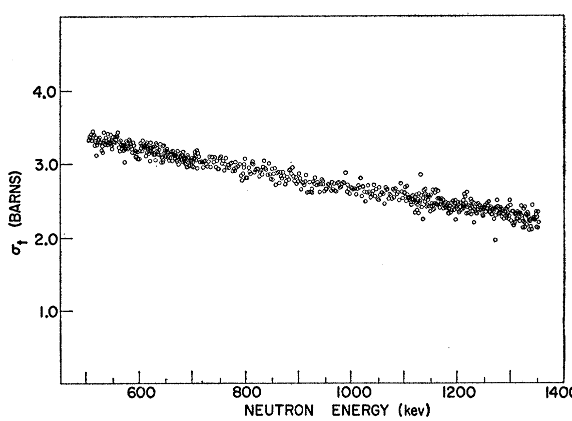

FIG. 1. Total neutron cross section of carbon as a function of neutron energy. Neutron energy spread was 5 kev or less for most of the points. The rms error in the values for the cross section is 2.7%.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

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[2] D. W. Miller, Phys. Rev. **78**, 806 (1950).

[3] J. E. Monahan and A. Langsdorf, Jr., Phys. Rev. **98**, 1147(A) (1955); A. Langsdorf, Jr., J. E. Monahan, and F. P. Mooring, Phys. Rev. **98**, 1148(A) (1955); see also C. W. Kimball, thesis, St. Louis University, 1958 (unpublished).

[4] A. O. Hanson, R. F. Taschek, and J. H. Williams, Revs. Modern Phys. **21**, 635 (1949); J. E. Monahan and F. P. Mooring (to be published).