Gamma-Gamma Directional Correlations in Cs^{133}†

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Directional correlation measurements have been made on the 356—82 kev, 301—82 kev, and 80—82 kev gamma-gamma cascades in Cs^{133} following the decay of 8-year half-life Ba^{133} with a coincidence scintillation spectrometer using NaI detectors. The observed correlation functions are:

$$W(\theta)=1+(0.042\pm0.005)P_2(\cos\theta)-(0.0041\pm0.0038)P_4(\cos\theta),$$
$$W(\theta)=1-(0.0257\pm0.011)P_2(\cos\theta)-(0.0002\pm0.008)P_4(\cos\theta),$$

and

$$W(\theta)=1+(0.0487\pm0.017)P_2(\cos\theta)+(0.0011\pm0.012)P_4(\cos\theta),$$

respectively, for the three cascades. These gamma-gamma directional correlations were found to be consistent with spin assignments of $\frac{7}{2}+$, $\frac{5}{2}+$, $\frac{3}{2}+$, $\frac{3}{2}+$, and $\frac{1}{2}+$ to the levels at the ground state, 82-kev, 162-kev, 383-kev, and 438-kev in Cs^{133}. The probable assignment of the multipolarities for different gamma rays is as follows: The 356-kev gamma ray is pure $E2$. The 82-kev gamma ray is a mixture of $(96.5\pm0.5)\%$ $M1$ and $(3.5\pm0.5)\%$ $E2$ with $\delta_{82}=-0.190\pm0.014$. The 301-kev gamma ray can have one of two possible mixtures: either $\delta_{301}=+0.123\pm0.004$ with a mixture of $(98.5\pm1.0)\%$ $M1$ and $(1.5\pm1.0)\%$ $E2$, or $\delta_{301}=-3.98\pm1.02$ with a mixture of $(6\pm2)\%$ $M1$ and $(94\pm2)\%$ $E2$. The value of $\delta_{301}=-3.98\pm1.02$ is more probable. The 80-kev gamma ray is also found to have two possible values of δ_{80}: either $\delta_{80}=+0.47\pm0.09$ with a mixture of $(82\pm6)\%$ $M1$ and $(18\pm6)\%$ $E2$, or $\delta_{80}=+7.0$ with a mixture of $(2.0\pm1.5)\%$ $M1$ and $(98.0\pm1.5)\%$ $E2$.

INTRODUCTION

THE electron capture decay of Ba^{133}, 8-year half-life, has been studied by several authors.[1–7] The most recently suggested decay schemes are those by Stewart and Lu,[6] and Ramaswamy *et al.*[7] The two decay schemes completely agree except for the gamma rays of energies 386 kev and 162 kev, and the electron capture leading to the excited state at 162 kev in Cs^{133}, which has been observed by Stewart and Lu[6] and not by Ramaswamy *et al.*[7] The decay scheme after Stewart and Lu[6] is shown in Fig. 1. There are no discrepancies involved as far as the gamma rays of interest are concerned in the present work. The 13% of the electron capture of Ba^{133} leading to the 162-kev excited level in Cs^{133} have been observed by Stewart and Lu,[6] but not by Ramaswamy *et al.*[7] who have found only two groups of electron capture, one with 70% leading to the 438-kev level and the other 30% to the 383-kev level. On the basis of the absence of the electron capture of Ba^{133} leading to the excited state at 162 kev in $_{55}Cs^{133}$, they have assigned a spin of $\frac{5}{2}+$ instead of $\frac{3}{2}+$ to the 162-kev level.

The ground state of $_{55}Cs^{133}$ has been measured[8] to be $\frac{7}{2}$, in agreement with the shell-model prediction of $g_{7/2}$.[9] The spin assignments to the other excited levels in Cs^{133} as shown in Fig. 1, are after Stewart and Lu.[6] The ground state of $_{56}Ba^{133}$ has a spin $\frac{1}{2}+$,[10] from systematics of the isomerism of this isotope, and agrees with the shell-model prediction of $s_{\frac{1}{2}}$.

The conversion coefficient and $K/(L+M)$ ratio measurements for different gamma rays have been

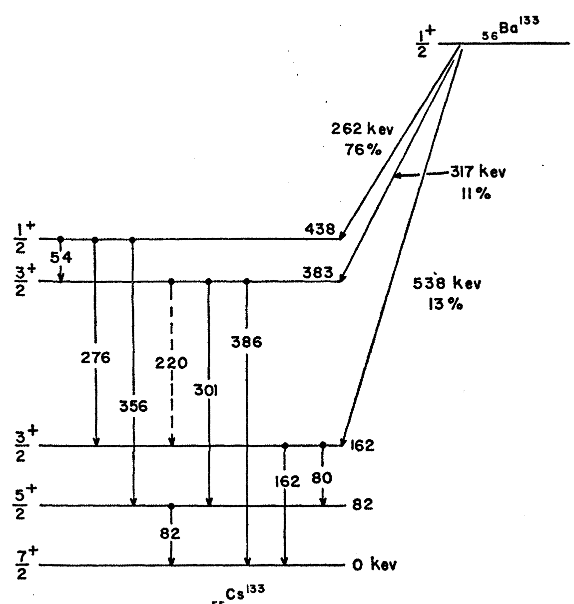

FIG. 1. Decay scheme of Ba^{133} (after Stewart and Lu[6]).

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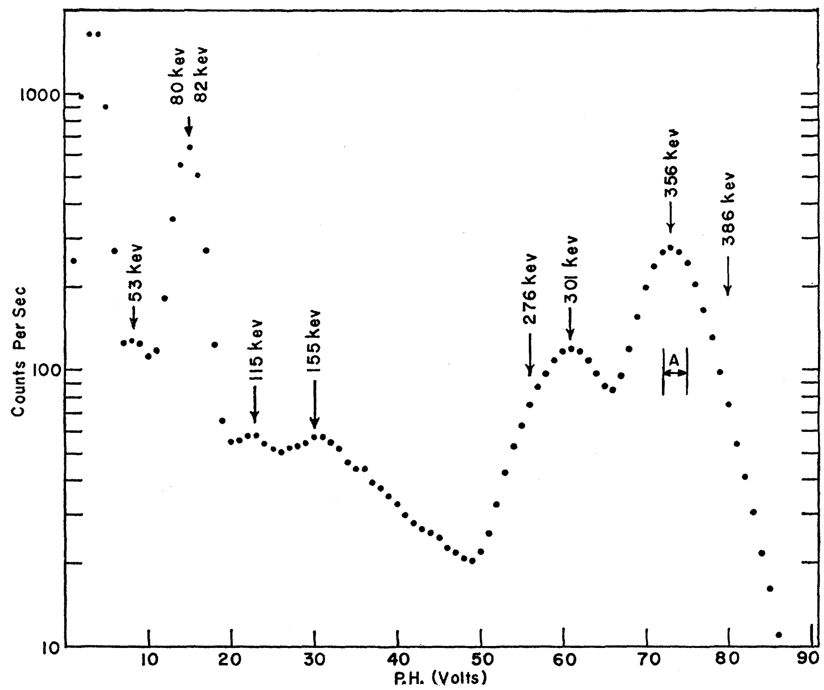

FIG. 2. Scintillation spectrum of the gamma rays following the decay of Ba^{133}.

carried out by several authors.[3,4,11–13] The results indicate that the 82-kev gamma ray is mostly $M1$ and may contain a small mixture of $E2$ (about 2% $E2$). The conversion coefficient measurements of other gamma rays are not very definite.

The gamma-gamma directional correlations of the 356—82 kev cascade in Cs^{133} have been measured by Clikeman and Stewart[14] and their results are:

$$A_2/A_0=+0.031\pm0.006,\quad A_4/A_0=-0.006\pm0.010.$$

The sample used was in the form of solid unenriched $BaCl_2$. We repeated this correlation using source material in the form of a liquid. The results obtained, though slightly higher, are quite in agreement within the statistics.

EXPERIMENTAL PROCEDURE

A conventional slow scintillation coincidence spectrometer was used throughout these experiments. The coincidence circuit had a resolving time of $2\tau\approx2.1$ μsec. The scintillation counter consisted of a 2-inch×2-inch NaI(Tl) crystal mounted on a RCA-6342 photomultiplier tube. A differential discriminator was used for energy selection.

Ba^{133} produced in fission was obtained from Oak Ridge and was in the form of HCl solution. The source was placed in a thin glass tube about 1 inch long and 0.027 inch in diameter. The strength of the sample used was about 0.1 microcurie. As the results of the correlation measurements of the 356—82 kev gamma cascade using a solid source[14] agree, within statistics, with those of the liquid source, the correlations should not be attenuated due to the extranuclear fields.

Figure 2 shows the single spectrum of Ba^{133}, while Fig. 3 and Fig. 4 show the coincidence spectrum of the three cascades of interest. The data were taken at intervals of 15° from 90° to 180°. The angle between the detectors was changed after every five minutes. Decentering of the sample was not allowed to be more than 1%. Any small decentering was corrected by dividing the true coincidence rate N_T by the single counting rates N_1 and N_2, i.e., N_T/N_1N_2.

A least-squares fit of the data was made to the function $w(\theta)=1+(a_2/a_0)\cos^2\theta+(a_4/a_0)\cos^4\theta$. Then the corresponding values of the coefficients A_2 and A_4 in the expansion $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ were calculated. These values of the coefficients were corrected for the finite angular resolution,[15] and the values of A_2 and A_4 were obtained.

The coefficients A_2 and A_4 can be written as $A_k=A_k^{(1)}A_k^{(2)}$, where $k=0$, 2, 4, etc., and each of these coefficients $A_k^{(\nu)}$ depend on the single gamma-ray transition in the cascade.[16]

The mixing parameter δ is defined as the ratio of the reduced matrix elements β and α for quadrupole and dipole radiation, respectively.[16] If $\delta=\beta/\alpha$, then δ^2 is equal to the ratio of the intensities of quadrupole and

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dipole radiation. Q, the quadrupole content, will be equal to $\delta^2/(1+\delta^2)$, and the dipole content will be $(1-Q)$.

RESULTS

356—82 kev Correlation

One differential discriminator was set at a photopeak of the 356-kev gamma ray as shown in Fig. 2, while the other was set to accept the photopeak of the 82-kev gamma ray. The plot of the correlation is shown in Fig. 5. The results obtained for the coefficients after correcting for geometry are:

$$A_2=+0.0420\pm0.0050,$$
$$A_4=-0.0041\pm0.0038,$$
$$A=+0.0618\pm0.007\ .$$

These results are in agreement with those obtained by Clikeman and Stewart[14] within the statistics. The values of the coefficients and the anisotropy are slightly higher as compared with the values obtained by Clikeman and Stewart[14] using a solid sample, but agree with the value of the anisotropy obtained by them using a liquid sample. The sign on the value of A_4 is more definite in the present work because the error on A_4 is smaller than its absolute value.

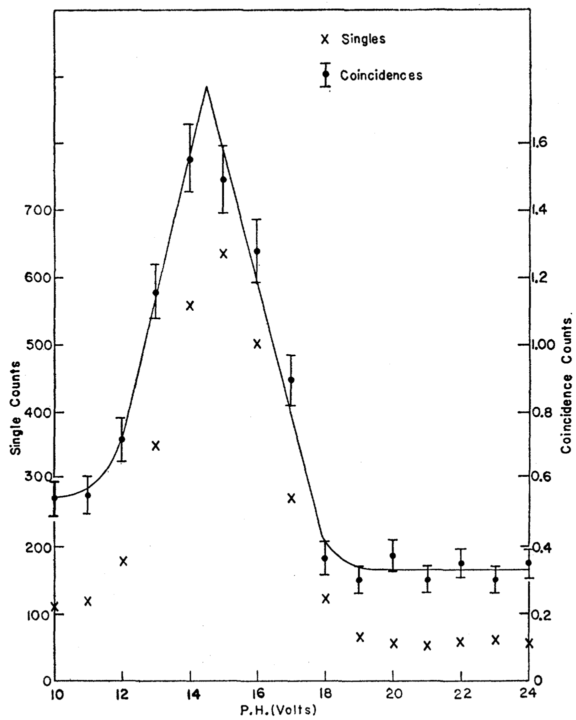

FIG. 4. Coincidence spectrum of the 82-kev and the 80-kev gamma rays.

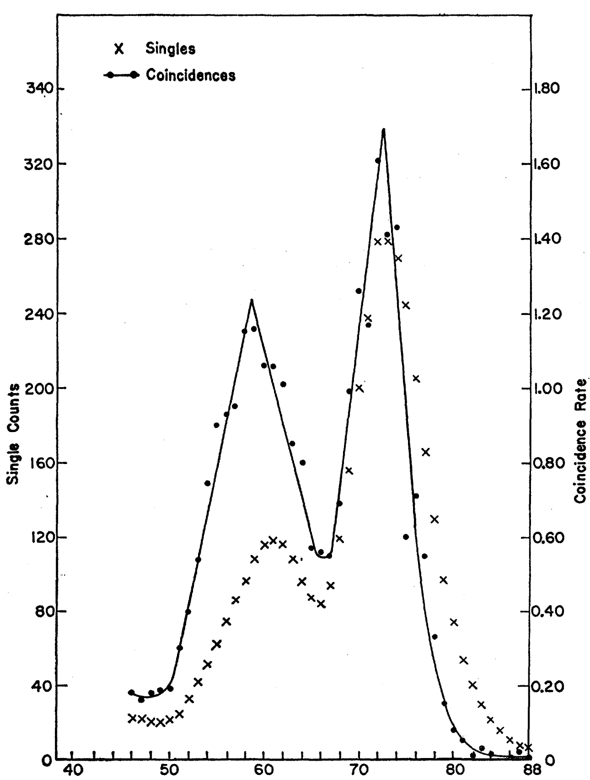

FIG. 3. Coincidence spectrum of the 82-kev gamma ray with the 301-kev and the 356-kev gamma rays.

301—82 kev Correlation

If we set the two discriminators at the two corresponding photopeaks, then there will always be some contribution of the 301-kev peak from the 356-kev gamma ray which is in coincidence with the 82-kev gamma ray. Hence, the correlation obtained will not be the true correlation. The following method was used for obtaining this correlation.

One of the discriminators was fixed at the photopeak of the 82-kev gamma ray, while the other was set at the photopeak of the 301-kev gamma ray. The correlation obtained is denoted by $W(\theta)$ and is shown in Fig. 6.

$$W(\theta)=\frac{N_{356}(\theta)+N_{301}(\theta)}{N_{356}(90°)+N_{301}(90°)},\qquad(1)$$

where $N_{356}(\theta)$ = the coincidence rate between the 356-kev and the 82-kev gamma rays at an angle θ; $N_{301}(\theta)$ = the coincidence rate between the 301-kev and the 82-kev gamma rays at an angle θ; and $N_{356}(90°)$, $N_{301}(90°)$ denote the coincidence rates of the 356-kev and the 301-kev gamma rays, respectively, with the 82-kev gamma ray at 90°.

Equation (1) can be written [dividing the numerator and the denominator of the right-hand side by $N_{356}(90°)$] as

$$\left(\frac{N_{356}(\theta)}{N_{356}(90°)}+\frac{N_{301}(\theta)}{N_{356}(90°)}\right)\Big/\left(1+\frac{N_{301}(90°)}{N_{356}(90°)}\right)=W(\theta),$$

or

$$\left(\frac{N_{356}(\theta)}{N_{356}(90^\circ)}+\frac{N_{301}(\theta)}{N_{301}(90^\circ)}\frac{N_{301}(90^\circ)}{N_{356}(90^\circ)}\right)\Big/\left(1+\frac{N_{301}(90^\circ)}{N_{356}(90^\circ)}\right)=W(\theta),$$

or

$$\frac{W_{\mathrm{I}}(\theta)+W_{\mathrm{II}}(\theta)E}{1+E}=W(\theta),$$

where $W_{\mathrm{I}}(\theta)=N_{356}(\theta)/N_{356}(90^\circ)$, $W_{\mathrm{II}}(\theta)=N_{301}(\theta)/N_{301}(90^\circ)$, and $E=N_{301}(90^\circ)/N_{356}(90^\circ)$. $W_{\mathrm{I}}(\theta)$ is known from the previous correlation, and E can be measured. Hence the value of $W_{\mathrm{II}}(\theta)$ can be calculated if $W(\theta)$ is known. To obtain the value of E, the extrapolation of the photopeaks of Au^{198} and Hg^{203} was used.

The experimental values of the coefficients A_2 and A_4 obtained by using the above method are:

$$A_2=0.0257\pm0.011,$$
$$A_4=0.0001\pm0.008,$$
$$A=0.0382\pm0.015.$$

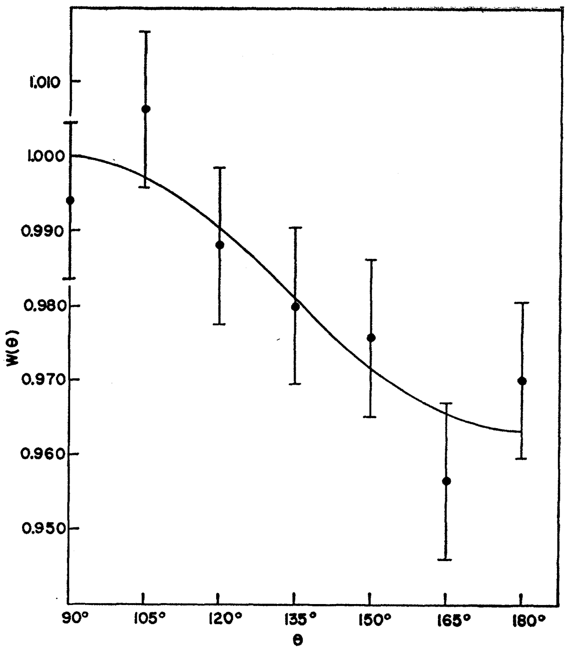

FIG. 6. Directional correlation of the (301+356)—82 kev cascades. Solid line is the least square fit of the experimental points. Flags indicate the standard deviation.

80—82 kev Correlation

The discriminator of each single spectrometer was set at the photopeaks of the 80-kev and the 82-kev gamma rays. The coincidence rate was obtained at different angles. But to this coincidence rate there is a contribution from the coincidences between the 82-kev gamma ray and the Compton tails of the higher energies gamma rays. The true coincidence rate for this correlation was obtained by subtracting this extra contribution as background (Fig. 3).

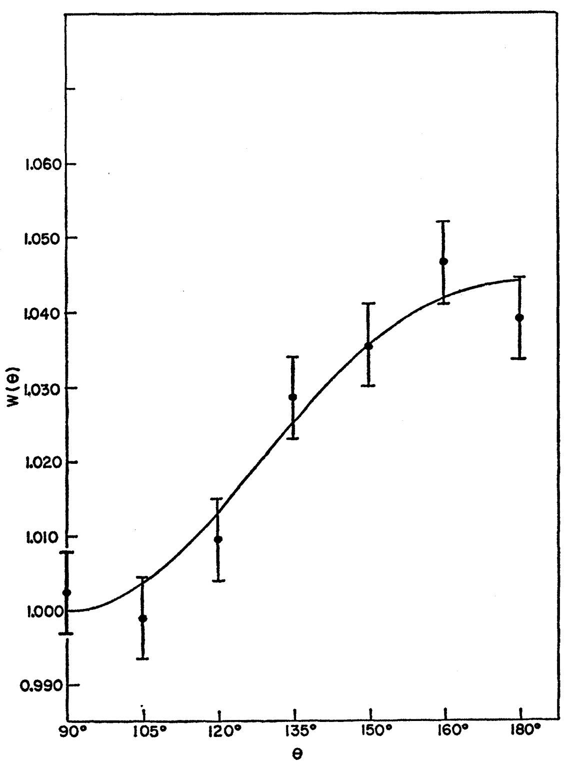

FIG. 5. Directional correlation of the 356—82 kev cascade. Solid line the least square fit of the experimental points. Flags indicate the standard deviation.

The results obtained for this correlation are:

$$A_2=+0.0487\pm0.0171,$$
$$A_4=+0.0010\pm0.0120,$$
$$A=+0.0754\pm0.0245.$$

The plot of the correlation after subtracting the background is shown in Fig. 7.

INTERPRETATION AND DISCUSSION

The ground-state spin of Cs^{133} has been measured[8] to be $\frac{7}{2}$, in agreement with the shell-model prediction of $g_{7/2}$.[9] On the basis of the log ft values for the transitions leading from the ground state of Ba^{133} to the excited levels in Cs^{133} at 438 kev, 383 kev, and 162 kev, as calculated by Stewart and Lu,[6] and the Coulomb excitation data given by Fagg[17]; the different states in Cs^{133} have been assigned spins by Stewart and Lu[6] as shown in Fig. 1. The assignment of spin $\frac{1}{2}^+$ to the level at 438 kev is still further confirmed by our correlation experiments on the 356—82 kev gamma cascade. From the allowed nature of the transition leading from the

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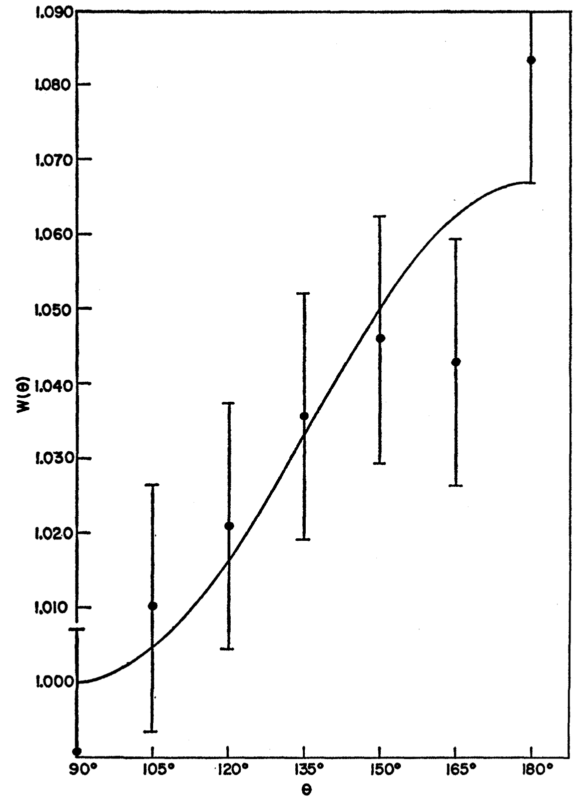

FIG. 7. Directional correlation of the 82—80 kev cascade. Solid line is the least square fit of the experimental points. Flags indicate the standard deviation.

ground state of $Ba^{133}(\frac{1}{2}+)$ to the 438-kev level, the spin of $\frac{1}{2}+$ or $\frac{3}{2}+$ is possible for this level. The assignment of $\frac{3}{2}+$ for the 438-kev level is eliminated on the grounds that it is not reached by Coulomb excitation of Cs^{133}. This assignment of $\frac{3}{2}+$ is also rejected on the grounds that it required A_4 to be positive for the 356—82 kev correlation, while experimentally it is found to be negative ($A_4=-0.0041\pm0.0038$).

The 356—82 kev correlation is explained by the sequence:

$$\frac{1+}{2} \xrightarrow[Q]{356} \frac{5+}{2} \xrightarrow[(D+Q)]{82} \frac{7+}{2}.$$

The experimental values of the coefficients are:

$$A_2^{\exp}=+0.0420\pm0.005,$$
$$A_4^{\exp}=-0.0041\pm0.0038.$$

The values of $A_2^{(1)}$ and $A_4^{(1)}$ for the quadrupole transition are obtained from the table of F coefficients[18]:

$$A_2^{(1)}=-0.5345,$$
$$A_4^{(1)}=-0.6172.$$

[18] M. Ferentz and N. Rosenzweig, Argonne National Laboratory Report ANL-5324 (unpublished).

Therefore the experimental values of $A_2^{(2)}$ and $A_4^{(2)}$ for the second transition in the cascade are

$$A_2^{(2)\,\exp}=-0.0786\pm0.0094,$$
$$A_4^{(2)\,\exp}=+0.0065\pm0.0062.$$

The theoretical plot of $A_2^{(2)}$ and $A_4^{(2)}$ versus Q is shown in Fig. 8. From the plot of $A_2^{(2)\,\exp}$ and $A_4^{(2)\,\exp}$, it is evident that the only value of Q for the 82-kev gamma ray which is consistent with the experimental values of these coefficients is

$$Q_{82}=0.035\pm0.005,$$

which gives

$$E2=(3.5\pm0.5)\%,$$
$$M1=(96.5\pm0.5)\%,$$
$$\delta_{82}=-0.190\pm0.014.$$

Knowing the value of the $E2$ mixture in $M1$ for the 82-kev gamma ray, we can find the mixture in the 301-kev gamma ray. The 301—82 kev correlation is explained by the sequence

$$\frac{3+}{2} \xrightarrow[(D+Q)]{301} \frac{5+}{2} \xrightarrow[(D+Q)]{82} \frac{7+}{2}.$$

The plot of $A_2^{(1)\,\exp}$ and $A_4^{(2)\,\exp}$ is shown in Fig. 9. This gives two values of Q for the 301-kev gamma transition:

$$Q_{301}=0.015\pm0.010, \qquad \delta_{301}=+0.123\pm0.004,$$

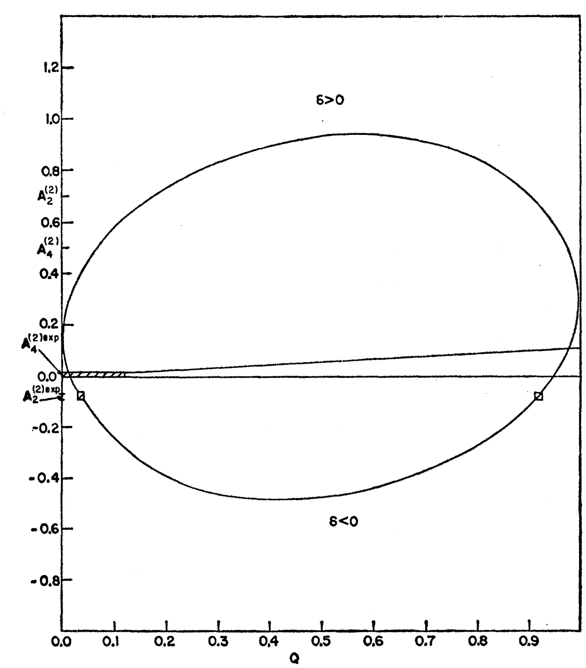

FIG. 8. $A_2^{(2)}$ and $A_4^{(2)}$ versus Q, the quadrupole intensity, for the 82-kev gamma ray $\frac{5}{2}+\rightarrow\frac{7}{2}+$. The shaded areas show the values of Q corresponding to the experimental values.

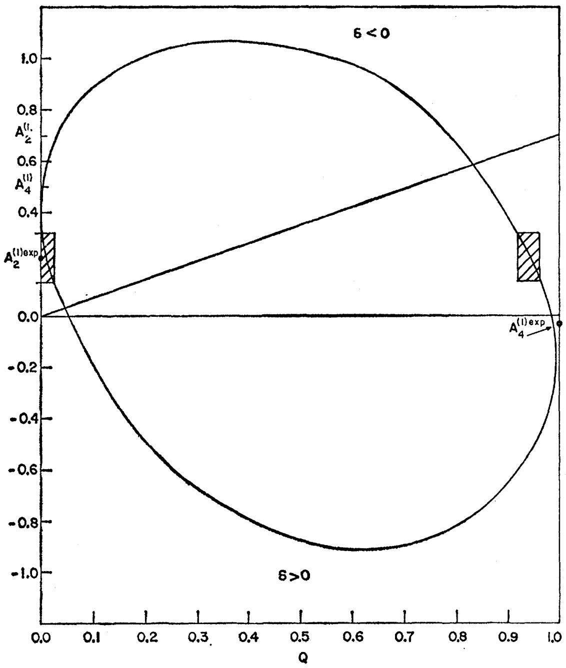

FIG. 9. $A_2^{(1)}$ and $A_4^{(1)}$ versus Q, the quadrupole intensity, for the 301-kev gamma ray $\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$. The shaded areas show the value of Q corresponding to the experimental value of $A_2^{(1)\mathrm{exp}}$. Value of $A_4^{(1)\mathrm{exp}}$ is such that any value of Q from 0 to 1 is possible (whole ellipse shaded).

and

$$Q_{301}=0.94\pm0.02, \qquad \delta_{301}=-3.98\pm1.02.$$

The value of $Q_{301}=0.015\pm0.010$ gives a mixture of $(98.5\pm1.0)\%M1$ and $(1.5\pm1.0)\%E2$, while the value $Q_{301}=0.94\pm0.02$ gives a mixture of $(6\pm2)\%M1$ and $(94\pm2)\%E2$. In the light of the fact that $E2$ transitions are unique in being, with few exceptions, considerably faster[19] than expected for a single-particle transition, when we compare the ratios of the intensities of $E2$ to $M1$ in the present case with the other experimentally found[19] values in this region of atomic number ($Z=56$), we find that the value of $Q_{301}=0.94\pm0.02$ is more probable. The value of $Q_{301}=+0.015\pm0.010$ cannot be completely rejected.

The 80—82 kev gamma-gamma correlation can be explained by the sequence

$$\frac{3^+}{2} \xrightarrow[D+Q]{80} \frac{5^+}{2} \xrightarrow[(D+Q)]{82} \frac{7^+}{2}.$$

The value of the mixture for the 80-kev transition can be found, as the value of δ_{82} for the 82-kev transition is known. The experimental values of the coefficients $A_2^{(1)\,\mathrm{exp}}$ and $A_4^{(1)\,\mathrm{exp}}$ are plotted in Fig. 10. In this case also, two values satisfy the experimental results:

$$Q_{80}=0.18\pm0.06, \qquad \delta_{80}=+0.47\pm0.09,$$

and

$$Q_{80}=0.980\pm0.015, \qquad \delta_{80}=+7.0\pm2.2.$$

The value of $Q_{80}=0.18\pm0.06$ gives a mixture of $(82\pm6)\%M1$ and $(18\pm6)\%E2$ while the value of $Q_{80}=0.98\pm0.015$ gives a mixture of $(2.0\pm1.5)\%M1$ and $(98\pm1.5)\%E2$. The comparison of the ratios of the intensities of $E2$ to $M1$ in the present case with the other experimentally found values in this region of atomic number, does not give a preference for one mixture over the other.

SUMMARY AND CONCLUSION

The ground-state spins of Ba^{133} and Cs^{133} are known and the spin assignments to the excited levels in Cs^{133} as suggested by Stewart and Lu[6] are shown in the decay scheme Fig. 1. The gamma-gamma directional correlations of the three different cascades in Cs^{133} are consistent with these spin assignments of $\frac{7}{2}^+$, $\frac{5}{2}^+$, $\frac{3}{2}^+$, $\frac{3}{2}^+$, and $\frac{1}{2}^+$ to the levels at the ground state, 82 kev, 162 kev, 383 kev, and 438 kev in Cs^{133}, respectively.

With the above suggested spin assignments, the multipolarity of the 356-kev gamma ray is $E2$[6] and the following multipolarities for the other gamma rays in Cs^{133} result from the gamma-gamma directional correlations. The 82-kev gamma ray is a mixture of

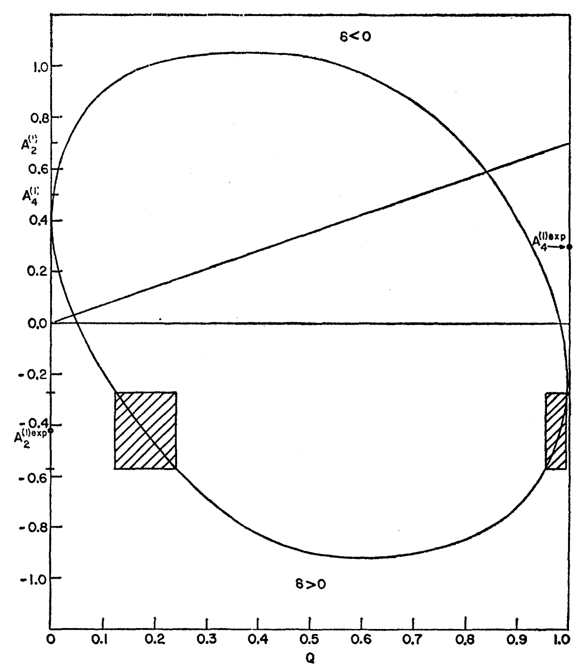

FIG. 10. $A_2^{(1)}$ and $A_4^{(1)}$ versus Q, the quadrupole intensity, for the 80-kev gamma ray $\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$. The shaded areas show the values of Q corresponding to the experimental value of $A_2^{(1)\mathrm{exp}}$. Value of $A_4^{(1)\mathrm{exp}}$ is such that any value of Q from 0 to 1 is possible (whole ellipse shaded).

[19] M. Goldhaber and A. W. Sunyar, in Beta- and Gamma-Ray Spectroscopy, edited by Kai Siegbahn (Interscience Publishers Inc., New York, 1955), p. 465.

(96.5±0.5)%$M1$ and (3.5±0.5)%$E2$ with $\delta_{82}=-0.190\pm0.014$. The 301-kev gamma ray can have one of the two possible mixtures: either $\delta_{301}=+0.123\pm0.004$ with a mixture of (98.5±1.0)%$M1$, and (1.5±1.0)%$E2$, or $\delta_{301}=-3.98\pm1.02$ with a mixture of (6±2)%$M1$ and (94±2)%$E2$. The value of $\delta_{301}=-3.98$ is more probable. The 80-kev gamma ray is also found to have two possible values of δ_{80}. Either $\delta_{80}=+0.47\pm0.09$ with a mixture of (82±6)%$M1$ and (18±6)%$E2$, or $\delta_{80}=+7.0$ with a mixture of (2.0±1.5)%$M1$ and (98.0±1.5)%$E2$.

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Decay of K^{42} and Sc^{44}†

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The low excited states of Ca^{42} and Ca^{44} have been studied in the decay of K^{42} and Sc^{44}, with special emphasis on the observation of weakly populated states. In the K^{42} decay, gamma rays have been seen at 0.31 Mev (1.1%), 0.49 Mev (<0.1%), 0.60 Mev (0.1%), 0.90 Mev (0.1%), 1.02 Mev (0.1%), 1.52 Mev (100%), 1.92 Mev (0.3%), and 2.42 Mev (0.2%). The coincidence sequence of the transitions has been measured and a level scheme constructed. In the Sc^{44} decay, gamma rays have been seen with energies and intensities of 0.68 Mev (3.2%), 1.02 Mev (3.1%), 1.12 Mev (4.7%), 1.16 Mev (100%), 1.50 Mev (1.7%), 1.72 Mev (0.8%), 2.28 Mev (0.2%), and 2.69 Mev (0.2%). Coincidence measurements were also taken for this isotope to clarify the cascade sequences, and a level scheme was constructed. A search was made for low-energy conversion electrons ($E<1$ Mev) in an effort to establish the existence or nonexistence of a low-lying 0^+ state in Ca^{44}, whose analog occurs as the second excited 1.84-Mev state in Ca^{42}. No such conversion electrons were seen, by either electron spectrometer studies or by electron-delayed gamma-ray coincidence measurements. An upper limit of 0.05% of the total decay of Sc^{44} was put on the population of such a state.

I. INTRODUCTION

NUCLEI that are within a few nucleons of being doubly magic are of special interest from a theoretical point of view. The interest stems from the ability of shell-model calculations to predict certain features of these nuclei in a straightforward manner. The Ca isotopes are of particular interest in this regard, since in the basic shell model they involve the coupling of the $f_{7/2}$ neutrons (between 20 and 28) with themselves, the 20 protons being a stable configuration. Several recent theoretical analyses[1–5] have had to rely on inadequate experimental information concerning the excited states of the Ca isotopes. The present effort is an attempt to obtain more information on the levels of Ca^{42} and Ca^{44} through a study of the decays of K^{42} and Sc^{44}. Although completely quantitative work was made difficult because the transitions of interest were extremely weak, enough new information has been obtained on a number of levels of Ca^{42} and Ca^{44} to clarify spin assignments, and in some cases to compare cascade-to-crossover transition probabilities.

The general features of the K^{42} decay have been summarized by Way *et al.*[6] The dominant decays are a 3.55-Mev beta transition (82%) to the ground state of Ca^{42}, and a 1.99-Mev transition to the first excited state of Ca^{42}. The 3.55-Mev beta-ray spectrum shape has been shown to be consistent with a unique first forbidden transition, and the log ft values of both decays indicate first forbiddenness. At the time this experiment was begun, only two gamma-ray transitions were known: the 1.52-Mev transition (100%) from the first excited state, and the 0.31-Mev line (~1%) from the second to the first excited state. During the course of this work two angular correlation measurements have been reported[7,8] for the 0.31–1.52-Mev gamma-ray cascade, and conversion electrons from the 1.84-Mev transition have been seen.[9] Both measurements very clearly indicate a 0-2-0 spin sequence. Three additional

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