Decay of Cs^{132}

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The singles and coincidence gamma-ray spectra of Cs^{132} have been investigated with scintillation spectrometers. Energies in keV (and relative intensities) of the gamma rays which were observed are 464(21±5), 509(5.1±1.5), 511(12±4), 569(2.7±0.8), 631(8.5±1.8), 669(1000±30), 1035(1.6±0.3), 1139(5.2±0.5), 1304(0.9±0.5), 1319(6.2±0.6), and 2000(0.53±0.06). From the results of these spectral studies and from gamma-gamma angular correlation measurements, it is proposed that Cs^{132} decays to levels with energies in keV (and spins) of 669±4(2+), 1300±10(2+), 1808±13(2 or 3), and 1988±12(2) in Xe^{132}, and 464±5(2+) and 1034±9(2+) in Ba^{132}. The ratios of the intensities of quadrupole to dipole radiation for the 631- and 1319-keV transitions in Xe^{132} and for the 569-keV transition in Ba^{132} were found to be 10, 0.006, and ≥200, respectively. The predominantly quadrupole character of the transitions between the second and first spin 2 levels is attributed to the collective behavior of the nuclei. From the ratio of decay by electron capture and by positron emission to the 669-keV level, the energy separation between Cs^{132} and Xe^{132} was estimated to be 2.15 MeV.

I. INTRODUCTION

A PREVIOUS investigation of 2.3-h I^{132} by this group established many of the properties for nine low-lying levels in Xe^{132}.[1] Since a study of Cs^{132} would be expected to disclose additional information about levels of Xe^{132}, an investigation of its gamma rays was consequently undertaken. This type of information provides a test of the numerous nuclear models that have been proposed to explain the properties of low-lying levels of even-even, medium-weight nuclei. It should also prove useful in the future development of these models.

The energy of the strongest transition of Cs^{132} has been determined by Whyte, Sharma, and Taylor[2] as 667.9±0.4 keV. They also found the presence of a weak 0.62-MeV gamma ray in coincidence with this transition. They gave its intensity as 0.5 to 1% of that of the 668-keV gamma ray. Several other weak transitions between 1.0 and 1.3 MeV have been reported by Bhatki, Gupta, and Jha,[3] and by Robinson and Fink.[4] A value of two has been measured for the ground-state spin of Cs^{132}.[5]

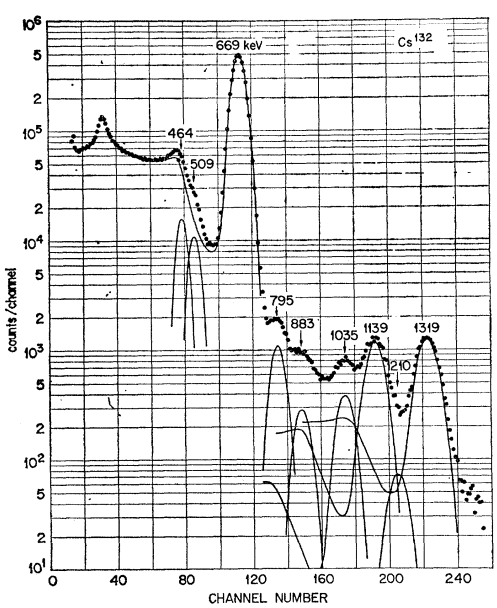

FIG. 1 Cs^{132} low-energy gamma-ray spectrum.

Beta-decay energy systematics indicate that Cs^{132} can also decay to Ba^{132} levels which have energies less than 1.2 MeV.[6] But no transitions in Ba^{132} have been reported from the study of Cs^{132}. However, Fagg[7] established through Coulomb excitation studies that the energy of the first 2+ level is 470 keV. In the present work the transition from this level and two transitions from the second 2+ level were observed.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. Source Preparation

The Cs^{132} was produced with the Oak Ridge 86-in. cyclotron by the nuclear reaction $Cs^{133}(p,pn)Cs^{132}$. The targets in the form of cesium oxide were dissolved in HCl and then precipitated as cesium silicotungstate in order to separate cesium from the other alkali metals and from barium. Further purification was effected by the precipitation of $CsClO_4$. In order to concentrate the cesium activity in a small volume of solution, the $CsClO_4$ was slurried with Dowex anion exchange resin in the Cl^- form. In this step the ClO_4^- was adsorbed by the resin and the resulting CsCl solution was conveniently used for the measurements.

[1] R. L. Robinson, E. Eichler, and N. R. Johnson, Phys. Rev. **122**, 1863 (1961).
[2] G. N. Whyte, B. Sharma, and H. W. Taylor, Can. J. Phys. **38**, 877 (1960).
[3] K. S. Bhatki, R. K. Gupta, and S. Jha, Nuovo cimento **4**, 1519 (1956).
[4] B. L. Robinson and R. W. Fink, Phys. Rev. **98**, 231 (1955).
[5] W. A. Nierenberg, J. C. Hubbs, H. A. Shugate, H. B. Silsbee, and P. O. Strom, Bull. Am. Phys. Soc. **1**, 343 (1956).
[6] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).
[7] L. W. Fagg, Phys. Rev. **109**, 100 (1958).

B. Gamma-Ray Spectra

The gamma rays were detected with 3-in.×3-in. NaI crystals which were coupled to 6363 DuMont photomultiplier tubes. The resolution of each detector was ~8% for the 662-keV gamma-ray peak of Cs^{137}. To reduce the background, the detectors were placed inside a lead shield with 4-in. wall thickness.

The singles gamma-ray spectra are shown in Figs. 1 and 2. For the low-energy spectrum (Fig. 1) the distance between the source and detector was 10 cm; for the high-energy spectrum (Fig. 2) it was 15 cm. They were decomposed as illustrated by using standards run under similar conditions. The Cs^{132} gamma-ray intensities determined from these spectra are given in Table I. Values are not listed for the 1.21- and 1.84-MeV gamma rays, since the peaks at these energies can be explained as the result of gamma-ray summing in the crystal.

The rates of decay of the gamma-ray peaks shown in Fig. 1 were determined from the analysis of four spectra taken with the same source over a period of two months. From the intense 669-keV gamma ray the half-life of Cs^{132} was computed to be 6.54±0.03 days. This compares favorably with the value of 6.48±0.03 days reported by Whyte *et al.*[2] The half-lives obtained for the 795- and 883-keV gamma rays demonstrate that they do not result from the decay of Cs^{132}. For the 795-keV gamma ray the half-life was found to be greater than 170 days. A spectrum observed in coincidence with this gamma ray showed a peak at 0.61 MeV. These two pieces of information indicate the presence of Cs^{134} which can result from the $Cs^{133}(n,\gamma)$ reaction induced by secondary neutrons. The half-life of the 883-keV gamma ray is ~26 days. This transition is probably from 33-day Rb^{84}.

Energies of the peaks at 669 and 1319 keV in Fig. 1 were obtained from the simultaneous measurements of standards and Cs^{132}. Energies of the other gamma rays listed in Table I were determined by the use of these peaks as internal standards.

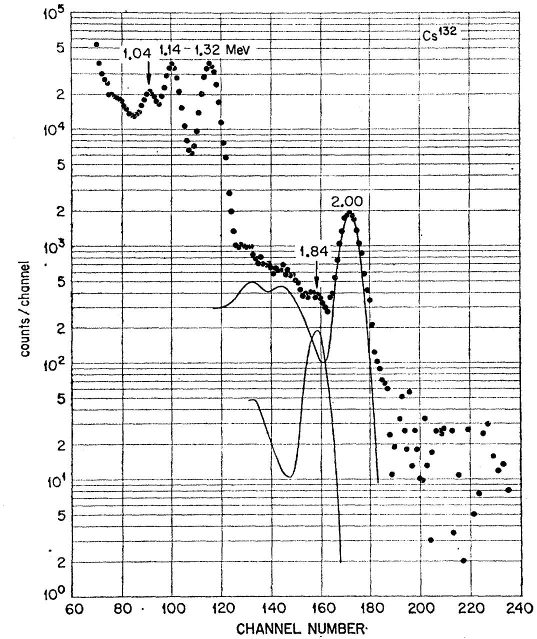

FIG. 2. Cs^{132} high-energy gamma-ray spectrum.

C. Gamma-Gamma Coincidence Spectra

The spectra in coincidence with the 464-, 509-, 669-, 1139-, and 1319-keV gamma rays were investigated. For these measurements the resolving time 2τ of the fast-slow coincidence circuit was 0.10 μsec and the distance between the source and each detector was either 5 or 10 cm. The spectra with chance counts subtracted are shown in Figs. 3 to 6. In computing the coincidence gamma-ray intensities which are included in Table I, corrections have been made for coincidences with events due to other gamma rays. Also, when known, corrections have been applied for the angular correlation between the coincidence gamma rays.

The spectrum in coincidence with the 669-keV gamma ray (Fig. 3) contains a peak at 631 keV not observed in the singles spectrum. This is probably the 0.62-MeV transition reported by Whyte *et al.*[2] The

TABLE I. Cs^{132} gamma-ray energies and relative intensities. The intensities are normalized to a value of 1000 for the 669-keV gamma ray in the singles spectrum.

$E\gamma$ (keV)	Singles spectrum	Spectra in coincidence with gamma rays of energies (keV): 464	509[a]	669	1139	1319
464±5	21±5					
509±7	17±4			18±4	<0.1	0.31±0.16[b]
569±6		2.7±0.8				
631±8			5.6±1.9	8.5±1.8		
669±4	1000±30		16±5		4.8±0.8	4.6±1.5
1035±12	1.6±0.3					
1139±11	5.2±0.5			5.0±0.6		
1304±20			0.58±0.20			
1319±10	6.5±0.6			6.6±0.7		
2000±30	0.53±0.06					

[a] The intensities are for the spectrum taken with $\theta = 90°$.
[b] This gamma ray is believed to result from coincidences with the 1304-keV gamma ray.

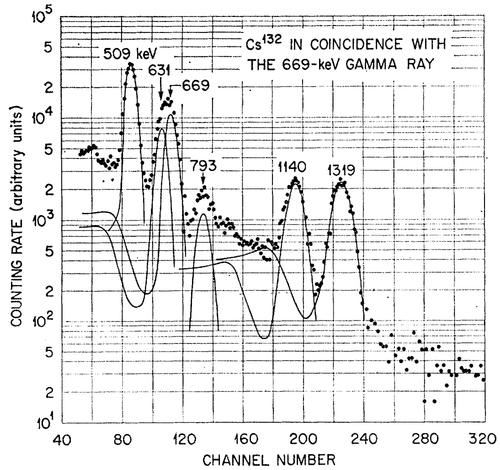

FIG. 3. Cs^{132} gamma-ray spectrum with a 110-keV window set at 669 keV. The angle between the two detectors was 130°.

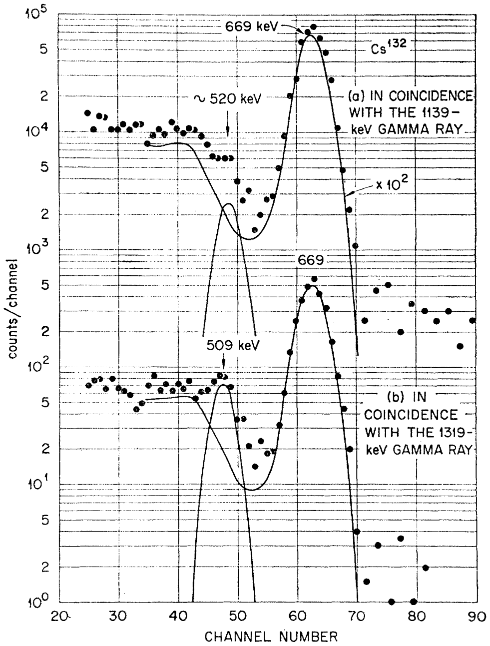

FIG. 5. Cs^{132} gamma-ray spectra with (a) a 70-keV window set at 1139 keV and (b) an 85-keV window set at 1319 keV. The angle between the two detectors was 90°.

795-keV gamma ray noted in the singles spectrum is also present here. A half-life determination of this transition made from a series of spectra in coincidence with the 669-keV gamma-ray peak showed its value is greater than 25 days. Since the 110-keV gating window was sufficiently broad to include events from a 0.61-MeV gamma ray, we concluded, as above, that the 0.793-MeV peak is due to Cs^{134}. Inclusion of the 631-keV gamma ray and Compton-scattered events of the 1139- and 1319-keV gamma rays in the gating window accounts for the presence of the 669-keV peak.

The spectrum in coincidence with the 509-keV gamma ray was observed for $\theta=90°$ and 180°, where θ is the angle between the two detectors. The former is shown in Fig. 4. The weak peaks at 450 and 510 keV can be explained as coincidences with other gamma rays in the gating window. The presence of a peak at 872 keV, which was found from a study of the singles spectrum to have a half-life of ~26 days, supports the suggestion that it is from the impurity Rb^{84}. (Rb^{84} decays partially by positron emission to the 879-keV level of Kr^{84}.[6]) In the spectrum with $\theta=180°$, there is a strong peak at 0.51 MeV. From this peak the intensity of the annihilation radiation was estimated to be 11 ± 5 in the units used in Table I. If our interpretation of the 872-keV gamma ray is correct, approximately 10% of this intensity results from the decay of Rb^{84}.

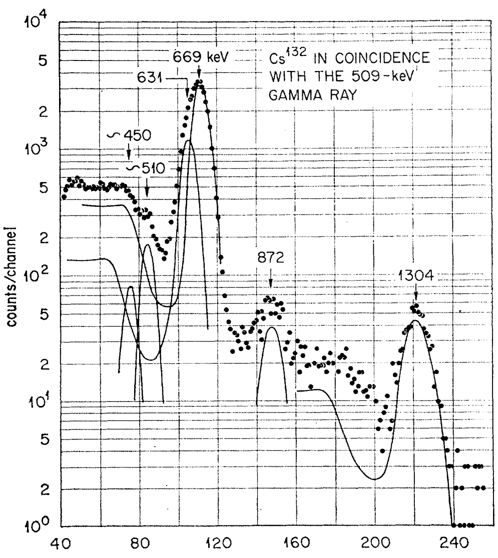

FIG. 4. Cs^{132} gamma-ray spectrum with a 35-keV window set at 509 keV. The angle between the two detectors was 90°.

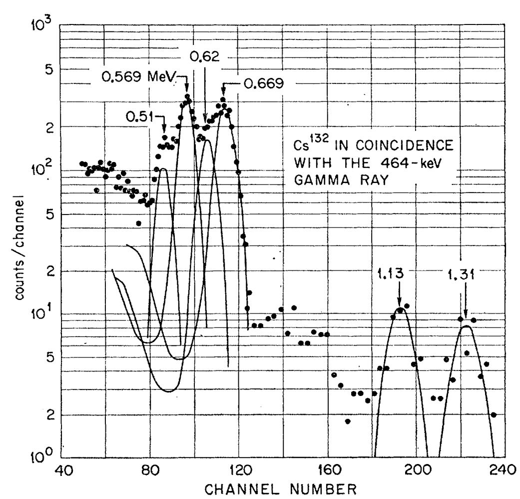

FIG. 6. Cs^{132} gamma-ray spectrum with a 35-keV window set at 464 keV. The angle between the two detectors was 90°.

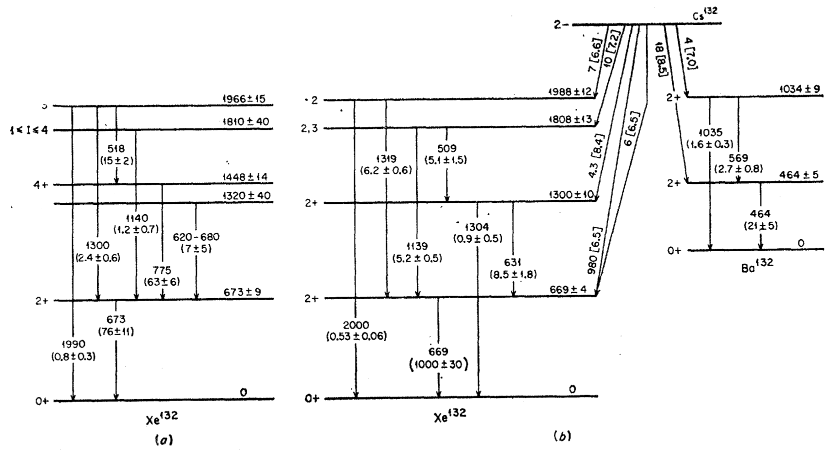

FIG. 7. (a) Transitions and energy levels of Xe^{132} below 2.0 MeV which occur in the decay of I^{132} as reported in reference 1. (b) Transitions and energy levels of Xe^{132} and Ba^{132} which occur in the decay of Cs^{132}. The pair of numbers with each gamma ray gives its energy in keV and relative intensity. Those pairs of numbers shown for decay by electron capture, beta-ray emission, and positron emission give the relative intensities and log *ft* values.

The spectra in coincidence with the 1139- and 1319-keV gamma rays are illustrated in Fig. 5. The weak transition at ~520 keV observed when gating on the 1139-keV peak is believed to be due to coincidences with events which result from the distributions of chance-summed 669-keV gamma rays and of higher energy gamma rays.

For the spectrum in coincidence with the 464-keV gamma ray, only 25% of the counts in the gating window were due to this gamma ray. Coincidences with the remaining counts explain entirely all the peaks in this spectrum (Fig. 6) except the one at 569 keV.

D. Decay Scheme

Energy levels and transitions of Xe^{132} and Ba^{132} compatible with the results in Table I are shown in Fig. 7. The levels of Xe^{132} with energies less than 2.0 MeV which are populated by $^{1}I^{132}$ have been included in Fig. 7 for comparison. From energy considerations alone, the (1304±20)- and (1319±10)-keV transitions could be one and the same. However, to achieve compatibility with all the results it appears necessary to treat them as two different gamma rays. To obtain the intensity of the 1304-keV gamma ray given in the figure, the value found for its intensity when gating on the peak at 509 keV was corrected for population of the 1300-keV level by electron-capture decay of Cs^{132}. This correction was determined from the difference of the intensities of the 631-keV gamma ray in the spectra in coincidence with the 669- and 509-keV gamma rays.

The intensity of the 509-keV gamma ray, $I_{509}=5.1\pm1.5$, is a weighted average of two values deduced from (1) the intensities of the 631- and 1304-keV gamma rays in the spectrum in coincidence with the 509-keV gamma ray ($I_{509}=6.2\pm1.9$), and from (2) the intensity of the 509-keV gamma ray in the coincidence spectrum which was taken with an 85-keV window centered at 1319 keV ($I_{509}=3.2\pm2.5$). The difference of this average intensity and the average intensity of the 509-keV transition as determined from the singles spectrum and from the spectrum in coincidence with the 669-keV gamma ray, is attributed to annihilation radiation of positrons. After correcting for the contribution of positrons from Rb^{84}, a value of 12±4 was obtained for the intensity of annihilation radiation from Cs^{132}. It is in agreement with the intensity value of 10±5 found from the spectrum for $\theta=180°$ in coincidence with the 509-keV gamma-ray peak. From the energy separation of Cs^{132} and Xe^{132} (see Sec. III), there can be positron groups to the 669-keV level and ground state of Xe^{132}. The present study can only establish that the intensity of a group to the ground state is <3. However, in view of the level spins, decay by positron emission should be primarily to the excited state. Therefore, the entire positron intensity of 6±2 is given to this group in Fig. 7.

Since the 464- and 1035-keV gamma rays are not in coincidence with the 669-keV gamma ray, and since their half-lives associate them with the decay of Cs^{132}, they are given as transitions in Ba^{132}. The energy of the 464-keV transition is consistent with the value of 470±7 keV reported by Fagg[7] for a Coulomb excited 2+ level of Ba^{132}. Coincidences between this transition and the 569-keV transition establish a second level at 1034 keV. Additional evidence is provided for this level by the 1035-keV gamma ray.

E. Gamma-Gamma Angular Correlations

For the investigation of the gamma-gamma angular correlations, spectra were taken in coincidence with the 669- and 464-keV gamma rays. Representative spectra are given in Figs. 3 and 6. The distance between the source and each detector was 10 cm. The source consisted of ~50 microliters of CsCl solution which was contained in a $\frac{1}{8}$-in. diam fluorothene thimble. Data with one exception were taken every 10° between 90° and 180° and were least-squares fitted to the equation $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ on an IBM 7090 computer. For the correlation of the 569- to 464-

TABLE II. Experimental angular correlation coefficients. They are compared with the theoretical coefficients for the spin sequences $I(D+Q)2(Q)0$ with $0 \leqslant I \leqslant 4$.

Sequence	δ	A_2	A_4
$0(Q)2(Q)0$[a]		+0.357	+1.143
$4(Q)2(Q)0$[a]		+0.102	+0.009
631−669-keV cascade		−0.256±0.030	+0.35 ±0.05
$1(D+Q)2(Q)0$	−0.005	−0.256	0.00
$2(D+Q)2(Q)0$	−3.2	−0.256	+0.30
$3(D+Q)2(Q)0$	+0.24	−0.256	0.00
1139−669-keV cascade		+0.134±0.019	+0.049±0.033
$1(D+Q)2(Q)0$	+0.34	+0.134	−0.079
$2(D+Q)2(Q)0$	−0.15	+0.134	+0.007
$3(D+Q)2(Q)0$	−0.30	+0.134	−0.007
1319−669-keV cascade		+0.304±0.016	+0.006±0.024
$1(D+Q)2(Q)0$	+0.53	+0.304	−0.166
$2(D+Q)2(Q)0$	+0.077	+0.304	+0.002
$3(D+Q)2(Q)0$	−0.84	+0.259	−0.034
569−464-keV cascade		−0.069±0.045	+0.39 ±0.09
$1(D+Q)2(Q)0$	+0.16	−0.069	−0.02
$2(D+Q)2(Q)0$	+ 94	−0.069	+0.33
$3(D+Q)2(Q)0$	−0.004	−0.069	0.00

[a] Since the theoretical coefficients for this sequence are unique, they are listed only once.

keV gamma-ray cascade the spectrum at $\theta = 180°$ could not be used. At this angle, the 569-keV gamma-ray peak was masked by an intense peak at 511 keV which resulted from annihilation radiation.

The experimental angular correlation coefficients which have been corrected for the finite angular resolution of the detectors[8,9] are given in Table II. The errors on the experimental coefficients include not only statistical errors, but also those which are introduced in the process of analyzing the data. This table also contains the theoretical coefficients for the spin sequences $I(D+Q)2(Q)0$ with values of I from 0 to 4.

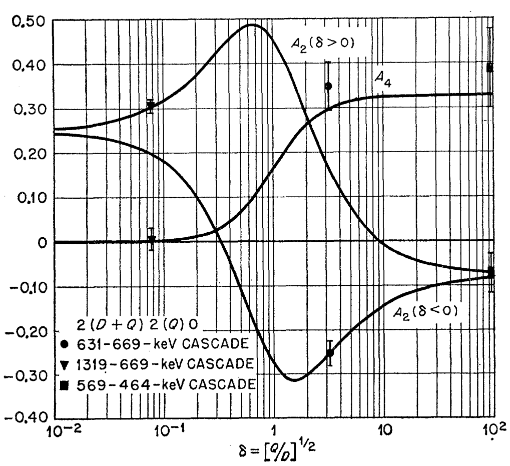

FIG. 8. Experimental angular correlation coefficients for three gamma-gamma cascades. The curves give the theoretical coefficients as a function of dipole-quadrupole mixing for the sequence $2(D+Q)2(Q)0$.

For $I=1$, 2, and 3, values of δ, where $\delta = (Q/D)^{1/2}$ in the notation of Biedenharn and Rose,[10] are those which give the best agreement between the theoretical and experimental coefficients.

The angular correlations of the 1319- to 669-keV, 631- to 669-keV, and 569- to 464-keV gamma-ray cascades are only compatible with spin assignments of 2 for the 1988- and 1300-keV levels of Xe^{132} and the 1034-keV level of Ba^{132}. Values of δ obtained from these correlations for the 1319-, 631-, and 569-keV transitions are $+0.077 \pm 0.025$, $-3.2_{-0.9}^{+0.7}$, and $> |14|$, respectively. Figure 8 shows the coefficients of these correlations along with the theoretical curves for the spin sequence $2(D+Q)2(Q)0$.

There is good agreement between the coefficients of the 1139- to 669-keV gamma-ray cascade and the theoretical coefficients for the spin sequences $2(98\% D+2\% Q)2(Q)0$ and $3(92\% D+8\% Q)2(Q)0$. Although agreement is poorer, the sequence $4(Q)2(Q)0$ cannot be ruled out conclusively.

III. DISCUSSION

The lowest three levels of Xe^{132} excited by Cs^{132} are probably the same as those observed at 673 ± 9, 1320 ± 40, and 1810 ± 40 keV in our study of I^{132}.[1] Although the energies of the (1988 ± 12)-keV level populated by Cs^{132} and the (1966 ± 15)-keV level populated by I^{132} are in reasonable agreement, their spins and the branching ratios of gamma rays from them are different. Therefore, it was concluded that they are not the same level. An upper limit for population of the 1966-keV level by Cs^{132} was estimated as 3% of the

[8] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[9] C. W. Reich (private communication).
[10] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

population of the 1988-keV level. This was based on the absence of a 775-keV gamma ray in the spectrum in coincidence with the 509-keV gamma-ray peak. The 35-keV gating window used for this spectrum would have included the 518-keV gamma ray which was found to be the strongest transition de-exciting the 1966-keV level [see Fig. 7(a)] and in coincidence with a 775-keV gamma ray.

The spin-2, 1300-keV level in Xe^{132} and 1034-keV level in Ba^{132} are assigned even parity since many even-even nuclei are known to have second 2^+ levels with energies approximately twice that of the first 2^+ levels. These parity assignments are supported by the typically predominant quadrupole character of the transitions between the second and first spin-2 levels. (The 631-keV transition in Xe^{132} and 569-keV transition in Ba^{132} consist of 91% and >99.4% $E2$ radiation, respectively.) The strong $E2$ character of these transitions is attributed to the collective behavior of the nuclei.

Relative intensities for decay of Cs^{132} to the levels of Xe^{132} by orbital electron capture and to levels of Ba^{132} by beta-ray emission are shown in Fig. 7. These were deduced from the gamma-ray intensities. From the ratio of decay by electron capture and by positron emission to the 669-keV level, the total energy separation between Cs^{132} and Xe^{132} was estimated to be 2.15 MeV.[11] For this energy the log ft values for decay to the Xe^{132} levels have been determined. They are also given in Fig. 7. The log ft values for possible decay of Cs^{132} to the levels at 1448 and 1966 keV that have been observed in the decay of I^{132} are greater than 9.2 and 8.2, respectively. The former value was obtained by placing an upper limit on the 775-keV gamma-ray intensity of 5×10^{-4} that of the 669-keV gamma-ray intensity. The log ft values given for the beta-ray groups in Fig. 7 are for an energy separation of 1.2 MeV between Cs^{132} and Ba^{132}. This energy has been predicted by beta-decay energy systematics.[6] The log ft values for decay to the 2^+ levels of both Xe^{132} and Ba^{132} suggest that the parity of the Cs^{132} ground state is odd.

Of the three spins for the 1808-keV level compatible with the angular correlation results ($I=2$, 3, or 4), only spins 2 and 3 are in agreement with the log ft value for decay to this level. It is not possible to determine conclusively which of these spins is correct from this investigation; however, failure to detect a ground-state transition does favor spin 3.

We have previously compared the levels of Xe^{132} populated by I^{132} with levels predicted by various nuclear models.[1] This comparison which is reproduced

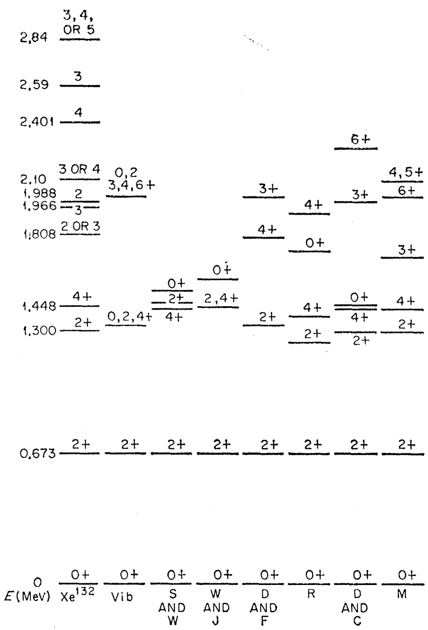

FIG. 9. Comparison of the Xe^{132} levels with levels predicted by the following nuclear models: Vib—pure vibrational model. S and W—model of Scharff-Goldhaber and Weneser. W and J—model of Wilets and Jean. D and F—model of Davydov and Filippov. R—model of Raz. D and C—model of Davydov and Chaban. M—model of Mallmann. These models are discussed in references 12–17. The parameters which were used are given in reference 1.

in Fig. 9[12–17] includes the information about the 1300-, 1808-, and 1988-keV levels obtained from the present study of Cs^{132}. As pointed out before, the second 2^+ and first 4^+ levels can be explained by all models except that of Davydov and Filippov.[14] However, none of the models can account for all four levels between 1.8 and 2.1 MeV. It is possible that a low-lying 0^+ level as predicted by several of the models does exist. Neither Cs^{132} nor I^{132} would be expected to populate a level of this spin with sufficient intensity to be observed.

ACKNOWLEDGMENT

We wish to express our appreciation to Dr. J. J. Pinajian for his help in preparing the Cs^{132} source material.

Note added in proof. Recent studies of the decay of Cs^{132} have been made by S. Jha, R. K. Gupta, H. G. Devare, and G. C. Pramila [Nuovo cimento **20**, 1067 (1961)]. Their suggested decay scheme contains the levels in Xe^{132} proposed in the present investigation as well as two additional levels at 1450 and 1700 keV.

[11] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950). They give the decay energy as a function of the capture-to-positron ratio for allowed transitions only. However, approximately the same energy is obtained for first-forbidden, non-unique transitions when $\alpha Z\ll 1$ and $\alpha Z/2R\gg 1$. [See H. Brysk and M. E. Rose, Revs. Modern Phys. **30**, 1169 (1958).]

[12] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).

[13] L. Wilets and M. Jean, Phys. Rev. **102**, 788 (1956).

[14] A. S. Davydov and G. F. Filippov, Nuclear Phys. **8**, 237 (1958).

[15] B. J. Raz, Phys. Rev. **114**, 1116 (1959).

[16] A. S. Davydov and A. A. Chaban, Nuclear Phys. **20**, 499 (1960).

[17] C. A. Mallmann, Nuclear Phys. **24**, 535 (1961).