Reinvestigation of ^{132}Cs Decay*

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(Received 28 December 1964)

There has been some disagreement in the literature as to the properties of the low-lying states in ^{132}Xe, and in particular as to the energy of the second excited state of this nucleus. The decay of ^{132}Cs has been reinvestigated by use of *p-i-n* lithium-drifted germanium detectors having high resolution, and it is found that the first and second excited states in ^{132}Xe are depopulated by transitions with respective energies of 668.8 $\pm$1.0 and 630.7$\pm$1.5 keV. In addition, gamma rays were also observed with the germanium detectors at energies of 464$\pm$3, 507$\pm$3, 511$\pm$3, 773$\pm$5, 1037$\pm$3, 1140$\pm$1.2, 1233$\pm$3, 1300.0$\pm$1.5, 1320.0$\pm$1.5, and 1985$\pm$5 keV. Gamma-gamma (NaI) coincidence measurements, made with a 100- by 200-channel multiparameter analyzer, revealed several new features of the decay. The excited levels observed in ^{132}Xe are at 668.8$\pm$1.0, 1299.5$\pm$2.0, 1442$\pm$3, 1808.3$\pm$2.2, and 1988.8$\pm$2.5 keV. Levels at 464$\pm$3 and 1037$\pm$3 keV in ^{132}Ba are also populated.

I. INTRODUCTION

IN earlier investigations[1,2] at this laboratory, the levels in ^{132}Xe populated by the decay of ^{132}I and ^{132}Cs were studied. In the decay of ^{132}I, Robinson, Eichler, and Johnson[1] reported that the intense gamma-ray peak at 667 keV was complex and probably contained at least four gamma rays of about that energy. From coincidence studies they[1] were able to determine that the first excited state in ^{132}Xe is at about 0.67 MeV, and that the second excited state lies at approximately 1.3 MeV and is de-excited by a gamma ray of about 0.65 MeV.

Devare[3] also studied the decay of ^{132}I, and from coincidence experiments assigned a 650-keV transition as depopulating the second excited level in ^{132}Xe at 1320 keV.

In another study, Hamilton, Goudsmit, and Jansen[4] made high-resolution measurements of the ^{132}I internal conversion electron spectrum in the region of 610–690 keV and found that there are actually seven gamma-ray transitions involved at 620.6, 630.0, 650.2, 652.1, 667.8, 669.7, and 671.5 keV.

Recently, Johnson, Wilsky, Hansen, and Nielsen[5] and Boyd and Hamilton[6] have re-examined the decay of ^{132}I. Unfortunately, the complex coincidence relationships that exist between these seven transitions with very similar energies in ^{132}I have made it impossible to determine unambiguously which one de-excites the second excited state in ^{132}Xe at about 1.3 MeV. It would be hoped that the data on ^{132}Cs decay could shed some light on this aspect, since only ^{132}Xe levels up to 2 MeV are populated[2,7] in this decay.

As a result of extensive gamma-gamma coincidence measurements and angular correlation determinations on the decay of ^{132}Cs, Robinson, Johnson, and Eichler[2] found that the second excited state in ^{132}Xe is de-excited by a 631-keV transition, and that this transition and another at 669 keV are the only ones present in this energy region. In agreement with these results, Taylor, Whyte, and McPherson[8] report the presence of 635- and 667.9-keV transitions from ^{132}Cs. However, Jha, Gupta, Devare, and Pramila,[7] who have made the only other extensive ^{132}Cs measurements in which a decay scheme is given, list 650 and 670 keV as the corresponding energies. This discrepancy in the energy of the lower member of the doublet still leaves some uncertainty as to the energy of the second excited state in ^{132}Xe.

Other investigations[9–12] have shown certain features of the ^{132}Cs decay, but there is still an obvious need for a high-resolution examination of its internal conversion electron spectrum. Unfortunately, one cannot easily obtain sources with sufficiently high specific activity for such measurements. The advent of lithium-drifted germanium detectors, however, has now made it possible to resolve very close-lying gamma-ray peaks, and these detectors were the major tool in the present

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‡ Work supported in part by a grant from the National Science Foundation.

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examination of ^{132}Cs. We also performed gamma-gamma (NaI) coincidence spectrometry using multiparameter analysis.

II. EXPERIMENTAL

The ^{132}Cs for the present measurements was produced by the nuclear reaction ^{133}Cs$(p,pn)^{132}$Cs with the external beam of the Oak Ridge 86-in. cyclotron. The cesium sulfate target was dissolved in HCl and then precipitated as cesium silicotungstate in order to separate cesium from the other alkali metals and from barium.

The lithium-drifted germanium detector[13] used in the present measurements was of the *p-i-n* type. The detector had a lithium-drift depletion depth of 3 mm and a 2 cm^2 surface area. It was mounted in an evacuated can which was attached by a miniature fitting to the low capacitance coaxial line of the preamplifier. This assemblage was immersed in a Dewar flask of liquid nitrogen as is illustrated in Fig. 1. The source was placed outside the Dewar directly opposite the detector. The resolution of this diode detector for the 661.6-keV gamma ray of ^{137}Cs ranged from 4 to 6 keV full width at half-maximum (FWHM) compared with about 50 keV for the resolution of our NaI detectors.

In Fig. 2, we show the energy region 400–700 keV taken with the lithium-drifted germanium detector. A biased amplifier was used to suppress the lower energy portion of the spectrum, i.e., channel zero corresponds to 400 keV.

Escape of Compton scattered photons from the detector produces a sizable low-energy background in the spectra taken with germanium detectors. This effect is evident in Fig. 2. Analysis of the energy region shown in Fig. 2, however, was simplified by the fact that the transitions in ^{132}Cs above the 668.8-keV peak are very weak, thus making it possible to compare the observed shape directly with that of ^{137}Cs which has a single gamma ray at 661.6 keV. With this information and the known resolution of our system, it was an easy matter to obtain the Gaussian-shaped full-energy peaks shown in Fig. 2 and to assign their energies. The energies shown are the best values as determined from four separate experiments.

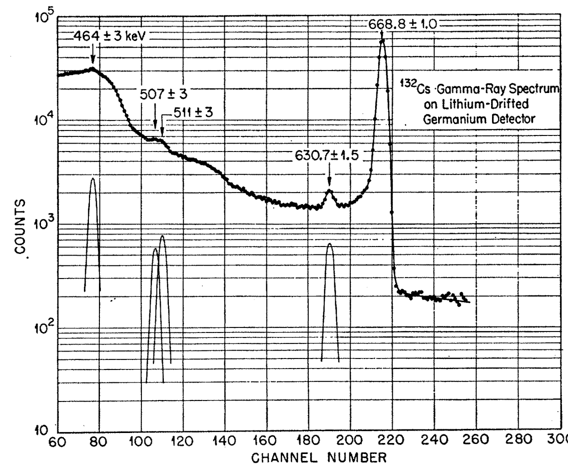

FIG. 2. Low-energy portion of ^{132}Cs gamma-ray spectrum taken with a lithium-drifted germanium detector.

With the excellent separation of the 630.7-keV gamma-ray peak from that at 668.8 keV, we are able to obtain a good measure of the relative intensities of these two transitions. From the peak areas and the photoelectric cross sections, the relative intensity of the 668.8- to 630.7-keV transition is found to be 1000 to 9.0±1.0. This is in good agreement with the value reported by Robinson *et al.*[2] They give the intensity of the 630.7-keV gamma ray as 8.5±1.8 in the same relative units.

It will be noted that the 569-keV gamma ray reported earlier[2] in the decay of ^{132}Cs and also observed in the gamma-gamma data of the present measurements is not observed in Fig. 2. This is not surprising since the transition is known to be very weak and, therefore, would be very difficult to detect above the large amount of Compton scattered radiation in this energy region. It is only possible to set a limit for the intensity of such a gamma ray as $\leq 2\pm1$ units relative to the 668.8-keV transition as 1000 units. This limit still overlaps the value 2.7±0.8 assigned by Robinson *et al.*[2]

That portion of the gamma-ray spectrum from about 700–1400 keV is shown in Fig. 3. Here the analysis was somewhat more difficult due to the poorer counting statistics. Except for the peak at 1258 keV, however,

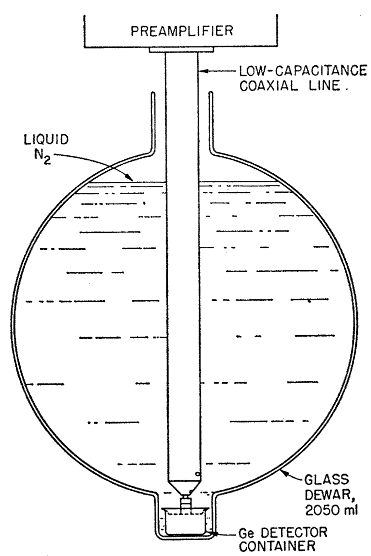

FIG. 1. Physical arrangement of lithium-drifted germanium detector. The diode detector is mounted in an evacuated can which attaches by a miniature fitting to the low-capacitance coaxial line of the preamplifier.

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[13] The germanium detector used in these measurements was prepared by R. J. Fox of the Instrument and Controls Division of the Oak Ridge National Laboratory. He is presently preparing a report with complete details on the fabrication and use of these detectors.

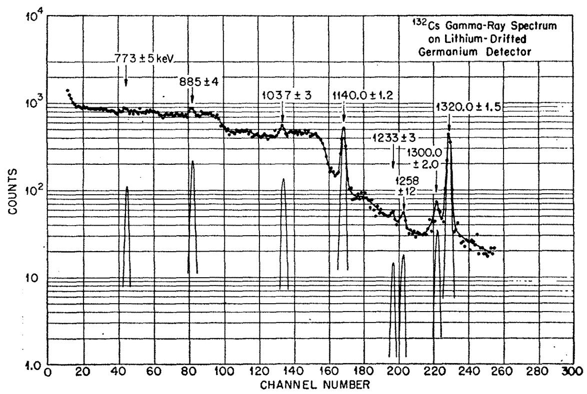

FIG. 3. Medium-energy region of ^{132}Cs gamma-ray spectrum taken with a lithium-drifted germanium detector.

the features of this spectrum were completely reproducible in three separate experiments. A very large limit of error is assigned for the peak at 1258 keV because its value varied several keV during the three measurements. It is not known whether these deviations are significant or if they simply represent a statistical fluctuation. Analysis of the 1300.0-keV gamma ray on the low-energy side of the 1320-keV peak was facilitated by use of the shape of the 1333-keV gamma ray of ^{60}Co. The ratio of intensities for the 1320.0- to 1300.0-keV transitions in Fig. 3 is 1.0 to 0.074 ± 0.010 compared with the ratio 1.0 to 0.14 ± 0.08 deduced by Robinson *et al.*[2] The only significant feature observed above 1320 keV was a poorly defined peak at 1985 keV.

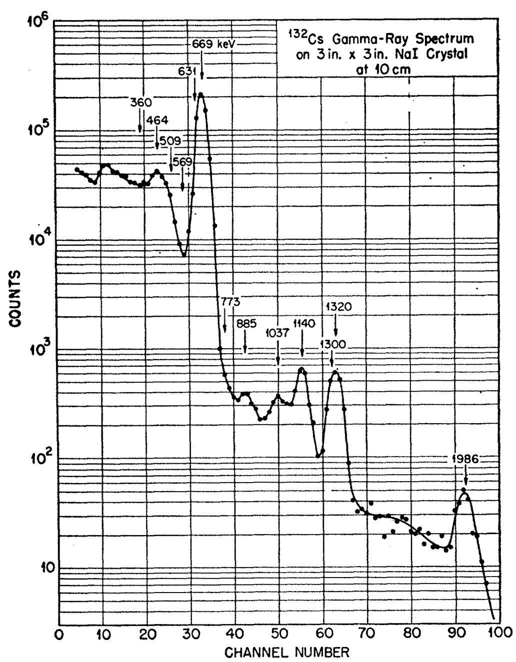

FIG. 4. Single-crystal gamma-ray spectrum of ^{132}Cs. This is a singles spectrum from the Y detector accumulated on a time-sharing basis with the coincidence spectra. With the pulse-height distribution at each channel position in this Y spectrum, there is a 200-channel associated coincidence spectrum in X. The energies on the spectrum represent the best values determined from either the single-crystal or the gamma-gamma coincidence measurements. Channel numbers represent the Y analog-to-digital converter address.

A summary of the ^{132}Cs gamma-ray energies observed in the measurements with the lithium-drifted germanium detector is given in Table I. As already mentioned, the numbers listed are the best energy values as determined from several experiments. The 885-keV peak was shown to decay with a long half-life and is presumed to result from the presence of a small amount of 26-day ^{84}Rb in the source.

We have also re-examined the gamma-gamma coincidence spectra of ^{132}Cs using a Victoreen 100×200 channel multiparameter analyzer.[14] For these measurements, the outputs of the two 3-in.×3-in. NaI scintillation detectors were amplified and fed to two analog-to-digital converters (ADC). One ADC had a full-scale range of 200 channels and was termed the X ADC; the other had a range of 100 channels and was termed the Y ADC. Whenever an event occurred in both the X and Y detectors within the fast coincidence resolving time 2τ of 90 nsec, the X and Y addresses generated by the two ADC units caused an event to be registered in a unique location within a 20 000-word ferrite-core memory matrix. The singles spectra from the X and Y detectors can be accumulated on a time-sharing basis with the coincidence spectra, and are stored in memory planes provided for the purpose. Coincidence measurements with such a system permit one to look for many subtle aspects that are often missed with conventional single-channel coincidence equipment because of the vast expense of time and labor and the loss of precision in multiple experiments.

TABLE I. ^{132}Cs gamma-ray energies measured with lithium-drifted germanium detector.

E_γ, keV	E_γ, keV
$464\ \pm3$	
$507\ \pm3$	1140.0 ± 1.2
$511\ \pm3$	$1233\ \pm3$
630.7 ± 1.5	$1258\ \pm12$
668.8 ± 1.0	1300.0 ± 2.0
$773\ \pm5$	1320.0 ± 1.5
$1037\ \pm3$	$1985\ \pm5$

The single-crystal gamma-ray spectrum of ^{132}Cs taken with a 3-in.×3-in.-NaI crystal is shown in Fig. 4. Channel numbers represent the Y address. The numbers on the spectrum represent gamma-ray energies (and the arrows the positions of the peaks) that were determined from either the single-crystal or the coincidence ex-

[14] Victoreen Instrument Company Model MP-204RT. The use of multiparameter pulse-height analyzers in radioactivity studies has been described elsewhere; e.g., see G. D. O'Kelley, D. A. Bromley, and C. D. Goodman, in *Proceedings of the Conference on Utilization of Multiparameter Analyzers in Nuclear Physics*, edited by L. J. Lidofsky (Office of Technical Services, Department of Commerce, Washington, D. C., 1962), pp. 49–59.

periments. In the discussion to follow, this figure serves to show the gating positions (channels) in Y, each of which has a 200-channel associated coincidence spectrum in X. It should be pointed out that in Fig. 4, the peak at 509 keV arises from two unresolved gamma rays, the 511-keV annihilation quanta and the 507-keV gamma ray of ^{132}Cs.

To illustrate a subtle problem which was resolved with the multiparameter analyzer, we show in Fig. 5 the 600–700-keV region of three ^{132}Cs coincidence spectra. These are spectra in the X dimension coincident with (a) $Y=33$, (b) $Y=32$, and (c) $Y=31$, where these Y values correspond to adjacent 20-keV-wide windows centered at 668, 648, and 628 keV, respectively. These three spectra illustrate quite clearly that there is a coincidence relationship between the intense ^{132}Cs peak at 668 keV and another of slightly lower energy (presumably the 630.7-keV transition). In curve (c) where the gating window is centered at 628 keV, we see a gamma-ray peak at 668 keV. This coincidence peak, which is only very slightly broadened over that expected for a single gamma ray of that energy, is primarily due to coincidences with the 631-keV gamma ray and with Compton events in the window from higher-energy gamma rays. (The coincidence data show that some of the higher-energy gamma rays are in coincidence with the 668.8-keV transition, but not with the 630.7-keV gamma ray.) For curve (a), the number of these Compton events in the window is essentially

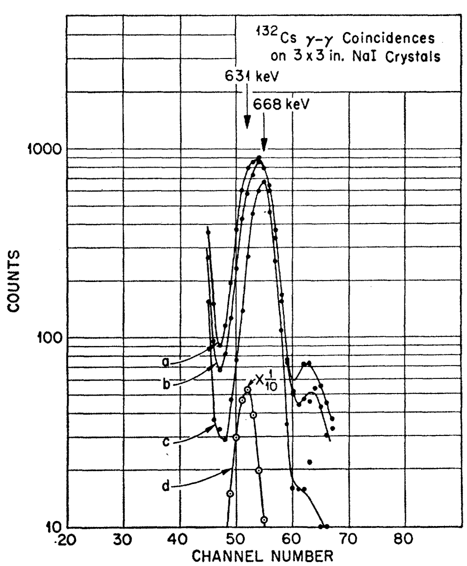

FIG. 5. ^{132}Cs gamma-gamma coincidence spectra (600–700-keV region only) taken with a 100-×200-channel multiparameter pulse-height analyzer. These spectra are portions of the X planes coincident with (a) $Y=33$, (b) $Y=32$, and (c) $Y=31$, where these Y values correspond to adjacent 20-keV-wide windows centered at 668, 648, and 628 keV, respectively. The difference between curves (a) and (c) is plotted in (d) which shows unmistakably the coincidence relationship between 668- and 631-keV gamma rays.

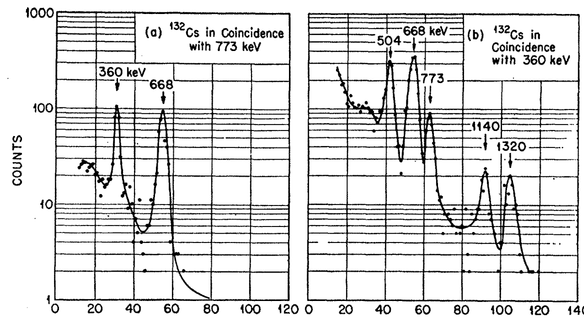

FIG. 6. (a) ^{132}Cs gamma-ray spectrum in coincidence with $Y=38$ (i.e., with a 20-keV window centered at 773 keV in the gamma-ray spectrum); (b) ^{132}Cs gamma-ray spectrum in coincidence with $Y=19$ (i.e., with a 20-keV window centered at 360 keV).

the same, but now a larger fraction of the gating events is from the 668.8-keV gamma ray (see Fig. 4), and this gives rise to a much broader coincidence peak. If curve (c) is subtracted from curve (a), one should get a distribution which emphasizes the part of the spectrum coincident only with the 630.7-keV gamma ray. This has been done and is displayed in Fig. 5(d) which is shown displaced by a factor of ten.

Note that on the high-energy side of curves (a), (b), and (c) of Fig. 5, there are indications of a weak gamma ray whose energy is about 773 keV. In the earlier work of Robinson *et al.*,[2] a much stronger 793-keV transition was observed in coincidence with 668 keV; however, it was attributed to ^{134}Cs on the basis of a half-life of >170 days for the decay of the peak. Their source of ^{132}Cs was prepared in the internal proton beam of the cyclotron where an appreciable neutron flux and the consequent production of ^{134}Cs is expected. Since the ^{132}Cs of the present measurements was prepared with an external beam of protons, one does not expect as much ^{134}Cs to be present. Thus, it would appear that the 773-keV transition which has been observed in the decay of ^{132}I may also be present in the decay of ^{132}Cs. The complete spectrum for $Y=33$ (668 keV) has been analyzed, and the number of 773-keV gamma rays per 668-keV gating gamma ray was found to be 0.0011. The method of analysis has been described previously.[15,16]

For a further look at the relationship of the 773-keV gamma ray, we show in Fig. 6(a), the X spectrum coincident with $Y=38$ (i.e., with a 20-keV window centered at 773 keV). In the analysis of this spectrum, it is found that there is one 360-keV gamma ray and one 668-keV gamma ray for each gating gamma ray of 773-keV energy. Also, the peak at 668 keV has the appropriate width for a single gamma ray of that energy, indicating that the 773-keV transition probably

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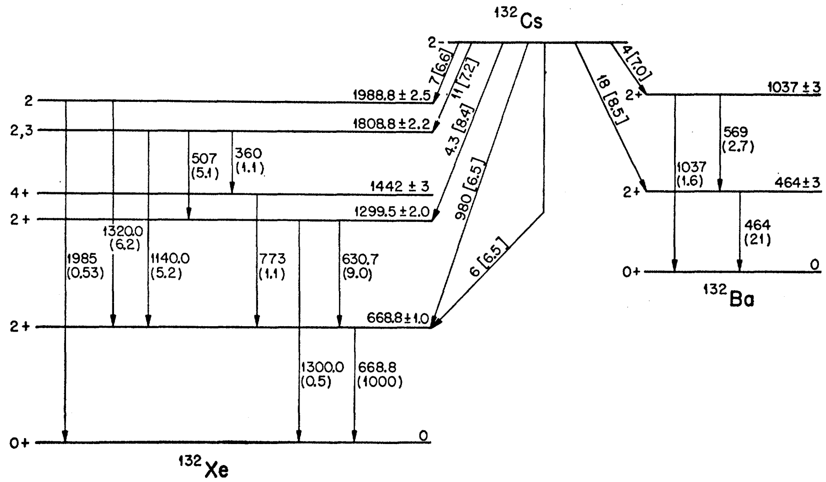

FIG. 7. Level schemes in ^{132}Xe and ^{132}Ba from the decay of ^{132}Cs. Relative gamma-ray intensities are given in parentheses below the gamma-ray energies which are in keV. The pairs of numbers shown for decay by electron capture, positron emission, and beta-ray emission give the relative intensities and logft values, the latter being in brackets.

cascades into the 668-keV level and not into that at 1298 keV (see Fig. 6) in ^{132}Xe.

Figure 6(b) shows the spectrum coincident with the 20-keV-wide gating window in Y centered at 360 keV. When this spectrum is corrected for coincidence events due to Compton-scattered photons from higher energy gamma rays, it is found that only the 668- and 773-keV gamma rays (of equal intensity) are in coincidence with the 360-keV transition.

In addition to the above mentioned transitions, the gamma-gamma coincidence data also indicate that there may be present very weak gamma rays at 101, 110, 147, and 165 keV. Otherwise, the coincidence results are in general agreement with the earlier work of Robinson *et al.*[2]

III. DISCUSSION

As already pointed out, the high-resolution internal conversion electron measurements for ^{132}I by Hamilton *et al.*[4] showed that there were seven transitions in ^{132}Xe with energies between 620 and 672 keV. Our present measurements show the value 668.8±1.0 keV for the energy of the first excited state in ^{132}Xe as is shown in Fig. 7. This is in good agreement with the value 667.8±0.3 keV by Hamilton *et al.*[4]

The present measurements have shown unambiguously that in the decay of ^{132}Cs, a transition of 630.7 ±1.5 keV cascades into the 668.8-keV excited level of ^{132}Xe. Thus, we are able to assign the second-excited-state energy as 1299.5±2.0 keV. This sum fits nicely with the measured energy of 1300.0±2.0 keV for the crossover transition and with the value 1298.1±0.5 obtained from the precision electron measurements of Hamilton *et al.*[4]

The next excited level in ^{132}Xe is at 1442±3 keV. This assignment is based on the observation of a weak 773-keV gamma ray in both the gamma-gamma coincidence experiments and in the measurements with the germanium detector. This level and the associated 773-keV gamma ray are well established from the ^{132}I decay[1,3] and also have been proposed in the ^{132}Cs decay by Jha *et al.*[7] Contrary to their report[7] that this level is fed by electron capture, our data show that the 1442-keV level is fed essentially 100% by a 360-keV gamma-ray transition, and that if there is any direct electron capture to the level, it can only be present in less than 25% of the intensity of the 773-keV transition. From this and the estimate[2] of 2.15 MeV for the total energy separation between ^{132}Cs and ^{132}Xe, the logft for possible decay to the 1442-keV level is >9.4.

The use of lithium-drifted germanium detectors has also made it possible to assign with improved accuracy the energies of the higher ^{132}Xe levels populated by ^{132}Cs. The energies of the levels 1808.8±2.2 and 1988.8 ±2.5 keV are based on the sums of coincident pairs of gamma rays at 1140.0 and 668.8 keV and 1320.0 and 668.8 keV, respectively.

The scheme does not include the weak 1233- and 1258-keV gamma rays observed with the solid-state detector and the 101-, 110-, 147-, and 165-keV peaks seen in the gamma-gamma coincidence data. It is felt that the information obtained on each of these transitions is insufficient to warrant their inclusion.

We find no indications for a 1700-keV ground-state transition or for a 1040-keV gamma ray cascading into the first excited level as reported by Jha *et al.*[7] Further, we are unable to find the crossover transition from the 1808.8-keV level to ground as was reported by these authors.[7] Some of the gamma-ray intensity assignments in the decay scheme of Fig. 7 are those of Robinson *et al.*[2] However, for several transitions, we have been able to improve the accuracy of the intensity assignments by use of lithium-drifted germanium detectors and by gamma-gamma coincidence measurements with a multiparameter analyzer, and for these transitions we use the new values. Specifically, the transitions for which new intensity assignments are made are at 360, 630, 773, and 1300.0 keV. The spin assignments for the ^{132}Xe and ^{132}Ba levels in Fig. 7 are those from the angular correlation measurements of Robinson *et al.*,[2] and the ground-state spin for ^{132}Cs is the measured value of Nierenberg *et al.*[17] There are two numbers on each electron capture or positron branch. One gives the relative intensity and the other in brackets gives the log*ft*. These log*ft* values support a negative parity assignment for ^{132}Cs.

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ACKNOWLEDGMENTS

The authors would like to thank R. J. Fox of the Oak Ridge National Laboratory for supplying the germanium detector and for his help and the use of his equipment in making some of the measurements. Thanks are also due G. D. O'Kelley and R. L. Robinson for their helpful comments concerning the manuscript, and R. L. Ferguson, G. J. Atta, and A. R. Jenkins for providing us with the computer programs for handling much of the data.

PHYSICAL REVIEW VOLUME 138, NUMBER 3B 10 MAY 1965

Nuclear Energy States of I^{129}†

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(Received 30 November 1964)

The quantum radiations emitted in the decay of Te^{129m}-Te^{129} have been investigated with application of a Ge(Li) detector, scintillation counters, coincidence techniques, and multichannel analysis. In addition to the well-known 27-keV gamma ray, twenty-three others have been detected at energies of 205, 250, 273, 277, 340, 448, 455, 482, 523, 548, 550, 630, 660, 698, 725, 770, 797, 810, 835, 945, 1085, 1112, and 1222 keV. Thus, six pairs of gamma rays are present which exhibit within each pair an energy difference of 27 keV. Excited states in I^{129} are established at 27, 277, 482, 550, 725, 797, and 1112 keV by this energy difference. Additional excited states are found at 837, 1065, 1222, and 1385 keV by coincidence experiments.

I. INTRODUCTION

THE nuclear energy levels of I^{129} have been investigated experimentally[1–10] through the β^- decay of Te^{129m}(33 day) and Te^{129}(70 min), and theoretically.[11,12] The earlier experiments[1–4] culminated in a level scheme proposed by Graves and Mitchell[4] who reported that Te^{129m} decays by de-excitation of the 106-keV isomeric state and by β^- decay to excited states in I^{129}, the β^- emission occurring in 5% of the transitions. More recent studies[6] have indicated β^- emission in 32% of the disintegrations. This result was suggestive of the need for further investigation of the β^- decay of Te^{129m}, and in the course of such measurements,[5,7–10] many previously undetected gamma rays were discovered. The various nuclear-structure diagrams of I^{129} resulting from some of the researches cited above[4,5,7,8,10] are depicted in Fig. 1.

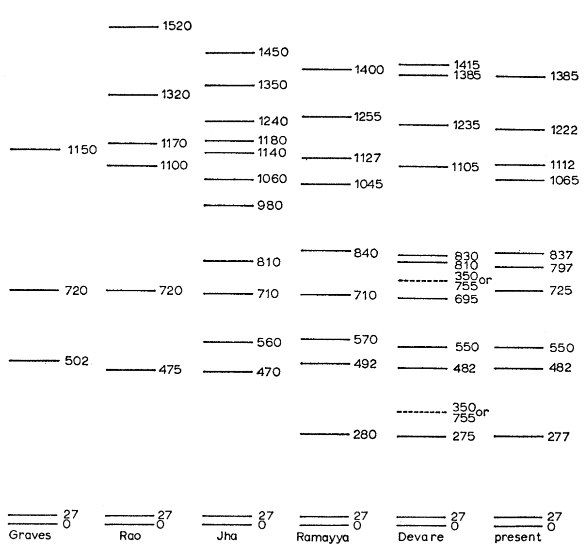

FIG. 1. Energy states of the nucleus of I^{129} as reported in previous studies. The structure indicated by the present results is also given. Energies are in keV.

† Supported in part by the National Science Foundation.
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