Levels of ^{130}Xe Populated in β Decay of ^{130}I and ^{130}Cs

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γ rays emitted in the β decay of 5^- ^{130}I and 1^+ ^{130}Cs have been studied with Ge(Li) and NaI(Tl) spectrometers. 24 transitions were observed in the decay of ^{130}I, and 16 were observed in the decay of ^{130}Cs. From the γ-ray singles spectra and from coincidence studies, the following excited levels of ^{130}Xe have been deduced: 536.1 (2^+), 1122.1 (2^+), 1204.5 (4^+), 1785.9, 1793.5, 1800.1, 1808.1, 1943.9 (5^+), 2016.1, 2150.6, 2171.3, 2223.3, 2242.8, 2361.8 (6^+), 2427.0, 2532.3, 2608.6, and 2752.3 keV. No evidence has been found for the population of a possible 0^+ "vibrational triplet" member at about twice the energy of the first excited state.

INTRODUCTION

According to the hydrodynamical model,[1] near-spherical even-even nuclei may undergo nearly harmonic quadrupole surface oscillations, resulting in a 0^+-2^+-4^+ triplet of states at about twice the energy of the 2^+ first excited state. However, very few even-even nuclei have been found to possess all three members of the predicted triplet.

On the basis of its location in the periodic chart of the nuclides, $_{54}{}^{130}Xe_{76}$ would be expected to be nearly spherical. It is convenient for study because its excited states are populated in the β decay of 5^- ^{130}I and 1^+ ^{130}Cs, so if ^{130}Xe possesses a 0^+-2^+-4^+ triplet of states, all three of these states should be populated. Both 4^+ (Ref. 2) and "0^+ or 2^+" (Ref. 3) excited states of ^{130}Xe have already been reported at about twice the energy of the first excited state. However, after observing γ rays emitted in (α,Xn) reactions on separated Te isotopes, Morinaga and Lark[4] deduced the existence of a 0^+, 2^+, 4^+, 6^+, 8^+ band of states of ^{130}Xe which they interpreted as resembling the spectrum of a deformed rotor. A later paper by Betigeri and Morinaga[5] reported excitation of an additional (2^+) state at 1126 keV by means of the (^{3}He,3*n*) reaction on ^{130}Te. The present study of the β decay of ^{130}I and ^{130}Cs has been undertaken in order to clarify the level structure of ^{130}Xe.

EXPERIMENTAL PROCEDURE

γ rays emitted by ^{130}I and ^{130}Cs were recorded with a 20-cc Ge(Li) detector, the spectrometer resolution being about 6 keV full width at half-maximum (FWHM) for 1-MeV γ rays. Scintillation detectors were also used for γ-γ coincidence experiments. The Ge(Li) spectra were analyzed by using the method of least squares to fit peaks, Compton edges, and a background continuum to the data. From these fits, information was obtained on peak location and intensity, and on the statistical uncertainties in these quantities. Calibration of the spectra was performed by representing energy as a third-order polynomial in channel number.

Standards used for energy calibration were annihilation radiation (Ref. 6), ^{207}Bi (Refs. 6 and 7), ^{56}Co (Ref. 8), ^{60}Co (Ref. 9), ^{137}Cs (Ref. 10), ^{131}I (Ref. 11), ^{22}Na (Ref. 6), and ^{88}Y (Ref. 6). The energies of intense γ rays from the isotopes under investigation were determined from spectra of these isotopes counted simultaneously with the standard isotopes. These intense γ rays were then used as calibration in determining energies of weaker γ rays observed only in spectra of ^{130}Cs or ^{130}I alone. Quoted uncertainties in the γ-ray energies include allowance for uncertainties in the energies of calibration photopeaks and for uncertainties in the locations of both the calibration photopeaks and the unknown photopeaks. In determining relative intensities of γ rays, an empirical relative photopeak efficiency curve was used.[12] The errors quoted for the relative intensities allow for ±10% uncertainty in relative photoefficiency values read from this curve, as well as for statistical uncertainty in the areas of the photopeaks in the spectra.

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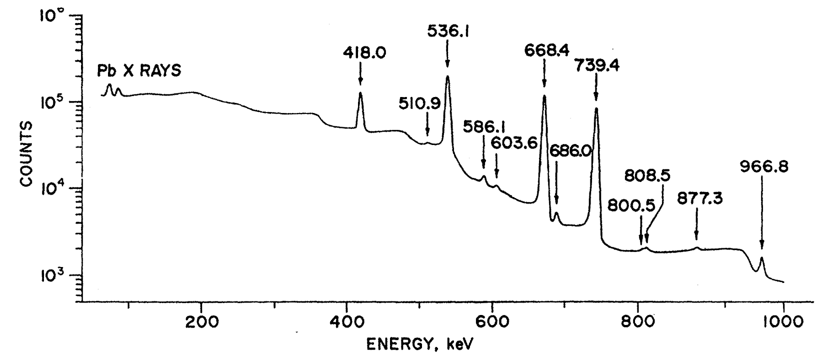

FIG. 1. Spectrum of low-energy γ rays emitted by ^{130}I, observed by Ge(Li) detector.

Decay of ^{130}I

Several groups[2,13,14] have studied the decay of ^{130}I. In the most recently published study,[2] a β-ray spectrometer and scintillation techniques were used to detect the radiations from ^{130}I; the following excited states of ^{130}Xe were deduced: 2^+ at 540 keV, 4^+ at 1210 keV, 5^+ at 1950 keV, and 6^+ at 2370 keV.

Sources of 12.5-h ^{130}I were prepared for the present study by neutron capture by ^{129}I. Iodine was chemically removed from the commercially obtained sources, either by sublimation or by precipitation as silver iodide. The decay of the source was followed for a week to make sure that none of the previously unreported γ rays was due to a long-lived contaminant. One source contained a small amount of 8-day ^{131}I as contaminant.

Figure 1 shows the low-energy γ rays emitted by ^{130}I. The peak with energy 510.9 ± 0.2 keV is believed to be a nuclear γ ray from ^{130}I, rather than annihilation radiation. This peak has the proper half-life for ^{130}I, but there is not enough energy available for ^{130}I to decay to ^{130}Te by β^+ emission.[13] Figure 2 shows the high-energy γ rays emitted by ^{130}I. The upper spectrum (a) is that of a source 13 cm from the detector; counts have been multiplied by 100 for clarity in reading the figure. The lower spectrum (b) is that of the same source placed in contact with the detector container. Sum peaks, visible in (b) and not in (a), are marked in (b); the 1272-, 1404-, and 1501-keV peaks also appear to be distorted in (b) by the presence of sum peaks of energy near the photopeak energies. The relative intensities of γ rays from ^{130}I are listed with the γ-ray energies in Table I. Interpretation of the sum peaks is given in Table II.

Coincidences between γ rays emitted by ^{130}I were studied using a 27 cc Ge(Li) detector gated by a 7.6-cm $\times$7.6-cm NaI(Tl) detector. However, only the previously known coincidences among the five strongest γ rays were observed.

The transition energies and the coincidence results were used in deducing levels of ^{130}Xe populated in the

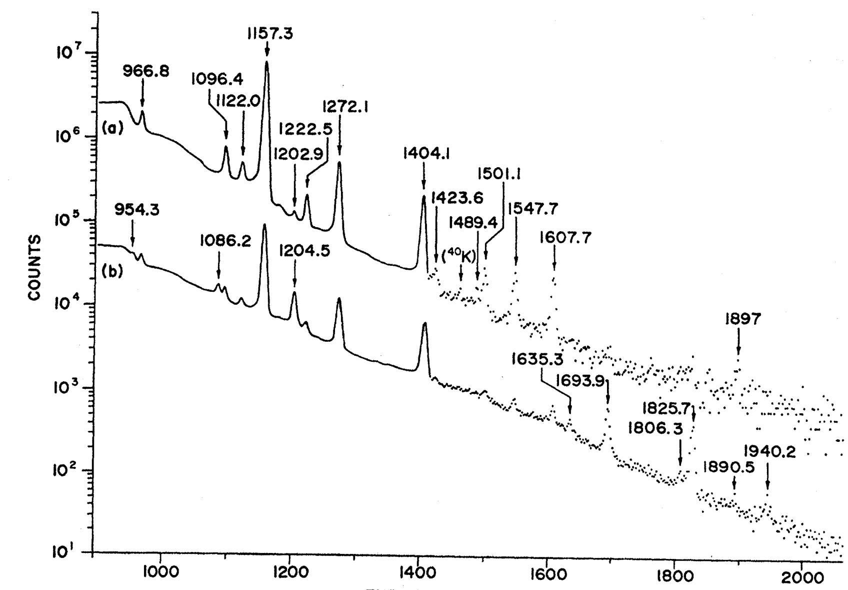

FIG. 2. Spectra of high-energy γ rays emitted by ^{130}I, observed by Ge(Li) detector. (a) Source 13 cm from detector, counts have been multiplied by 100. (b) Source in contact with detector.

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TABLE I. Energies and relative intensities of γ rays from ^{130}I, measured in this study.

Energy (keV)	Relative intensity
418.0±0.1	32.6 ± 4.6
510.9±0.2[a]	0.62± 0.09
536.1±0.1	100.
586.1±0.1	1.58± 0.23
603.6±0.1	0.59± 0.09
668.4±0.1	94.0 ±13.0
686.0±0.1	0.93± 0.13
739.4±0.1	80.8 ±11.0
800.5±0.5	0.07± 0.02
808.5±0.2	0.21± 0.03
877.3±0.2[a]	0.18± 0.03
966.8±0.1	0.77± 0.11
1096.4±0.1[a]	0.50± 0.07
1122.0±0.2	0.23± 0.03
1157.3±0.1	11.4 ± 1.6
1202.9±0.5[a]	0.02± 0.006
1222.5±0.1	0.18± 0.03
1272.1±0.1	0.78± 0.11
1404.1±0.1	0.36± 0.05
1423.6±0.3[a]	0.03± 0.006
1489.4±0.5[a]	0.01± 0.003
1501.1±0.2[a]	0.04± 0.008
1547.7±0.3	0.04± 0.007
1607.7±0.4[a]	0.04± 0.007

[a] Not fitted into level scheme of Fig. 6.

TABLE II. Analysis of sum peaks in Fig. 2(b).

Energy (keV)	Component γ rays (keV)
954.3±0.2	(418.0±0.1)+ (536.1±0.1)
1086.2±0.2	(418.0±0.1)+ (668.4±0.1)
1204.5±0.1	(536.1±0.1)+ (668.4±0.1)
≈1275	(536.1±0.1)+ (739.4±0.1)
≈1408	(668.4±0.1)+ (739.4±0.1)
≈1502	(536.1±0.1)+ (966.8±0.1)
1635.3±0.6	(668.4±0.1)+ (966.8±0.1)
1693.9±0.3	(536.1±0.1)+(1157.3±0.1)
1806.3±0.4	(536.1±0.1)+(1272.1±0.1)?
1825.7±0.2	(668.4±0.1)+(1157.3±0.1)
1890.5±1.5	(668.4±0.1)+(1222.5±0.1)
1940.2±1.0	(536.1±0.1)+(1404.1±0.1)

decay of ^{130}I. Sum peaks observed in Fig. 2(b) indicate coincidences between the 668.4-keV γ ray and the 966.8- and 1222.5-keV γ rays; this is the only evidence for levels at 2171.3 and 2427.0 keV. Levels of ^{130}Xe are deduced at 536.1±0.1, 1122.1±0.1, 1204.5±0.1, 1808.1 ±0.1, 1943.9±0.2, 2171.3±0.2, 2361.8±0.2, 2427.0 ±0.2, 2608.6±0.2, and 2752.3±0.2 keV. These levels are shown in the level scheme of Fig. 6. Eight of the 24 transitions observed in the decay of ^{130}I have not been placed in this level scheme. Consideration of the γ-ray energies would allow placement of additional levels of ^{130}Xe at 1632.5 and 2143.8 keV. These hypothesized levels would apparently be populated directly in the decay of 5^- ^{130}I, but no transition from either level to the 4^+ level at 1204.5 keV has been observed; since it is then very hard to understand what the nature of the hypothesized levels could be, they have not been included in Fig. 6.

The transition intensities shown in the left half of Fig. 6 are given in percent of decays of ^{130}I. The log*ft* values and relative intensities of the transitions from ^{130}I were calculated from the intensities of the γ rays (Table I) and the maximum energy[2] of 1.042 MeV for the β-ray group populating the 1943.9-keV state of ^{130}Xe.

Angular correlations between the five strongest γ rays from ^{130}I were studied. Since these γ rays are so much more intense than the newly discovered weak γ rays, the angular-correlation results should not be significantly affected by the presence of those weaker transitions. Three 7.6-cm×7.6-cm NaI(Tl) detectors were used simultaneously. The gating detector and one other observed the source along perpendicular axes; the angle θ between the gating detector and the third detector was varied. Coincidences between the two pairs of detectors were recorded simultaneously but routed into separate halves of the memory of a 400-channel analyzer. The angular correlation was determined by normalizing the number of coincidence counts in the detector at θ to the number of coincidence counts in the detector at 90°, then observing the variation of this normalized coincidence counting rate as θ was varied. The results were consistent with the results of Smith *et al.*[14] The angular-correlation studies do not determine unambiguously the dipole-quadrupole mixing ratios for the transitions de-exciting the 1943.9- and 2361.8-keV levels, so the spins of these levels are not determined uniquely. The 1943.9 and 2361.8 keV-levels have spins of either 5 or 6.

Decay of ^{130}Cs

The energy of the most energetic positrons emitted by ^{130}Cs was measured by Smith *et al.*[15] as 1.97 MeV. Several groups[3,16–18] have studied γ rays emitted in the decay of ^{130}Cs. A 535-keV, 2^+ excited state and a 1122-keV, 0^+ or 2^+ excited state in ^{130}Xe have been deduced.[3]

Sources of ^{130}Cs were prepared for the present study by the (α,n) reaction on sodium iodide. Beryllium and aluminum absorbers were used to degrade the 42-MeV α beam of the Lewis Research Center cyclotron to about 14 MeV for bombardments. Iodine was removed from the target material by precipitation as silver iodide. The cesium activity was then separated by an extraction method.[19] With this method, cesium (and rubidium) are selectively extracted from basic tartrate

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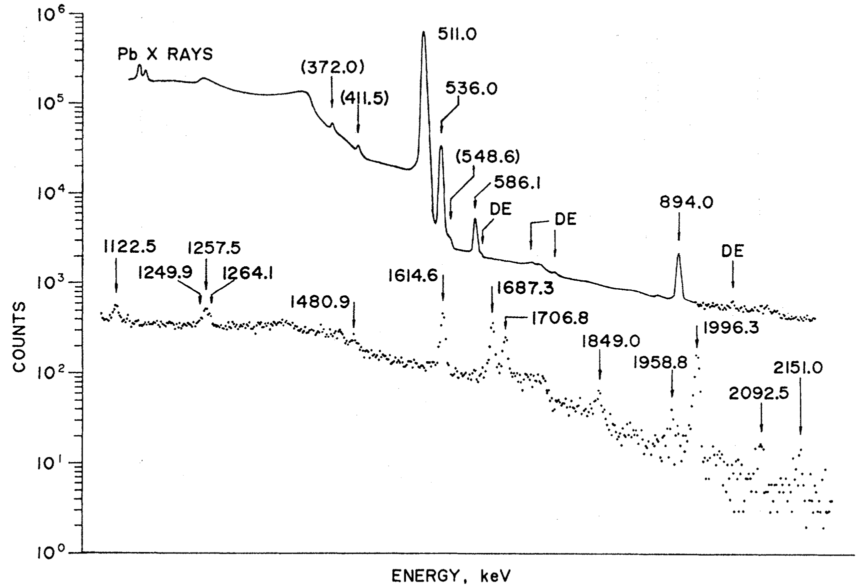

FIG. 3. Spectrum of γ rays emitted by ^{130}Cs, observed by Ge(Li) detector. Energies of γ rays emitted by the ^{129}Cs contaminant are given in parentheses.

solutions with a solution of 4-sec-butyl-2(α-methylbenzyl) phenol in cyclohexane. The chemical treatment required approximately 15 min to complete.

Figure 3 shows a γ-ray spectrum of ^{130}Cs obtained by adding Ge(Li) spectra of six sources made in successive bombardments. Double-escape peaks are labeled "DE," and parentheses enclose the energies of three γ rays from ^{129}Cs, the only contaminant observed. Relative intensities of all nuclear γ rays from ^{130}Cs were determined from this spectrum. The relative intensity of the annihilation radiation was determined in a separate experiment. These relative intensities are given with the γ-ray energies in Table III.

The γ rays of energy 511.0, 536.0, 586.1, 894.0, and 1996.3 keV were sufficiently intense that their half-lives could be obtained. The weighted average of these results was a value of 29.9±0.1 min. for the half-life of ^{130}Cs.

Coincidences between γ rays emitted by ^{130}Cs were studied with two 7.6-cm×7.6-cm NaI(Tl) detectors. These detectors observed the source along perpendicular axes and were shielded from each other by 5 cm of lead. The 4096-channel pulse-height analyzer was used in the two-dimensional mode (64×64 channels) so all coincident events seen by the two detectors could be recorded simultaneously.

Figures 4 and 5 show some of the coincidence results. The singles spectrum observed by one detector is at the top of Fig. 4. Shown also are spectra seen by the same detector in coincidence with the channel corresponding to annihilation radiation (a), and in coincidence with channels centered at approximately 550 keV (b), and 600 keV (c). Counts in spectra (a) and (b) have been multiplied by 100 and 10, respectively, to make the plot more clear. The 511-, 536-, and 586-keV γ rays are not clearly resolved in these spectra. Nevertheless, Fig. 4 offers good evidence that the 894, 1615, 1687, 1707, and 1996 γ rays, and at least one of the three γ rays with energy near 1260 keV are coincident with the 536-keV γ ray. Furthermore, of these γ rays only the 894-keV γ ray is coincident with the 586-keV γ ray. Figure 5 shows that the 1122-keV γ ray is in coincidence with the 894-keV γ ray; in the coincidence spectrum, the intensity of the 1122-keV peak is markedly enhanced over that in the singles spectrum.

Excited states in ^{130}Xe have been deduced from these coincidence results, from the energy and intensity values of Table III, and from those cases in which the sum of the energies of two γ rays coincides with the energy of a third. These states are at 536.0±0.1, 1122.1±0.2, 1785.9±1.5, 1793.5±0.6, 1800.1±0.9, 2016.1±0.2, 2150.6±0.3, 2223.3±0.3, 2242.8±0.3, and 2532.3±0.5 keV. These levels are shown in the level scheme in Fig.

TABLE III. Energies and relative intensities of γ rays from ^{130}Cs, measured in this study.

Energy (keV)	Relative intensity
511.006±0.002[a]	2290 ±320
536.0 ±0.1	100
586.1 ±0.1	11.6 ±1.7
894.0 ±0.1	10.5 ±1.5
1122.5 ±0.4	1.8 ±0.3
1249.9 ±1.5	0.5 ±0.2
1257.5 ±0.6	2.1 ±0.4
1264.1 ±0.9	1.1 ±0.3
1480.9 ±0.9	0.8 ±0.3
1614.6 ±0.3	6.1 ±0.9
1687.3 ±0.3	4.7 ±0.7
1706.8 ±0.3	3.3 ±0.5
1849.0 ±0.7[b]	0.67±0.14
1958.8 ±1.0[b]	0.34±0.09
1996.3 ±0.5	4.0 ±0.6
2092.5 ±1.1[b]	0.26±0.07
2151.0 ±1.3	0.20±0.06

[a] Annihilation radiation. Energy value adopted from Ref. 6.
[b] Not fitted into level scheme of Fig. 6.

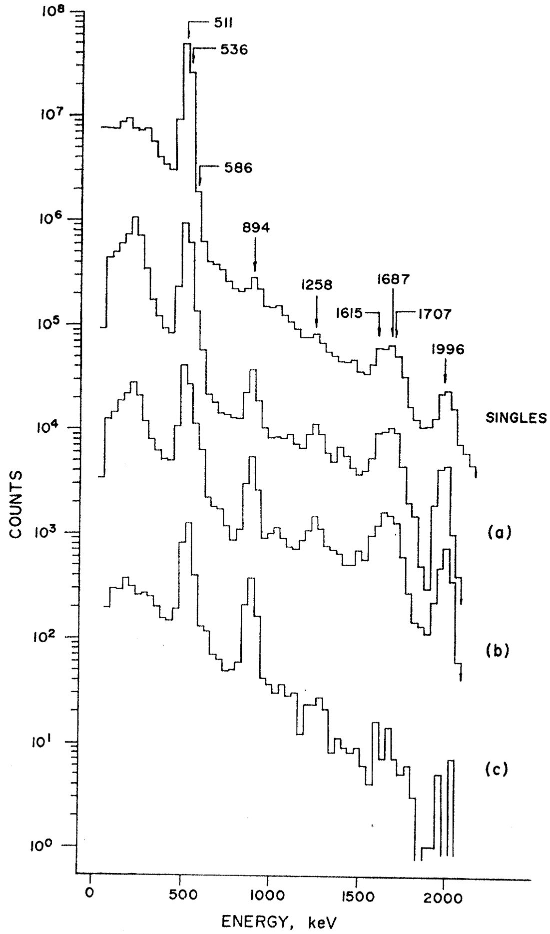

FIG. 4. Scintillation spectra of γ rays emitted by ^{130}Cs: (a) in coincidence with annihilation radiation, counts have been multiplied by 100; (b) in coincidence with $\approx$550 keV, counts have been multiplied by 10; (c) in coincidence with $\approx$600 keV.

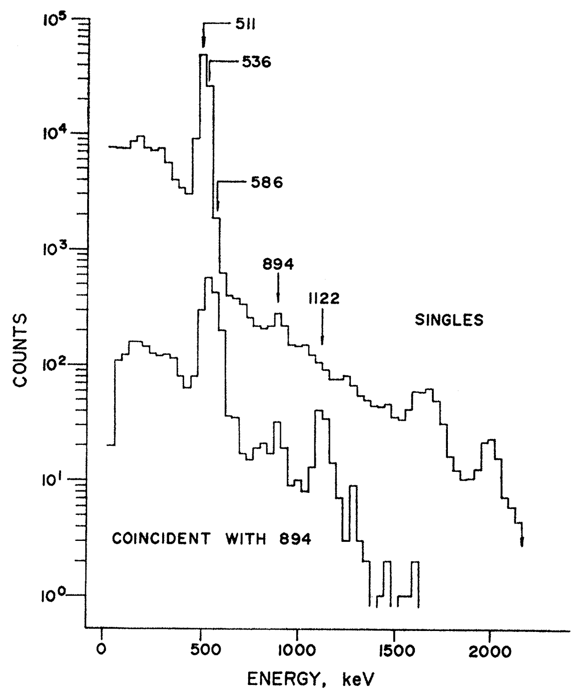

FIG. 5. Scintillation spectrum of γ rays emitted by ^{130}Cs in coincidence with 894 keV, compared with singles spectrum.

6. All but three of the γ rays observed in the decay of ^{130}Cs have been placed in this scheme.

The transition intensities shown in the right half of Fig. 6 are given as percents of all decays of ^{130}Cs; the 1.6% β^- decay to ^{130}Ba (Ref. 15) has been included. The logft values and relative intensities of the transitions from ^{130}Cs were calculated from the intensities of the γ rays (Table III) and the maximum positron energy[15] of 1.97 MeV. For each of the levels populated by positron emission, the intensity ratio of K-electron capture to positron emission was assumed to be the value obtained theoretically[20] for allowed β decay. Capture of electrons from higher shells was assumed to be 10% of that from the K shell.

DISCUSSION OF RESULTS

The results of the present study of the β decay of ^{130}I and ^{130}Cs to ^{130}Xe are summarized in the level scheme of Fig. 6.

Only two levels of ^{130}Xe have been found at approximately twice the energy of the 2^+ first excited state. The character of the 1204.5-keV state was determined[2,14] to be 4^+. Gföller and Flammersfeld[3] ascribed a character of 0^+ or 2^+ to the 1122.1-keV state because it is populated in the decay of 1^+ ^{130}Cs. They did not observe a transition from this level to the ground state of ^{130}Xe, but such a transition has been observed in the present study. It is thus possible to discard the 0^+ alternative. A (2^+) character is assumed for the 1122.1-keV state on the basis of the systematics of the even Xe isotopes (Fig. 7).

The γ-ray branching ratio for the de-excitation of the 1122.1-keV state, denoted $(2^+)'$, has been determined to be $I[(2^+)' \to 0^+]/I[(2^+)' \to 2^+] = 0.15 \pm 0.03$. If one neglects internal conversion and assumes that both transitions are pure electric quadrupole, the ratio of the reduced transition probabilities for the two modes of de-excitation of the 1122.1-keV state is

$$\frac{B(E2;\,(2^+)' \to 0^+)}{B(E2;\,(2^+)' \to 2^+)} = \frac{I(1122.1\text{ keV})}{I(586.1\text{ keV})}\left(\frac{586.1}{1122.1}\right)^5 = 0.0058 \pm 0.0012.$$

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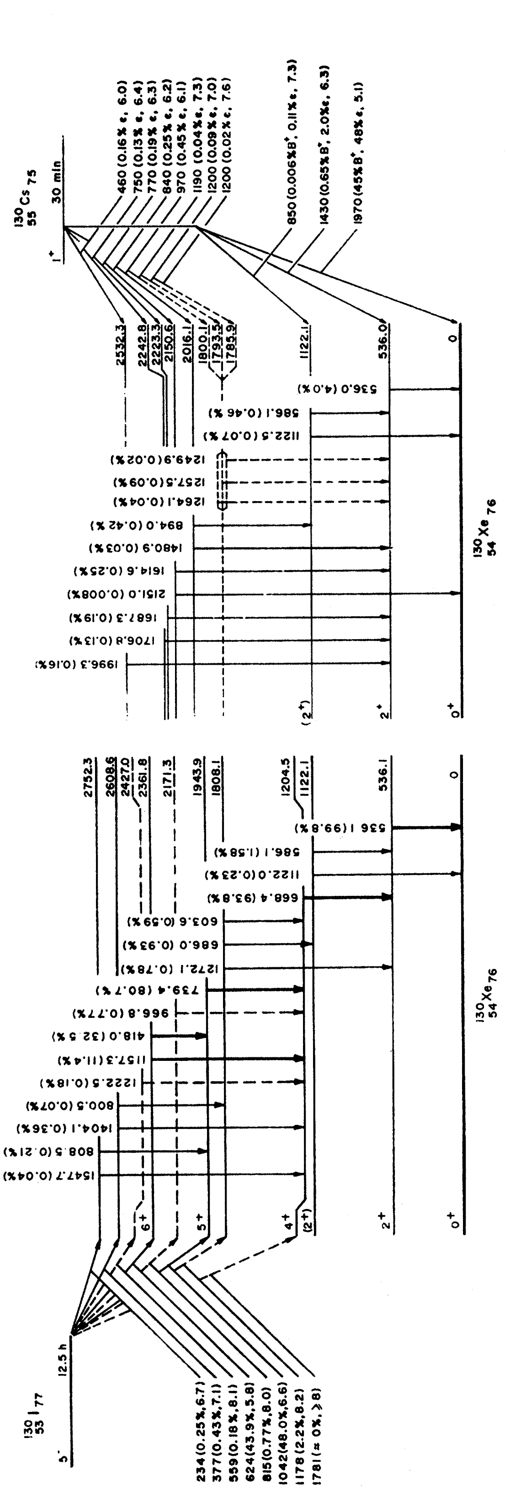

FIG. 6. Levels of ^{130}Xe populated in the β decay of ^{130}I and ^{130}Cs. Energies are given in keV. γ ray intensities, expressed in terms of percent of decays of the indicated parent isotope, are given in parentheses. The spin assignment in the decay of ^{130}I, except that of the 1122.1-keV state, are from Ref. 2.

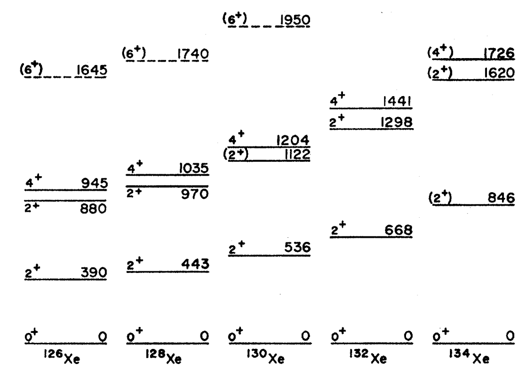

FIG. 7. Excited states of even Xe isotopes. Data are taken from Refs. 5, 21–24, and the present work.

The analogous ratios, computed from the data of Refs. 21–24, are 0.020 for ^{134}Xe, 0.0015 for ^{132}Xe, and 0.012 for ^{128}Xe.

No evidence was found for the existence of a possible 0^+ level of ^{130}Xe at about twice the energy of the first excited state. In particular, no γ ray was observed that could be interpreted as a transition from such a 0^+ level to the 536.1-keV level, and no γ rays were observed to populate such a 0^+ level in the de-excitation of higher levels of ^{130}Xe. If there were a 0^+ level of ^{130}Xe degenerate with the (2^+) level at 1122.1 keV, the 0^+ level should be populated in the decay of 1^+ ^{130}Cs but not in the decay of 5^- ^{130}I. Then the presence of the $0^+ \rightarrow 2^+$ transition would make the branching ratio $I(1122.1\text{ keV})/I(586.1\text{ keV})$ appear smaller when the parent isotope is ^{130}Cs than when the parent isotope is ^{130}I. However, in the present study, the same detector was used to study the decay of both ^{130}I and ^{130}Cs, and in each case the same value of the branching ratio was observed within 10%. Hence, it appears that if there is a 0^+ state of ^{130}Xe at about twice the energy of the first excited state, it is populated at most very weakly in the decay of ^{130}Cs. Note that the preceding discussion has not considered the possibility that such a 0^+ level is populated but that it is de-excited solely by $E0$ conversion electrons to the ground state. There also remains the possibility that the 0^+ "vibrational triplet state" of ^{130}Xe exists but, because of the nature of the nuclear potential, does not lie low enough in energy so that it could be recognized as such.[25,26]

If the 1808.1-keV level of ^{130}Xe is populated directly in the decay of 5^- ^{130}I, the most likely spin for this level is 4. The fact that transitions lead from this level to both 2^+ and 4^+ levels suggests that this level does not have very high spin, while any spin less than 4 would

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require that the β transition populating this level would be at least unique first forbidden.

Morinaga and co-workers[4,5] have reported exciting a level of ^{130}Xe at about 1950 keV during reaction studies. Although they did not directly measure the spin of this level, they assumed it to be 6^+. If normal selection rules apply, a 6^+ level of ^{130}Xe could be populated in the decay of 5^- ^{130}I. However, Daniel *et al.*[2] assigned a character of 5^+ to a level of ^{130}Xe at about 1950 keV populated in the decay of ^{130}I. It is possible that this is the same level, for in the present study of the decay of ^{130}I, no evidence was found for the existence of an additional level of ^{130}Xe close to that whose energy is measured as 1943.9 keV.

Very recently Bergstrom *et al.*[27] have performed an experiment in which exicted states of ^{130}Xe are populated in the (α,Xn) reaction on separated tellurium isotopes, and the angular distribution of the de-excitation γ rays is measured with respect to the α beam. These workers report populating a 6^+ level at 1945 keV and a 5^- level at 2060 keV. With normal selection rules, population of a 5^- level of ^{130}Xe in the decay of 5^- ^{130}I would be allowed, but no evidence was found for such a level in the present study. It must be stressed that unusual selection rules may apply, so that excited states of ^{130}Xe populated in the reaction studies may not be populated in β decay.

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Transitional Nuclei. II. Higher Vibrational States in Nucleus ^{154}Gd†

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Isotopically separated ^{154}Eu has been used in conjunction with sources prepared from neutron irradiation of isotopically separated ^{153}Eu to study the γ-ray spectra and concomitant level structure of ^{154}Gd. Several levels which have been identified as collective levels are found to have two-phonon character. A collective $K=2$ vibrational state has been proposed at 1531.39 keV and can be described as a coupled ($\beta\gamma$) two-phonon state. Members of the rotational band built on this state have been identified at 1531.39±0.07, 1660.94±0.07, and 1790.4±0.3 keV with spin and parity of 2^+, 3^+, and 4^+, respectively. A possible second band at 1292.7 keV has been found to possess two (β) phonon characteristics. Evidence is found for the breakdown of the simple $E2$ selection rules for transitions from higher phonon bands.

1. INTRODUCTION

In deformed nuclei the various vibrations can be characterized by ν, where $\nu=0$ is commonly termed the β vibration and $\nu=2$ the γ vibration. The $\beta(\gamma)$ vibrational band is then constructed by setting $n_\beta=1$ and $n_\gamma=0$ (or vice versa for the γ band). Although few, if any, cases have been found to date, it is possible within the framework of the model to have a coupled vibrational mode with $n_\beta=1$ and $n_\gamma=1$, which will then have[1] $K^\pi=2^+$. Of course, one can also have $n_\beta=2$, $n_\gamma=0$, in which case a band with $K^\pi=0^+$ results. For $n_\beta=0$, $n_\gamma=2$, two bands are expected to occur, one with $K=K_0+\nu=4$ and one with $K=|K_0-\nu|=0$. There is also the possibility that one may find mixed vibrational bands, particularly at the edges of the strong deformation region. Recently, calculations have been published by Kumar *et al.*[2,3] who treat such bands. In an extensive study[4] of the γ-ray spectra from the decay of ^{154}Eu and the resulting level structure of ^{154}Gd, several levels were found to decay predominantly to the β- and γ-vibrational bands. It is suggested here that these levels form two-phonon bands which may be of mixed character. The nomenclature $I^\pi K_{n_\beta}{}^{n_\gamma}$ is used here.[5]

2. EXPERIMENTAL PROCEDURE

For a discussion of the experimental techniques, the reader is referred to Ref. 4, where these details are discussed along with a presentation and analysis of the complete decay scheme. The intensities of the γ rays from 100 to 1010 keV were remeasured with the Compton suppression spectrometer. Both an isotopically separated ^{154}Eu source and a ^{154}Eu source prepared by neutron irradiation of an isotopically separated ^{153}Eu followed by an ion-exchange column separation were used.

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[1] Aa. Bohr and B. Mottelson, Lecture Notes, Copenhagen, 1966 (to be published).

[2] K. Kumar, Nucl. Phys. **A92**, 653 (1967).

[3] K. Kumar and M. Baranger, Nucl. Phys. **A92**, 608 (1967).

[4] R. A. Meyer, Phys. Rev. **170**, 1089 (1968).

[5] Here we adopt the convention that n_γ represents the number of γ phonons and n_β the number of β phonons.