Excited States of ^{128}Xe†

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Gamma rays accompanying the decay of 25-min ^{128}I and 3-min ^{128}Cs have been studied with 8-cc and 30-cc Ge(Li) spectrometers. Coincidences between γ rays were studied using two 7.6-cm$\times$7.6-cm NaI(Tl) scintillators. In the decay of ^{128}I, γ rays of the following energies were observed (relative intensities in parentheses): 443.3 (100.0), 526.4 (9.9), 743.3 (1.0), 969.7 (2.7), and 1139.9 (0.08) keV. In the decay of ^{128}Cs, γ rays of the following energies were observed (relative intensities in parentheses): 443.0 (100.0), 511.1 (414.0), 526.5 (7.3), 613.5 (0.93), 969.5 (1.6), 1030.8 (0.61), 1139.9 (4.0), 1304.9 (0.47), 1514.2 (0.14), 1631.0 (0.36), 1685.9 (0.32), 1981.9 (0.11), 2041.8 (0.074), 2157.2 (0.62), 2193.0 (0.13), 2277.8 (0.040), 2365.2 (0.15), 2398.2 (0.052), 2419.9 (0.082), 2592.4 (0.011), 2840.5 (0.011), and 2862.2 (0.016) keV. A level scheme for ^{128}Xe has been constructed with levels at 443.2 (2^+), 969.6 (2^+), 1583.1 ($0^+,1^+,2^+$), 2275.2, 2484.3, 2600.5, 2841.1, and 2862.8 keV. The most important result of these studies is that no evidence has been found for the existence of a 0^+ member of a possible two-phonon vibrational triplet.

INTRODUCTION

According to the hydrodynamical model, near-spherical even-even nuclei may undergo nearly harmonic quadrupole vibrations. For these nuclei the two-phonon excitation should consist of a close lying 0^+-2^+-4^+ "vibrational triplet" at about twice the energy of the one-phonon state. But even with the increased sensitivity of recent experiments, very few near-spherical nuclei have been found to possess all three members of the predicted triplet; above $Z=50$, ^{122}Te is the only nucleus definitely proved to have all three.[1–3] Recently some supposedly near-spherical even-even nuclei have been found to have large quadrupole and magnetic moments for the 2^+ first excited state. This raises serious doubts as to the validity of the conventional picture of nuclear vibrations.[4–6]

Because of the uncertain state of the theory, it is of interest to reexamine the levels of near-spherical even-even nuclei. The nucleus ^{128}Xe is of particular importance. Studies of the beta decay of 1^+ ^{128}I and 1^+ ^{128}Cs[2] indicate that ^{128}Xe has a 2^+ second exited state at 990 keV. Morinaga and Lark[7] reported the 4^+ level at 1041 keV during a study of (α,xn) reactions on Te. Two studies[8,9] suggest the existence of a 0^+ triplet member, but they disagree on its location. If the existence of the 0^+ level could be confirmed, ^{128}Xe would be one of the few even-even nuclei known to possess a complete 0^+-2^+-4^+ triplet. To clarify the situation on the low-spin levels of ^{128}Xe, a study of the decay of ^{128}I and ^{128}Cs has been performed here with the use of high-resolution Ge(Li) γ-ray spectrometers.

DECAY OF ^{128}I

Sources of 25 min ^{128}I were made by exposing reagent-grade iodine to the neutron flux in a low-power solution-type reactor for 1 h. No chemical separation was performed. The intensity of contaminating activities, formed in fast-neutron-induced reactions, was negligible.

The γ rays from ^{128}I were observed with a 30-cc Ge(Li) detector. Figure 1 shows a spectrum taken over a period of 170 min. During this time the source was moved so as to maintain constant counting rate in the pulse-height analyzer. The source distance, however, was always large enough to exclude summing of γ rays

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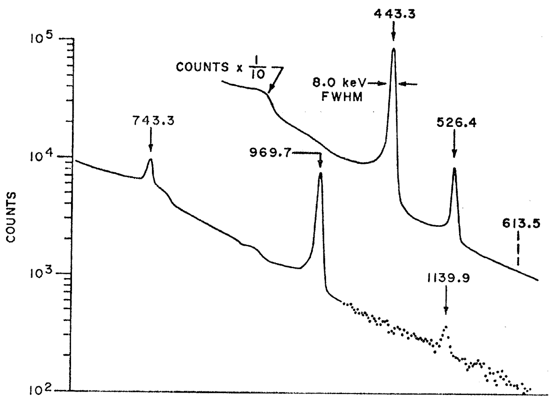

FIG. 1. Spectrum of γ rays from ^{128}I, observed with 30-cc Ge(Li) detector.

in the detector. The energies and relative intensities of the γ rays observed[10] are given in Table I.

DECAY OF ^{128}Cs

Sources of 3-min ^{128}Cs in equilibrium with its parent 2.4 day ^{128}Ba were made by bombarding chemically pure cesium chloride with approximately 100-MeV protons in the Carnegie Institute of Technology synchrocyclotron. Short-lived barium activities were allowed to decay before chemical separation was begun. Iodine, xenon, and cesium activities were removed, and barium was precipitated as the nitrate. The only contaminant observed was 12 day ^{131}Ba.

The low-energy γ rays from ^{128}Ba-^{128}Cs were observed with an 8-cc Ge(Li) detector. Figure 2 shows a spectrum

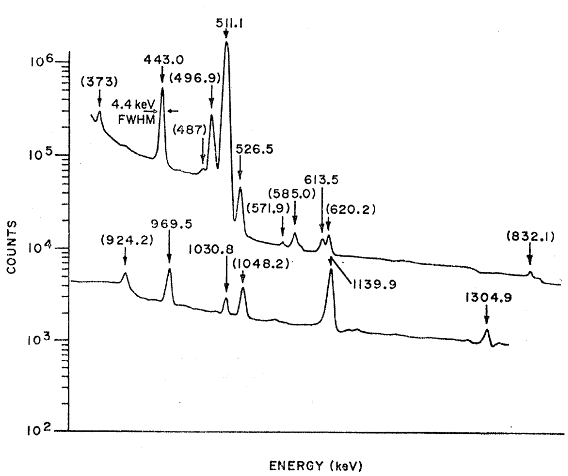

FIG. 2. Spectrum of low-energy γ rays from ^{128}Ba-^{128}Cs, observed with 8-cc Ge(Li) detector. Energies of γ rays from the ^{131}Ba contaminant are given in parentheses.

[10] The spectra obtained in studies reported in this paper were analyzed with a peak-fitting computer program written by T. Fessler of NASA Lewis Research Center. An empirical photo-efficiency curve has been used in determining relative intensities of γ rays. The calibration procedure is described in a NASA Technical Note (to be published) by the present authors.

TABLE I. Energies and relative intensities of γ rays from ^{128}I.

Energy (keV)	Relative intensity
443.3±0.2	100.0
526.4±0.2	9.9 ±1.4
743.3±0.2[a]	1.0 ±0.1
969.7±0.2	2.7 ±0.4
1139.9±0.4	0.08±0.01

[a] This γ ray is from ^{128}Te, which is also formed in the decay of ^{128}I.

taken two days after the bombardment of cesium. The 30-cc Ge(Li) detector was used to detect low-intensity, high-energy γ rays. A spectrum obtained with this detector is shown in Fig. 3. Double-escape peaks do not stand out in this spectrum. By following the decay of the source and by reference to previous studies,[11] γ rays from the contaminating ^{131}Ba were identified; their energies are indicated in parentheses in Figs. 2 and 3. The energies and relative intensities of the γ rays from ^{128}Ba-^{128}Cs are given in Table II. The small energy ($\approx$0.4 MeV) available[2] for the decay of ^{128}Ba into ^{128}Cs implies that most of the observed γ rays are emitted when ^{128}Cs decays into ^{128}Xe. One γ ray, with energy 273.1 keV, is too intense to fit plausibly at any one place in the ^{128}Xe level scheme, so it is assumed to be emitted in the decay of ^{128}Ba into ^{128}Cs.

Coincidences between γ rays were studied with two 7.6-cm×7.6-cm NaI(Tl) scintillators placed 90° apart. The coincidence circuit had a resolving time of 50 nsec. Figure 4 shows the γ-ray spectrum in coincidence with a window set on the 443.2-keV peak. Figure 5 shows the spectrum in coincidence with a window set on the high-

TABLE II. Energies and relative intensities of γ rays from ^{128}Ba-^{128}Cs.

Energy (keV)	Relative intensity
273.1±0.3[a]	59.0 ± 9.0
443.0±0.3	100.0
511.1±0.2[b]	414.0 ±60.0
526.5±0.3	7.3 ± 1.0
613.5±0.3	0.93 ± 0.1
969.5±0.3	1.6 ± 0.2
1030.8±0.3[c]	0.61 ± 0.09
1139.9±0.3	4.0 ± 0.6
1304.9±0.3	0.47 ± 0.08
1514.2±0.5	0.14 ± 0.02
1631.0±0.3	0.36 ± 0.05
1685.9±0.3[c]	0.32 ± 0.05
1981.9±0.5[c]	0.11 ± 0.02
2041.8±0.7	0.074± 0.01
2157.2±0.3	0.62 ± 0.09
2193.0±0.4[c]	0.13 ± 0.02
2277.8±0.8	0.040± 0.008
2365.2±0.3[c]	0.15 ± 0.02
2398.2±0.6	0.052± 0.009
2419.9±0.4	0.082± 0.01
2592.4±1.1[c]	0.011± 0.003
2840.5±1.1	0.011± 0.003
2862.2±0.8	0.016± 0.003

[a] The half-life of this γ ray precludes interpreting it as the isomeric transition from ^{133m}Ba. This transition is attributed to the decay of ^{128}Ba into ^{128}Cs.
[b] Annihilation radiation.
[c] Not placed in level scheme of Fig. 6.

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energy side of the annihilation peak to include the 526.4-keV γ ray. The results of these coincidence studies are consistent with the levels of ^{128}Xe deduced from the Ge(Li) γ-ray spectra. The existence of the uncertain level of ^{128}Xe at 2275.2 keV is deduced primarily from the appearance of the peak at 1300 keV in both of these coincidence spectra.

DISCUSSION OF RESULTS

Results of this work are summarized in the ^{128}Xe level scheme shown in Fig. 6. All γ rays observed in the decay of ^{128}I, as well as 15 out of 21 γ rays attributed to the decay of ^{128}Cs, have been fitted into this level scheme.

The most important result of these studies is that no evidence has been found for the existence of a hypothesized 0^+ level near the 969.6-keV 2^+ level of ^{128}Xe. Transitions to a 0^+ level would be allowed in the decay of both 1^+ ^{128}I and 1^+ ^{128}Cs. While it might be argued that a γ ray from such a state to the 443.2-keV level is concealed under one of the many peaks in Fig. 2, there is no evidence of such a γ ray in Fig. 1. It is still possible that the de-excitation γ ray from a 0^+ level is concealed under the 526.4- keV peak. Otherwise, consideration of statistics in the spectrum of Fig. 1 indicates that population of a 0^+ excited state of ^{128}Xe near the 969.6-keV 2^+ level must happen in less than 0.006% of the ^{128}I decays. (In obtaining this estimate, no allowance has been made for the possibility that the hypothesized 0^+ level is de-excited solely by $E0$ conversion electrons to the ground state.) Furthermore, transitions from higher states of ^{128}Xe to the 969.6-keV level are observed. If there is a 0^+ level near this level but not degenerate with it, then there should be transitions to the 0^+ level also; they are not observed.

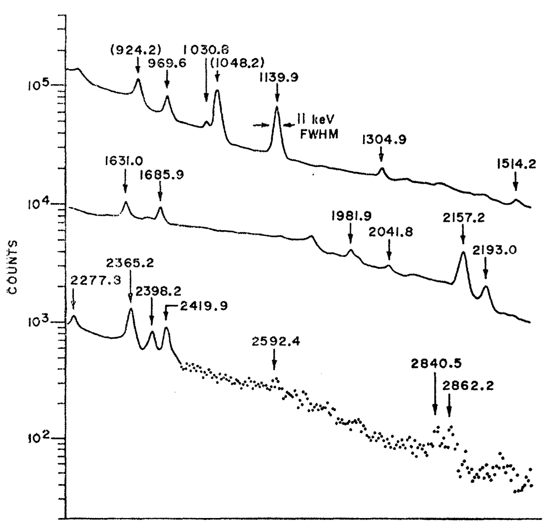

FIG. 3. Spectrum of high-energy γ rays from ^{128}Ba-^{128}Cs, observed with 30-cc Ge(Li) detector. Energies of γ rays from the ^{131}Ba contaminant are given in parentheses.

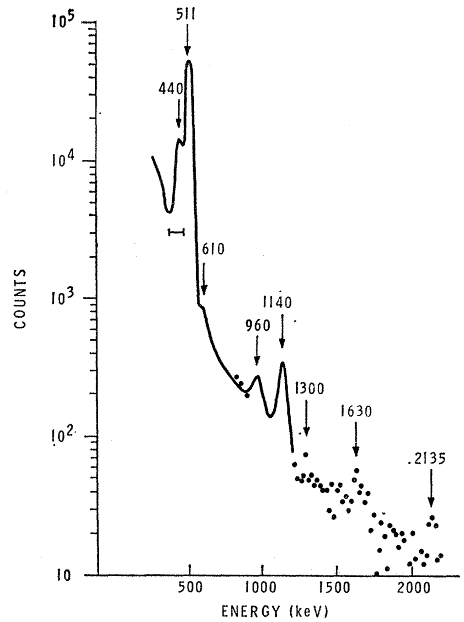

FIG. 4. Spectrum of γ rays in coincidence with the 443.2-keV γ ray of ^{128}Cs, observed with NaI(Tl) detector.

Two-phonon transitions are forbidden between levels of a harmonic oscillator. Hence, the second 2^+ excited state of ^{128}Xe does not closely approximate a pure harmonic-oscillator state because the transition from this level to the ground state is relatively strong. The ratio of intensities of γ rays emitted in its decay is found to be $I(526.4\text{ keV})/I(969.6\text{ keV})=4.0\pm0.4$. Then if the

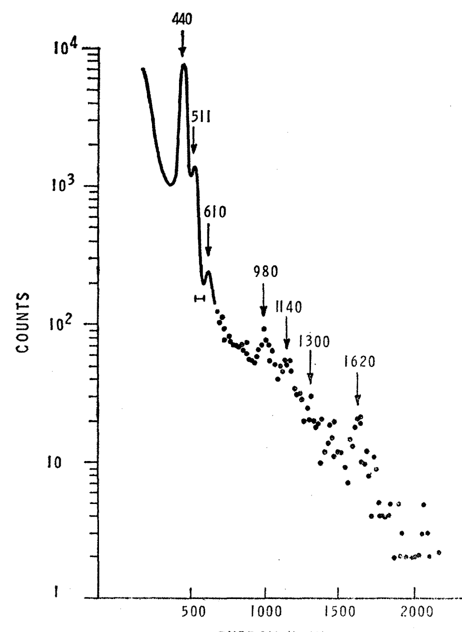

FIG. 5. Spectrum of γ rays in coincidence with the 526.4-keV γ ray and annihilation radiation of ^{128}Cs, observed with NaI(Tl) detector.

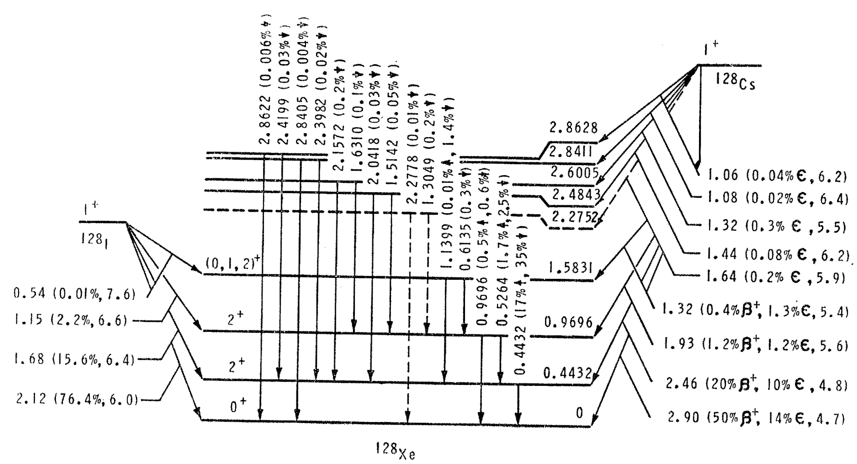

FIG. 6. Level scheme of ^{128}Xe. Energies are quoted in MeV. γ-ray intensities, expressed in terms of percent of decays of the ^{128}I($\leftarrow$) or ^{128}Cs($\rightarrow$) parent isotope, are given in parentheses.

small amount of internal conversion is neglected, the ratio of the reduced transition probabilities for the two modes of de-excitation of the second excited state ($2^{+\prime}$) is

$$\left[\frac{B(E2;\,2^{+\prime}\rightarrow 0^+)}{B(E2;\,2^{+\prime}\rightarrow 2^+)}\right]=\left(\frac{I(969.6\text{ keV})}{I(526.4\text{ keV})}\right)\left(\frac{526.4}{969.6}\right)^5$$
$$=0.012\pm 0.001.$$

This may be compared with values of the corresponding ratio in other near-spherical even-even nuclei: 0.0092 in ^{122}Te, 0.0042 in ^{126}Te, and ≤ 0.000003 in ^{196}Pt.[12]

The character of the 1583.1-keV state of ^{128}Xe is not yet clear, but several conclusions may be drawn about this state. In the present study, confirmation has been found for a report[13] that this state is weakly populated in the decay of ^{128}I. Only the 1139.9-keV transition from this state is observed in the ^{128}I decay. If in the decay of ^{128}I the 613.5-keV γ ray is only $\frac{1}{4}$ as intense as the 1139.9-keV γ ray, as is the case in the ^{128}Cs decay, it would be lost in the statistics in Fig. 1. If both transitions are assumed to be $E2$, the ratio of the reduced transition probabilities for th: two modes of de-excitation of the 1583.1-keV state is

$$\left[\frac{B(E2;\,J\rightarrow 2^+)}{B(E2;\,J\rightarrow 2^{+\prime})}\right]=\left(\frac{I(1139.9\text{ keV})}{I(613.5\text{ keV})}\right)\left(\frac{613.5}{1139.9}\right)^5$$
$$=0.19\pm 0.04.$$

Thus the 613.5-keV transition is enhanced over the 1139.9-keV transition. Hence the 1583.1-keV state is not interpreted as a two-phonon 0^+ vibrational state which has been displaced in energy by anharmonicity in the nuclear potential. This is because no current model can explain why the transition between two two-phonon states should be faster than the transition to the one-phonon state. If one wishes instead to interpret the 1583.1-keV state as basically a three-phonon state, the 613.5-keV γ ray would be a one-phonon transition, and the 1139.9-keV γ ray, a two-phonon transition. Since the 1139.9-keV transition is still fairly strong compared with the 613.5-keV transition, one would have to assume the supposed three-phonon state has other kinds of excitation mixed into it.[14]

Results on the beta rays of ^{128}I and on the total strength of electron capture decay of ^{128}I to ^{128}Te have been adopted from the work of Benczer *et al.*[15] The end-point energy of the most energetic positron group from ^{128}Cs has been taken from the Nuclear Data Sheets.[2] The electron-capture–to–positron-emission intensity ratio for the decay from ^{128}Cs to each level of ^{128}Xe has been calculated from the theoretical work of Perlman and Wolfsberg.[16] When these results are combined with the results of the present study, absolute intensities and logft's can be computed for decay to the levels of ^{128}Xe. No allowance has been made for internal conversion of the observed transitions. The results of the computations are shown in Fig. 6. Since the logft of 5.4 indicates that population of the 1583.1-keV state of ^{128}Xe is allowed in the decay of 1^+ ^{128}Cs, that state may be assumed to be $(0,1,2)^+$. Then the logft of 7.6 indicates that the decay of 1^+ ^{128}I to the same state is retarded.

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