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EXCITED STATES OF XENON 128

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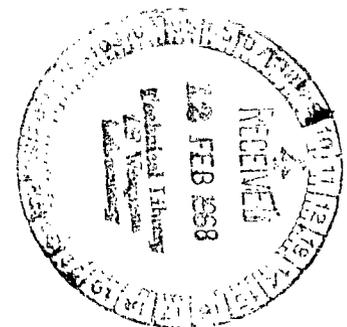
Lewis Research Center
Cleveland, Ohio

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SUMMARY

Gamma rays accompanying the decay of 25 minute iodine 128 (^{128}I) and 3 minute cesium 128 (^{128}Cs) have been studied with 8- and 30-cubic centimeter lithium-drifted germanium spectrometers. Coincidences between gamma rays were studied using two 7.6 by 7.6 centimeter thallium-activated sodium iodide scintillators. In the decay of ^{128}I, gamma rays of the following energies were observed (relative intensities in parentheses): 443.3 (100.), 526.4 (9.9), 743.3 (1.0), 969.7 (2.7), and 1139.9 (0.08) keV. In the decay of ^{128}Cs, gamma rays of the following energies were observed (relative intensities in parentheses): 443.0 (100.), 511.1 (414.), 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 of Xenon 128 (^{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.

According to the hydrodynamical model, the near-spherical even-even nucleus ^{128}Xe could be expected to have a close-lying 0^+ - 2^+ - 4^+ "vibrational triplet" at about twice the energy of the first excited state. Population of the 0^+ and 2^+ members of such a triplet would be allowed in the decay of 1^+ ^{128}I and 1^+ ^{128}Cs. A 2^+ level of ^{128}Xe at about twice the energy of the first excited state had been found in previous investigations. In the present study a search was made for the predicted 0^+ triplet member. No evidence has been found for the existence of such a level.

INTRODUCTION

According to the hydrodynamical model, near-spherical even-even nuclei may undergo nearly harmonic quadrupole vibrations. For these nuclei the two-phonon second excited state should consist of a close lying 0^+ - 2^+ - 4^+ "vibrational triplet" at about twice the energy of the one-phonon first excited 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 atomic number $Z = 50$, tellurium 122 (^{122}Te) is the only nucleus definitely proved to have all three (refs. 1 to 3 and unpublished data). 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 (refs. 4 to 7).

Because of the uncertain state of the theory, it is of interest to re-examine 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 (ref. 3) indicate that ^{128}Xe has a 2^+ second excited state at 990 keV. Morinaga and Lark (ref. 8) claim to have observed the 4^+ level at 1041 keV during a study of (α, xn) reactions on Te. Two studies (refs. 9 and 10) 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 with the use of high-resolution lithium-drifted germanium (Ge(Li)) gamma-ray spectrometers.

ANALYSIS OF GAMMA-RAY SPECTRA

Gamma-ray spectra were recorded with 8- and 30-cubic-centimeter "five-sided" Ge(Li) detectors. These spectra were analyzed with the help of a FORTRAN IV computer program. First, plots of the data from the pulse-height analyzer were made. Then the experimenter examined the plots and determined the approximate location of peaks. Finally the computer program analyzed the vicinity of each of these selected peaks. The program used the method of least squares to fit a Gaussian curve to each peak and to estimate the continuum on which each peak was located. From the analysis of these fitted Gaussian curves, information was obtained on the peak location and intensity, and on the errors in these two quantities.

The location of a peak was taken as the location of the symmetry axis of the fitted Gaussian curve. For an unknown peak it was necessary to convert this location to an

TABLE I. - GAMMA RAY ENERGIES

USED IN CALIBRATION[a]

Emitting isotope	Gamma-ray energy, keV
Cesium 137	661.595±0.076
Bismuth 207	569.62±0.06
	1063.51±0.08
Manganese 54	835.12±0.21
Sodium 22	511.006±0.002
	1274.7±0.2
Yttrium 88	898.0±0.3
	1836.1±0.2
Zinc 65	1115.6±0.18
Cobalt 56	846.5±0.2
	1238.6±0.2
	[b]1576.9±0.3
	1770.8±0.4
	[b]2180.3±0.5
	2598.9±0.3
	3202.3±0.5
Barium 131	585.1
	620.2
	832.0
	924.4
	1048.2

[a]Values were taken from refs. 3,
   11, and 12, and unpublished data.
[b]Double-escape peak.

energy. Therefore calibration spectra of gamma rays of known energy E were recorded under counting conditions as close as possible to those for the unknown isotopes. (Table I lists isotopes and gamma-ray energies used in calibration (refs. 3, 11, and 12)). The peak-fitting program was used to analyze these spectra to determine locations x of peaks corresponding to the known gamma rays. A detector-analyzer system calibration curve

$$E(x) = a_0 + \sum_{i=1}^{3} a_i x^i \qquad (1)$$

was assumed, and the method of least squares was used to fit this polynomial to the calibration points (x, E). This fitting yielded the coefficients of the polynomial. Then equation (1) could be used in computing the energies of unknown gamma rays. Uncertainties in gamma-ray energies were estimated as the combined result of uncertainties

Energy, keV

0   200   400   600   800   1000   1200   1400   1600   1800

Relative photopeak detection efficiency, $\varepsilon^{photo}_{(E_1)}/\varepsilon^{photo}_{(E_2)}$

10^1

10^0

10^{-1}

Isotope

○ Silver 110m
□ Cobalt 56
△ Hafnium 181
◇ Iodine 131
▽ Antimony 125
▷ Sodium 22
◁ Bismuth 207
◊ Yttrium 88

1800   2000   2200   2400   2600   2800   3000   3200   3400   3600

Energy, keV
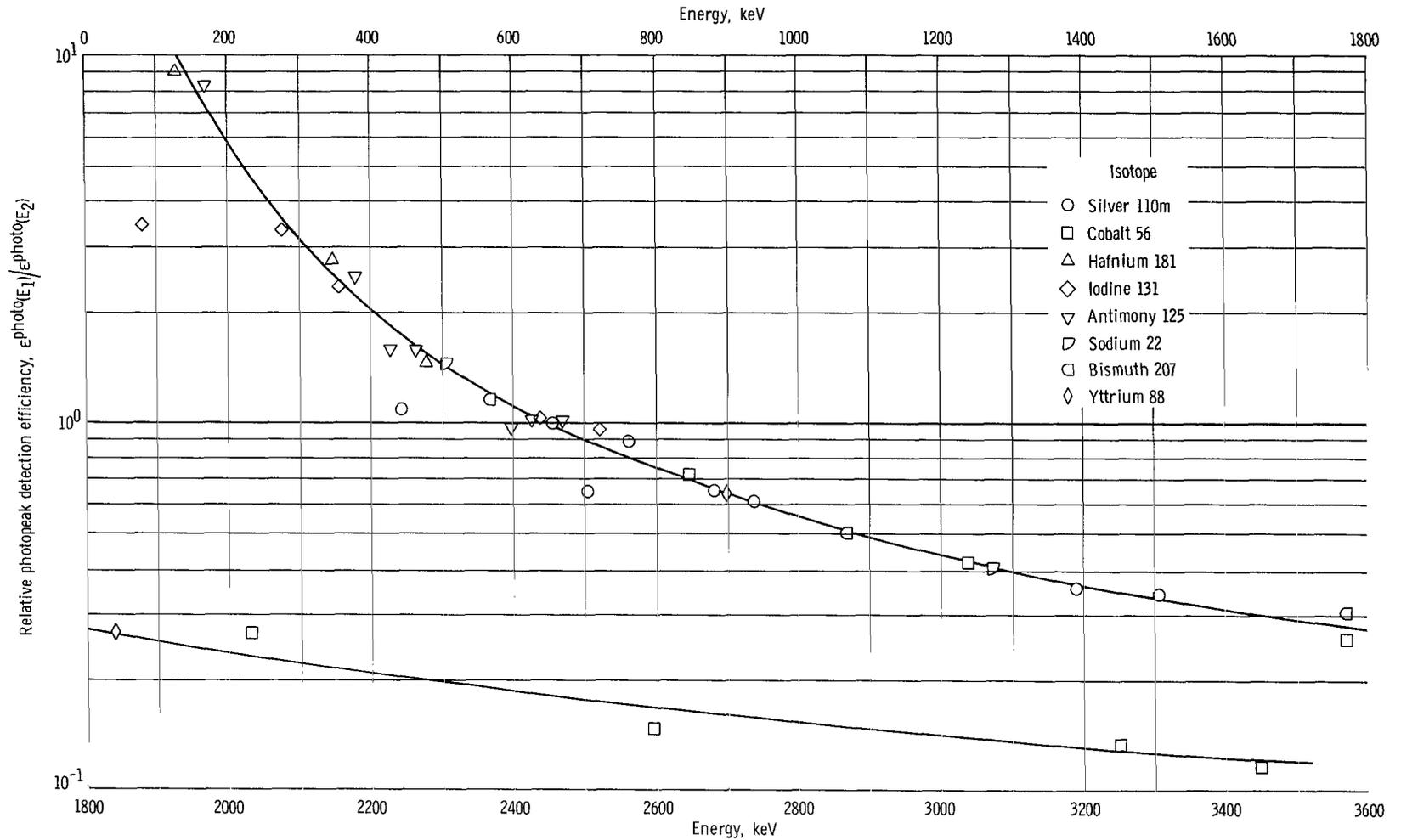
Figure 1. - Empirical relative photopeak detection efficiency curve for the 30-cubic-centimeter lithium-drifted germanium detector. Actual relative gamma ray intensities were obtained from references 3, 12, and 13. The energy scale at the top of the graph applies to the upper curve, and the energy scale at the bottom, to the lower curve.

in the calibration-peak energies (table I) and in the determination of peak locations in both the calibration gamma-ray spectra and the unknown gamma-ray spectra.

The area under the fitted Gaussian curve was taken as the measure of the observed intensity of a gamma-ray photopeak. However the photopeak detection efficiency of a Ge(Li) detector is a function of gamma-ray energy, so correction must be made for this in deducing actual gamma-ray intensities. For gamma rays of energy E, the following relation holds:

$$I^{obs}(E) = I(E) \cdot \epsilon^{photo}(E) \cdot \Omega \tag{2}$$

where $I^{obs}(E)$ is the observed intensity of the photopeak corresponding to detection of gamma rays of energy E, I(E) is the actual intensity of gamma rays of energy E emitted by the source, $\epsilon^{photo}(E)$ is the photopeak detection efficiency for gamma rays of energy E, and Ω is the solid angle subtended by the detector as seen from the source. Given the relative intensities of gamma rays of energy E_1 and E_2 emitted by one source (fixed Ω) the relative photopeak detection efficiency $\epsilon^{photo}(E_1)/\epsilon^{photo}(E_2)$ can be obtained from the observed relative photopeak intensities. By this method an empirical relative photopeak-detection efficiency curve can be constructed for a detector. Figure 1 shows this curve (refs. 3, 12, and 13) for the 30-cubic-centimeter Ge(Li) detector. This curve is not very accurate because the values for the actual relative intensities of gamma rays are generally not well known even for the standard sources. It is estimated that, from this curve, the relative photopeak-detection efficiency may be determined to ±10 percent for a given photopeak energy. With this curve and equation (2), relative observed intensities of photopeaks may be converted to actual relative intensities of gamma rays emitted by an unknown source. The error quoted on the relative gamma-ray intensities is the result of error both in the fitting of the Gaussian to the data and in the use of the relative photopeak detection efficiency curve.

EXPERIMENTAL RESULTS

Decay of Iodine 128

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

The gamma rays from [128]I were observed with a 30-cubic centimeter Ge(Li) detec-
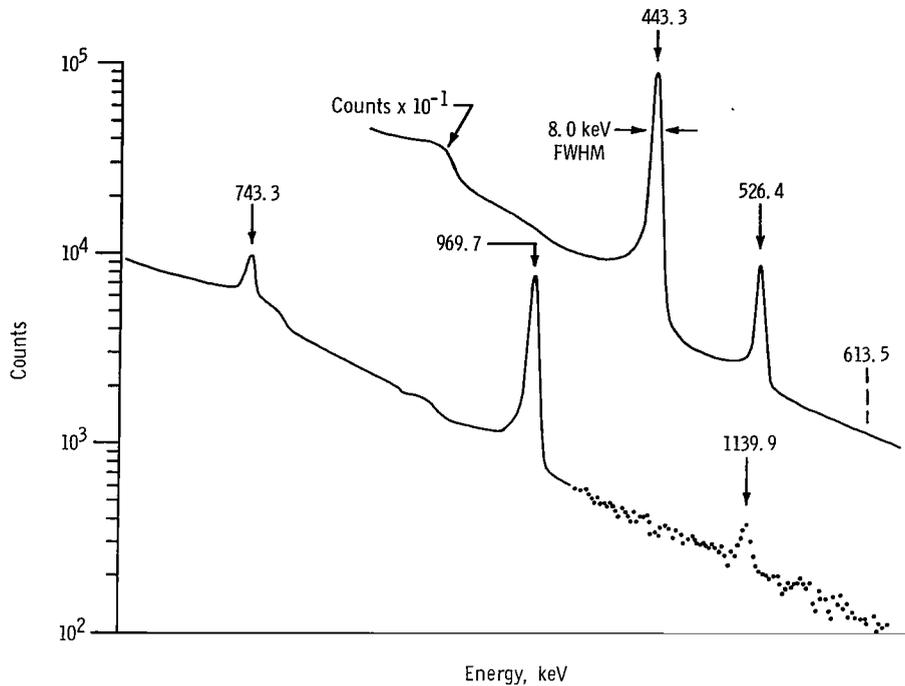
Figure 2. - Spectrum of gamma rays from iodine 128 observed with 30-cubic-centimeter lithium-drifted germanium detector.

TABLE II. - ENERGIES AND

RELATIVE INTENSITIES

OF GAMMA RAYS FROM

IODINE 128.

Energy, keV	Relative intensity
443.3±0.2	100.0
526.4±0.2	9.9±1.4
a743.3±0.2	1.0±0.1
969.7±0.2	2.7±0.4
1139.9±0.4	0.08±0.01

aThis gamma ray is from ^{128}Te, which is also formed in the decay of ^{128}I.

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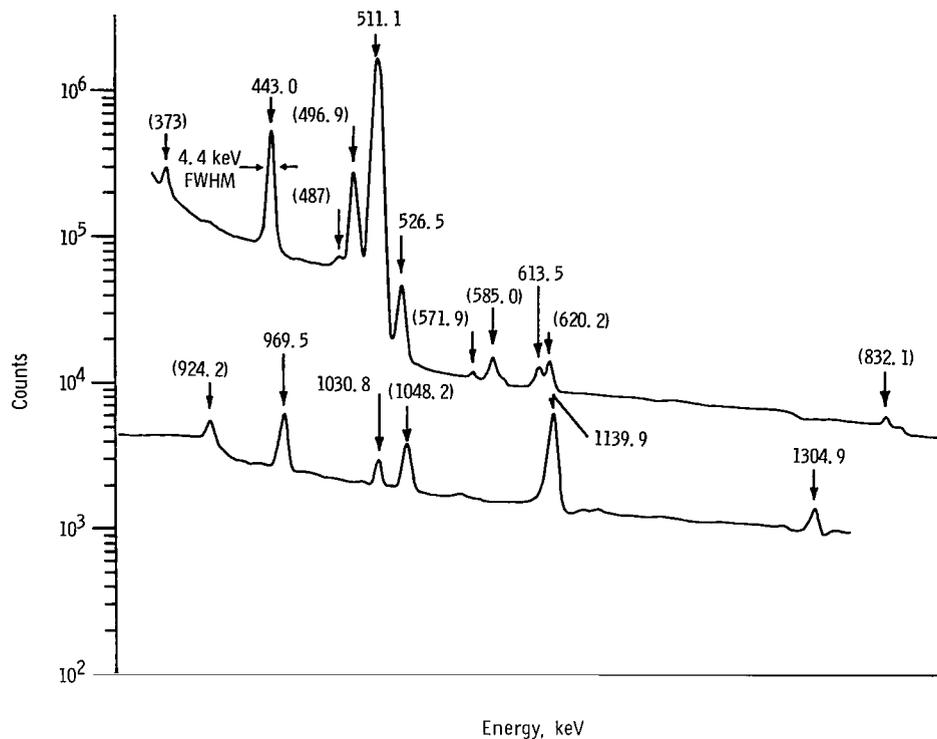
Figure 3. – Spectrum of low-energy gamma rays from barium 128 – cesium 128 observed with 8-cubic-centimeter lithium-drifted germanium detector. Gamma-ray energies from barium 131 contaminant are given in parentheses.

tor. Figure 2 shows a spectrum taken over a period of 170 minutes. During this time the source was moved to maintain constant counting rate in the pulse-height analyzer. The source distance, however, was always large enough to exclude summing of gamma rays in the detector. The energies and relative intensities of the gamma rays observed are given in table II.

Other studies were performed in which spectra were stored for successive 25-minute intervals while the source remained in a fixed position. These studies demonstrated that all the gamma rays reported in table II decayed with a 25-minute half life. This result supports the belief that none of the gamma rays arose from the decay of some impurity in the source.

Decay of Cesium 128

Sources of 3-minute ^{128}Cs in equilibrium with its parent 2.4-day barium 128 (^{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.

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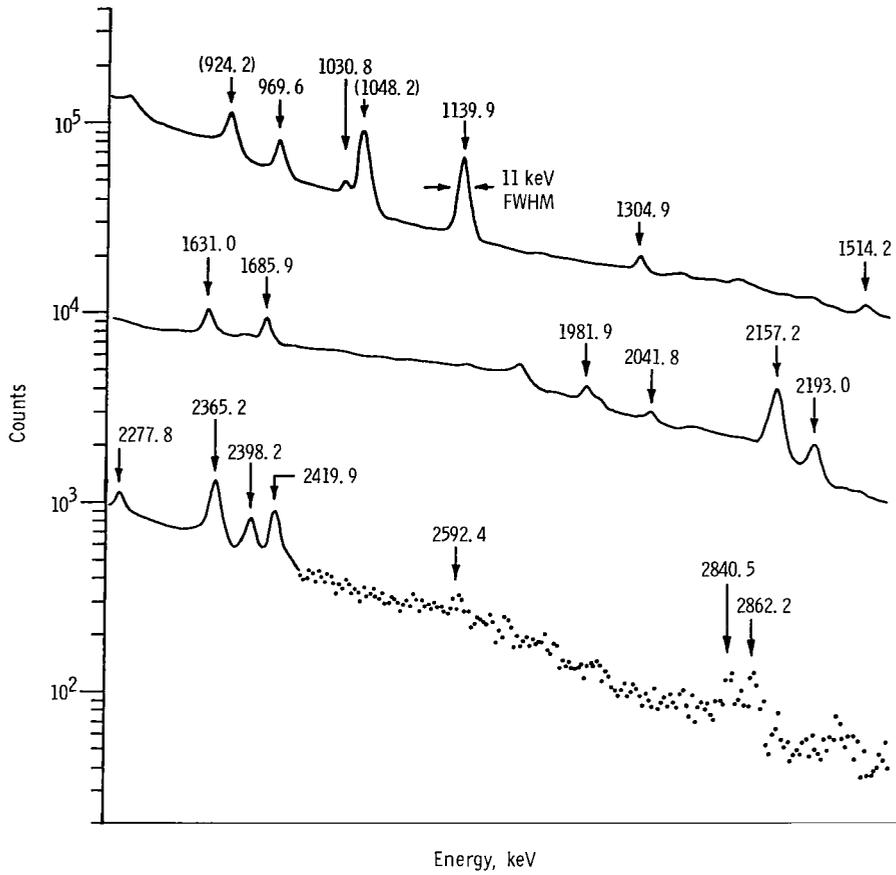
Figure 4. - Spectrum of high-energy gamma rays from barium 128 - cesium 128 observed with 30-cubic-centimeter lithium-drifted germanium detector. Gamma-ray energies from barium 131 contaminant are given in parentheses.

TABLE III. - ENERGIES AND RELATIVE INTENSITIES

OF GAMMA RAYS FROM BARIUM 128 - CESIUM 128

Energy, keV	Relative intensity	Energy, keV	Relative intensity
[a]273.1±0.3	59±9	[c]1981.9±0.5	0.11±0.02
443.0±0.3	100	2041.8±0.7	.074±0.01
[b]511.1±0.2	414±60	2157.2±0.3	.62±0.09
526.5±0.3	7.3±1	[c]2193.0±0.4	.13±0.02
613.5±0.3	.93±0.1	2277.8±0.8	.040±0.008
969.5±0.3	1.6±0.2	[c]2365.2±0.3	.15±0.02
[c]1030.8±0.3	.61±0.09	2398.2±0.6	.052±0.009
1139.9±0.3	4.0±0.6	2419.9±0.4	.082±0.01
1304.9±0.3	.47±0.08	[c]2592.4±1.1	.011±0.003
1514.2±0.5	.14±0.02	2840.5±1.1	.011±0.003
1631.0±0.3	.36±0.05	2862.2±0.8	.016±0.003
[c]1685.9±0.3	.32±0.05		

[a]The half-life of this gamma ray precludes interpreting it as the isomeric transition from $^{133\ m}$Ba. Because of its intensity, this transition is attributed to the decay of ^{128}Ba into ^{128}Cs.

[b]Annihilation radiation.

[c]Not placed in level scheme of fig. 7.

The only contaminant observed was 12-day ^{131}Ba.

The low-energy gamma rays from ^{128}Ba-^{128}Cs were observed with an 8-cubic-centimeter Ge(Li) detector. Figure 3 shows a spectrum taken 2 days after the bombardment of cesium. The 30-cubic-centimeter Ge(Li) detector was used to detect low-intensity, high-energy gamma rays. A spectrum obtained with this detector is shown in figure 4. Double-escape peaks do not stand out in this spectrum. By following the decay of the source and by reference to previous studies (ref. 11), gamma rays from the contaminating ^{131}Ba were identified; their energies are indicated in parentheses in figures 3 and 4. The energies and relative intensities of the gamma rays from ^{128}Ba-^{128}Cs are given in table III.

Coincidences between gamma rays were studied with two 7.6- by 7.6-centimeter thallium-activated sodium iodide (NaI(Tl)) scintillators placed 90° apart. The coincidence circuit had a resolving time of 50 nanoseconds. Figure 5 shows the gamma-ray spectrum in coincidence with a window set on the 443.2-keV peak. Figure 6 shows the spectrum in coincidence with a window set on the high-energy side of the annihilation peak to include the 526.4 keV gamma ray. The results of these coincidence studies are consistent with the levels of ^{128}Xe deduced from the Ge(Li)-detector gamma-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.
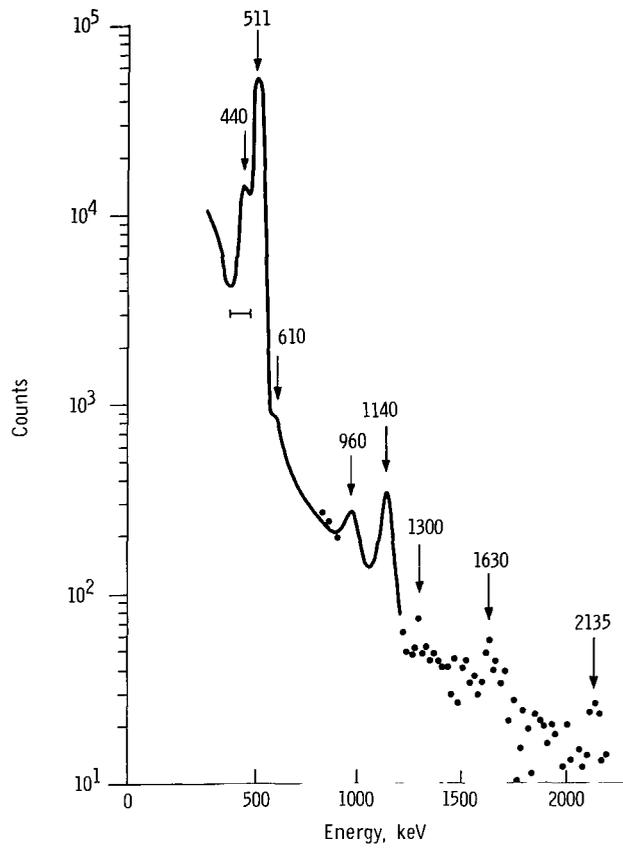
Figure 5. – Spectrum of gamma rays in coincidence with 433.2-keV gamma ray of cesium 128 observed with NaI(Tl) detector.

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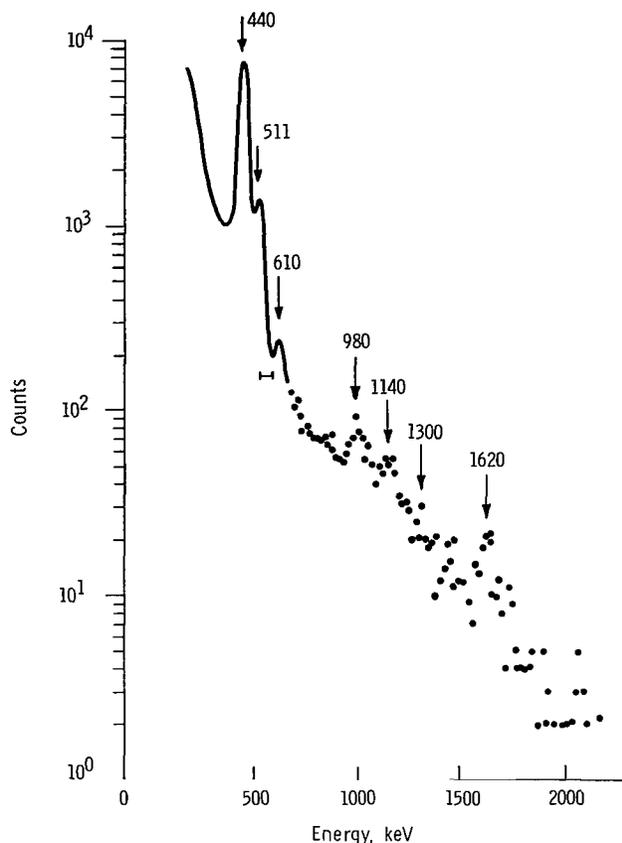
Figure 6. - Spectrum of gamma rays in coincidence with
526.4-keV gamma ray and annihilation radiation of
cesium 128 observed with NaI(Tl) detector.

DISCUSSION OF RESULTS

Results of this work are summarized in the ^{128}Xe level scheme shown in figure 7.
All gamma rays observed in the decay of ^{128}I, as well as 15 out of 21 gamma 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. Although it might be argued that a gamma ray from such a state to the 443.2 keV level is concealed under one of the many peaks in figure 3, there is no evidence of such a gamma ray in figure 2. It is still possible that the de-excitation gamma ray from a 0^+ level is concealed under the 526.4 keV peak. Otherwise, consideration of statistics in the spectrum of figure 2 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 percent of the ^{128}I decays. Furthermore, transitions from
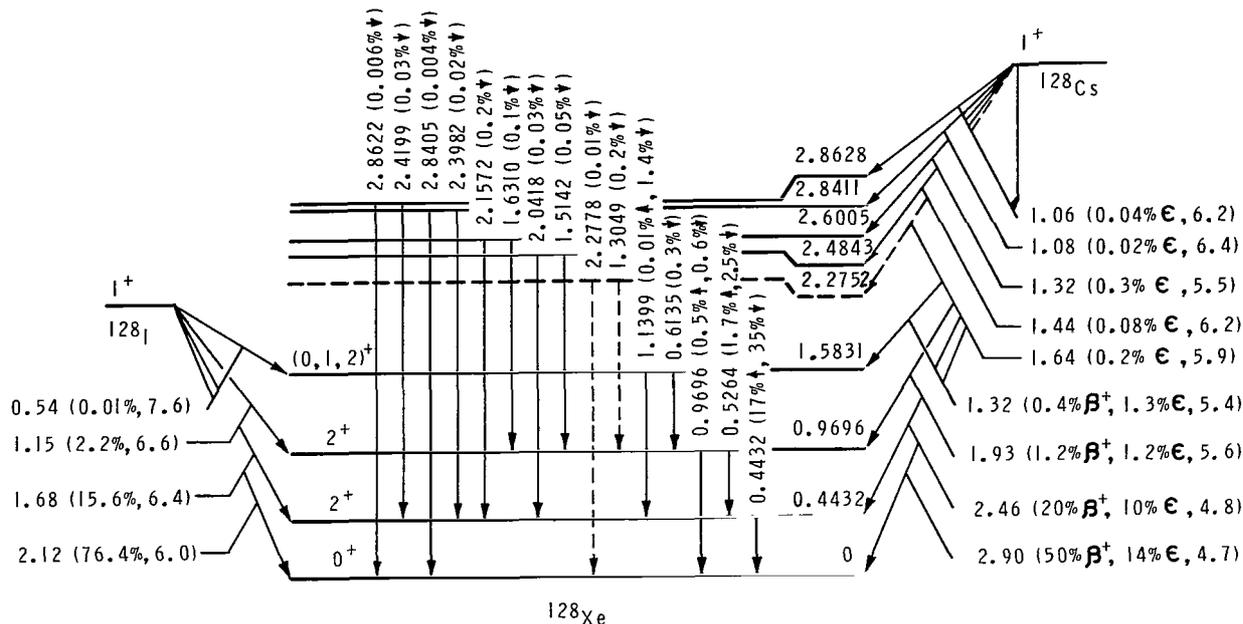
Figure 7. - Level scheme of xenon 128. Energy values are in MeV. Gamma-ray intensities, expressed in terms of percent of decays of iodine 128 (←) or cesium 128 (→) parent isotope, are given in parentheses.

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; however, they are not observed.

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 gamma rays emitted in its decay is found to be I(526.4 keV)/I(969.6 keV) = 4.0±0.4. Then, if the 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 $(2^{+'})$ is

$$\left[\frac{B(E2;\ 2^{+'} \to 0^+)}{B(E2;\ 2^{+'} \to 2^+)}\right] = \left(\frac{I(969.6\ \text{keV})}{I(526.4\ \text{keV})}\right)\left(\frac{526.4}{969.6}\right)^5 = 0.012\pm0.001$$

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 platinum-196 (^{196}Pt) (values computed from data in ref. 3).

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 tentative report (ref. 14) that this state is weakly populated in the decay of

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^{128}I. Only the 1139.9-keV transition is observed in the ^{128}I decay. If in the decay of ^{128}I the 613.5-keV gamma ray is only one-fourth as intense as the 1139.9-kev gamma ray as is the case in the ^{128}Cs decay, it would be lost in the statistics in figure 2. If both transitions are assumed to be electric quadrupole, the ratio of the reduced transition probabilities for the two modes of de-excitation of the 1583.1-keV state is

$$\left[\frac{B(E2:\ J \to 2^+)}{B(E2;\ J \to 2^{+'})}\right] = \left(\frac{I(1139.9\ keV)}{I(613.5\ keV)}\right)\left(\frac{613.5}{1139.9}\right)^5 = 0.19 \pm 0.04$$

No current model can explain why the transition between two two-phonon states should be faster than the transition to the one-phonon state. Hence, the 1583.1-keV state cannot be interpreted as a two-phonon 0^+ vibrational state which has been displaced in energy by anharmonicity in the nuclear potential. If instead the 1583.1-keV state is interpreted to be basically a three-phonon state, the state must be assumed to contain an admixture of other types of excitation. (These conclusions are based on private communication with R. A. Sorensen of Carnegie Institute of Technology.)

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. (ref. 15). The end point energy of the most energetic positron group from ^{128}Cs has been taken from the Nuclear Data Sheets (ref. 3). 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 (ref. 16). When these results are combined with the results of the present study, absolute intensities and log ft's can be computed for decay to the levels of ^{128}Xe. The computed values are shown in figure 7. Since the log ft 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 log ft of 7.6 indicates the decay of 1^+ ^{128}I to the same state is retarded.

Since even the low-lying states of ^{128}Xe are not now understood it is not appropriate to speculate about the character of the higher excited states.

Results on the electron capture decay of ^{128}I to ^{128}Te are given in the appendix.

CONCLUSION

An experimental investigation of low-lying excited states of the near-spherical even-even nucleus ^{128}Xe has been performed. It is found that these levels are not well

described by the conventional picture of nearly harmonic quadrupole vibrations. No evidence has been found for the existence of a 0^+ member of the predicted second excited state vibrational triplet. Even the 2^+ second excited state, which is observed, does not have the properties expected for a pure harmonic oscillator state. No current theory satisfactorily explains the nature of the low-lying states of ^{128}Xe.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, June 29, 1967,
            129-02-04-06-22.

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APPENDIX - DECAY OF IODINE 128 INTO TELLURIUM 128

In addition to decaying by β^- emission to ^{128}Xe, the nucleus ^{128}I decays by electron capture to ^{128}Te. Benczer, et al. (ref. 15) measured the ratio of the intensity of K-electron capture transitions to the intensity of 443.3-keV gamma rays; the value 0.316 was obtained. This ratio and the value (ref. 3) of 1.2 MeV for the energy available in the decay of ^{128}I into ^{128}Te are adopted by the present authors. Furthermore, it is assumed (ref. 17) that L-electron captures are one-eighth as frequent as K-electron captures. These assumptions make possible the computation of the intensities and log ft's for feeding to the ground state and first excited state of ^{128}Te. The results are that 6.0 percent of the ^{128}I decays populate the ground state of ^{128}Te with log ft 5.0, and 0.2 percent of the ^{128}I decays populate the 743.3 keV level of ^{128}Te with log ft 5.8.

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