Neutron-capture gamma rays from the 9.47-eV resonance in $^{129}Xe(n, \gamma)^{130}Xe$

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The γ-ray spectrum from neutron capture in the 9.47-eV resonance in ^{129}Xe has been studied. A target of Na_4XeO_6 was irradiated in a thermal neutron beam and in a monochromatic neutron beam of 5.16-, 9.47-, and 14.1-eV energy from a crystal diffraction neutron monochromator. The resulting γ-ray spectra were studied with Ge(Li) detectors of $\simeq$20-, $\simeq$25-, $\simeq$30-, and $\simeq$40-cm^3 active volume. γ rays were assigned to the $^{129}Xe(n\ \gamma)^{130}Xe$ reaction by a comparison of these spectra. Ge(Li)-Ge(Li) coincidence measurements were carried out on resonance with the 20- and 30-cm^3 Ge(Li) detectors in combination. Only a few very intense transitions were observed in coincidence. The data obtained in the present work together with the information from earlier radioactive-decay studies indicate the population of levels in ^{130}Xe by neutron capture in the 9.47-eV resonance with energies 536.1 $\pm$ 0.2, 1122.1 $\pm$ 0.3, 1204.4 $\pm$ 0.5, 1631.8 $\pm$ 0.7, 1785.9 $\pm$ 0.8, 1792.1 $\pm$ 0.6, 1807.9 $\pm$ 0.4, 2017.0 $\pm$ 0.5, 2058.7 $\pm$ 0.9, 2081.4 $\pm$ 0.9, 2171.0 $\pm$ 1.3, 2222.6 $\pm$ 0.6, 2241.5 $\pm$ 0.6, 2385.1 $\pm$ 0.5, 2501.9 $\pm$ 0.5, 2544.4 $\pm$ 0.9, 2632.4 $\pm$ 1.7, (2762.7 $\pm$ 0.5), 2885.6 $\pm$ 1.1, 2953.5 $\pm$ 0.5, 2977.5 $\pm$ 1.0, 3071.1 $\pm$ 0.8, 3150.1 $\pm$ 0.7, 3188.8 $\pm$ 0.6, (3243.2 $\pm$ 1.3), 3298.0 $\pm$ 1.2, 3325.1 $\pm$ 0.8, 3405.2 $\pm$ 0.7, 3534.2 $\pm$ 0.6, 3621.9 $\pm$ 0.7, 3685.6 $\pm$ 1.0, 3780.0 $\pm$ 1.2, 3892.2 $\pm$ 1.5, (3960.1 $\pm$ 1.0), 3976.3 $\pm$ 1.5, and 3985.6 $\pm$ 1.0 keV. The neutron separation energy of ^{130}Xe is 9254.7 $\pm$ 1.3 keV. The observation of the 9254.2 $\pm$ 2.1 keV primary-capture γ ray to the 0+ ground state of ^{130}Xe clearly establishes the spin of the 9.47-eV resonance in ^{129}Xe as 1+.

[NUCLEAR REACTIONS $^{129}Xe(n,\gamma)$, $E = 9.47$ eV; measured E_γ, I_γ, γ-γ coin. in ^{130}Xe. ^{130}Xe deduced levels, transitions, Q, J, π.]

I. INTRODUCTION

For nuclei such as ^{130}Xe, which lie in or near the valley of stability, it is usually possible to study the properties of individual energy levels by a wide variety of nuclear reactions such as Coulomb excitation, stripping and pickup reactions, inelastic scattering, etc., as well as in radioactive decay. The isotopes of Xe, including ^{130}Xe, provide an exception because of the few stable isotopes of the neighboring elements I and Cs and the chemical nature of Xe itself. Xe targets have been confined to the gaseous form or the inherently unstable compounds XeF_2 or XeF_4. In either case expense has limited the experimenter to the use of natural Xe which has nine stable isotopes.

One common source of spectroscopic information about nuclei is the (n,γ) reaction which has been widely studied since the advent of the Ge(Li) detector made it possible to resolve the many peaks of the typical complex primary-capture γ-ray spectrum. The $Xe(n,\gamma)$ reaction has been studied by Bartholomew and Naqvi[1] with a magnetic pair spectrometer and NaI coincidence measurements and by Monaro, Kane, and Ikegami[2] with a NaI pair spectrometer. These authors used natural targets of gaseous Xe and XeF_4, respectively. They were able to observe the decay of the two most intense primary-capture γ rays in ^{132}Xe and their results are summarized in the compilation of Bartholomew *et al.*[3] The γ-ray spectrum from thermal neutron capture on natural Xe, which contains contributions from nine isotopes of Xe, is clearly too complicated to be understood by the use of present techniques. The problem of obtaining neutron-capture spectra from individual isotopes has now been overcome in two quite separate ways.

Groshev, Govor, Demidov, and Rakhimov[4] have succeeded in preparing a target of XeF_2 enriched to 93% in ^{129}Xe. By studying the thermal-neutron-capture spectrum from this enriched target and comparing it with the spectrum from a natural XeF_2 sample they are able to assign γ rays to the $^{129}Xe(n,\gamma)^{130}Xe$ reaction. These authors studied the γ-ray spectrum in the energy intervals 0.4–1.5 and 4.5–9.5 MeV. A large number of high-energy γ rays were observed and assumed to be primary-capture γ rays populating low-lying levels in ^{130}Xe. Only a few intense γ rays were observed in the lower-energy region.

We have undertaken a comprehensive study of the $Xe(n,\gamma)$ reaction by an alternative method with the aim of obtaining information about the level structure of several of the Xe isotopes. Briefly our method of studying neutron capture in the Xe isotopes is to use a target of the stable Xe salt, sodium perxenate (Na_4XeO_6). Although this target contains natural Xe it is possible to use the neutron monochromator[5] at the Brookhaven high flux beam reactor (HFBR) to provide neutrons of the energy of a single Xe resonance and hence study the capture γ rays from the individual Xe isotopes. The neutron monochromator provides a continuous monoenergetic beam of neutrons from 0.01–26 eV, and Xe has three resonances within this range. These are at 5.16, 9.47, and 14.1 eV and belong to ^{124}Xe, ^{129}Xe, and ^{131}Xe, respectively. We have studied the neutron-capture γ rays from all three of these resonances. In addition we have also studied the thermal-neutron-capture spectrum with a clean filtered thermal neutron beam.[5] The results obtained on the decay of the 14.1-eV resonance in the ^{131}Xe$(n,\gamma)^{132}$Xe reaction have been reported previously.[6] In the present work we report the results of our observations on the decay of the 9.47-eV resonance in the ^{129}Xe$(n,\gamma)^{130}$Xe reaction.

Prior to the present work our knowledge of the properties of the energy levels of ^{130}Xe was derived mainly from studies[7–16] of the radioactive decay of ^{130}I and ^{130}Cs. The ground states of these isotopes have spins and parities 5+ and 1+, respectively, and a 9-min isomer of ^{130}I 2+. The selective nature of the β-decay process leads to the population of states in ^{130}Xe with spins differing by at most a few units of angular momentum from the spins of the initial states. Thus a study of these decays should provide information about levels in ^{130}Xe with spins ranging from 0–6.

Fessler, Julian, and Jha[12] have studied the singles γ-ray spectra from both of these decays with Ge(Li) detectors. They also studied γ-γ coincidences with NaI detectors. Qaim[13] studied the γ rays from ^{130}I, both in singles and coincidence, with Ge(Li) detectors. His coincidence measurements were restricted to spectra in coincidence with a small number of digital gates set on prominent low-energy lines. Qaim also studied β-γ coincidences in this decay. These authors agree reasonably well in their measurements of the energies and intensities of the γ rays assigned to the decay of ^{130}I, but they differ in their placing of several of these γ rays. Levels in ^{130}Xe at 536.1(2+), 1122.1(2+), 1204.5(4+), 1808.1, 1944.0, 2016.1, 2150.6, 2170.5, 2223.3, and 2361.8 keV appear to be well established in these decay studies. Qaim[13] also reports a level at 1632.8 keV with spin and parity 4+. Bakiev, Baskova, Vasil'ev, Mokhsen, Murav'eva, Sorokin, Chugai, and Shavtvalov,[14] in singles and coincidence studies of the γ rays of ^{130}I and ^{130}I^m, have proposed new levels in ^{130}Xe at 2242.8-, 2296-, 2427.0-, 2502-, and 2008.6-keV excitation energy. The existence of a number of other energy levels is suggested in one or the other of these papers (see Sec. III).

The γ rays from the decay of the states at 536.1, 1122.1, 1204.5, and 1944.0 keV have also been observed in studies[17–19] of the Te$(\alpha, xn\gamma)$ and Te-$(^3$He$, xn\gamma)$ reactions. These authors also report levels at 2059.1 (5−) and 2696.0 (8+) keV. They suggest that the latter is fed by an isomeric level of undetermined energy with lifetime ≤ 50 μsec.

Very recently two new studies of the decay of ^{130}I^m, ^{130}I^g, and ^{130}Cs have been conducted by Hopke, Jones, Walters, Prindle, and Meyer[15] and by Meyer and Walters.[16] These authors propose even parity, and hence allowed β decay for the isomeric state and ground state of ^{130}I in contrast with the assumption of odd parity for these states in earlier work. On this basis a number of new spin and parity assignments were made. In particular 0+ states are proposed at energies of 1793.9 and 2017.0 keV, and 4+ states at 1808.2, 2427.2, 2622.4, and 2811.9 keV. The 1632.6-keV level is assigned spin and parity 3+ rather than 4+ as proposed by Qaim.[13]

The present paper reports measurements of the γ rays from the 9.47-eV resonance in the ^{129}Xe-$(n,\gamma)^{130}$Xe reaction over the energy range 0.1–9.5 MeV. The ground state of ^{129}Xe has spin and parity $\frac{1}{2}$+, hence the spin and parity of the 9.47-eV resonance may be 0+ or 1+. Ribon[20] has concluded that the spin of this resonance is probably 1+ on the basis of resonance shapes in neutron-transmission measurements. This result is confirmed in the present work by the observation of a primary-capture γ ray to the 0+ ground state of ^{130}Xe. Thus, the decay of the 9.47-eV resonance may be expected to populate (see Sec. III) low-lying low-spin (0–2) states in ^{130}Xe by dipole transitions. The experimental procedure and results are described in Sec. II. The construction of the level scheme is discussed in Sec. III. Finally, the resulting level scheme is discussed in Sec. IV.

II. EXPERIMENTAL METHODS AND RESULTS

A. Equipment

The crystal diffraction neutron monochromator at the HFBR, which was designed specifically for (n,γ) studies, has been described fully in a previous publication.[5] For our present purpose it is sufficient to state that it provides a continuous beam of monoenergetic neutrons over the energy range 0.01–26 eV. A beam current of 2×10^5 neutrons/sec is obtained on a 6.4-cm^2 target at an energy of 1 eV. The energy dependence of the beam intensity is roughly $1/E$. The angular resolution of the monochromator is 12′, giving an energy resolution of $\Delta E \sim 1.1$ eV at 9.47 eV.

The target consisted of ~5 g of anhydrous Na_4XeO_6 enclosed in an aluminum capsule. The sodium perxenate was prepared from XeF_6 by the method of Appelman and Malm.[21] The only impurities of any significance present in this material were small amounts of NaF and MgF_2. Although natural Xe contains nine stable isotopes the thermal-neutron-capture spectrum is dominated by neutron capture in ^{129}Xe and ^{131}Xe which contribute 24.6 and 66.9% of the total capture cross section. At the 9.47-eV resonance ^{129}Xe is expected to contribute more than 98% of the capture cross section of natural Xe.

This target was irradiated in beams of 5.16-, 9.47-, and 14.1-eV neutrons from the monochromator in order to study the capture γ-ray spectra from the three known resonances. It was also irradiated in the thermal neutron beam at the HFBR, which has an intensity of $\sim 7\times 10^7$ neutron/sec over 1 cm^2 with a Cd ratio $>2\times 10^4$, in order to study the thermal-neutron-capture γ-ray spectrum.

The γ-ray singles spectra were studied with Ge(Li) detectors of ~20-, ~25-, ~30-, and ~40-cm^3 active volume. Coincidences between γ rays were studied with the 20- and 30-cm^3 detectors in combination. Both the electronic equipment and the procedures used in analyzing the data have been described in detail in previous publications.[22]

B. Energy and intensity measurements

The singles γ-ray spectra following neutron capture at the 5.16-eV (^{124}Xe), 9.47-eV (^{129}Xe), and 14.1-eV (^{131}Xe) resonances and at thermal

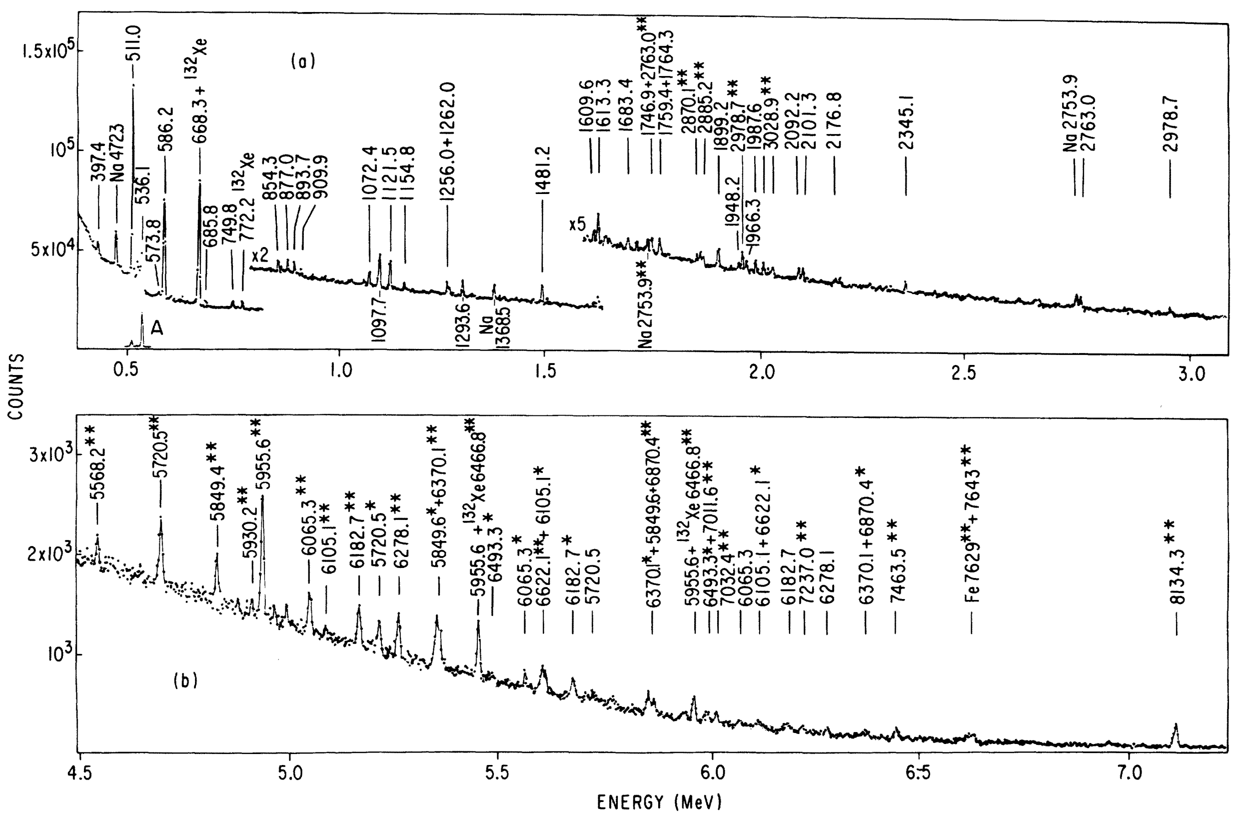

FIG. 1. The neutron-capture γ-ray spectrum from a Na_4XeO_6 target irradiated in a monoenergetic neutron beam (9.47-eV energy) from the crystal diffraction neutron monochromator at the HFBR (see Ref. 5) taken with a 25-cm^3 Ge(Li) detector. The energy dispersion is ~2.4 keV/channel. The upper (a) and lower (b) halves of the figure show the spectrum from 0.3–3.2 and 4.5–7.2 MeV, respectively. The measured γ-ray energies are indicated on the figure and single- and double-escape peaks marked with one and two asterisks, respectively. γ rays from the ^{131}Xe$(n,\gamma)^{132}$Xe reaction and from other background sources are marked appropriately. This spectrum was accumulated in two days running. A small section of the spectrum near the intense 536.1-keV γ ray had overflowed the memory of the TMC analyzer. To show the relative intensity of the 536.1-keV γ ray a portion of a spectrum run for 6 h under identical conditions A is plotted on the same scale as (a).

energy were studied over the energy range 0.1–9.5 MeV with several different Ge(Li) detectors (see above) in a number of runs of varying length, dispersion, and energy range. It was then possible to assign γ rays to the $^{129}Xe(n,\gamma)^{130}Xe$ reaction by a careful comparison of the spectra taken at different neutron energies.

An example of part of the γ-ray singles spectrum at the 9.47-eV resonance is shown in Fig. 1. This spectrum was accumulated in two days running with a 25-cm^3 Ge(Li) detector. One- and two-escape peaks are noted with one and two asterisks, respectively. The upper half of the figure [Fig. 1(a)] shows the spectrum from ~300–3200 keV. At the low-energy end of the spectrum a short section [marked (a)] had overflowed the memory of the multichannel analyzer and a spectrum run for ~6 h under identical conditions has been plotted on the same scale to indicate the relative intensity of the 536.1-keV peak which had overflowed. Figure 1(b) shows the same spectrum from ~4.5–7.2 MeV.

In general, the peaks belonging to ^{130}Xe are readily distinguished from those due to γ rays from the other Xe isotopes and other elements in the target and close surroundings, since most of these other peaks disappear completely in the 9.47-eV resonance spectrum. Doubts arise in the case of very weak peaks and care must be exercised since a few background lines have the same or greater intensity relative to the ^{130}Xe lines in the resonance spectrum. For example, the intensities of the 1368.5- and 2753.9 keV γ rays, which are emitted in the decay of the ^{24}Na produced by the $^{23}Na(n,\gamma)^{24}Na$ reaction in the target, depend on the immediate past history of the target. The prominent doublet at 7629-7643 keV, which is due to the $^{56}Fe(n,\gamma)^{57}Fe$ reaction in the steel of the second collimator of the monochromator also appears more clearly on resonance because of the configuration of the neutron monochromator. These contaminant lines are marked on the figure.

The tail of the 14.1-eV resonance in ^{131}Xe lies beneath the 9.47-eV resonance and we expect this isotope to contribute to the observed spectrum. A number of the most intense peaks from the $^{131}Xe(n,\gamma)^{132}Xe$ reaction were observed in the spectrum. Some of these are indicated in Fig. 1. Where they coincide in energy with a γ ray from ^{130}Xe the intensity of the ^{130}Xe line listed in Table I has been corrected for their presence using the measured[6] relative intensities of the $^{131}Xe(n,\gamma)^{132}Xe$ lines. The most intense ^{132}Xe lines are marked on Fig. 1.

The energies of the lines assigned to ^{130}Xe were determined in different ways in the low-energy (0.1–2.8-MeV), medium-energy (2.8–5.0-MeV), and high-energy (5.0–9.5-MeV) regions of the spectrum as explained below.

In the low-energy region of the spectrum the energies of the lines assigned to ^{130}Xe were determined in the following way. First the energies of the intense lines below 700 keV were determined from a thermal-neutron-capture spectrum recorded together with the spectrum of γ rays from radioactive sources of ^{133}Ba and ^{137}Cs. The energies of the ^{130}Xe lines were obtained by comparison with the known energies[23,24] of the lines from the radioactive sources. The energies of these intense ^{130}Xe lines together with the energies[25] of the γ rays from the decay of ^{24}Na, which is produced in the target by the $^{23}Na(n,\gamma)^{24}Na$ reaction, then provided a calibration for the 9.47-eV resonance γ-ray spectrum up to 3.0 MeV. At intervals during both measurements the same spectrum was routed into a separate section of the analyzer memory together with a set of pulser peaks from a precision pulser[26] The positions of the pulser peaks could then be used to correct for the nonlinearity of the electronic system.

In the high-energy region of the spectrum the following procedure was used to determine the energies of the γ rays. The 9.47-eV resonance neutron-capture γ-ray spectrum was recorded together with a set of pulser peaks flanking the γ-ray peaks. This permitted the determination of the intervals between the peaks of the intense 5955.6-keV γ ray in ^{130}Xe and the other ^{130}Xe γ-ray lines in terms of pulser units. The pulser units could then be converted into energy units using the well-known energy differences between the total capture, one- and two-escape peaks. The energy of the 5955.6 ± 0.5-keV γ ray was then obtained by comparison with the energy[27] of the 5739.7-keV γ ray from Sm in a series of neutron-capture spectra from a combined Na_4XeO_6 and natural Sm target with neutrons of 9.47, 9.25, and 9.0 eV. The energies of the remaining lines assigned to ^{130}Xe were then obtained by combining this energy with the energy differences measured in the experiment described above. In the case of very weak lines which are only observed in the spectra run for long periods, which do not have the superimposed pulser peaks, the peak energies were obtained by interpolation of strong neighboring lines.

In the medium-energy region it is much more difficult to determine the energies of the observed γ rays because of the high density of lines and the fact that they are superimposed on a background due to higher-energy γ rays. The positions and areas of many of the peaks in this region were determined graphically because they are members of unresolved multiplets. Because of the com-

TABLE I. Energies, relative intensities, and assignments of γ rays observed in the $^{129}Xe(n,\gamma)^{130}Xe$ reaction at the 9.47-eV resonance.

E_γ (keV)	I_γ (relative)	Level From To
136.5 ± 1.1	1.4 ± 0.5	3325.2–3188.8
161.5 ± 1.1	0.28 ± 0.06	2385.1–2222.6
178.7 ± 1.0	0.19 ± 0.06	...
191.8 ± 0.7	2.0 ± 0.3	2953.5–2762.7
209.6 ± 0.8	0.20 ± 0.05	3534.2–3325.2
246.0 ± 0.6	0.8 ± 0.2	2632.4–2385.1 3780.0–3534.2
252.1 ± 0.8	0.29 ± 0.07	2885.6–2632.4
261.9 ± 0.6	0.08 ± 0.02	...
397.4 ± 0.5	0.30 ± 0.07	...
500.1 ± 0.5	0.14 ± 0.05	2885.6–2385.1
522.8 ± 0.2 [a]	1.0 ± 0.2	...
536.1 ± 0.3 [b,c]	100.	536.1–g.s.
573.8 ± 0.5	0.41 ± 0.06	2632.4–2058.7
586.2 ± 0.2 [b]	24. ± 3.	1122.1–536.1
603.7 ± 0.3	0.57 ± 0.08	1807.9–1204.4
622.8 ± 0.5	0.46 ± 0.10	...
668.3 ± 0.4 [d]	8.9 ± 1.5	1204.4–536.1 3621.9–2953.5
685.8 ± 0.4	0.66 ± 0.08	1807.9–1122.1 3071.1–2385.1
698.1 ± 0.8	0.20 ± 0.08	...
736.8 ± 1.1	0.08 ± 0.06	2977.5–2241.5 3621.9–2885.6
749.8 ± 0.6 [e]	1.1 ± 0.1	...
762.7 ± 0.7	0.43 ± 0.09	...
765.7 ± 0.7	0.10 ± 0.06	3150.1–2385.1
792.4 ± 0.8	0.17 ± 0.07	...
806.8 ± 0.8	0.13 ± 0.06	2977.5–2171.0
825.7 ± 0.8	0.11 ± 0.06	2632.4–1807.9 3870.0–2953.5 3976.3–3150.1
833.3 ± 0.8	0.07 ± 0.05	...
836.8 ± 0.8	0.16 ± 0.05	3985.6–3150.1
854.3 ± 0.8	1.1 ± 0.2	2058.7–1204.4
862.3 ± 0.8	0.27 ± 0.06	...
877.0 ± 0.7	0.96 ± 0.10	2081.4–1204.4
893.7 ± 1.1	0.89 ± 0.13	2017.0–1122.1 2953.5–2058.7 3780.0–2885.6
909.9 ± 0.9	0.60 ± 0.12	3150.1–2241.5
914.9 ± 1.3	0.11 ± 0.06	3892.2–2977.5 3985.6–3071.1
936.2 ± 1.1	0.15 ± 0.03	2953.5–2017.1
942.8 ± 1.3	0.15 ± 0.07	...
959.3 ± 1.0	0.26 ± 0.10	2977.5–2017.0
966.6 ± 1.2	0.43 ± 0.08	2171.0–1204.4
981.1 ± 0.9	0.12 ± 0.07	3960.1–2977.5
986.7 ± 1.0	0.10 ± 0.04	...
1020.8 ± 0.9	0.38 ± 0.09	3243.2–2222.6 3405.2–2385.1
1028.1 ± 1.2 [d]	0.25 ± 0.10	...
1048.7 ± 1.5	0.37 ± 0.10	...
1053.6 ± 1.3	0.16 ± 0.03	3071.1–2017.0 3685.6–2632.4
1060.1 ± 0.7	0.59 ± 0.14	...
1072.4 ± 0.6	1.8 ± 0.2	...
1080.1 ± 1.3	0.15 ± 0.06	...
1095.7 ± 0.6 [a,c]	4.7 ± 0.2	1631.8–536.1
1106.5 ± 1.2	0.21 ± 0.09	...
1121.5 ± 0.8	4.2 ± 0.3	1122.1–g.s.
1126.1 ± 1.2	0.14 ± 0.10	3298.0–2171.0
1154.8 ± 0.6	0.47 ± 0.10	3325.2–2171.0
1175.8 ± 0.6	0.16 ± 0.06	...
1181.3 ± 0.9	0.06 ± 0.05	2385.1–1204.4 3405.2–2222.6
1219.9 ± 0.6	0.22 ± 0.07	...
1249.4 ± 0.8	0.10 ± 0.06	1785.9–536.1
1256.0 ± 0.5	1.8 ± 0.2	1792.1–536.1
1262.7 ± 0.8	1.0 ± 0.1	2385.1–1122.1 3071.1–1807.9
1271.7 ± 0.5	0.52 ± 0.11	1807.9–536.1
1293.0 ± 0.3 [f]	...	...
1311.4 ± 0.7	0.32 ± 0.10	3534.2–2222.6
1355.3 ± 1.0	0.22 ± 0.10	3985.6–2632.4
1379.5 ± 0.4	0.37 ± 0.09	2501.9–1122.1 3621.9–2241.5
1388.8 ± 1.0	0.16 ± 0.07	3405.2–2017.0
1421.5 ± 1.1	0.22 ± 0.10	...
1450.8 ± 1.1	0.32 ± 0.11	3243.2–1792.1 3621.9–2171.0
1459.7 ± 0.3	1.1 ± 0.2	...
1481.2 ± 0.5	3.4 ± 0.9	2017.0–536.1
1602.1 ± 0.7	0.79 ± 0.18	...
1609.6 ± 1.1	{ 2.7 ± 0.3	3243.2–1631.8
1613.3 ± 0.7		3405.2–1792.1
1631.6 ± 0.8	0.69 ± 0.33	...
1683.4 ± 1.1	0.28 ± 0.13	...
1686.9 ± 1.1	0.39 ± 0.13	2222.6–536.1
1705.0 ± 0.6	1.0 ± 0.2	2241.5–536.1
1726.6 ± 1.1	≤0.2	3534.2–1807.9
1746.9 ± 1.0	0.4 ± 0.2	3534.2–1785.9
1759.4 ± 1.0	{ 2.0 ± 0.3	...
1764.3 ± 1.0		2885.6–1122.1 3780.0–2017.0 3985.6–2222.6
1813.9 ± 1.0	0.19 ± 0.10	3621.9–1807.9 3985.6–2171.0
1848.9 ± 1.2	0.67 ± 0.25	2385.1–536.1
1899.2 ± 0.5	2.8 ± 0.4	3685.6–1785.9
1948.2 ± 1.3	0.6 ± 0.2	3071.1–1122.1
1966.3 ± 0.9	0.73 ± 0.15	2501.9–536.1
1979.6 ± 0.9	0.14 ± 0.10	...
1987.6 ± 0.7 [d]	0.26 ± 0.15	3780.0–1792.1
2008.0 ± 0.9	1.5 ± 0.5	2544.1–536.1
2028.8 ± 0.9 [d]	1.3 ± 0.4	3150.1–1122.1
2066.5 ± 0.7	0.15 ± 0.08	3188.8–1122.1
2092.2 ± 1.2 [e]	1.1 ± 0.2	3298.0–1204.4

TABLE I *(Continued)*

E_γ (keV)	I_γ (relative)	Level From–To
2101.3 ± 1.1	1.5 ± 0.3	3892.2–1792.1
2176.8 ± 1.1	1.1 ± 0.3	3298.0–1122.1 3985.6–1807.9
2283.0 ± 0.9	0.14 ± 0.07	3405.2–1122.1
2308.7 ± 0.5	0.29 ± 0.08	···
2345.1 ± 0.7	1.6 ± 0.4	3976.3–1631.8
2378.6 ± 1.1	0.23 ± 0.13	···
2496.4 ± 1.1	0.6 ± 0.2	···
2612.7 ± 1.1	0.7 ± 0.3	3150.1–536.1
2653.8 ± 0.9	0.7 ± 0.3	3188.8–536.1
2763.0 ± 0.4	0.82 ± 0.24	2762.7–g.s. 3298.0–536.1
2870.1 ± 2.0	0.27 ± 0.12	3405.2–536.1
2885.2 ± 0.8	0.7 ± 0.2	2885.6–g.s.
2978.7 ± 0.6	0.82 ± 0.15	2977.5–g.s.
3028.9 ± 0.8	0.16 ± 0.08	···
3330.0 ± 1.5	1.7 ± 0.5	···
3943.2 ± 1.4	0.5 ± 0.1	···
3975.2 ± 2.4	0.3 ± 0.1	3976.3–g.s.
4064.9 ± 2.4	0.24 ± 0.08	···
4080.5 ± 1.5	0.15 ± 0.06	···
4226.3 ± 2.0	0.44 ± 0.09	···
4290.6 ± 2.0	0.45 ± 0.10	···
4444.4 ± 2.0	0.16 ± 0.06	···
4497.3 ± 2.0	0.19 ± 0.06	···
4505.2 ± 2.0	0.32 ± 0.07	···
4534.5 ± 2.4	0.22 ± 0.10	···
4546.6 ± 1.0	0.14 ± 0.05	···
4687.9 ± 2.4	0.27 ± 0.08	···
4713.0 ± 1.0	0.27 ± 0.07	···
4746.1 ± 2.4	0.19 ± 0.05	···
4769.1 ± 1.0	0.17 ± 0.06	···
4794.9 ± 2.4 4804.2 ± 2.4	{0.56 ± 0.09	··· ···
4822.8 ± 2.4	0.19 ± 0.05	···
4858.1 ± 0.8	0.25 ± 0.06	···
4876.0 ± 0.6	0.31 ± 0.07	···

E_γ (keV)	I_γ (relative)	Level From–To
4912.5 ± 0.6	0.31 ± 0.06	···
4927.4 ± 2.4 4934.4 ± 2.4	{0.77 ± 0.16	··· ···
4987.8 ± 2.4	0.30 ± 0.06	···
5007.4 ± 2.4	0.19 ± 0.06	···
5045.5 ± 2.4	0.13 ± 0.06	···
5074.3 ± 2.4	0.05 ± 0.05	···
5094.1 ± 2.4	0.27 ± 0.10	···
5150.1 ± 2.4	0.22 ± 0.07	···
5209.6 ± 0.7	0.31 ± 0.06	···
5269.1 ± 2.4	0.13 ± 0.05	9254.7–3985.6
5278.4 ± 2.4	0.08 ± 0.05	9254.7–3976.3
5295.4 ± 1.0	0.08 ± 0.04	9254.7–3960.1
5362.7 ± 0.6	0.26 ± 0.07	9254.7–3892.2
5475.5 ± 0.5	0.14 ± 0.05	9254.7–3780.0
5568.2 ± 0.7	0.40 ± 0.09	9254.7–3685.6
5632.1 ± 2.4	0.04 ± 0.03	9254.7–3621.9
5720.5 ± 0.7	1.0 ± 0.1	9254.7–3534.2
5849.6 ± 0.8	0.63 ± 0.15	9254.7–3405.2
5930.2 ± 1.4	0.13 ± 0.06	9254.7–3325.2
5955.6 ± 0.5	1.9 ± 0.5	9254.7–3298.0
6011.6 ± 0.9	0.26 ± 0.08	9254.7–3243.2
6065.3 ± 0.9	0.65 ± 0.09	9254.7–3188.8
6105.1 ± 1.5	0.25 ± 0.07	9254.7–3150.1
6182.7 ± 2.5	1.0 ± 0.3	9254.7–3071.1
6278.1 ± 0.7	1.1 ± 0.3	9254.7–2977.5
6300.5 ± 2.3	1.3 ± 0.3	9254.7–2953.5
6370.1 ± 0.7	1.3 ± 0.2	9254.7–2885.6
6493.3 ± 1.3	0.30 ± 0.08	9254.7–2762.7
6622.1 ± 1.1	0.70 ± 0.08	9254.7–2632.4
6870.4 ± 1.5	0.27 ± 0.13	9254.7–2385.1
7011.6 ± 2.0	0.15 ± 0.04	9254.7–2241.5
7032.4 ± 1.1	0.15 ± 0.04	9254.7–2222.6
7237.0 ± 1.3	0.10 ± 0.03	9254.7–2017.0
7463.5 ± 2.1	0.20 ± 0.03	9254.7–1792.1
8134.3 ± 1.6	0.57 ± 0.10	9254.7–1122.1
8718.1 ± 1.7	0.05 ± 0.03	9254.7–536.1
9254.2 ± 2.1	0.08 ± 0.04	9254.7–g.s.

[a] A small fraction of the intensity attributed to this γ ray may be due to the presence of a γ ray of similar energy from the In(n,γ) reaction.

[b] The energy of this γ ray was used in the determination of the neutron separation energy.

[c] No entry appears in column IV because the energy of this γ ray was used to define the level energy.

[d] Allowance has been made for the presence of a line from the ^{131}Xe(n,γ)^{132}Xe reaction at this energy in calculating the intensity of this γ ray.

[e] Doublet.

[f] A γ ray of this energy may be present in the decay of the 9.47-eV resonance but it is not possible to tell from our spectra since a γ ray of the same energy appears in the 5.16- and 14.1-eV spectra.

plexity of this part of the spectrum the pulser was not used. Instead certain lines were adopted as references and the energies of the other lines were calculated from the energies of these adopted standards on the assumption that there is a linear relationship between energy and channel number in the intervening regions. In calculating the error on the energies derived in this way some allowance was made for possible nonlinearities in the region between the reference line and the line in question. The lines adopted as energy standards were the following: 2753.9 ± 0.12 keV (^{24}Na full energy peak, Ref. 24); 2885.6 ± 0.6 and 2978.9 ± 0.6 keV (full energy peaks seen in the low-energy part of the spectrum); 3691.0 ± 1.0, 3890.5 ± 0.6, and 4546.2 ± 0.7 keV (two-escape peaks of lines seen in the high-energy spectrum of ^{130}Xe).

The measured energies of all the lines assigned to ^{130}Xe are listed in column 1 of Table I. Column 2 gives the measured intensities of these γ rays relative to the intensity of the 536.1-keV γ ray ($I=100$). These measurements were made in several runs with different detectors. The relative efficiency curves for these detectors were measured by the method described by Kane and Mariscotti.[28]

C. γ-γ coincidences

γ-γ coincidences were studied at the 9.47-eV resonance. The Ge(Li) detectors of 20- and 30-cm^3 volume were used in 180° geometry. The detectors were set to cover the energy ranges 0–900 keV and 0–1500 keV, respectively. The pulses from both counters were stored in 128 × 128-channel format in the 16 384-channel memory of a TMC pulse-height analyzer.

The spectrum in coincidence with each individual γ ray could be obtained with a computer program[29] which permitted the summing of spectra coincident with individual channels in the γ-ray peak and the subtraction of the sum of an equal number of background spectra. The net coincidence spectra obtained in this way are not corrected for random coincidences; these are not expected to be significant. They must be interpreted with caution since a peak usually occupies a single channel at the energy dispersion used in these measurements.

The counting rate in this experiment was very low. As a result only coincidences between the most intense γ rays were observed. The results obtained are listed in Table II.

III. CONSTRUCTION OF THE LEVEL SCHEME

The level scheme obtained for ^{130}Xe is shown in Fig. 2. It was constructed from the results summarized in Tables I and II together with our previous knowledge[7-19] of the ^{130}Xe level scheme.

The intense 536.1- and 586.2-keV γ rays observed in the low-energy spectrum and found to be in coincidence are readily identified as the transitions known[12,13] to deexcite the 2+ (536.1-keV) and 2+′ (1122.1-keV) levels in ^{130}Xe. The 9254.2-, 8718.1-, and 8134.3-keV γ rays were then assigned as the primary transitions from the capture state to the ground, 536.1-, and 1122.1-keV states on the basis of the following evidence:

(a) The measured differences in energy between these three γ rays are 535.4 ± 1.2 and 583.8 ± 2.4 keV. These are in agreement with the measured energies, 536.1 ± 0.3 and 586.2 ± 0.2 keV, of the γ rays between these levels.

(b) The neutron separation energy obtained from the energy sums, 9254.2, 8718.1 + 536.1, and 8134.3 + 536.1 + 586.2 keV is 9254.7 ± 1.3 keV in excellent agreement with the value of 9259 ± 7 keV given in the atomic mass table of Mattauch, Thiele, and Wapstra.[30] It is also in good agreement with the value of 9255 ± 2 keV measured by Groshev *et al.*[4] but this does not constitute independent evidence for these assignments since these authors obtain their value in the same manner as the present authors. Thus these data establish the 9254.2-, 8718.1-, and 8134.3-keV γ rays as primary transitions to the 0, 536.1, and 1122.1-keV states in ^{130}Xe and lead to a value of 9254.7 ± 1.3 keV for the neutron separation energy of ^{130}Xe. This value is corrected for the recoil energy of the nucleus following γ-ray emission.

The remainder of the level scheme was then constructed as follows:

(a) It was assumed that the observed high-energy γ rays ($E_\gamma > 5.0$ MeV) are primary transitions from the capture state to a low-lying state in ^{130}Xe. The difference in energy between this transition and the neutron separation energy then provided a preliminary value for the energy of the level (E_L).

(b) A search of the observed γ-ray spectra was then made for γ rays whose energies equaled the difference in energy between E_L and the energies of levels already established in this or previous work. These secondary transitions were normally placed on the basis of the energy fit alone but in some cases the assignment was supported by the coincidence results or by the results of the radioactive-decay studies. In the absence of further supporting evidence a level was only placed in the scheme if three transitions were found which fitted as feeding or deexciting the level, two of which did not fit elsewhere.

(c) A precise value of E_L was then found from the weighted mean of values obtained from all the transitions feeding or deexciting the level.

TABLE II. Results of γ-γ coincidence measurements.

γ ray (keV)	Coincident peaks [a]
536	586, 669, (910), (960), 1090, (1340), (1435)
586	536, (960), (1300), (1510)
669	536, (850)
1090	536.

[a] The error on the quoted energies is ±12 keV. Doubtful peaks are indicated by parentheses.

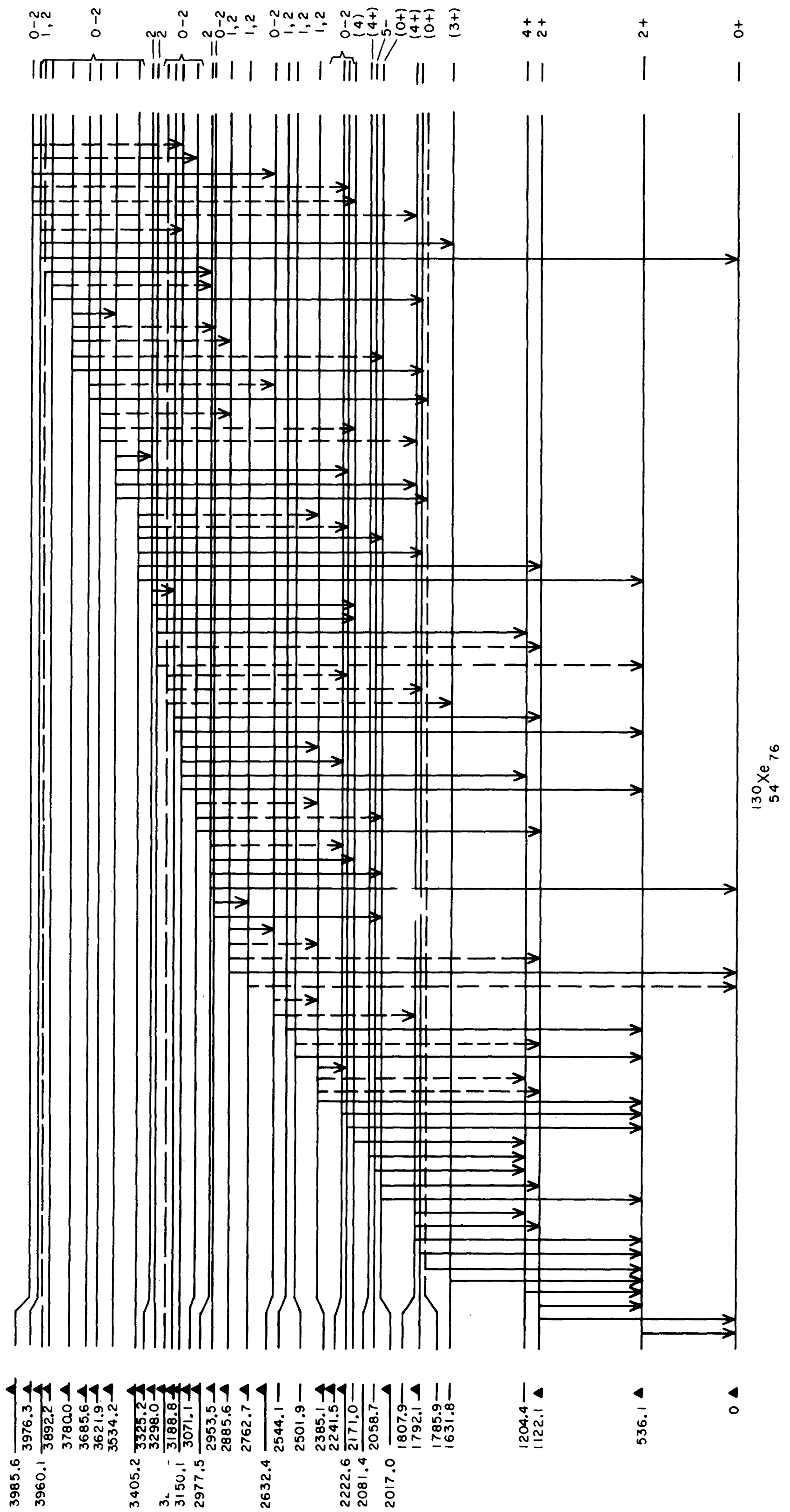

FIG. 2. The ^{130}Xe level scheme obtained from the present work. The measured level energy in keV is shown on the left. A solid triangle on the left indicates that the level is fed by a primary transition after neutron capture in the 9.47-eV resonance. Where a transition fits in more than one place in the level scheme it is shown as a dashed line. If the transition fits in only one place it appears as a solid line. The levels which appear as dashed lines are those for which primary-capture γ-rays were observed but the evidence did not meet fully the criteria required for inclusion in the level scheme (see Sec. III). The suggested spin and parity assignments shown on the right are those indicated by the data available at present.

(d) Steps (b) and (c) were then repeated using these more precise values of E_L. The third column of Table I lists the energy levels between which the observed transition fits in energy. Where a γ ray fits in energy in more than one position in the level scheme it is shown as a dashed line in Fig. 1. If it fits in only one position it is shown as a solid line.

In general, where a level is observed to be populated in both the (n,γ) reaction and radioactive decay it is found that the measured energies and relative intensities of the transitions deexciting the level are in excellent agreement, although, on the whole, the values obtained from the latter are more precise because of the lower background.

The energies of the primary-capture γ rays measured in the present work are in reasonable agreement with those measured in thermal capture by Groshev *et al.*[4] These authors report a larger number of primary transitions than were observed in the present work. This may be due to the well-known Porter-Thomas fluctuations in primary-capture γ-ray intensities or to the fact that we observe only γ rays from the 1+ resonance at 9.47 eV, whereas the thermal capture spectrum will be the result of the decay of both 0+ and 1+ resonances in ^{129}Xe populated in unknown proportions. Unfortunately, because of the statistical nature of the decay process no conclusions can be drawn from the failure to observe a particular transition at an individual resonance. These authors only observed a handful of transitions in the low-energy region of the spectrum.

The observation of the 9254.2-keV primary transition to the ground state clearly establishes the spin and parity of the capture state as 1+, thus confirming the tentative assignment made by Ribon.[20] Some comments on the properties of individual levels in ^{130}Xe follow.

A. Ground state, 536.1-, and 1122.1-keV states

All three of these levels were observed to be populated in the decay of the 9.47-eV resonance. The first two excited states in ^{130}Xe at 536.1 and 1122.1 keV are well established from earlier studies[7-14] of radioactive decay and $(\alpha, xn\gamma)$ reactions.[17-19] Both have been assigned spin and parity 2+, which is consistent with the population of these levels from the capture state. The 2+ assignment to the 536.1-keV level is based on the Coulomb excitation[31] of this level. No direct measurement of the spin and parity of the 1122.1-keV level has been made but it decays to the 0+ ground state and 2+ first excited state, which restricts the spin to 1 or 2. The assignment of spin and parity 2+ to this level rests on the level systematics of the even Xe isotopes. The measured γ-ray branching ratio to the ground state and first excited 2+ state is 0.175 ± 0.026. This is in excellent agreement with the values of 0.15 ± 0.03 and 0.172 ± 0.045 for the same quantity measured by Fessler, Julian, and Jha[12] and Qaim,[13] respectively. If we assume that both transitions are of pure $E2$ multipolarity then the ratio of the reduced transition probabilities for the 1121.5- and 586.2-keV transitions from this 2+′ state is

$$\frac{B(E2;\, 2+'-0+)}{B(E2;\, 2+'-2+)} = 0.0064 \pm 0.0005\,,$$

where the weighted mean of the measured branching ratios has been used and the internal conversion of the two transitions has been allowed for. This value is similar to the corresponding ratios for the other even Xe isotopes (see Ref. 12). The hindrance of the two-phonon transition relative to the one-phonon transition is exactly that expected for the decay of a two-phonon 2+ state on the basis of the vibrational model.[32] Thus the 2+ assignment is extremely plausible.

B. 1204.4 ± 0.5-keV state

This level decays to the 2+ first excited state by the intense 668.3-keV transition which is observed to be in coincidence with the 536.1-keV γ ray. The failure to observe a primary transition to this level is consistent with the assignment of 4+ spin and parity which rests on the measurement of pure $E2$ multipolarity[9] for the 668.3-keV transition and angular correlations[8] involving this transition. This is supported by the measured angular distribution of this transition in the Te-(α, xn) reaction.

C. 1631.8 ± 0.7-keV state

Qaim[13] has proposed a level at 1632.8 keV decaying by γ rays of 1096.7 and 510.8 keV to the 2+ levels at 536.1 and 1122.1 keV. He assigns spin and parity 4+ to this level on the basis of the measured $\log ft$ in the ^{130}I β decay and the observed γ decay to levels of spin and parity 2+. On the other hand Hopke *et al.*,[15] on the basis of the very low limit on the direct β decay of ^{130}I to this level ($\log ft > 10.2$) where ^{130}I is assumed to have 5+ spin and parity, propose a 3+ assignment.

It was not possible to determine whether a γ ray of 510.8 keV exists in the neutron-capture spectrum because of the presence of annihilation radiation. A moderately intense γ ray of 1095.7 ± 0.6 keV is present in the spectrum at the 9.47-eV resonance. It does not fit elsewhere in the level scheme and a γ ray at approximately this energy is observed to be in coincidence with the 536.1-keV transition. γ rays of 1609.6- and 2345.1-keV energy, which belong to ^{130}Xe, also fit in energy as feeding this level from levels at 3243.2 and 3976.3 keV, respectively. The former transition also fits elsewhere in the level scheme.

These results indicate that the 1631.8-keV level is populated indirectly in the decay of the 9.47-eV resonance. The failure to observe a primary γ ray to such a level is consistent with spin and parity assignments of either 3+ or 4+. The rather strong indirect population of the 1631.8-keV level suggests that the 3+ assignment is the more probable. It has by now been rather extensively demonstrated in examples of slow neutron capture in which a large number of deexciting transitions are observed, as in the present case, that it is often possible, in favorable cases, to deduce the spin of a final state from the intensity of its population, or conversely, to determine the spins of resonances from the strengths with which low-lying states of known spin are populated. This is to be expected, since the lower states are populated via many cascades of transitions which have almost exclusively dipole or quadrupole character, so that the probability of populating a level decreases rapidly as the difference between its spin and that of the capture state increases. The population strength also decreases with increasing excitation energy. Here, for example, where the 9.47-eV resonance has spin 1, the 2+ states at 536 and 1122 keV are populated with intensities of 100 and 28, respectively (exclusive of direct primary transitions), and the 4+ states at 1204 and 1807 keV with intensities of 9 and 1.7, respectively. The 5− state at 2059 keV is populated with intensity 1 and the population of the 6+ state at 2361 keV was not observed with an intensity limit of ~0.2. These and other levels fall into clearly identifiable groups according to spin, which are separated by a factor of ~3 in population intensity for each unit of spin at a given excitation energy. The measured population intensity of 8.3 for the 1631.8-keV level is consistent with spin 3 and about a factor 3 greater than that expected from the population of known 4+ states.

D. 1785.9 ± 0.8- and 1792.1 ± 0.6-keV states

In their study of the decay of 30-min ^{130}Cs Fessler, Julian, and Jha[12] observed γ rays of 1249.9, 1257.5, and 1264.1 keV. From their γ-γ coincidence studies with NaI counters they concluded that at least one of these transitions is in coincidence with the 536.1-keV γ ray. These authors then placed all three γ rays as feeding the 536.1-keV level from levels at 1785.9, 1793.5, and 1800.1 keV, although the reasons for placing all three of these γ rays in this way are not clear from the text.

The present work provides weak evidence for a level at 1785.9 keV, confirms the existence of the 1792.1-keV level, and provides no evidence for a 1800.1-keV level. A weak γ ray at 1249.4 ± 0.8 keV may be identified with the 1249.9-keV γ ray observed in the decay of ^{130}Cs and placed as deexciting the 1785.9-keV level. γ rays of 1746.9 and 1899.2 keV fit in energy as feeding this level from the 3534.2- and 3685.6-keV levels, but they are considerably more intense than the 1249.4-keV transition. They do not fit elsewhere in the level scheme. No evidence for this level was seen by Hopke *et al.*[15] or by Meyer and Walters[16] in the ^{130}I and ^{130}Cs decays.

A level at 1792.1 keV is populated by a primary-capture γ ray of 7463.5-keV energy and by γ rays of 1450.8, 1987.6, and 2101.3 keV from the levels at 3243.2, 3780.0, and 3892.2 keV. The 1450.8-keV γ ray also fits elsewhere in the level scheme. A γ ray of 1256.0 ± 0.5-keV energy was observed which fits well as the transition from this state to the level at 536.1 keV. There is a good balance in intensity between this transition and the four possible transitions feeding the level. It seems reasonable to conclude that a level at 1792.1 keV is populated in the (n,γ) reaction. The observation of a primary transition to this level restricts the spin to 0, 1, or 2. On the basis of the strong feeding of the state in the ^{130}Cs (1+) decay, the absence of any direct feeding in the decay of $^{130}I^m$ (2+), and the absence of a γ transition to the 0+ ground state, Hopke *et al.*[15] tentatively propose that this is a 0+ state.

With reference to the proposed level at 1800.1 keV, decaying by a 1264.1-keV γ ray to the 536.1-keV level (reported by Fessler, Julian, and Jha[12]), a γ ray of 1262.7 keV was observed in the present work, but it fits in two other places in the level scheme.

One of these assignments, connecting the 2385.1- and 1122.1-keV levels has also been proposed by Hopke *et al.*,[15] who observed a γ ray of 1263.8-keV energy in the ^{130}Cs decay. This assignment is consistent with the observation by Fessler, Julian, and Jha of coincidences between the 536.1-keV γ ray and γ rays with ~1260-keV energy and eliminates any need to invoke the existence of a 1800.1-keV level.

E. 1807.9 ± 0.4-keV state

A level at this energy has been observed[12,13,15] in the decay of ^{130}I. The three γ rays known to deexcite this level are all present in the (n,γ)

spectrum. A comparison of the measured energies and relative intensities of these γ rays with the same quantities measured by Fessler, Julian, and Jha and Qaim in the decay of ^{130}I shows excellent agreement. Five other γ rays of 825.7-, 1262.7-, 1726.6-, 1813.9-, and 2176.8-keV energy fit as feeding this level from the 2632.4-, 3071.1-, 3534.2-, 3621.9-, and 3985.6-keV levels although they all fit elsewhere with the exception of the 1726.6-keV transition. No primary transition was observed to this level.

We conclude that a level at 1807.9 keV is fed indirectly in the decay of the 9.47-eV resonance. Spin and parity 4+ appear well established on the basis of the logft value [in the ^{130}I (5+) decay], the absence of a direct population in the ^{130}I^m (2+) decay, and the observed γ decay to levels with spins and parities 2+ and 4+. Present evidence is consistent with this assignment.

F. 1943.9-keV state

A level at this energy is populated[12,13,15] in the decay of ^{130}I and was also reported by Bergstrom *et al.*[19] in their study of the ^{128}Te$(\alpha, 2n)^{130}$Xe reaction. It decays by a single 739.5-keV transition to the 4+ state at 1204.4 keV. In a number of recent papers[9,12,13] the authors have assumed that this level has 5+ spin and parity. Since there is now conclusive evidence that the spin and parity is in fact 6+, this point deserves some clarification.

The 5+ assignment rests solely on a measurement of the angular correlation of the 739-keV γ ray with the succeeding 536- and 668-keV transitions performed a number of years ago.[33] The results suggested that the 739-keV transition has predominantly $E2$ character with a small admixture of $M1$ strength (89% $E2$, according to Ref. 9) although the authors themselves did not rule out pure $E2$ character, and accordingly assigned either 5+ or 6+ spin and parity to the level. The experimental A_2 and A_4 coefficients for the 739-536-keV correlation were 0.109 ± 0.015 and -0.029 ± 0.021, respectively, while the theoretical coefficients for a $6(\underline{Q})\,4(Q)\,2(\underline{Q})\,0$ cascade are 0.102 and 0.0091, respectively. The internal-conversion coefficient of the 739-keV transition is consistent with the pure $E2$ value, but a small $M1$ admixture cannot be ruled out.[9]

In the work of Bergstrom *et al.*[19] the angular distribution of the 739-keV γ ray has the characteristic shape observed for other pure $E2$ transitions, but again, a small $M1$ component would be admissible. From the energy systematics of the quasi-rotational bands observed in this work, the 6+ level in ^{130}Xe would be expected to appear at about the energy of the 1943-keV state.

Recently, the angular correlation of the 739-keV γ ray with succeeding transitions in the ^{130}I decay has been remeasured in two separate experiments—by Holmberg and Luukko,[11] and by Bakiev *et al.*[14] In the results of both of these groups the A_4 coefficient for the 739-536-keV correlation was positive, consistent with pure quadrupole character for the 739-keV transition.

In the present experiment the population of the 1943-keV state was not observed. The upper limit on the intensity of the deexciting 739-keV transition is ~0.1, which may be compared with a population intensity of 1 for the 2059-keV 5− state and a limit of ~0.2 on the population of the 2361-keV 6+ state. If the 1943-keV state had spin 5 it would probably have been populated with an intensity greater than the limit of 0.1 obtained, on the basis of arguments similar to those discussed in connection with the 1631.8-keV state. We conclude that a 6+ assignment for the 1943-keV level is almost certainly correct.

G. 2017.0 ± 0.5-keV state

A level at 2016.1 keV populated in the ^{130}Cs decay which is deexcited by transitions of 1480.9 and 894.0 keV to the 536.1- and 1122.1-keV levels was proposed by Fessler, Julian, and Jha[12] on the basis of coincidences of the 894.0-keV γ ray with γ rays of ≈550, ≈600, and 1122 keV, and confirmed in later work.[15]

A primary transition of 7237.0 ± 1.3 keV fits as populating such a level. γ rays of 1481.2- and 893.7-keV energy were also observed in the present work but in the intensity ratio 3.8, which differs markedly from the ratio 0.08 observed in the decay of ^{130}Cs. A number of other γ rays of energy 936.2, 959.3, 1053.6, 1388.8, and 1764.3 keV fit as populating this level from the levels at 2953.5, 2977.5, 3071.1, 3405.2, and 3780.0 keV. The 936.2- and 959.3-keV transitions do not fit elsewhere. The observed γ ray of 209.6-keV energy would fit in energy as deexciting this level but it was not observed in the radioactive-decay studies.

We conclude that a level at 2017.0 keV is populated in the (n, γ) reaction. The large difference in the observed relative intensities of the 1481.2- and 893.7-keV γ rays from this level is most probably due to the 1481.2-keV transition's being a doublet in the (n, γ) spectrum since otherwise it should appear much more strongly in coincidence with the 536.1-keV transition in Fig. 4(a) of Ref. 12. The observation of the primary transition to this level indicates spin 0, 1, or 2. Hopke *et al.*[15] propose that this level is probably a 0+ state since, similar to the 1792.1-keV level, it is populated in the ^{130}Cs decay but not in the ^{130}I^m decay and does not decay to the ground state.

H. 2058.7 ± 0.9-keV state

Bergstrom *et al.*[18] observed an intense 854.9-keV γ ray in the ^{128}Te$(\alpha, 2n)^{130}$Xe reaction which they placed as feeding the 1204.4-keV 4+ state on the grounds that it was too intense to fit elsewhere. They observed that the angular distribution of this γ ray with respect to the beam direction has a large negative A_2 coefficient which is only consistent with a spin change of one unit. Since the level only decays to the 4+ level, they assign spin and parity 5−.

Three transitions were observed in the present work which fit between this level and levels at 1807.9, 1204.4, and 1122.1 keV with energies of 252.1, 854.3, and 936.2 keV. From their intensities relative to that of the 854.3-keV transition it is unlikely that the 252.1- and 936.2-keV transitions deexcite this level since they would have been observed by Bergstrom *et al.* and also in the ^{130}I decay.[12,13,15] The 854.3-keV γ ray does not fit elsewhere. The observed γ rays of 573.8 and 893.7 keV fit as feeding this level from the levels at 2632.4 and 2953.5 keV, but since the 2632.4- and 2953.5-keV levels have spins 0, 1, or 2, these assignments appear unlikely. The 573.8-keV transition does not fit elsewhere in the level scheme. Their combined intensities are consistent with feeding this level. It seems reasonable to conclude that the 2058.7-keV level is weakly populated by secondary transitions in the (n, γ) reaction.

I. 2081.4 ± 0.9-keV state

In the ^{130}I decay Hopke *et al.*[15] placed a state at 2081.98 keV on the basis of deexciting transitions of 877.35- and 1545.78-keV energy to the 1204.4- and 536.1-keV levels and a 280.09-keV transition from the 2362.4-keV level populating the state. They proposed 4+ spin and parity for the level.

A γ ray of 877.0-keV energy is observed in the (n, γ) reaction. The 1545-keV γ ray was not observed; its intensity would have been about at the threshold for detection. We conclude that this state is weakly populated in the (n, γ) reaction.

J. 2150.6-keV state

A level at this energy was first proposed by Fessler, Julian, and Jha.[12] It was based on the observation of γ rays of 2151.0- and 1614.6-keV energy, which fit in energy as transitions to the ground state and first excited states. This assignment was reinforced in the work of Hopke *et al.*[15] with the assignment of a 1028.6-keV transition to the 1122.1-keV level. In the present work a 1028.9-keV γ ray was observed; a weak γ ray of 1614.6 keV would be obscured by the multiplet at 1609.6-1613.3 keV. Thus this state may be populated indirectly in the decay of 9.47-eV resonance, but the evidence is inconclusive. Groshev *et al.*[4] do not report a primary γ ray of the appropriate energy in their thermal-neutron-capture study.

K. 2171.0 ± 1.3-keV state

A level at this energy, decaying by a single γ ray of 966.8 keV to the 1204.4-keV level, was proposed first by Fessler, Julian, and Jha[12] on the basis of the observation of the summing of this γ ray with the 668.4-keV γ ray in the decay of ^{130}I. This placement was confirmed by Qaim.[13] Additional deexciting transitions of 539.10-, 363.46-, and 227.55-keV energy have been reported by Hopke *et al.*[15]

A γ ray of 966.6 ± 1.2 keV was observed in the (n, γ) reaction, which may be the same γ ray as that observed in decay, but it also fits as deexciting the level at 3188.8 keV. The 539-keV γ ray would have been obscured by the intense 536.1-keV γ ray. Transitions of 806.8, 1126.1, and 1154.8 keV fit in energy as feeding this level from the levels at 2977.5, 3298.0, and 3325.2 keV. They do not fit elsewhere. In addition, the 1450.8- and 1813.9-keV transitions also fit between this level and the levels at 3621.9 and 3985.6 keV. These transitions also fit elsewhere in the level scheme. The assignment of transitions of 1072.4- and 1609.6-keV energy, which would fit as populating the 2171.0-keV level from other established levels, was ruled out on intensity grounds.

It seems reasonable to conclude that this level is fed indirectly in the decay of the 9.47-eV resonance. The spin of this level is probably 4 since it is fed in the decay of the 5+ ground state of ^{130}I and not in the decay of ^{130}I^m, and is apparently populated by transitions from several states with spins 0, 1, or 2 populated by primary transitions from the 1+ resonance capture state.

L. 2222.6 ± 0.6-keV state

A level at this energy, decaying only to the 536.1-keV state by a 1687.3-keV transition was proposed first by Fessler, Julian, and Jha[12] in the ^{130}Cs decay on the basis of observed 536.1-1687.3-keV coincidences and confirmed by Hopke *et al.*[15]

A γ ray of 1686.9 ± 1.1 keV was observed in the present work which may be identified with the transition deexciting this level. In addition, a

7032.4-keV primary transition to this level was observed. A γ ray of 1311.4 keV, which only fits as feeding this level from the 3534.2-keV level, was also observed.

Four of the γ rays assigned to ^{130}Xe, of energies 966.6, 1020.8, 1181.3, and 1764.3 keV, fit between the 2222.6-keV level and the levels at 3188.8, 3243.2, 3405.2, and 3985.6 keV as well as elsewhere in the level scheme. As in the case of the 2171.0-keV level (see Sec. III K) it is clear from the measured intensities of the γ rays that they cannot all feed this level since their combined intensity greatly exceeds that of the 1686.9-keV transition.

The observation of a primary transition to this level and the transition to a 2+ state indicate spin 0, 1, or 2. No information is available on the parity of this state.

M. 2241.5 ± 0.6-keV state

A level at 2242.8 keV decaying by a 1706.8-keV transition to the 536.1-keV level was proposed by Fessler, Julian, and Jha[12] on the basis of observed 1706.8-536.1-keV coincidences in the decay of ^{130}Cs.

In the present work a 7011.6-keV primary transition to a level at this energy was observed. A 1705.0 ± 0.6-keV γ ray was also observed which fits as the transition to the 536.1-keV level. In addition, γ rays of 736.8-, 909.9-, and 1379.5-keV energy were observed which fit as transitions from the levels at 2977.5, 3150.1, and 3621.9 keV. The 736.8-keV transition also fits elsewhere. If all of these transitions fit here there is good agreement between the intensities of the incoming and outgoing transitions.

The observation of a primary transition and the observed decay to a level of spin 2 indicate spin 0, 1, or 2 for this level. Again no information is available on the parity of this state.

N. 2361.8 ± 0.2-keV state

A level at this energy was established in the early studies[8-10] of ^{130}I decay. Fessler, Julian, and Jha[12] and Qaim[13] confirm the existence of this level which decays by γ rays of 418.0 and 1157.2 keV to the 1944.0- and 1204.5-keV levels. This level was first assigned spin and parity 6+ on the basis of conversion-electron measurements[9] and γ-γ angular correlations,[8,12] but later angular-correlation results indicate a spin of 5.[11,14] This level does not appear to be populated in the decay of the 9.47-eV resonance, which is consistent with its high spin. Hopke *et al.*[15] suggest a 5+ assignment for this state since it is not populated in the Te(α, xn)^{130}Xe reaction[19] and is strongly populated in the decay of ^{130}I ($\log ft = 5.8$).

O. 2385.1 ± 0.5-keV state

This level is fed by the 6870.4-keV primary transition and by the weak 500.1- and 765.6-keV transitions from the levels at 2885.6 and 3150.1 keV. It decays by the 1848.9-keV transition to the 536.1-keV 2+ state. None of these transitions fit elsewhere in the level scheme. A level at this energy has recently been reported in both the ^{130}Cs and ^{130}I^m decays[15,16] with an additional 1263.8-keV transition placed as populating the 1122.1-keV level. A 1262.7-keV transition is observed in the present work with the same branching relative to the 1848.9-keV transition as in the decay studies,[15,16] although it also satisfies another energy combination as well.

γ rays of 246.0, 685.8, 1020.8, and 1181.3 keV also fit between this level and the levels at 2632.4, 2071.1, 3405.2, 1204.4, and 1122.1 keV. These γ rays also fit in energy elsewhere in the level scheme.

The observed feeding and deexcitation here indicate spin 0, 1, or 2, with spin 0 ruled out by the population by ^{130}I^m.

P. 2501.9 ± 0.5-keV state

A level at 2502 keV, decaying by transitions of 1380, 1966, and 2502 keV energy was proposed by Bakiev *et al.*[14] in the decay of ^{130}I^m. Hopke *et al.*[15] and Meyer and Walters[16] have also reported the population of this level in both the ^{130}I^m and ^{130}Cs decays, but with a relatively much weaker ground-state transition than that reported in Ref. 14. They assign 1± or 2+ spin and parity to the state. In the present work no primary transition to this level is observed, although such a transition would be allowed for the assigned spin and parity. γ rays with energies of 1379.5 ± 0.4 and 1966.3 ± 0.9 keV are observed with an intensity ratio close to that reported in Ref. 15. No ground-state transition was observed; according to the results of Ref. 15 it should have been below the threshold for detection. We conclude that the 2501.9-keV level is probably populated indirectly by neutron capture in the 9.47-eV resonance of ^{129}Xe.

Q. States at 2427.0, 2532.2, and 2608.6 keV

Levels at these energies have been proposed by either Fessler, Julian, and Jha[12] or Qaim,[13] and confirmed by Hopke *et al.*[15] The γ rays which these authors place as deexciting these levels were not observed in the present work. We conclude that these levels are not populated in the decay of this resonance. The 246-keV transition observed here evidently is not identical with that observed in the decay of ^{130}I, and assigned there as connecting the 2608.6- and 2361.8-keV levels, since the stronger 800- and 1403-keV transitions from the 2608.6-keV level are not seen here.

R. 2544.1 ± 0.9-keV state

The existence of a level at this energy has recently been proposed in studies of the $^{130}I^m$ decay by Meyer and Walters.[16] A 2008.3-keV transition to the 536-keV first excited state and a weaker 2544.03-keV ground-state transition were observed. In the thermal-neutron-capture work of Groshev *et al.*, a primary transition to a level at this energy was reported. In the present work a primary transition to this level is not seen, but a 2008.0-keV transition does appear which is otherwise unassigned. It thus is probable that this level is indirectly populated in the resonance neutron capture. The primary transition in thermal neutron capture and deexciting transitions to the ground state and 2+ first excited state indicate a spin of 1 or 2 for this level.

S. 2632.4 ± 1.7-keV state

This level is populated by the intense 6622.1-keV primary transition and by the 252.1-, 1053.6-, and 1355.3-keV transitions from the 2885.6-, 3685.6-, and 3985.6-keV levels. The 1053.6-keV transition also fits as deexciting the 3071.1-keV level.

The level decays to the 1807.9- and 2385.1-keV levels via transitions of 825.7- and 246.0-keV energy. These transitions also fit in other positions in the level scheme. While the 573.8-keV transition fits in energy as the transition to the 2058.7-keV level, this placement cannot be correct since the 2058.7-keV level has spin and parity 5−. The observation of the intense primary-capture γ ray indicates spin 0, 1, or 2 for this level.

The existence of a level at 2628.38 keV has recently been suggested[16] from new results on the $^{130}I^m$ decay. From the difference in the measured energies of the two levels (~4 keV) it appears that the levels in question are not identical.

T. 2762.7 ± 0.5-keV state

This level is indicated by the observation of the 6493.3-keV primary transition. The 2763.0-keV γ ray fits as the ground-state transition from such a level but it also fits between the 3298.0- and 536.1-keV levels.

A level at this energy has also recently been proposed independently by Meyer and Walters on the basis of the observation of a 2762.60-keV γ ray in the $^{130}I^m$ decay.[16] If the 2763.0-keV γ ray is placed correctly here then the spin of the level must be 1 or 2. Otherwise spin 0 cannot be ruled out.

U. States above 2800 keV

The remaining energy levels above 2800 keV which are shown in Fig. 2 are listed in column 1 of Table III. All of them are fed by primary transitions from the neutron-capture state. The energies of these primary transitions are listed in column 2 of Table III. Table III also lists, opposite the level energies, the energies of the transitions which fit as deexciting the level. Those transitions which fit in more than one place are shown in parentheses.

All of the levels listed in Table III, with the exception of the 3243.2- and 3960.1-keV levels, fulfill the criteria for the inclusion of a level in the level scheme as outlined at the beginning of Sec. III. Three transitions fit as deexciting the

TABLE III. Properties of ^{130}Xe levels above 2800 keV.

Level energy [a] (keV)	Primary transition (keV)	Energies of transitions deexciting level [b]
2885.6 ± 1.1	6370.1 ± 0.7	2885.2, (1764.3), 500.1, 252.1
2953.5 ± 0.5	6300.5 ± 2.3	936.2, 191.8
2977.5 ± 1.0	6278.1 ± 0.7	2978.7, 959.3, 806.8, (736.8)
3071.1 ± 0.8	6182.7 ± 2.5	1948.2, (1053.6), (685.8)
3150.1 ± 0.7	6105.1 ± 1.5	2612.7, 2028.8, 909.9, 765.7
3188.8 ± 0.6	6065.3 ± 0.9	2653.8, 2066.5
(3243.2 ± 1.3)	6011.6 ± 0.9	(1609.6), (1450.8), (1020.8)
3298.0 ± 1.2	5955.6 ± 0.5	(2763.0), (2176.8), 2092.2, 1126.1
3325.2 ± 0.8	5930.2 ± 1.4	1154.8, 136.5
3405.2 ± 0.7	5849.6 ± 0.8	2870.1, 2283.0, 1613.3, 1388.8, (1181.3), (1020.8)
3534.2 ± 0.6	5720.5 ± 0.7	1746.9, 1726.6, 1311.4, 209.6
3621.9 ± 0.7	5632.1 ± 2.4	(1813.9), (1450.8), (736.8)
3685.6 ± 1.0	5568.2 ± 0.7	1899.2, (1053.6)
3780.0 ± 1.2	5475.5 ± 1.5	1987.6, (1764.3), (893.7), (825.7), (246.0)
3892.2 ± 1.5	5362.7 ± 0.6	2101.3, (914.9)
(3960.1 ± 1.0)	5295.4 ± 1.0	981.1
3976.3 ± 1.5	5278.4 ± 2.4	3975.2, 2345.1, (825.7)
3985.6 ± 1.0	5269.1 ± 2.4	(2176.8), (1813.9), (1764.3), 1355.3, (914.9), 836.8

[a] Level energies shown in parentheses belong to levels which do not meet fully the criteria for inclusion in the level scheme (see Sec. III). Such levels appear as dashed lines in Fig. 2.

[b] The energies of transitions which fit in more than one place in the level scheme are given in parentheses.

3243.2-keV level but they all fit elsewhere or are too intense to fit in this position. In the case of the 3960.1-keV level the 981.1-keV γ ray fits as the transition to the 2977.5-keV level. This was the only transition found to fit as deexciting this level. Both of these levels are shown as dashed lines in Fig. 2 since they do not meet the required criteria for inclusion in the level scheme.

The observation of primary transitions to all of the levels above 2800 keV indicates spin 0, 1, or 2 for these levels, although spin 3 cannot be ruled out for those levels fed by very weak primary transitions. In the case of the levels at 2977.5 and 3976.3 keV ground-state transitions are observed which limit their spins to the values 1 or 2.

IV. DISCUSSION

The level scheme shown in Fig. 2 summarizes the present results. In general we find that where a level in ^{130}Xe is populated in the (n,γ) reaction and the radioactive decay of ^{130}I or ^{130}Cs there is excellent agreement between the present results and recent decay studies.[12,13,15,16] A number of levels proposed in the decay studies do not appear to be populated in the decay of the 9.47-eV resonance. Levels established in the ^{130}Cs decay at 2151, 2495, 2533, and 2629 keV[12,15] are not seen in the present work. These levels should have low spin and might be populated by primary dipole transitions from the neutron-capture state. The failure to observe a number of transitions, though, must be expected from the Porter-Thomas fluctuations in the partial γ-ray widths of neutron resonances. It has been proposed[12,13] that levels at 2427.0, 2532.2, 2608.6, and 2752.3 keV are fed in the decay of the spin-5 ground state of ^{130}I. These are expected to have relatively high spin. As a result we do not expect them to be populated directly in the decay of the 9.47-eV resonance and it appears that they are not populated indirectly.

From studies of the (n,γ) reaction and of radioactive decay a large amount of information now exists concerning the level structure of ^{130}Xe. Approximately 40 energy levels are established up to 4 MeV excitation, their decay modes determined, and in a number of cases, spins and parities assigned.

No single striking feature is observed in the present level scheme. The properties of the first three excited states are typical of a vibrational nucleus, which is characterized by a triplet of states of spins 0+, 2+, and 4+ at twice the energy of the first excited 2+ state. The 1122.1- (2+) and 1204.4- (4+) keV states may be identified as members of the two-phonon triplet. The interpretation of the 1122.1-keV state as a two-phonon state is supported by the strong hindrance of the ground-state transition relative to the transition to the 2+ first excited state (see Sec. III A). Possible candidates for the 0+ member appear only at much higher energies, 1792.1 and 2017.0 keV, respectively. The lower of these two states is deexcited by transitions with roughly equal $B(E2)$ values to the 2+ 536.1- and 1122.1-keV levels, while the deexcitation of the upper state is overwhelmingly to the 1122.1-keV level. Clearly a fuller comparison with this and other models requires much more experimental information, such as the $M1$-$E2$ mixing of the transition between the 2+ states, the position of the two-phonon 0+ state, and the lifetimes and moments of all these levels.

It is clear from Fig. 2 that existing information on ^{130}Xe is very incomplete. Much more information about the spins, parities, lifetimes, and single-particle character of the known levels is required. Further measurements on the ^{129}Xe-$(n,\gamma)^{130}$Xe reaction with the aim of obtaining more precise γ-ray energies and γ-γ coincidence relationships are clearly required, as well as charged-particle experiments, both preferably carried out with enriched isotopes.

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