Radioactive Decay of $^{130}I^m$, $^{130}I^g$, and ^{130}Cs to Levels of ^{130}Xe

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The level structure of ^{130}Xe has been determined from the β decay of $^{130}I^m$, $^{130}I^g$, and ^{130}Cs. The γ rays emitted in the decay of these species have been observed with high-resolution Ge(Li) detectors and Ge(Li)-Ge(Li) γ-γ coincidence experiments have been performed. Decay schemes for these three isotopes have been deduced. The half-life of $^{130}I^g$ has been measured as 12.36 ± 0.01 h.

[RADIOACTIVITY $^{130}I^m$, $^{130}I^g$ [from $^{129}I(n,\gamma)^{130}Te(p,n)$], ^{130}Cs [from $^{127}I(\alpha,n)$]; measured E_γ, I_γ, $t_{1/2}$, $\gamma\gamma$ coinc. ^{130}Xe deduced levels, J, π. Enriched target. Ge(Li) detectors.]

I. INTRODUCTION

The structure of the even-even Xe isotopes is of considerable interest as the levels of the lighter nuclides show rotational characteristics and the levels of nuclides near closed shell ^{136}Xe are characteristic of vibrational nuclei. ^{130}Xe is an interesting nuclide, whose vibrational character appears to be less clear-cut than that of the higher-A isotopes. The level structure of ^{130}Xe has been previously studied by a variety of methods: $Te(\alpha, xn\gamma)$,[1] $^{130}Te(^3He, 3n)^{130}Xe$,[2] the β decay of $^{130}I^g$,[3,4] and positron and electron-capture decay of ^{130}Cs.[3] An isomeric state in ^{130}I has been previously reported,[5] and a partial description of its γ and β^- decay branching has also been given.[4,6,7] In our studies to characterize the decay of $^{130}I^m$, it was found that the level scheme of ^{130}Cs and $^{130}I^g$ could be considerably clarified so a complete investigation of the decay properties of $^{130}I^m$, $^{130}I^g$, and ^{130}Cs was undertaken.

In initial studies[8] of these decays at the Massachusetts Institute of Technology (MIT), a number of levels were postulated for ^{130}Xe on the basis of coincidence studies for which only one γ decay branch was observed. In order to look for other γ branches, more sensitive techniques available at the Lawrence Livermore Laboratory (LLL) were utilized to locate many of the very weak γ rays observed in the decay of $^{130}I^g$.

II. EXPERIMENTAL PROCEDURE

A. Source Preparation

Sources of $^{130}I^g$, $^{130}I^m$ were produced by irradiation of ^{129}I (1.56×10^7 yr), obtained from the Oak Ridge National Laboratory (ORNL), in the MIT reactor at a flux of 2×10^{13} $n\,cm^{-2}\,sec^{-1}$. The target was in the form of NaI dissolved in basic sodium sulphite solution and was greater than 99% radiochemically pure. After irradiation the target was transferred via the pneumatic tube facility of the MIT reactor to the receiving laboratory, where the solution was acidified and the iodine coprecipitated with AgCl. The precipitate was collected on filter paper and mounted for counting.

Sources of ^{130}Cs were obtained by bombardment of spectroscopically pure LiI with 30-MeV ^4He ions in the MIT cyclotron. The target material was then dissolved in 1 N HNO_3 and the solution passed through an ammonium molybdophosphate (AMP) column.[9] After elution with a solution of 1 M NH_4NO_3 in 1 N HNO_3 only Cs remained on the column. The column served directly as the source to be counted.

Sources were prepared at LLL by irradiating ^{130}Te with 14-MeV protons at the Livermore cyclotron. The tellurium was washed once with water. A solution containing 0.5 ml 6 M NaOH, 0.5 ml of KI solution equivalent to 5 mg of iodine, and 2 ml of fresh 30% H_2O_2 solution was slowly added to the flask. After 15 min the solution was gently heated and allowed to evaporate until almost dry. The flask was then cooled to room temperature. A solution containing 7 ml of 6 M HCl and 1 ml of 1 M $NaClO_3$ was added to the flask. Next, 25 ml of butylacetate was added along with enough 10 M HCl (1–4 ml) to cause the formation of ICl (green color). The flask was stoppered and allowed to stand for 15 min. The mixture was then transferred to a separatory funnel and the butylacetate separated. A second 25-ml portion of butylacetate was added, equilibrated and separated. The 25 ml of H_2O and the combined butylacetate fractions were placed in a clean separatory funnel and enough fresh 7% H_2SO_3 solution added (1–4 ml) to completely reduce the iodine. The water fraction was equilibrated with an equal volume of toluene, then 5 ml of 4 *M* HNO_3 was added while stirring. The 1 *M* $NaNO_2$ was added one drop at a time until no brown color (I_3^-) remained in the aqueous phase. The toluene layer was washed three times with equal volumes of water. The iodine was then reduced into a fresh aqueous phase using 7% H_2SO_3, one drop at a time, until both phases were colorless. Next, 3 mg each of Fe Fe and La were added as the chloride to the separated aqueous phase. The solution was made basic with a few drops of 6 *M* NaOH. Insoluble hydroxides were then separated by centrifuging. The iron and lanthanum scavenging step was repeated three times. After this the solution was filtered through Whatman No. 42 filter paper and made acid with a few drops of 6 *N* HCl. Palladium chloride was added to precipitate PdI_2. The PdI_2 was washed once with water and once with ethyl alcohol. The PdI_2 was then dryed for 10 min at 1000°C and mounted for counting.

B. Spectroscopic Measurements

The γ-ray spectra taken at MIT were recorded using the electronics and multichannel analyzer system described by Ragaini, Gordon, and Walters.[10] Two Ge(Li) detectors were used which had nominal active volumes of 26 cm^3 and 45 cm^3 and which gave over-all system full width at half maximum for the 1332-keV line of ^{60}Co of 2.3 and 2.8 keV, respectively. The resulting spectra were transferred to computer-compatible magnetic tape and analyzed using a program written by Hopke.[11] Energy calibrations were done before and after each series of spectra using standard γ-ray sources. The centroids and energies of these standard peaks were fitted using the method of least squares, with energy as a fourth-order polynomial function of channel number.

The γ-γ coincidence experiments were conducted using both of these Ge(Li) detectors positioned at 90°C to each other. Cross-over timing was employed and the resolving time of the system was approximately 100 nsec. The two analog signals were led into gated 20-MHz analog-to-digital converters, and the pairs of coincident addresses were stored in the buffer memory system. When this memory was filled, the contents were recorded on magnetic tape. The contents of the tape could then be analyzed either by using a system of digital gates associated with the multichannel analyzer or with a computer program on a large computer. Because of the short half-lives involved, sources were replaced periodically with freshly prepared samples.

The γ-ray spectra for the $^{130}I^g$ were taken using 6- and 19-cm^3 Ge(Li) detectors, as well as the LLL Compton suppression spectrometer. The high-energy γ-ray calibrations were taken with a mixed source of $^{130}I^g$ and ^{56}Co. The lower-energy lines were calibrated against ^{203}Hg (279.188 keV), ^{137}Cs (661.646 keV), ^{54}Mn (834.823 keV), and ^{60}Co (1173.221 keV).[12]

C. Half-Life Determination of $^{130}I^g$

Four point sources of ^{130}I were prepared for the determination of the half-life, and as a purity check. These samples were counted for seven half-lives of the ^{130}I. At the end of measurement these samples were counted on Ge(Li) diodes. The only impurities observed in these spectra were small amounts of ^{124}I, ^{126}I, and ^{131}I. At the time of the first count 99.88% of the γ activity was due to ^{130}I. The samples were counted on a 3.8-cm-diam×2.5-cm-thick NaI(Tl) detector with a thin Be window and a 1607-mg/cm^2 Be absorber. Discriminator settings permitted all impulses in the energy range 20 to 10 000 keV to be recorded. The stability of the counter was monitored with a ^{238}U standard.

The half-life for each sample was calculated by a nonlinear least-squares computer program[13] in which each point was weighted as the reciprocal of its variance. The half-lives observed for each sample were combined to give a final average weighted as the reciprocal of its variance. For the least-squares calculation the half-lives of other observed activities were fixed at the following values:

$^{124}I = 4.17$ days,

$^{126}I = 13.05$ days,

$^{131}I = 8.06$ days.

The observed half-life of ^{130}I was 12.36 ± 0.01 h. This half-life value is in agreement with literature values of Andersson, Rudstam, and Sorensen[14] (12.3 ± 0.1 h), Aagaard *et al.*[15] (12.5 ± 0.1 h), and Livingood and Seaborg[16] (12.6 ± 1.0 h).

III. RESULTS

The spectrum of γ rays observed in the decay of ^{130}Cs is shown in Fig. 1. The spectrum of $^{130}I^m$ is shown in Fig. 2. The energies and intensities of the ^{130}Cs transitions are given in Table I and these quantities for $^{130}I^m$ are presented in Table II. Table I also shows the energies of the γ rays observed for ^{130}Cs decay by Fessler, Julian, and Jha.[3] Our intensities values are also in agreement with their intensity values. We observe several transitions that they do not report.

The β branching for $^{130}I^m$ was previously measured by Kellershon, Comar, and Riviere[6] to be approximately 15% by observation of a β spectrum with end-point energies of 2.5 MeV (13.5%) and 1.9 MeV (1.5%), and by Quaim[4] to be 16% with a 14.4% β branch of 2480 ± 50 keV and 1.6% β branch of 1850 ± 80 keV. The β branching ratio can also be calculated from the growth and decay of the prominent γ transitions. From these data, a β^- branch of (17 ± 3%) can be calculated. The ratio of (n, γ) cross sections for $^{130}I^g$ and $^{130}I^m$, σ_g/σ_m, is 0.661 ± 0.080.

Table III summarizes the γ-γ coincidence data from the decay of both ^{130}Cs and $^{130}I^m$. From the coincidence data and precise energy sums and differences, the decay scheme shown in Fig. 3 was constructed. All of the observed transitions have been placed in this scheme. The intensity of the 2093.4-keV transition is so low that it could not be seen in the γ-γ coincidence data. It has been tentatively placed feeding the 2^+ state at 536.3 keV. It could also feed the ground state, but all other levels that feed the ground also feed the first and/or second excited state with some intensity. As no such γ rays were observed, a level was placed at 2629.6 keV.

The relative positron branches to the first three levels were obtained from the γ-ray relative intensities and the theoretical ratios of electron capture to positron decay given in the curves of Zweifel.[17] From these data, the total ground state to ground-state branch of 94.4% was calculated. It was assumed that there was no strength for the transition from $^{130}I^m$ to the ground state of ^{130}Xe.

The $\log ft$ values were calculated using the nomograph of Verrall, Hardy, and Bell.[18] The energy available for β^- decay, Q_{β^-}, was calculated to be 3025 ± 20 keV from the data of Daniel *et al.*,[19] and the measured value of the isomeric transition energy and is in agreement with the value of 3016 ± 50 keV given by Quaim.[4] The energy available for the electron-capture decay of ^{130}Cs, Q_{EC}, was determined from the end-point energy of 1.97 MeV for the ground-state positron energy spectrum.[19] The decay scheme presented for ^{130}Cs is in good agreement with that of Fessler, Julian, and Jha.[3]

The Compton-suppressed γ-ray spectrum obtained at LLL for $^{130}I^g$ decay is shown in Fig. 4. The γ-ray energies and intensities determined at LLL are tabulated in Table IV. The results of the γ-γ coincidence studies are tabulated in Table V. The decay scheme derived from these data is shown in Fig. 5. The $\log ft$ values calculated using the computer code of Larsen and Lanier are given in Table VI.[20]

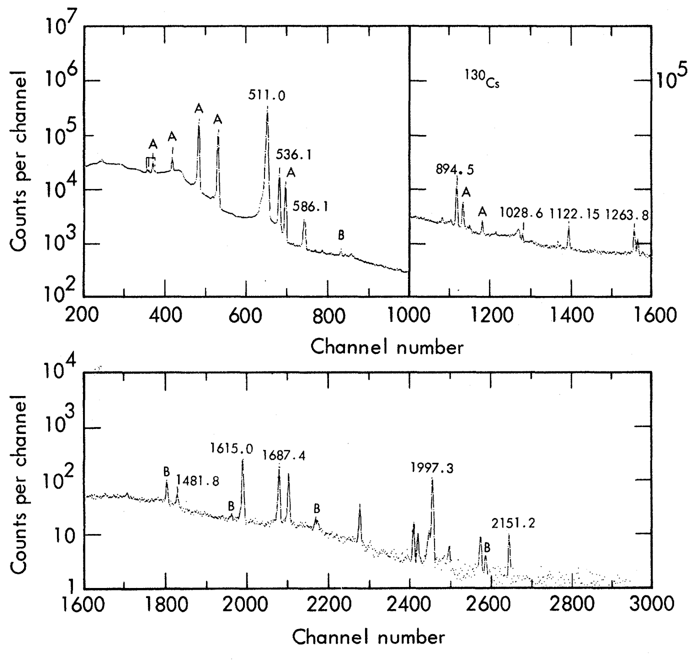

FIG. 1. γ-ray spectrum of ^{130}Cs. The peaks marked A and B arise from ^{129}Cs decay and background, respectively.

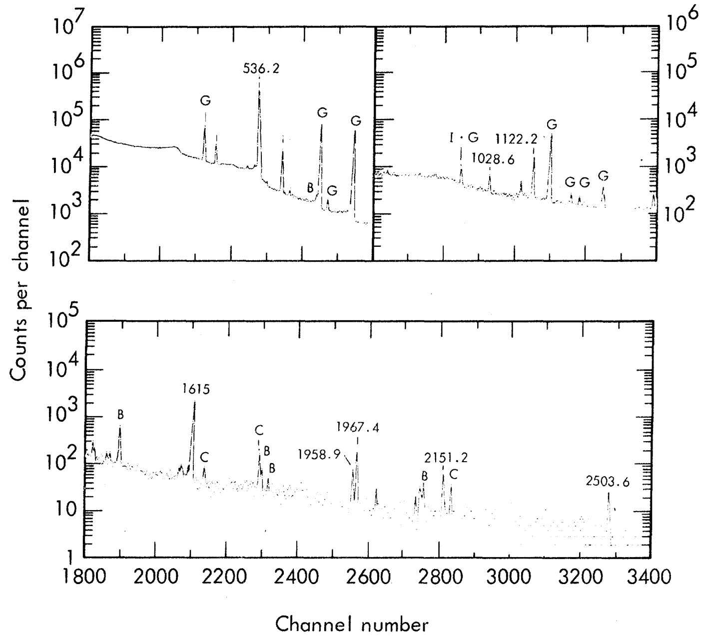

FIG. 2. γ-ray spectrum of $^{130}I^m$. The peaks marked B, C, G, and I arise from background, the decay of ^{37}Cl, the decay of $^{130}I^g$, and the decay of ^{128}I, respectively.

IV. SPINS AND PARITIES

A. Spins and Parities of the ^{130}I Isomers

Our data have led us to propose positive parities for the ground state and isomer of ^{130}I. The ground state of ^{130}I has been shown[21] to have a spin of 5 and the L-subshell ratios for the isomeric transition (IT) have been found to be consistent with an $M3$ assignment.[7] We searched the spectrum of low-energy γ rays carefully for the 48.2-keV IT. The upper intensity limit that we could set for possible 48.2-keV γ rays, when combined with the intensity of L x rays, is consistent with the theoretical α_K value[22] for a 48.2-keV $M3$ transition. It is, however, a factor of 20 lower than should be present if the transition were $E3$. Thus, the isomer must have the same parity as the ground state.

The ground state of even-even ^{130}Xe is 0^+ and the first excited state has spin and parity of 2^+. The next two excited states at 1122 and 1204 keV have spins and parities of 2^+ and 4^+, respectively. The 4^+ assignment for the 1204-keV level arises from its heavy population (not necessarily directly) in the β decay of spin-5 $^{130}I^g$, from its position in the γ deexcitation cascade of high-spin states of ^{130}Xe populated in the ^{128}Te(α, $2n$)

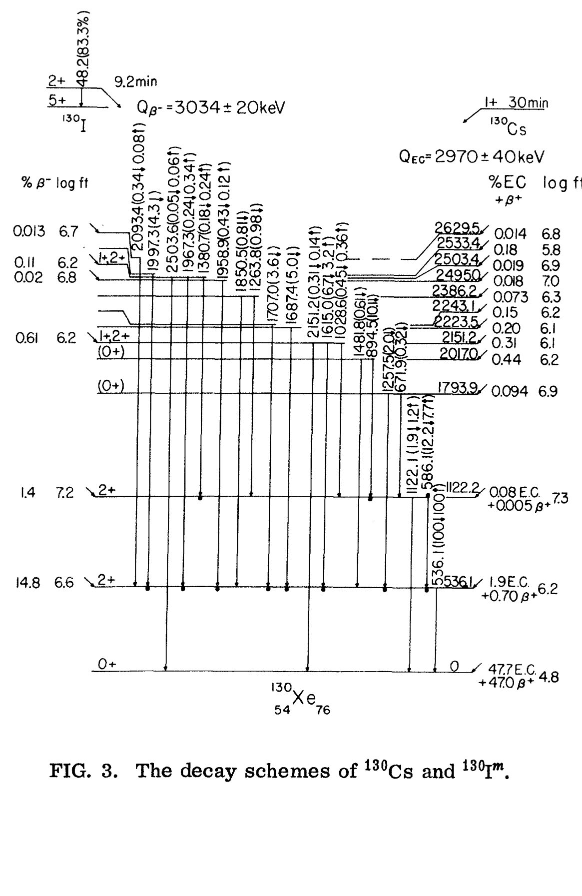

FIG. 3. The decay schemes of ^{130}Cs and $^{130}I^m$.

reaction,[23] and from its failure to feed the ground state directly. States at 1944, 2059, and 2696 keV were also observed by Bergstrom *et al.*[23] and assigned spins and parities of 6^+, 5^-, and 8^+, respectively.

Daniel *et al.*[19] postulated a negative parity for $^{130}I^g$ on the basis of β-γ angular correlation measurements. Such an assignment was also supported by the $\log ft$ value of 8.8 for the β transition to the 4^+ level at 1204 keV. However, it was not consistent with the $\log ft$ value of 5.6 for β decay to the 5^+ level at 2362 keV.

In view of the $M3$ character of the IT from $^{130}I^m$, the spin of $^{130}I^m$ must be 2. If $^{130}I^g$ is 5^-, $^{130}I^m$ should be 2^-. The $\log ft$ values for β decay of $^{130}I^m$ fall in a narrow range from 6.2 to 7.2. These $\log ft$ values are nearly identical to the $\log ft$ values for the allowed decay of 1^+ ^{130}Cs.[17] They are substantially lower than the $\log ft$ values observed[24] for the decay of 2^- ^{124}I.

We suggest therefore that the parities of the isomers of ^{130}I are positive. The high $\log ft$ value observed for the decay of 5^+ $^{130}I^g$ to the 4^+ level of 1204 keV is similar to the high $\log ft$ value observed[25] for the decay of 5^+, 1.2-min $^{124}Sb^{m_1}$ to the 4^+ level at 1249 keV in ^{124}Te. The low $\log ft$ values for decay to the 6^+ and 5^+ levels at 1944 and 2362 keV are also similar to those observed in the decay of $^{124}Sb^{m_1}$ to similar levels in ^{124}Te.

The spin and parity values[26] for ^{124}I (2^-), ^{126}I (2^-), ^{128}I (1^+), ^{130}I (2^+ and 5^+), ^{132}I (4^+),[27] and ^{134}I (4^+ and 8^-)[28] may be understood by a careful consideration of the coupling rules for odd-odd nuclei described by Brennan and Bernstein.[29] The applicability of these rules above $Z=50$ has not been fully established, in part owing to a lack of data for many nuclides. Three protons are present in I nuclides above the closed shell at $Z=50$ and occupy either the $g_{7/2}$ and/or $d_{5/2}$ orbitals. Varying numbers of neutrons are present and are filling the $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ orbitals up to $N=82$. Three rules were elucidated by Brennan and Bernstein, two strong rules for coupling between two particles or between two holes and a third weaker rule for particle-hole coupling. Strongest coupling ($R1$) to $J=|j_p - j_n|$ was found where $j_p = l_p \pm \frac{1}{2}$ and $j_n = l_n \mp \frac{1}{2}$. Strong coupling ($R2$) to isomers with $J=|j_p + j_n|$ and $|j_p - j_n|$ was found where $j_p = l_p \pm \frac{1}{2}$ and $j_n = l_n \pm \frac{1}{2}$. Weaker particle-hole coupling ($R3$) was observed leading predominantly to $J = j_p + j_n - 1$. The 2^- assignments for ^{124}I and ^{126}I are obtained only by coupling a $g_{7/2}$ proton to an $h_{11/2}$ neutron and fall under $R1$. In ^{128}I, the 1^+ state can also only be formed by coupling a $d_{5/2}$ proton

TABLE I. Energies and intensities of transitions following decay of ^{130}Cs.

E_γ (ΔE_γ)[a]	E_γ[b] (Fessler *et al.*)	I_γ[c]
510.95(10)	511.006	2320
536.1(3)	536.0	100[d]
586.1(3)	586.1	12.2[d]
671.9(5)		0.32
894.5(2)	894.0	10.1
1028.6(3)		0.45
1122.2(2)	1122.5	1.9
1257.5(3)	1257.5	2.0
1263.8(3)	1264.1	0.98
1380.7(4)		0.18
1481.8(3)	1480.9	0.61
1615.0(2)	1614.6	6.7
1687.4(2)	1687.3	5.0
1707.0(2)	1706.8	3.6
1850.5(3)	1849.0	0.81
1958.9(4)	1958.8	0.43
1967.4(5)		0.24
1997.3(3)	1996.3	4.3
2093.4(5)	2092.5	0.34
2151.2(4)	2151.0	0.31
2503.6(4)		0.05

[a] Errors for the transition energies are based on statistical deviations for several measurements and allowance for systematic error in the calibration technique. The figure in parentheses represents the error in the last place(s) as the value quoted to the left of it.

[b] Reference 3.

[c] Errors in intensities are 10% for intensities greater than 3, 20% intensities in the range 0.5–2 and 50% for intensities less than 0.5.

[d] These intensities have been determined after subtraction of contributions from the 534.8- and 588.8-keV transitions from the decay of ^{129}Cs. The contributions are calculated using the intensity of the 371.9-keV line and the relative intensities of Graeffe and Walters (Ref. 9).

TABLE II. Energies and intensities of transitions following decay of $^{130}I^m$.

E_γ(ΔE_γ)[a]	I_γ
536.1(3)	100
586.1(3)	7.7
1028.6(3)	0.36
1122.1(3)	1.2
1380.7(4)	0.24
1615.0(3)	3.2
1958.9(5)	0.12
1967.4(4)	0.34
2093.4(5)	0.08
2151.2(4)	0.14
2503.6(4)	0.06

[a] Error for the transition energies are based on statistical deviations for several measurements and allowance for systematic error in the calibration technique. The figures in parentheses represent the error in the last place(s) as the value quoted to the left of it.

TABLE III. γ-γ coincidences following decay of ^{130}Cs and $^{130}I^m$. The symbol † denotes coincident in decay of $^{130}I^m$. The symbol × denotes coincident in decay of ^{130}Cs. The symbol * denotes coincident in decay of both $^{130}I^m$ and ^{130}Cs.

	E_{gate}															
E_γ	511	536	586	894	1028	1123	1257	1263	1381	1615	1687	1707	1851	1958	1968	1997
511.0	×	×	×													
536.2	×		*	×	*		×	?	†	*	×	×	?	×	×	×
586.1	×	*		×	?				†							
894.5		×	×			×										
1028.6																
1122.6	×			×												
1257.5		×														
1263.8		?	?													
1380.7		†	†													
1615.0		?														
1687.4		×														
1707.0		×														
1850.5																
1940.9		×														
1967.4		†														
1997.3		×														

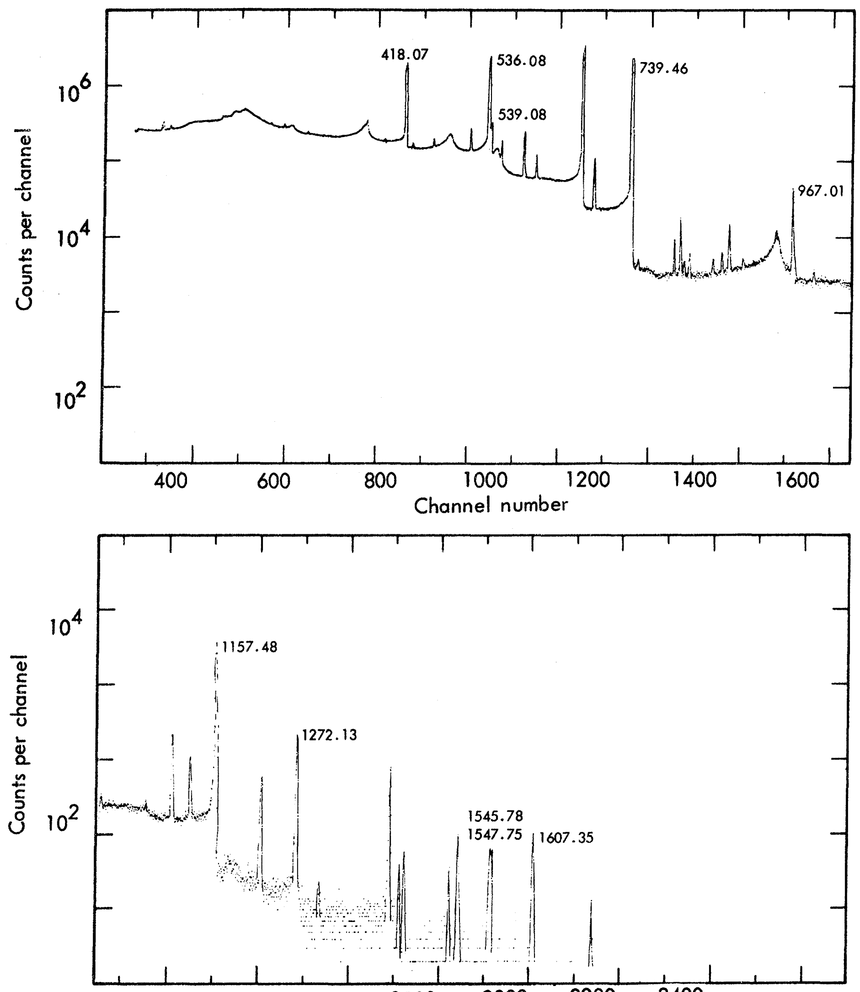

FIG. 4. γ-ray spectrum of $^{130}I^g$.

to a $d_{3/2}$ neutron, again an example of $R1$. Because of the filling of the $h_{11/2}$ orbital, it is likely that by $A=128$ ($N=75$) the $h_{11/2}$ orbital is over half filled and no longer able to participate in strong coupling with $d_{5/2}$ or $g_{7/2}$ particles. It is not clear why 1^+ is not also the ground state of ^{130}I. The ground states of ^{129}Te and ^{129}I are $\frac{3}{2}^+$ and $\frac{7}{2}^+$, respectively, and 2^+ and 5^+ isomers observed in ^{130}I are easily seen to fall under $R2$. As the $d_{5/2}$ state in ^{129}I is only 28 keV above the $g_{7/2}$ ground state, the 1^+ state suggested by $R1$ should be quite low. The 4^+ states in ^{132}I and ^{134}I appear to be examples of $R3$ coupling of the $g_{7/2}$ proton with the $d_{3/2}$ neutron hole. The 4^+ state could also be formed by a $g_{7/2}$-$s_{1/2}$ coupling with the $s_{1/2}$ state in ^{131}Te at 300 keV above the $d_{3/2}$ state. The 8^- isomer in ^{134}I also appears to be $R3$ coupling of the $g_{7/2}$ proton with the $h_{11/2}$ neutron hole. Again, $d_{5/2}$-$h_{11/2}$ would give an 8^- state and such 8^- isomers are well known in Sb nuclides.

B. Spins and Parities of the Levels of ^{130}Xe

The low $\log ft$ values for transitions to the states in ^{130}Xe populated in the electron capture and β^+ decay of ^{130}Cs (1^+) limit the spin and parities to values $0^\pm$, $1^\pm$, and $2^\pm$. Moreover, the levels at 2151.2 and 2503.4 keV feed the 0^+ ground state by γ emission and hence must have spins and parities of $1^\pm$ or 2^+. The two levels at 1793.9 and 2017.0 keV are strongly fed in the decay of ^{130}Cs, are not fed in the decay of 2^+ $^{130}I^m$, and do not feed the 0^+ ground state. They are tentatively assigned as 0^+ states.

The states of 1808.2, 2427.2, 2622.4, and 2811.9 keV are all fed in the allowed β decay of 5^+ $^{130}I^g$ and decay to the 2^+ state at 1122.2 keV and are thus restricted to a spin and parity assignment of 4^+. The state of 2362.1 keV is strongly fed in the decay of 5^+ $^{130}I^g$ and does not decay to any of the lower-lying 2^+ states. As it was not observed by Bergstrom *et al.*[23] it is most likely a 5^+ state.

The level at 1632.6 keV poses an interesting problem as it does not appear to be fed by β decay by any of the three possible parents, although the limits for nonfeeding from 2^+ $^{130}I^m$ are not very strict. Its γ decay to the 2^+ and 4^+ levels at 536.1, 1122.2, and 1204.6 keV restrict spin and parity values to $3^\pm$, 4^+, and 2^+. The 2^+ assignment is quite unlikely owing to the absence of any observable β^+ or electron-capture (EC) feeding from 1^+ ^{130}Cs. The 4^+ assignment is also rendered unlikely by the absence of β feeding by the 5^+ $^{130}I^g$ isomer. Finally, negative-parity possibility is eliminated by the character of the γ-ray feeding, as well as by systematic evidence. In the even-even Xe isotopes the lowest negative-parity states observed are generally 5^- and 7^-. As the 5^- is known to be located at 2059.6 keV, there

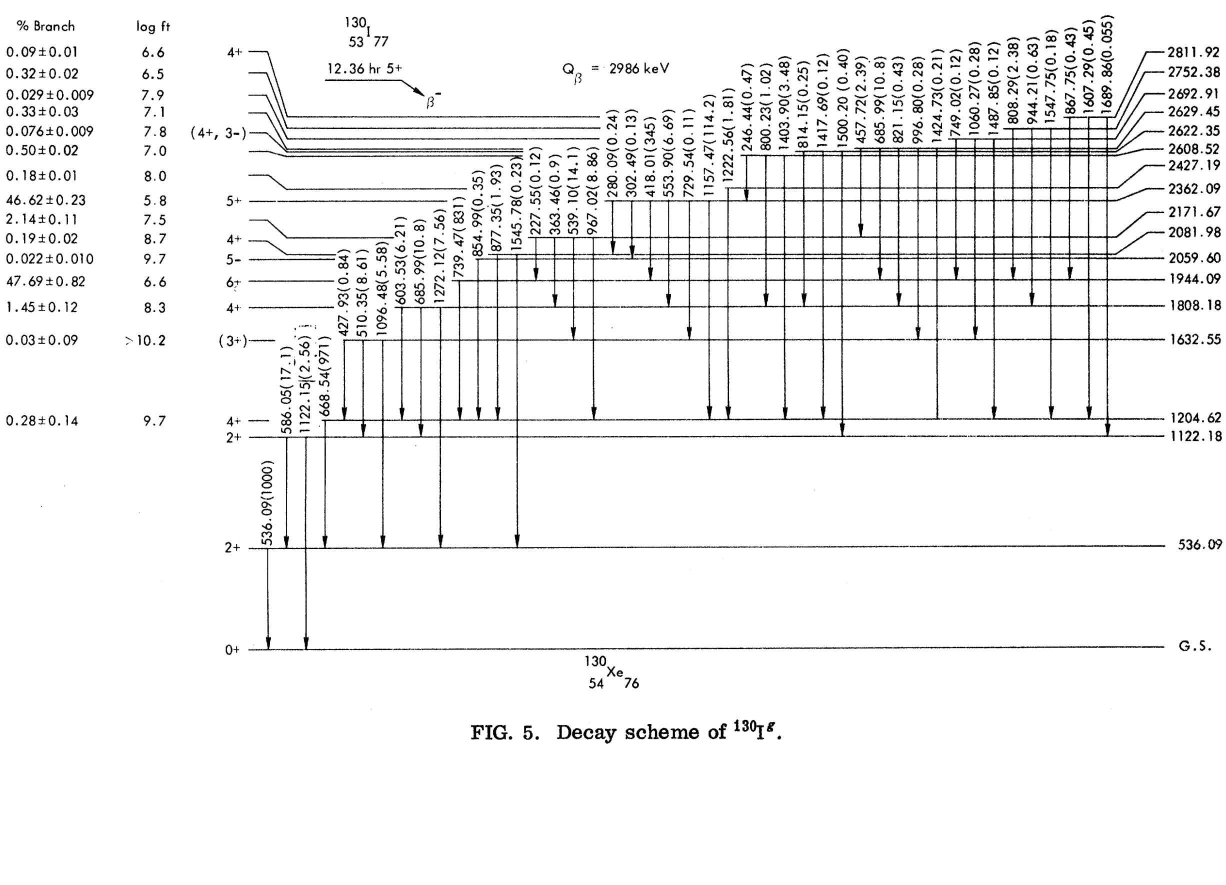

FIG. 5. Decay scheme of $^{130}I^g$.

seems little likelihood that any other negative-parity state would exist below that point. The intensity ratio for the γ rays at 227.5 and 539.1 keV are in the ratio expected for transitions that are predominantly $E2$. The 1632.6-keV level is also fed by the 2629.9-keV level. The latter level does not feed either of the two lower-lying 2^+ levels at 536.1 and 1122.2 keV and hence likely has a spin ≥ 5. The $\log ft$ value for β decay sets an upper limit of 6 for the 2629.9-keV level, hence assignments of 6^+ and 4^+, 5^+ and 4^+, or 5^+ and 3^+ are consistent for the 2629.9- and 1632.6-keV levels. If, however, the absence of β decay to the 1632.6-keV level is noted to reduce the likelihood of the 4^+ possibility, then the 5^+ and 3^+ possibility provides assignments for the levels at 2629.9 and 1632.6 keV, respectively, most consistent with all of the data.

V. DISCUSSION

The ^{130}Xe nucleus has six neutron holes in the closed shell at $N=82$ and four protons beyond the closed shell at $Z=50$. A useful theoretical description of the ^{130}Xe levels below 3 MeV must include both collective excitations and neutron and proton two-quasiparticle states. First, we will consider the β- and γ-transition rates in and out of the observed levels and then consider various interpretations of the ^{130}Xe structure.

We show in Table VII a breakdown of the possible two-quasiparticle states that can result by unpairing either $g_{7/2}$ and $d_{5/2}$ protons or $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ neutrons. Such a table is especially useful in interpreting the observed β decay. The 5^+ ground state of ^{130}I can only be formed by the $(\pi g_{7/2}\nu d_{3/2})_{5^+}$ coupling. The 2^+ isomer of ^{130}I can be a combination of the $(\pi g_{7/2}\nu d_{3/2})_{2^+}$ and $(\pi d_{5/2}\nu s_{1/2})_{2^+}$ couplings with energy considerations favoring the strength of the former.

In the β^- decay of ^{130}I, the 77th neutron decays to become the 54th proton. The only allowed path available is $\nu d_{3/2}\to\pi d_{5/2}$, as the other possibilities, $\nu d_{3/2}\to\pi g_{7/2}$ and $\nu s_{1/2}\to\pi d_{5/2}$ or $g_{7/2}$ are second-forbidden transitions. Because of the low-Q value,

TABLE IV. Energies and intensities of transitions following decay of ^{130}I^g.

$E_\gamma(\Delta E_\gamma)$ [a] (in keV)	$I_\gamma(\Delta I_\gamma)$ [b]	From/To [c]	$E_\gamma(\Delta E_\gamma)$ [a] (in keV)	$I_\gamma(\Delta I_\gamma)$ [b]	From/To [c]
158.800(180)	0.20(7)		814.150(106)	0.25(5)	2622/1808
190.460(121)	≤0.005	2362/2172	821.151(78)	0.43(5)	2629/1808
227.547(158)	0.12(5)	2172/1944	854.985(99)	0.35(5)	2060/1204
246.435(52)	0.47(5)	2609/2362	867.748(215)	0.43(6)	2812/1944
280.091(108)	0.24(7)	2362/2081	877.354(39)	1.93(8)	2082/1204
293.480(200)	≤0.05		897.040(160)	0.21(5)	2705/1808
302.490(62)	0.13(5)	2362/2060	944.206(78)	0.63(14)	2753/1808
363.460(74)	0.9(2)	2172/1808	967.018(17)	8.86(13)	2172/1204
418.005(20)	345(1)	2362/1944	996.804(162)	0.28(5)	2629/1633
427.941(42) [d]	1.18	1633/1204	1060.070(166)	0.17(5)	2693/1632
457.723(23)	2.39(15)	2629/2172	1094.286(197)	0.28(8)	
510.350(23)	8.61(20)	1633/1122	1096.480(25)	5.58(9)	1633/536
536.086(16)	1000(5)	536/g.s.	1122.145(31)	2.56(8)	1122/g.s.
539.095(31)	14.1	2172/1633	1157.471(11)	114.2(9)	2362/1204
553.897(11)	6.69(16)	2362/1808	1222.564(32)	1.81(5)	2427/1204
586.052(23)	17.1(2)	1122/536	1272.124(20)	7.56(11)	1808/536
603.531(12)	6.21(21)	1808/1204	1304.690(296)	0.049(2)	2427/1122
623.036(316)	0.17(11)	2705/2082	1403.897(20)	3.48(12)	2609/1204
668.539(11)	971(6)	1204/536	1417.690(125)	0.12(2)	2622/1204
685.989(10)	10.8(2)	1805/1122	1424.734(146)	0.21(2)	2629/1204
729.544(219)	0.11(8)	2362/1633	1487.850(146)	0.12(2)	2692/1204
739.476(15)	831(7)	1944/1204	1500.200(87)	0.40(2)	2622/1122
749.019(140)	0.12(5)	2693/1944	1545.777(231)	0.23(4)	2082/536
771.020(469)	0.04(3)		1547.754(231)	0.18(4)	2752/1204
800.234(33)	1.02(5)	2609/1808	1607.288(119)	0.45(3)	2812/1204
808.286(18)	2.38(6)	2753/1944	1689.860(250)	0.055(10)	2812/1122

[a] The error quoted is in eV. These errors represent 1 standard deviation. The standards used to calibrate are known to within 10 to 25 eV. This error should be added in quadrature. The figures in parentheses represent the error in the last place(s) as the value quoted to the left of it.

[b] The error is 1 standard deviation. For γ rays above 200 keV the relative error for any two γ rays different in energy greater than 200 keV is to be taken as 3%.

[c] Assignment of the γ ray to the decay scheme. Level is referred to by its energy to 1 keV.

[d] Doublet: 427.933 with intensity of 0.84(11); 429.120 with intensity of 0.34(11).

decay of core neutrons to four-quasiparticle levels is not possible. Thus, β^- decay of either ^{130}I state $(\pi g_{7/2}\nu d_{3/2})_{2^+}$ or $(\pi g_{7/2}\nu d_{3/2})_{5^+}$ will lead to configurations of $(\pi g_{7/2}\pi d_{5/2})$ with J^π of 1^+, 2^+, 3^+ or $(\pi g_{7/2}\pi d_{5/2})$ with J^π of 4^+, 5^+, 6^+, respectively.

The β decay of ^{130}I should populate the two-quasiparticle proton states with configurations $(g_{7/2}d_{5/2})$ as listed in Table VII. For 5^+ ^{130}I, β^- decay is observed to strongly feed the 6^+ state at 1944 keV with a $\log ft$ of 6.6 and the 5^+ state at 2362 keV with a $\log ft$ of 5.8. As there is no simple way to make a 5^+ collective state except as a member of a four-proton octuplet, or a 5^+ member of a quasi-γ band, the 5^+ level at 2362 keV appears to be singularly selected as the $(\pi g_{7/2}\pi d_{5/2})_{5^+}$ state shown in Table VII. Table VII lists three ways to form two-quasiparticle 6^+ states in addition to a collective 6^+ state. The slightly higher $\log ft$ for β decay to the 6^+ state at 1944 keV suggests the state is not a pure $(\pi g_{7/2}\pi d_{5/2})_{6^+}$ state but has significant amounts of the other configurations mixed in with it. It is interesting to note that none of the lower-lying 4^+ states have any low $\log ft$ value.

The β^- decay of the 2^+ ^{130}I isomer leads to less clear-cut conclusions. The study was not sensitive enough to determine whether β feeding directly to the 3^+ state at 1632 existed or not. The two lowest $\log ft$ values are for branches to two levels that could readily be the 1^+ and 2^+ members of the $(\pi g_{7/2}\pi d_{5/2})$ multiplet.

In the β^+ and EC decay of 1^+ ^{130}Cs, with a configuration of $(\pi d_{5/2}\nu d_{3/2})_{1^+}$, the 55th proton decays to the 76th neutron and the only allowed path is $\pi d_{5/2} \rightarrow \nu d_{3/2}$. The $\pi d_{5/2} \rightarrow \nu s_{1/2}$ and $\pi d_{5/2} \rightarrow \nu h_{11/2}$ transitions are second and third forbidden, respectively. Thus the decay of ^{130}Cs $(\pi d_{5/2}\nu d_{3/2})_{1^+}$ will lead to states with $(\nu d_{3/2}\nu d_{3/2})_{0^+,2^+}$ configurations. Thus decay to the ground state is expected

TABLE V. γ-γ coincidence following the decay of $^{130}I^g$.

	E_{gate}								
E_γ	418	510	536	554	586	603	668	686	739
418			×				×		×
510			×		×			?	
536	×	×		×	×	×	×	×	×
554			×		×	×		×	
586		×	×					×	
603			×	×			×		
668	×		×			×			×
686			×	×	×		×		
739	×		×				×		
800			×			×	?	×	
808			×				×		×
877			?						
967			×				×		
1097			×						
1122		×		×				×	
1158			×				×		
1223			?				×		
1272			×	×			×		
1405			×				×		
1426							×		
1489			×				×		
1502			×				×		
1548			×				×		
1608			×				?		

	E_{gate}												
E_γ	800	808	877	967	1097	1122	1158	1223	1272	1405	1502	1548	1608
536	×	×	×	×	×		×	×	×	×	×	×	?
554						?							
586	×												
603	×												
668	?	×	×	×			×	×		×	×	×	×
686	×					×							
739		×							×				

to be strong and is found to have a logft value of 4.8.

Besides the simple vibrational interpretation or its anharmonic extension, several interpretations of the collective states of such transitional nuclei have been attempted. In one, Mariscotti, Scharff-Goldhaber, and Buck[30] and Scharff-Goldhaber and Goldhaber[31] have utilized the concept of a variable moment of inertia (VMI) to interpret the yrast bands observed in even-even nuclei such as the Xe nuclides. In that interpretation, nuclei in which the ratio of the energy of the first 4^+ level to the energy of the first 2^+ level (E_{4^+}/E_{2^+}) is greater than 2.23 are considered as deformed whereas those for which $1.82 \leq (E_{4^+}/E_{2^+}) \leq 2.23$ are considered spherical. For ^{130}Xe, that ratio is 2.246 placing it in the area of applicability and very near the border between the deformed and spherical regions. In another interpretation, a quasi-rotational interpretation has been utilized by Sakai[32] to provide a smooth cataloging of the systematic transition from the structure shown by spherical nuclei to that exhibited by deformed nuclei.

We show in Fig. 6 low-lying levels of ^{130}Xe displayed both in a vibrational sequence and in a quasirotational sequence. The quasirotational sequence also shows the $0^+, 2^+, 4^+, 6^+, 8^+$ sequence fitted by the VMI interpretation. The state at 2386.2 keV was selected as the 2^+ member of the 3-photon qunitriplet as it decays more strongly to the second 2^+ state than the first 2^+ state.

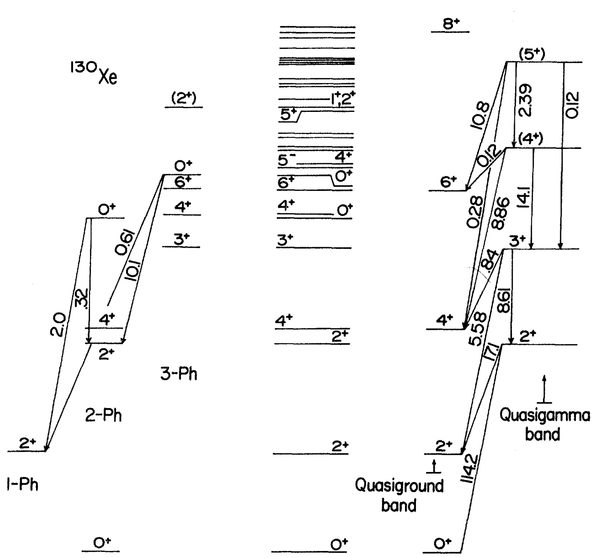

FIG. 6. The levels of ^{130}Xe displayed by classification. The levels to the left are displayed in a vibrational interpretation, all levels are shown in the center, and the levels to the right are displayed in a quasirotational interpretation. The intensity of the transition from the second 2^+ state to ground should read 2.56 instead of 114.2.

The 3^+ level at 1632 keV is an important state in the quasiband sequence. Its position in ^{130}Xe can be predicted[32] to be at 1597 keV and it is expected to decay predominantly to the 2^+ level at 1122 keV. The reduced decay rates indicate about 80% branching to the 1122-keV level and 20% to the 4^+ level at 1205 keV. This compares with a ratio of 67% to 33% observed for the 3^+ level at 1808 keV in ^{132}Xe. If this level is to be the 3^+ member of the quasi-γ band, it should be fed strongly by the 4^+ member of a quasi-γ band. A level at 2171 keV does feed the 3^+ in the strength (~50%) predicted by the quasiband formulation.[32] However, the 2171-keV level could just as well be a four-phonon level as it strongly feeds two other states that can be classified as three-phonon levels and it exhibits only very weak branches to lower levels. In addition, a level exists at 2629 keV that decays strongly to the 4^+ level at 2171 keV. This level could be a 5^+ member of the quasi-γ band, however, the 458-keV energy difference is substantially lower than predicted from the energies of the lower members of the imaginary band.

None of the 4^+ states fed in the β^- decay showed any γ-ray cascade through any 2^+ state into the 0^+ state at 1793 keV, hence we have no evidence for the possible presence of any quasi-β band.

Two parameters emerge from the VMI fitting procedure[30] for a nuclide, $\mathcal{g}_0$, the ground-state moment of inertia, and σ, the softness parameter. We show in Table VIII the values deduced by Mariscotti, Scharff-Goldhaber, and Buck for

TABLE VI. Logft values for $^{130}I^g$ decay. $Q_\beta = 2986 \pm 20$ keV, $t_{1/2} = 12.36 \pm 0.01$ h (error in brackets).

E (keV) [a]	% β branch	Logft
536.081(14)	...	...
1122.175(17)	...	...
1204.621(16)	0.28(14)	9.686(218)
1632.554(20)	0.07(9)	9.822(559)
1808.179(17)	1.45(12)	8.276(45)
1944.092(20)	47.69(82)	6.559(32)
2059.601(55)	0.022(10)	9.707(200)
2081.977(40)	0.19(2)	8.732(58)
2171.666(24)	2.14(11)	7.516(44)
2362.088(18)	46.62(23)	5.766(49)
2427.187(36)	0.184(5)	8.003(55)
2608.518(23)	0.50(2)	6.988(79)
2622.353(61)	0.076(9)	7.752(95)
2629.450(29)	0.33(3)	7.086(91)
2692.912(109)	0.029(9)	7.859(167)
2752.381(26)	0.32(2)	6.492(125)
2811.923(97)	0.09(1)	6.626(170)

[a] For errors quoted see footnote a in Tables I and IV.

TABLE VII. Two-quasiparticle states in ^{130}Xe.

Configuration	States								
Protons									
$(g_{7/2})^2$		2^+		4^+		6^+			
$(d_{5/2})^2$		2^+		4^+					
$(g_{7/2}d_{5/2})$	1^+	2^+	3^+	4^+	5^+	6^+			
Neutrons									
$(d_{3/2})^2$		2^+							
$d_{3/2}s_{1/2}$	1^+	2^+							
$(h_{11/2})^2$		2^+		4^+		6^+		8^+	10^+
$d_{3/2}h_{11/2}$				4^-	5^-	6^-	7^-		
$s_{1/2}h_{11/2}$					5^-	6^-			

TABLE VIII. Values of $\mathcal{J}_0$ and σ from the VMI fitting procedure Ref. 30.

Nucleus	$\mathcal{J}_0$	σ
^{130}Xe	0.000 01	1.06×10^8
^{130}Ce	0.0103	0.079

^{130}Ce, a nucleus that is well into the deformed region and for ^{130}Xe a nucleus at the boundary between the regions characterized by Scharff-Goldhaber and Goldhaber[31] deformed and spherical. As that transition from deformed to spherical is characterized by a shift of $\mathcal{J}_0$ from positive values to negative values, ^{130}Xe may be seen to qualify well for a transitional purpose as its $\mathcal{J}_0$ of 0.000 01 is effectively zero for calculational purposes (i.e., a value of −0.000 01 would have little effect on the outcome of the calculations). These values for ^{130}Xe for $\mathcal{J}_0$ and σ suggest a nucleus with a broad asymmetric potential well, centered nonetheless at essentially zero deformation for the ground state. It is unfortunate that β-decay parents with high spins do not exist among the lower-mass cesium nuclides that would permit a systematic examination of the character of the lowest 6^+ state (found at 1944 keV in ^{130}Xe). This state in ^{130}Xe is both a part of the ground-state quasiband and also shown by its β^- and γ-ray feeding to have quasiparticle character. The lowest 6^+ state in ^{120}Xe lies at 1396 keV and the VMI parameters of $\mathcal{J}_0 = 0.0056$ and $\sigma = 0.971$ suggest a much narrower potential well no longer centered at zero deformation. The changing character of the 6^+ state would offer important information on the behavior of two-quasiparticle states as nuclides undergo the transition from spherical to deformed shape. This same information could be gained if the 1^+ and 3^+ states could be identified and systematically followed in the even-even Xe isotopes.

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[1]H. Morinaga and N. L. Lark, Nucl. Phys. **67**, 315 (1965).
[2]M. G. Betigni and H. Morinaga, Nucl. Phys. **A95**, 176 (1967).
[3]T. E. Fessler, G. M. Julian, and S. Jha, Phys. Rev. **174**, 1472 (1968).
[4]S. M. Quaim, Nucl. Phys. **A150**, 145 (1970).
[5]D. D. Wilkey and J. E. Willard, J. Chem. Phys. **44**, 970 (1966).
[6]C. Kellershon, D. Comar, and R. Riviere, C.R. Acad. Sci. **B265**, 88 (1967).
[7]C. E. Bemis, Jr., J. F. Emery, and N. K. Aras, Oak Ridge National Laboratory Report No. ORNL-3994, 1966 (unpublished), p. 17.
[8]P. K. Hopke, A. G. Jones, and W. B. Walters, Bull. Am. Phys. Soc. **15**, 623 (1970).
[9]G. Graeffe and W. B. Walters, Phys. Rev. **153**, 1321 (1967).
[10]R. C. Ragaini, G. E. Gordon, and W. B. Walters, Nucl. Phys. **A99**, 597 (1967).
[11]P. K. Hopke, Laboratory for Nuclear Science, Chemistry Progress Report, Massachusetts, Institute of Technology, 1969 (unpublished), p. 34.
[12]γ-ray energies from: (a) R. Gunnink, Lawrence Livermore Laboratory, private communication, (b) R. Greenwood, Idaho Falls, private communication.
[13]R. H. Moore and R. K. Zeigler, Los Alamos Scientific Laboratory Report No. LA-2367, 1960 (unpublished).
[14]G. Andersson, G. Rudstam, and G. Sorensen, Ark. Fys. **28**, 37 (1965).
[15]P. Aagaard, G. Andersson, J. O. Burgman, and A. C. Pappas, J. Inorg. Nucl. Chem. **5**, 105 (1957).
[16]J. J. Livingood and G. T. Seaborg, Phys. Rev. **54**, 775 (1958).
[17]P. F. Zweifel, Phys. Rev. **107**, 329 (1957).
[18]R. I. Verrall, J. C. Hardy, and R. E. Bell, Nucl. Instrum. Methods **42**, 258 (1966).
[19]H. Daniel, M. Kuntze, B. Martin, P. Schmidlin, and H. Schmitt, Nucl. Phys. **63**, 145 (1965).
[20]J. T. Larsen and R. G. Lanier, Computer Codes for Calculation of Log *ft* Values, Lawrence Livermore Laboratory, 1970 (unpublished).
[21]I. Lingren, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1966).
[22]R. S. Hager and E. C. Seltzer, Nucl. Data **A4**, 1 (1968).
[23]I. Bergstrom, C. J. Herrlander, A. Kerek, and A. Luukka, Nucl. Phys. **A123**, 99 (1969).
[24]R. C. Ragaini, W. B. Walters, and R. A. Meyer, Phys. Rev. **187**, 1721 (1969).
[25]R. A. Meyer, W. B. Walters, and R. C. Ragaini, Nucl. Phys. **A127**, 595 (1969).
[26]C. M. Lederer, J. Hollander, and I. Perlman, *Table of*

Isotopes, (Wiley, New York, 1967).

[27]J. H. Hamilton, H. K. Carter, and J. J. Pinajian, Phys. Rev. **C1**, 666 (1970).

[28]H. Erten, C. D. Coryell, and W. B. Walters, Bull. Am. Phys. Soc. **14**, 1225 (1969).

[29]M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).

[30]M. A. J. Mariscotti, G. Scharff-Goldhaber, and B. Buck, Phys. Rev. **178**, 1864 (1969).

[31]G. Scharff-Goldhaber and Alfred Goldhaber, Phys. Rev. Lett. **24**, 1349 (1970).

[32]M. Sakai, Nucl. Phys. **A104**, 301 (1967); and Institute for Nuclear Study (Tokyo) Report No. INS-J-130, 1971 (unpublished).