Weak coupling in the odd-mass Xe nuclides: Decay of 6.2-h ^{127}Cs to levels of odd-neutron ^{127}Xe

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Gamma-ray and conversion electron singles and coincidence spectroscopy have been performed on the decay of 6.2-h ^{127}Cs to levels of ^{127}Xe and 30-h ^{129}Cs to levels of ^{129}Xe. From these data, new levels, transition multipolarities, and spin and parity assignments are derived. The systematic structure of the odd-mass Xe nuclides with $69 \leq N < 81$ is shown and the results of various calculations are discussed. Support for the use of relatively weak coupling models to describe these nuclides is enumerated.

I. INTRODUCTION

The Xe nuclides have proven to be a fertile ground for attempts to account for the properties of nuclides undergoing a transition from a closed shell structure observed near $N=82$ to structures that have increased deformation near mid shell. Systematic changes in the magnetic dipole and electric quadrupole moments and mean square charge radii for the Ba and Cs nuclides have been interpreted[1,2] as indicating smooth increases in deformation as neutrons are removed from the $N=82$ closed shell. The ground state moments of the I isotopes, however, show much less variation with neutron number and can be comprehended without recourse to descriptions that require large deformation. Mean square charge radii and isotope shift measurements for the Xe nuclides have been reported and construed to indicate growing deformation as neutrons are removed from the $N=82$ closed shell, but with considerably less deformation present than in the Cs and Ba nuclides.[3] Interpretation of these structures has been supported by a considerable body of new and detailed data acquired by radioactive decay and in-beam nuclear spectroscopy.[4,5,6]

It has been possible to describe the properties of closed shell ^{136}Xe and adjacent ^{135}Xe by large shell model calculations.[7,8] The dynamic deformation model has been used to describe the levels of ^{132,130}Xe.[9] The even-even nuclides ^{126,128,130}Xe have been shown to have structures that are remarkably close to the O(6) limit of the interacting boson model (IBM).[10,11,12] These nuclides have also been the focus of a number of additional calculations using a variety of models.[13–16] Extension of these calculations to the mid-shell region has been limited by the scarcity of data, consequently some earlier calculations[17] did not attempt to account for the low-energy 0^+ levels and sizable $E0$ transitions that have been recently observed in ^{118,120,122}Xe.[18] These $E0$ transitions have been interpreted as an indicating of shape mixing between normal configurations involving four protons beyond the closed shell at $Z=50$ and intruder configurations, in which an additional pair of protons from below the closed shell has been promoted across the $Z=50$ shell closure.[19,20] Support for this interpretation has been found in the magnetic moments measured for the $\frac{9}{2}^+$ isomers in ^{119,121}I and ^{119,121}Cs that indicate a $g_{9/2}$ hole structure rather than a complex collective structure.[21,22] In the mid-shell even-even Te nuclides, similar $E0$ transitions have been observed[23] and described theoretically with IBM-2 calculations that involve mixing of normal collective level structures with particle-hole intruder structures.[24,25]

With the improved description of the even-even Xe core structures, it is now critical to investigate the structure of the odd-mass Xe nuclides to determine the interaction between the odd neutron and the adjacent even-even core. A number of studies of the structures of odd-mass Xe nuclides have recently been reported, largely focusing on intermediate and higher spin states populated in in-beam reactions induced by protons, ^{3,4}He, and heavier ions.[26–33] Interpretations of the observed data have varied considerably. For example, support for a relative weak core-neutron coupling is obtained from the measurement of the magnetic moment of the $\frac{7}{2}^+$ level at 342 keV in ^{127}Xe.[34] The 0.241(9) g factor that was measured has been interpreted as being quite close to the value that would be expected for a $g_{7/2}$ neutron with only a small admixture of collective core-coupled states. On the other hand, the nearly identical g factor of 0.264(10) for the 296-keV $\frac{7}{2}^+$ level in ^{125}Xe has been fit using triaxial rotor calculations with a $\beta=0.23$ and $\gamma=17°$.[35] Part of the variability of these calculations arises from limitations in the available experimental data. Much of the data comes from in-beam studies where information on the low-spin levels is lacking. Although use of particle-plus-rotor calculations with triaxiality has been reasonably successful in describing the higher-spin levels, its validity has been questioned.[36] In many particle-rotor calculations, one of the low-spin levels ($\frac{7}{2}^-$ or $\frac{9}{2}^-$) rises steeply with increasing deformation and with increasing triaxiality while the other falls. Both the $\frac{7}{2}^-$ and $\frac{9}{2}^-$ levels fall in energy as neutrons are removed from the closed shell in the Xe nuclides.[37]

In an extensive series of interacting boson-fermion model (IBFM) calculations, Cunningham[38] attempted to fit both the positive-parity and negative-parity levels in the odd-mass Xe and Ba nuclides. Where relatively complete data are available for ^{131,129}Xe, good agreements were obtained for the levels below 1 MeV. Owing to the lack of data for low-spin levels, complete tests of the model were not made for the lighter Xe nuclides and the predicted positions of many low-spin levels below 1500 keV were not reported.

More recently, the structure of ^{127}Xe has taken on new importance as the ^{127}I$(\nu,e^-)^{127}$Xe could be used to build a neutrino detector.[39] The evaluation of its usefulness rests on the ability to determine the wave functions of the low-energy levels and to determine the neutrino capture rates to the various possible final states. Initial calculations in the literature show some differences in the transition rates.[40,41]

We have studied the decay of ^{127,129}Cs to augment existing data for the low-spin levels in the odd-neutron ^{127,129}Xe daughter nuclides which lie in the center of the region where the core structures are described by the nearly pure IBM $O(6)$ limiting symmetry. The odd-mass ^{123,125,127,129}Cs nuclides have ground state spin and parity of $\frac{1}{2}^+$ and their radioactive decay populates low-spin $\frac{1}{2}^+$ and $\frac{3}{2}^+$ levels, resulting in complementary data for the in-beam studies. Moreover, if shape coexistence is present in the odd-neutron daughter Xe nuclides, the levels populated in decay have the same spin and parity as the $s_{1/2}$ and $d_{3/2}$ single particle orbitals that are the lowest two levels in the odd-mass Xe nuclides, and hence $\frac{1}{2}^+$ to $\frac{1}{2}^+$ and $\frac{3}{2}^+$ to $\frac{3}{2}^+$ transitions could exhibit $E0$ strength. Other studies underway[42] and recently completed[43] will focus on the structures of mid-shell nuclides ^{119,121}Xe that lie adjacent to nuclides where shape coexistence has been indicated and where considerable data for the higher-spin levels is also available.

II. EXPERIMENTAL PROCEDURES

The study of the electron capture (EC)/β^+ decay of 6.2-h $\frac{1}{2}^+$ ^{127}Cs into levels of ^{127}Xe and 30-h $\frac{1}{2}^+$ ^{129}Cs to levels of ^{129}Xe was completed using the UNISOR on-line mass separator associated with the Holifield Heavy Ion Research Facility (HHIRF) at the Oak Ridge National Laboratory (ORNL).[44] A 145-MeV ^{32}S beam from the 25 MV folded-tandem accelerator was directed upon a target comprised of two foils each of 2 mg/cm^2 ^{98}Mo and ^{100}Mo, which made up the window of a FEBIAD-B2 ion source.[45] The heavy-ion reaction products were ionized to a uniform single positive charge within the ion source and extracted towards the UNISOR mass analyzing magnet, which separated the masses with a resolution of $\Delta M/M=1000$. Sources of ^{127}Cs and ^{129}Cs were simultaneously implanted into copper foils placed in the focal plane of the collection chamber. The chosen foil positions corresponded to mass dispersion distances determined experimentally using a stable natural Xe beam. The sources were collected for periods no longer than 12 h for the ^{127}Cs experiment, after which the foil was removed from the collection chamber and a new foil was positioned in its place. Owing to the long half-life of ^{129}Cs, only a single source was collected during a three-day period.

The foil containing the ^{127}Cs activity, when removed from the collection chamber, was placed in a separate vacuum chamber where two germanium detectors and a silicon detector were used to accumulate gamma-ray and conversion electron singles spectra and gamma-gamma and electron-gamma coincidence data. The one coaxial germanium detector was a 71-cm^3 n-type Ge detector with a full width at half-maximum (FWHM) of 1.9 keV for the 1332-keV gamma-ray transition in ^{60}Co. The other coaxial germanium detector was a 60-cm^3 Ge(Li) detector with a FWHM of 2.2 keV at 1332 keV. The electron detector was a Si(Li) surface barrier detector with an active area of 200 mm^2 and a 3-mm depletion layer. The FWHM was measured to be 3.1 keV for the 975-keV conversion electron transition from ^{207}Bi decay. The gamma-ray detectors were placed at 90° to each other, with a source-to-detector distance of 5 mm for the Ge(Li) detector and 50 mm for the Ge detector. The Si(Li) conversion electron detector was placed at 90° to the Ge detector, and was positioned 10 mm from the ^{127}Cs activity. The ^{129}Cs activity was counted in a configuration that was identical to the one use for ^{127}Cs except for the use of different detectors.

Gamma-ray coincidence data were collected between the two Ge gamma-ray detectors, and conversion electron-gamma coincidence data were collected only between the Si(Li) electron detector and the Ge detector. The coincidence data were written as energy-energy-time events to magnetic tape using one of the three HHIRF Concurrent 3230 computer systems. Gamma-ray and conversion electron singles data were collected with the Ge gamma-ray detector and the Si(Li) electron detector, respectively, using the Tennecomp TP-5000 data collection system that is part of the UNISOR facility. The singles spectra collected were transferred to the HHIRF concurrent 3230 computer system for analysis.

III. EXPERIMENTAL RESULTS

The gamma-rays assigned to the decay of ^{127}Cs are listed in Table I. Conversion electron intensities were mea-

TABLE I. Gamma-ray transitions observed following the beta/electron capture decay of ^{127}Cs.

Energy[a]	Intensity[b]	From	To
77.36[c]	0.030(3)	420	342
90.7	0.32(1)	412	321
115.13	0.026(1)		
124.70	18.1(2)	125	0
172.4[d,f]	0.03(2)	297	125
175.11	0.186(3)	587	412
188.4[c,d]		510	321
196.73	0.604(8)	321	125
201.6[e]	0.014(4)	712	510
211.57	0.130(5)	587	375
217.48	0.066(5)	342	125
250.71	0.06(2)	375	125
265.51	0.207(3)	587	321
287.16	6.09(7)	412	125
308.07	0.019(3)	720	412
321.54	2.08(2)	321	0
330.27[c]	0.011(1)	1306	976
336.1	0.017(2)	712	375
343.98	0.091(3)	931	587
369.41[c]	0.014(2)	712	342
375.35	0.721(9)	375	0
385.20	0.148(3)	510	125
388.71	0.018(2)		
390.05	0.084(2)	712	321
400.20	0.021(6)		
401.90	0.050(6)		
405.68[c]	0.025(4)	530	125
411.95	100	412	0
421.00	0.021(3)	931	510
427.00	0.013(3)		
439.53	0.016(1)		
458.5	0.006(1)		
462.31	8.08(8)	587	125
480.3	0.006(1)		
519.13	0.075(2)	931	412
526.2	0.005(3)		
534.6	0.007(2)		
545.5	0.007(1)		
548.0	0.005(1)		
555.7	0.25(4)	931	375
556.57[e]	0.042(7)	878	321
586.7[e]	0.037(4)	712	125
587.01	6.7(1)	587	0
588.8		931	342
594.8	0.01(1)	1306	712
595.3	0.08(1)	720	125
603.57	0.026(1)	1535	931
606.66	0.017(1)	1583	976
609.6[d,e]	0.06(1)	931	321
609.9[d,e]	0.04(1)	1197	587
634.4	0.009(5)		
646.60	0.017(2)		
654.51	0.022(1)	976	321
658.6	0.005(1)		
659.32	0.010(1)		
678.84	0.020(1)		
691.1[c]	0.004(1)	1403	712
719.2[e]	0.05(1)	1306	587
720.2[e]	0.03(1)	720	0
727.07	0.019(1)		
731.07	0.023(1)		
736.9	0.005(1)		
766.0	0.004(1)		
768.1	0.006(1)		
776.07[c]	0.012(1)	1306	530
785.4[c]	0.007(1)	1717	931
794.7	0.008(1)		
796.5	0.006(1)	1306	510
806.34	0.723(8)	931	125
814.58	0.042(3)	1535	720
816.2	0.005(3)		
821.0	0.015(2)		
822.98	0.228(4)	1535	712
830.3	0.008(1)	1806	976
835.4	0.004(1)		
860.4	0.007(1)		
862.56[c]	0.012(1)	1583	720
875.26	0.068(2)	1197	321
894.31	0.030(1)	1306	412
920.4	0.003(1)		
923.9	0.012(1)		
930.8[e]	0.030(7)	1306	375
931.10[c]	0.66(1)	931	0
947.6[c]	0.008(1)	1535	587
964.69[c]	0.028(1)	1306	342
976.3[c]	0.003(1)	976	0
984.78	0.119(2)	1306	321
990.64	0.060(1)	1403	412
995.54	0.059(1)	1583	587
1004.4[c]	0.0003(1)	1535	530
1024.64	0.027(1)	1535	510
1070.0	0.003(1)		
1072.0[e]	0.04(1)	1197	125
1073.0[e]	0.025(9)	1583	510
1081.05	0.032(1)	1403	321
1086.3	0.009(1)	1806	720
1110.86	0.024(1)	1831	720
1120.14	0.037(1)		
1129.7	0.007(1)	1717	587
1146.2	0.004(1)	1558	412
1154.6	0.008(1)		
1159.18	0.071(1)	1535	375
1170.73	0.092(2)	1583	412
1178.5	0.002(1)		
1181.57	0.170(2)	1306	125
1188.3[c]	0.015(1)	1775	587
1192.38[c]	0.019(1)	1535	342
1196.87[c]	0.368(4)	1197	0
1207.1[c]	0.006(1)	1583	375
1213.08	0.074(2)	1535	321
1219.3	0.018(1)	1806	587
1236.5	0.017(1)	1558	321
1261.09	0.147(2)	1583	321

TABLE I. (*Continued*).

Energy[a]	Intensity[b]	From	To	Energy[a]	Intensity[b]	From	To
1290.3[c]	0.021(1)	1612	321	1457.86[c]	0.018(1)	1583	125
1296.4[c]	0.007(1)	1806	510	1484.98	0.042(1)	1806	321
1306.31[c]	0.316(5)	1306	0	1487.3[c]	0.007(1)	1612	125
1321.4[c]	0.004(1)	2033	712	1509.3	0.015(1)	1831	321
1341.2	0.014(1)	1717	375	1519.2[c]	0.012(1)	1895	375
1362.1	0.004(3)			1534.62[c]	0.134(2)	1535	0
1363.5	0.025(3)	1775	412	1558.3[c]	0.009(1)	1558	0
1365.8[c]	0.008(1)	1741	375	1582.66[c]	0.069(1)	1583	0
1385.3[c]	0.003(1)	1973	587	1592.3[c]	0.020(1)	1717	125
1394.7	0.025(3)	1717	321	1649.6[c]	0.017(1)	1775	125
1396.1	0.005(3)			1681.68	0.035(1)	1806	125
1402.56[c]	0.086(2)	1403	0	1716.6[c]	0.040(1)	1717	0
1409.81	0.180(3)	1535	125	1741.4[c]	0.0020(3)	1741	0
1419.12	0.085(3)	1831	412	1770.4[c]	0.0020(3)	1895	125
1431.1[c]	0.006(1)	1806	375	1774.9[c]	0.027(1)	1775	0
1433.7[c]	0.003(1)	1558	125	1806.5[c]	0.0045(4)	1806	0
1438.4	0.0006(5)			1831.0[c]	0.0050(4)	1831	0
1446.1[c]	0.004(1)	2033	587	1895.0[c]	0.0009(3)	1895	0
1452.7	0.038(5)	1775	321	1909.0[c]	0.0020(3)	2033	125
1455.2[c]	0.008(4)	1831	375	1973.4[c]	0.022(1)	1973	0

[a]Uncertainty in energy is as follows: ±0.05 for energies given to two significant features beyond the decimal point; ±0.1 for energies given to one significant figure beyond the decimal point below 1750 keV; ±0.2 for energies given to one significant figure beyond the decimal point above 1750 keV.
[b]Number in parentheses is the uncertainty in the last reported digit for the intensity.
[c]Gamma-ray placed through energy summation.
[d]Gamma-ray energy reported is the energy difference between the initial and final excitation levels.
[e]Intensity derived from coincidence data.
[f]Intensity derived by subtracting out intensity due to daughter contamination.

sured and calculated conversion coefficients for some of the more intense transitions in the decay of ^{127}Cs are listed in Table II. The conversion coefficients were calculated relative to the experimentally determined K-conversion coefficient (α_K) value of 0.38 for the 124.70-keV transition in ^{127}Xe, as this transition is known to have only a 1% $E2$ multipolarity admixture.[46,47] The conversion electron intensities used to derive the conversion coefficients were determined using a Si(Li) detector efficiency curve calculated from a second-order polynomial fit of calibration data collected for ^{207}Bi and several of the well-known conversion lines in ^{127}Cs. In Table III are listed gamma-rays which were observed in selected coincidence gates set on transitions in the decay of ^{127}Cs. The proposed level scheme for ^{127}Xe populated in the EC/β^+ decay of ^{127}Cs is shown in Fig. 1. From the analysis of both the singles and coincidence data, we have proposed the population of levels in ^{127}Xe at 297, 342, 375, 412, 510, 530, 712, 720, 976, 1612, 1717, 1741, 1895, and 2033 keV which had not previously been identified in EC/β^+ studies of ^{127}Cs. We have only shown log ft values and beta-feeding percentages for the high-intensity beta transitions in Fig. 1.[48,49] The beta branching and log ft values derived from our data for all of the EC/β^+ branching are presented in Table IV.

There are several gamma-ray peaks assigned to the decay of ^{127}Cs which have proven to be multiplets. Resolution of several of these doublets has been aided considerably through the use of data from in-beam reaction studies. The 556-keV gamma-ray peak is the lowest energy peak with multiple placements. The lower member of the doublet was observed to be coincident with the 375-keV ground state transition while the upper member of the doublet was observed to be coincident with both the 197-keV and 321-keV transitions that depopulate the level at 321 keV.

The most intense member of the 587-keV triplet is the 587.0-keV ground state transition, and this transition is observed to be in coincidence with the 344-, 719.8-, 966-, and 1219-keV gamma rays, all which populate the 587.0-keV level from above. The lower member of the 587-keV triplet, the 586.7-keV transition that populates the first excited state in ^{127}Xe, was observed to be in coincidence with the 125-keV ground state transition and the 594.8-keV transition. The upper member of the triplet at 588.8 keV was observed in the gate of the 217-keV gamma-ray transition which depopulates the level at 342 keV to the first excited state at 125 keV.

The lower member of the doublet at 595 keV is a transition between levels at 1306 keV and 712 keV and is observed to be coincident with the 586.7-keV transition that depopulates the level at 712 keV. The upper member of the doublet is a transition that populates the first excited state at 125 keV and is observed to be in coincidence with the 125-keV ground state transition as well as with the 1111-keV gamma-ray transition which populates the level at 720.0 keV.

The members of the doublet at 610 keV, the 609.6- and

609.9-keV transitions, are found to be in coincidence with the 321-keV ground state transition and the 462-keV transition to the first excited state, respectively. The upper member of the 720-keV doublet has been identified as a ground state transition and is observed in the coincidence gate of the 815-keV gamma-ray transition, which populates the 720.0-keV level. The lower member of the 720-keV doublet, the 719.8-keV transition, populates the 587.0-keV state and is in coincidence with the 212-, 462-, and 587.0-keV transitions that depopulate the 587.0-keV level.

The 930.8-keV member of the 931-keV doublet is placed between levels at 1306 keV and 375 keV as a 931-keV transition is observed in the 375-keV coincidence gate, and vice versa. The possibility that a second 375-keV transition could exist and that it populates the 931.1-keV level was ruled out due to the absence of an 806-keV transition in the coincidence spectrum for the 375-keV gamma-ray. Additionally, the presence of the 251-keV transition, which decays into the first excited state from the level at 375 keV, in the 931-keV coincidence gate supports the proposed 931-keV doublet placement.

All of the levels that we observe up through the 712-keV level have been observed in in-beam studies. Above that point, only the levels at 931, 1306, 1835, 1585, and

TABLE II. Experimental conversion coefficients for transitions following the beta/electron capture decay of ^{127}Cs.

Transition energy (keV)	Conversion coefficient ($\times 10^{-3}$)[a]		Theoretical K conversion[b] $M1(\times 10^{-3})$	$E2(\times 10^{-3})$
90.7	$-K$	780(110)	980	1732
124.70	$-K$	380(50)	387	625
	$-L$	57(8)		
	$-M$	7.8(12)		
175[c]	$-K$	360(60)	153	205
196.73	$-K$	100(10)	110	137
	$-L$	11(2)		
211.57	$-K$	73(13)	90.4	108
217.48	$-K$	76(19)	83.5	97.6
265.51	$-K$	45(10)	49.4	50.9
287.16	$-K$	45(6)	40.2	39.5
	$-L$	6.6(9)		
321.54	$-K$	36(5)	30.0	27.7
	$-L$	2.7(5)		
375.35	$-K$	19(3)	20.3	17.3
411.95	$-K$	16(2)	15.9	13.0
	$-L$	2.3(3)		
	$-M$	0.9(1)		
462.31	$-K$	9.1(13)	11.9	9.27
	$-L$	1.4(2)		
	$-M$	0.55(8)		
556[c]	$-K$	7.8(15)	7.56	5.57
558[c]	$-K$	6.7(9)	6.61	4.81
	$-L$	0.91(13)		
720[c]	$-K$	2.9(14)	4.05	2.87
806.34	$-K$	3.1(5)	3.10	2.19
822.98	$-K$	3.1(7)	2.96	2.09
931[c]	$-K$	2.5(4)	2.22	1.58
1181.57	$-K$	0.98(26)	1.30	0.961
1196.87	$-K$	1.3(2)	1.26	0.936
	$-L$	0.20(8)		
1213.08	$-K$	1.5(5)	1.23	0.915
1261.09	$-K$	1.4(3)	1.12	0.844
1306.31	$-K$	0.80(14)	1.04	0.790
1534.62	$-K$	0.53(10)	0.731	0.585
1582.66	$-K$	0.59(14)	0.684	0.553

[a]Conversion coefficients normalized to 125-keV transition K-conversion coefficient experimental value of 380×10^{-3} from Spalek *et al.* (Ref. 46). The number(s) in parentheses is the error in the last digit(s) of the value for the experimental conversion coefficient.

[b]Calculated from Rösel *et al.* (Ref. 47).

[c]The transition is not resolved in gamma-ray singles, and the conversion coefficient calculated is for the total gamma-ray intensity and total conversion electron intensity observed for the unresolved multiplets.

TABLE III. Coincidence table for ^{127}Cs beta/electron capture decay into levels of ^{127}Xe.

Gated gamma (keV)	Gamma rays observed in coincidence (keV)								
91	125	197	287	321	462				
125	91	197	218	287	338	385	462	555.7	586.7
	595.3	806	815	823	875	985	1071	1120	1154
	1182	1261	1296	1410	1682				
172	125								
175	125	147	167	181	287	412	594.8	827	
197	91	125	330	556.6	655	683	770	823	875
	956	985	1081	1213	1229	1261			
202	385	822							
212	197	214	321	344	685				
217	125	589	717	823	980	1261			
265	125	321	378	1242					
287	100	125	175	241	449	519	823	948	996
	1120	1171	1419						
308	104	370	411	545	815				
321	91	141	188	212	265	284	390	398	556.6
	594.8	609.6	655	719.8	823	830	845	875	985
	996	1056	1081	1171	1213	1237	1261	1395	1419
	1453	1485	1509						
336	375	823	1126						
344	125	197	212	375	385	412	462	587.0	
375	336	555.7	604	823	930.8	1159	1341		
385	125	202	421	458	513	785	823	894	1025
	1073								
390	125	197	207	299	321	330	563	610	823
412	519	577	882	991	1086	1110	1146	1171	1306
	1364	1419	1438						
462	125	275	344	474	553	609.9	719.8	815	976
	996	1130	1220						
519	412								
555.7/556.6	125	197	251	321	375				
586.7/587.0	125	287	344	375	390	594.8	607	719.8	823
	996								
594.8/595.3	125	212	228	375	586.7	815	1086	1111	
604	125	202	217	860	931.1				
609.6/609.6	125	197	212	321	375	462			
655	125	197	220	265	321	607	802		
678	412	480	736	806					
719.8/720.2	212	462	587.0	815					
806	125	321	375	604					
815	308	720.2							
823	125	197	202	321	336	369	375	390	547
	587.0	636	712						
830	244	321	375	655					
875	125	197	321	1285					
894	412								
930.8/931.1	125	197	251	321	375	395	604		
985	125	197	321						
991	161	412							
996	125	462	587.0						
1071/1073	125	188	230	235	321				
1111	595.3								
1159	125	251	308	375					
1171	91	241	248	412					
1182	125								
1213	125	321							
1219	462	587.0							
1237	321								
1261	125	197	321						

TABLE III. (*Continued.*)

Gated gamma (keV)	Gamma rays observed in coincidence (keV)		
1290	168	321	412
1341	375		
1364	412		
1395	125	161	321
1410	125		
1419	412		
1453	197	321	
1485	197	321	
1509	197	321	

1973 keV have been observed and these five were only observed in the low angular momentum $^{127}I(p,n\gamma)^{127}Xe$ reaction study.[33]

The purpose of the study of ^{129}Cs decay to levels of ^{129}Xe was to measure the conversion coefficients for the more intense higher-energy gamma rays and to examine the gamma-ray singles spectrum for evidence of population of the three $\frac{5}{2}^{+}$ levels at 442, 525, and 693 keV that have been identified by some in-beam studies to populate the 39-keV level by gamma rays at 402.6, 485.7, and 653.4 keV. In Table V are listed the observed gamma-rays and in Table VI are listed the conservation coefficients measured for the gamma-ray transitions up to the 906-keV transition. None of the transitions showed

TABLE IV. Beta/EC feeding in decay of ^{127}Cs to levels in ^{127}Xe.

Energy	Feeding (%) EC and beta	EC	Beta[a]	log ft
2033	0.01	0.01		6.55
1973	0.02	0.02		6.81
1895	0.03	0.03		7.07
1831	0.09	0.09		6.81
1806	0.08	0.08		6.91
1775	0.08	0.08		7.00
1741	0.01	0.01		8.23
1717	0.11	0.11		7.02
1612	0.02	0.02		8.04
1583	0.28	0.28		6.90
1558	0.02	0.02		8.06
1535	0.51	0.51		6.71
1403	0.12	0.12		7.56
1306	0.50	0.50		7.03
1197	0.33	0.33		7.32
976	0.01	0.01	0.00	9.03
931	1.13	1.13	0.00	7.02
878	0.03	0.03	0.00	8.68
720	0.03	0.03	0.00	8.79
712	0.00	0.00	0.00	
587	9.60	9.53	0.07	6.33
530	0.01	0.01	0.00	9.43
510	0.03	0.03	0.00	8.86
420	0.07	0.07	0.00	8.76
412	68.5	66.7	1.8	5.52
375	0.15	0.15	0.00	8.25
342	0.00	0.00	0.00	
321	0.78	0.75	0.03	7.55
297	0.03	0.03	0.00	9.19
125	5.18	4.84	0.34	6.86
0	12.4[b]	11.0	1.4	6.55

[a]Calculated using the theoretical log-f_0^+ as tabulated by Gove and Martin (Ref. 48).
[b]Ground state beta/electron capture feeding from Gelletly *et al.* (Ref. 49).

any excess conversion intensity beyond that associated with $M1/E2$ transitions. As for weak gamma rays, we found no evidence for intensity at 403, 486, and 653 keV.

IV. SPIN AND PARITY ASSIGNMENTS

The spin-parity assignments proposed for levels populated in the decay of ^{127}Cs are given along with the proposed level scheme shown in Fig. 1. The ground state spin of $\frac{1}{2}^+$ for ^{127}Xe has been well established using direct measurement techniques.[50] Spin and parity of $\frac{3}{2}^+$ are established for the 125-keV level by the strong cascades through this level in reaction studies[27-31] and the strong beta population in the decay of $\frac{1}{2}^+$ ^{127}Cs. Spin and parity of $\frac{9}{2}^-$ are required for the isomer at 297 keV by the observed half-life and conversion coefficient. Similarly, the half-life, conversion coefficient, and g factor[34] support a $\frac{7}{2}^+$ assignment for the level at 342 keV.

A possible level has been proposed at 420 keV based on its depopulation by a 77-keV transition to the $\frac{7}{2}^+$ level by three previous investigators.[29,30,33] We do observe a weak transition at that energy, but its intensity is below our detection limits for observation in coincidence gates.

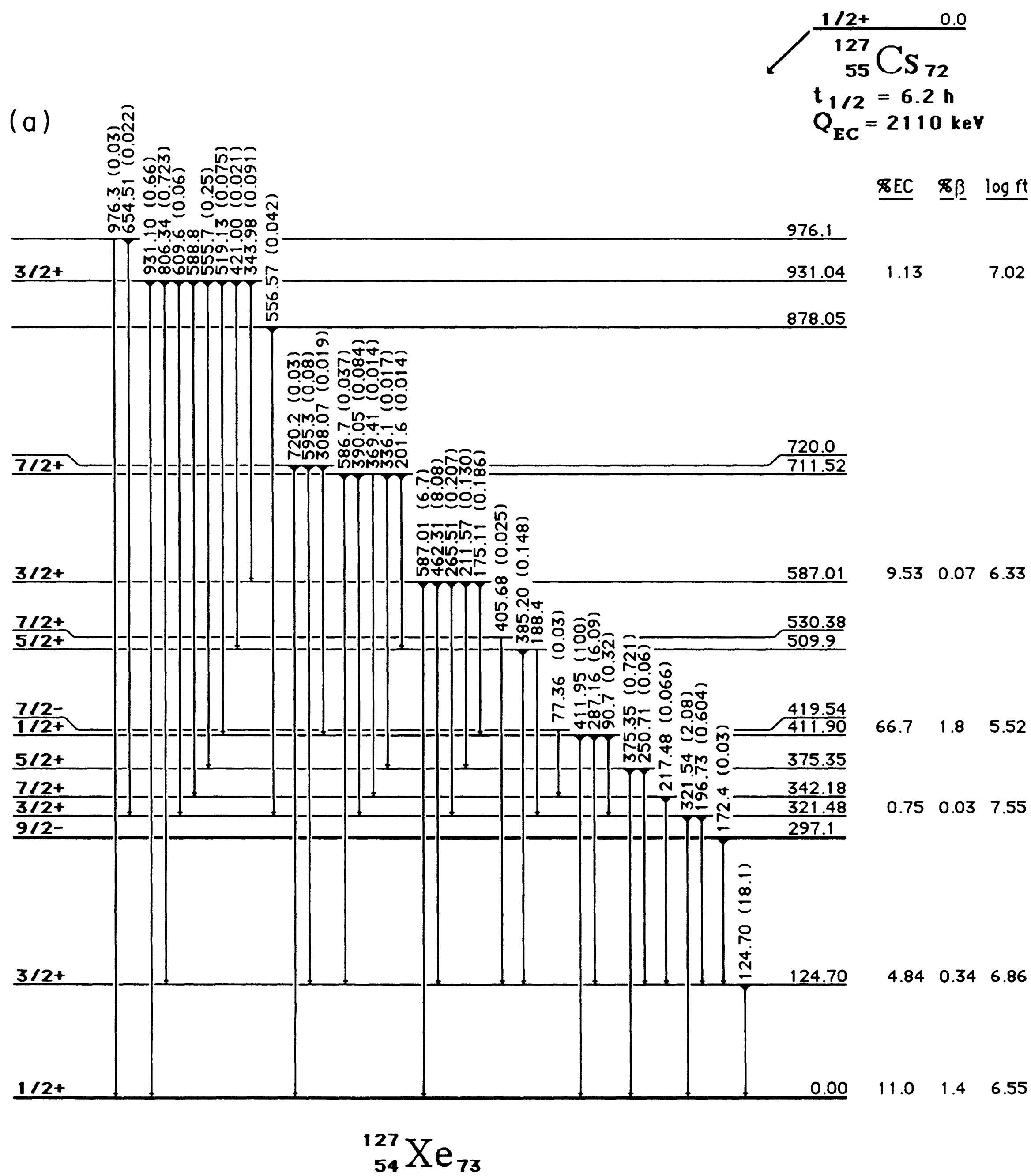

FIG. 1. (a) Proposed level scheme for decay of 6.2-h ^{127}Cs to ^{127}Xe (0–1.0 MeV). (b) Proposed level scheme for decay of 6.2-h ^{127}Cs to ^{127}Xe (1.1–1.6 MeV). (c) Proposed level scheme for decay of 6.2-h ^{127}Cs to ^{127}Xe (1.6–2.1 MeV).

Moreover, this transition was not observed in the recent $(\alpha,2n\gamma)$ study by Urban *et al.*[28] suggesting that it is a lower-spin level. If it were a lower-spin level, however, we should have observed it in greater strength. Irving *et al.*[29] observed the 77-keV transition only in the $(\alpha,n\gamma)$ reaction and also reported a number of gamma rays in its coincidence gate and proposed a number of higher-energy levels that depopulated only to this level. None of these levels depopulate to any other levels, however. Helppi *et al.*[30] also observed the 77-keV transition in the $(^{3}He,4n\gamma)$ reaction but, like Lönnroth *et al.*[33] reported no other transitions that populated the proposed level at 420 keV. As this level does not appear to be either a high-spin or low-spin level, we conclude that it must be the low-energy $\frac{7}{2}^-$ level. We note that there is an unidentified transition at about 121 keV in the spectra shown by both Helppi *et al.* and by Irving *et al.* that would represent depopulation to the $\frac{9}{2}^-$ isomer. Because of the long life of the isomer, that transition would not appear in coincidence spectra. Such a position for the $\frac{7}{2}^-$ level would be consistent with its known position 503 keV above the $h_{11/2}$ single particle level in ^{131}Xe and as the lowest negative-parity level in ^{123}Xe.[51] Alternatively, the

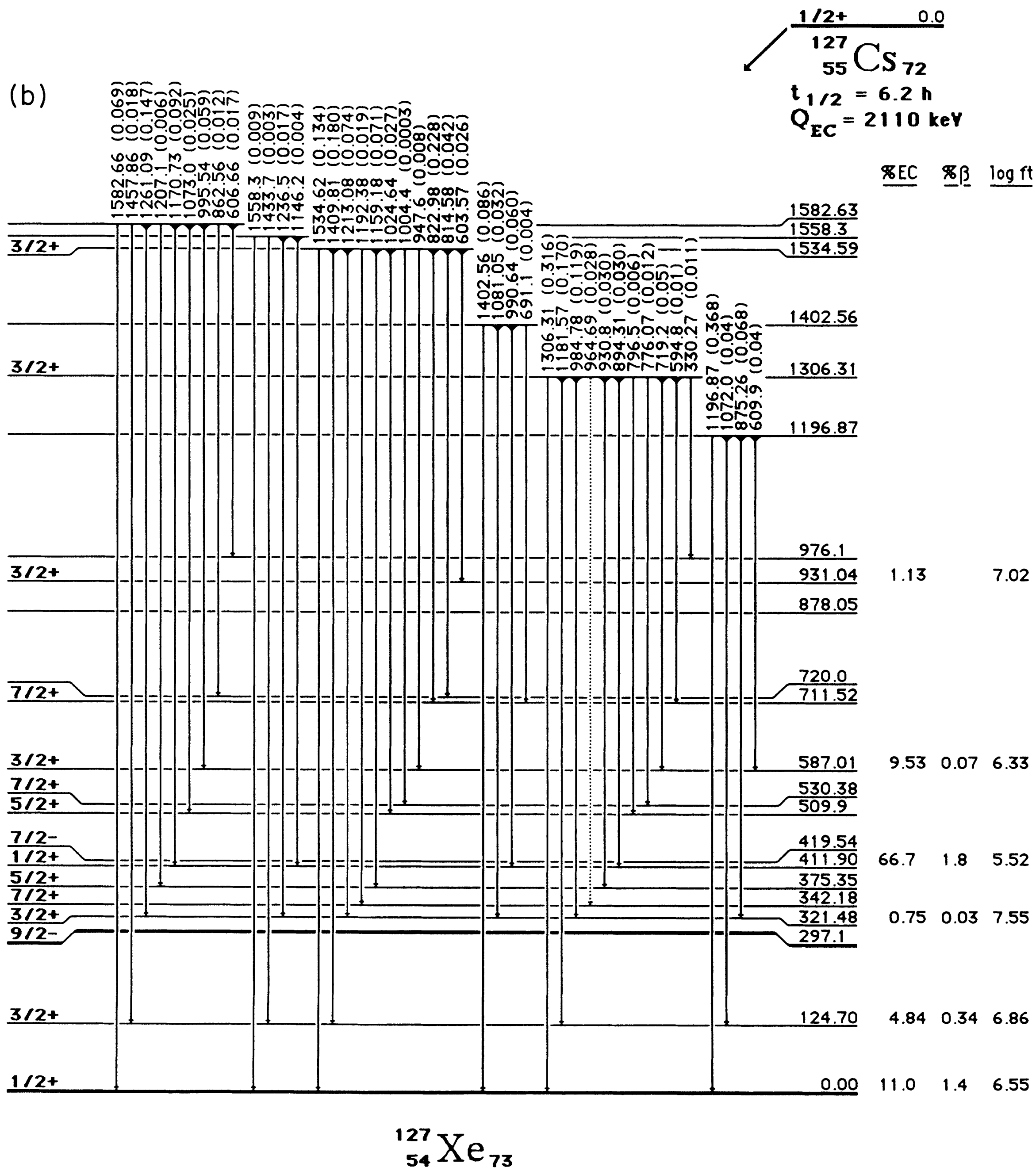

FIG. 1. (*Continued*).

217–77-keV coincidences observed by Irving *et al.* could lie in another nuclide, a possibility to be drawn from the fact that none of the transitions in coincidence with the 77-keV transition they observe originate from levels that populate any other known levels in ^{127}Xe.

The levels at 321, 412, 587, 931, 1197, 1306, 1535, 1583, 1612, 1741, 1775, 1806, 1831, 1895, 1973, and 2033 keV are populated with sufficient intensity in beta decay that they must have spins of $\frac{1}{2}$ or $\frac{3}{2}$. The conversion coefficients that we have measured are all consistent with *M*1/*E*2 multipolarity, supporting positive parity for these levels. For the levels at 375, 510, 530, 712, 720, 878, 976, 1403, and 1558 keV, the imbalance in population and depopulation is so small as to be possibly covered by unplaced weak transitions. Indeed, the absence of strong beta population supports the higher-spin values given by other investigators[28–30,33] for the levels at 375, 510, 530, and 712 keV. On the other hand, our failure to observe any population of the well-known $\frac{5}{2}^+$ level at 805 keV and $\frac{7}{2}^+$ level at 905 keV shown in Fig. 2 suggests that lev-

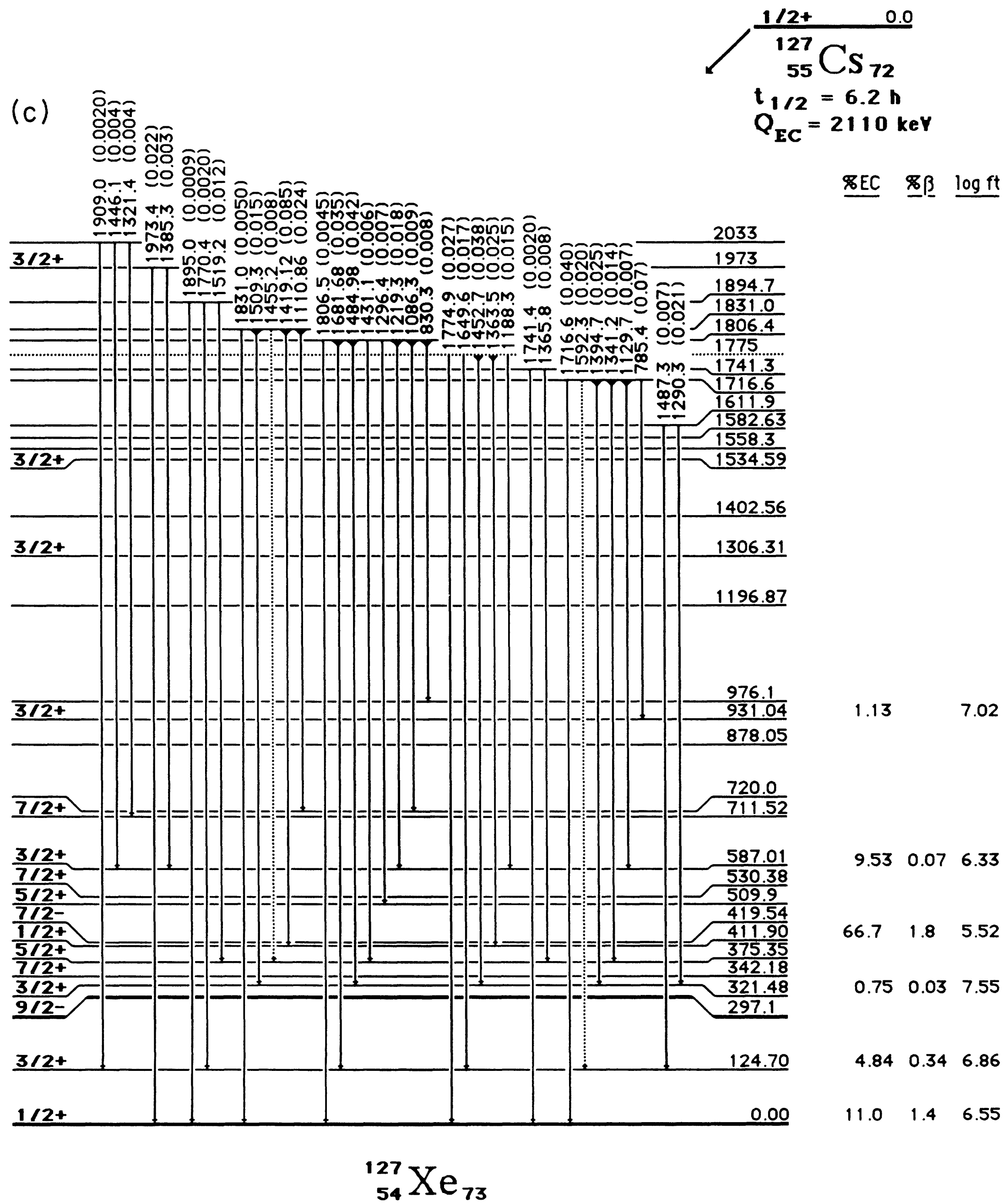

FIG. 1. (*Continued*).

els that we observe above 800 keV are quite likely to be $\frac{1}{2}$ or $\frac{3}{2}$ levels.

Many levels in this latter group have been observed in the previous in-beam studies and have spin and parity assignments proposed by previous investigators. For example, $\frac{5}{2}^+$ assignments have been proposed by Lönnroth *et al.*[33] on the basis of $(p,n\gamma)$ data for the levels at 375, 510, 587, 712, 805, 1306, and 1973 keV. Conflicts are seen between these assignments and the beta population that we observe for the levels at 587, 1306, and 1973 keV. They also propose spin and parity assingments of $\frac{3}{2}^+$ for levels at 125, 321, 412, 931, 1535, and 1583 keV. The gamma-ray branches that we observe from the levels at 931 and 1535 keV to the $\frac{7}{2}^+$ at 342 keV excludes other possible assignments, thereby fixing those levels as $\frac{3}{2}^+$ levels. In a subsequent study[28] using the $(\alpha,xn\gamma)$ reaction that imparts more angular momentum to the compound nucleus, the angular distribution and intensity values provide strong support for the $\frac{3}{2}^+$ assignment at 321 keV, $\frac{5}{2}^+$ for the 375- and 510-keV levels, and $\frac{7}{2}^+$ for the 342-, 530-, and 712-keV levels. These assignments are supported, in part, by previous investigations[29,30] and by our observations.

The most serious discrepancies concern the levels at 412 and 587 keV. Lönnroth *et al.*[33] propose $\frac{3}{2}^+$ and $\frac{5}{2}^+$ for these levels, respectively, while our data and other in-beam data[29] support $\frac{1}{2}^+$ and $\frac{3}{2}^+$, respectively. The strong beta decay that we observe populating the 587-keV level unquestionably excludes the $\frac{5}{2}^+$ assignment and the angular distribution data of Irving *et al.* excludes $\frac{1}{2}^+$, leaving only an assignment of $\frac{3}{2}^+$

The 412-keV level is not observed in any of the other in-beam studies, indicating low spin. The conversion coefficient data are consistent with a pure $M1$ transition as would be required for a $\frac{1}{2}^+$ to $\frac{1}{2}^+$ transition. Angular correlation measurements reported by Garcia *et al.*[52] exclude the $\frac{3}{2}^+$ assignment for the 412-keV level and also exclude the $\frac{1}{2}^+$ assignment for the 321-keV level. Lönnroth *et al.*[33] observe a small angular anisotropy that could easily be perturbed by the 405-keV transition that they do not report, but which is observed with large intensities and anisotropies by the other groups[29,30] that have studied these levels. There is some concern as to the reliability of the angular distribution data reported by Lönnroth *et al.* In the same paper, large angular anisotropies are reported for the 412-keV gamma ray in ^{129}Xe that has been established as a $\frac{1}{2}^+$ level by Marest *et al.*[53] While they concur with the $\frac{1}{2}^+$ assignment, they make no comment about the discrepancy between that assignment and the large angular anisotropy that they report.

TABLE V. Gamma-ray transitions observed following the beta/electron capture decay of ^{129}Cs.

Energy[a]	Intensity[b]	Intensity[c]	Peak multiplicity[d]
29.60	115(3)	274(10)	
33.63	39(1)	63.0(19)	
39.55	8.5(2)	9.7(3)	
93.31	2.74(15)	2.13(6)	*D*
129.3	0.010(6)		
177.05	1.00(2)	0.88(1)	
194.7	0.010(4)		
200.4	0.007(15)		
220.5	0.022(7)		
266.82	0.92(2)	0.89(1)	
270.35	0.70(1)	0.695(8)	
278.62	4.59(8)	4.32(9)	
282.16	0.85(2)	0.79(1)	
302.6		≤0.01	
318.19	8.2(1)	8.0(1)	
321.81	0.20(2)	0.23(2)	
357.64	0.012(5)	0.019(3)	
371.92	100(2)	100(3)	*D*
391.4	0.024(3)		
411.50	71.4(12)	72.9(3)	
492.88	0.039(2)	0.037(3)	
510.75		0.0185(25)	
534.46	0.089(8)	0.100(5)	*D*
548.92	10.3(2)	11.1(1)	
588.49	1.77(3)	2.01(4)	*T*
624.17	0.092(3)	0.097(2)	
646.2	0.017(2)		
742.1	0.008(2)		
864.84	0.089(4)	0.105(3)	
906.41	0.65(2)	0.746(4)	*D*
945.92	0.190(5)	0.227(2)	
1074.3	0.002(1)		

[a]Uncertainty in energy is ±0.05 for energies given to two significant figures beyond the decimal point and ±0.1 for energies given to one significant figure beyond the decimal point.

[b]Number in parentheses is the uncertainty in the last reported number for the intensity.

[c]The intensity is taken from Meyer *et al.* (Ref. 58). The number in parentheses is the error in the last reported number for the intensity.

[d]Peak multiplicity denotations: *D*=doublet, *T*=triplet.

V. DISCUSSION

A. Structure of ^{126}Xe and ^{127}Xe

Our interest in this nuclide was stimulated by the opportunity to search for $E0$ admixtures for $M1/E2$ transitions between the higher-energy $\frac{1}{2}^+$ and $\frac{3}{2}^+$ levels populated in beta decay and the lower-energy $\frac{1}{2}^+$ and $\frac{3}{2}^+$ levels. $E0$ components for these transitions would arise if there were significant differences in the deformation bought on by admixtures of particle-hole intruder states at higher energies. Of particular interest are the levels that might arise from coupling of the $s_{1/2}$ and $d_{3/2}$ levels with the $s_{1/2}$ and $d_{3/2}$ levels with the 0^+ level at 1313 keV in the ^{126}Xe core. These could be among the six levels ranging from 1197 to 1583 keV shown in Fig. 1(b). The only conversion coefficient that indicates any possible excess intensity that might be attributed to an $E0$ admixture is the 1261-keV transition for which the measured conversion coefficient of 0.0014(3) is within one standard deviation above the 0.001 12 value for an $M1$ transition. The absence of any significant E0 strength is consistent with the absence of $E0$ strength for the decay of the 1313-keV 0^+ level in the ^{126}Xe core that was determined at the same time as this investigation was performed.[20]

These new data now permit us to make a detailed examination of the levels of ^{127}Xe arising from coupling of the single neutron with the levels of the adjacent core nuclide ^{126}Xe. In Fig. 3 are shown the levels of ^{126}Xe taken from our companion study[20] and from detailed in-beam studies.[54,55] Also shown are the low-spin levels of ^{127}Xe identified in this study along with the multiplets that would arise from zeroth order coupling of the $s_{1/2}$, $d_{3/2}$, and $g_{7/2}$ single particle levels to the adjacent Xe core. Because there are so few $\frac{1}{2}^+$ and $\frac{3}{2}^+$ levels that arise from these couplings, we can examine their positions with respect to the zeroth order coupling with some precision. Up to an energy of 700 keV, all six levels arising from the $(s_{1/2}+2_1^+)_{3/2,5/2}$, $(d_{3/2}+2_1^+)_{1/2,3/2,5/2,7/2}$ configurations are identified. From 600 to 1100 keV, we note that the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ levels at 720, 878, 931, and 976 keV that we now propose in the region near the 2_{2^+} and 4_{1^+} levels is exactly the number (four) predicted by simple weak coupling. They would arise from the

$$(s_{1/2}+2_2^+)_{\underline{3/2},5/2},\quad (d_{3/2}+2_2^+)_{\underline{1/2,3/2},5/2,7/2}\ ,$$

and

$$(g_{7/2}+2_1^+)_{\underline{3/2},5/2,7/2,9/2,11/2}$$

configurations. The additional higher-spin levels shown in Fig. 2 at 646, 712, 805, and 938 keV could be the other four members of the latter multiplet. No low-spin levels would be produced by coupling of the $s_{1/2}$ and $d_{3/2}$ levels to the 4_1^+ level. At higher spin in this same region three additional $\frac{5}{2}^+$, three additional $\frac{7}{2}^+$, two additional $\frac{9}{2}^+$, and one additional $\frac{11}{2}^+$ levels are indicated. From in-beam work it has been possible to identify the $\frac{11}{2}^+$ level (at 1081 keV), one of the two $\frac{9}{2}^+$ levels (at 898 keV), and

TABLE VI. Experimental conversion coefficients for transitions following the beta/electron capture decay of ^{129}Cs.

Transition energy (keV)		Conversion coefficient[a] ($\times 10^{-3}$)	Theoretical K conversion[b] $M1(\times 10^{-3})$	$E2(\times 10^{-3})$
93.3	$-K$	610(50)	876	1540
	$-L$	130(10)		
	$-M$	21(40)		
177.0	$-K$	117(8)	145	170
	$-L$	27(4)		
	$-M$	13(3)		
266.8	$-K$	43(4)	48.5	49.5
	$-L$	9.2(19)		
270.4	$-K$	41(4)	46.9	47.4
278.6	$-K$	39(3)	43.4	43.1
	$-L$	5.1(5)		
282.2	$-K$	42(4)	41.9	41.4
318.2	$-K$	28(2)	30.7	28.5
	$-L$	4.8(3)		
	$-M$	1.1(1)		
321.8	$-K$	5.0(5)	29.7	27.4
371.9	$-K$	18(1)	20.6	17.8
	$-L$	3.3(2)		
	$-M$	0.066(6)		
411.5	$-K$	16(1)	16.0	13.2
	$-L$	2.5(2)		
	$-M$	0.54(4)		
548.9	$-K$	6.9(5)	7.82	5.97
	$-L$	1.1(1)		
	$-M$	0.031(4)		
588.5	$-K$	5.8(4)	6.60	4.97
	$-L$	1.3(2)		
	$-M$	0.30(7)		
624.2	$-K$	9(2)	5.74	4.28
906.4	$-K$	2.3(3)	2.37	1.74

[a]Conversion coefficients normalized to 411-keV K-conversion coefficients experimental value of 16.0×10^{-3} for a pure $M1$ transition from Rösel *et al.* (Ref. 47). The number(s) in parentheses is the error in the last digit(s) of the value for the experimental conversion coefficient.
[b]Calculated from Rösel *et al.* (Ref. 47).

six other levels for a total of eight of the nine suggested levels which are shown in Fig. 2.

Above these, there is a discernable gap and then from 1100–1600 keV, all six $\frac{1}{2}^+$ and $\frac{3}{2}^+$ levels that would arise from coupling to the core are identified. Twelve more levels are called for between 1600 and 2100 keV, and we see that we found six with multiple gamma emission and another three with two depopulating gamma rays that sum to suggest a placement. For the very high-energy gamma rays, the limitation of Q supports these placements.

For this perspective, *all* of the levels suggested by the zeroth order coupling up to 1200 keV are identified within about 200 keV of the zeroth order position and nearly all of the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ levels suggested up to 2100 keV have also been identified.

Additional support for the notion of weak coupling can be found in the ^{124}Te(^{3}He,n)^{126}Xe and ^{125}Te(^{3}He,n)^{127}Xe reaction studies.[56] In the former reaction, strong two-proton transfer has been observed to a level near 2.60 MeV and additional strength to levels between 2.60 and 3.11 MeV. Comparable transfer is observed to a level near 1.84 MeV, and additional strength around 2.79 MeV. In view of the 90-keV uncertainty in these neutron energies, these data indicate that the $\frac{1}{2}^+$ level that arises from coupling the 1760-keV 0^+ to the $\frac{1}{2}^+$ ground state is among the levels at 1775, 1806, 1831, or 1895 keV. The small change in position of the two-proton transfer strength for the ^{126}Xe product relative to the ^{127}Xe product indicates that strength has neither been split nor significantly changed in energy and that the ^{126}Xe core is only weakly coupled to the single neutron in the $s_{1/2}$ level.

B. Systematic evolution of structure in the odd-mass Xe nuclides

The above analysis provides strong support for those descriptions of the odd-mass Xe nuclides that use relatively weak particle-core coupling. In this section, we

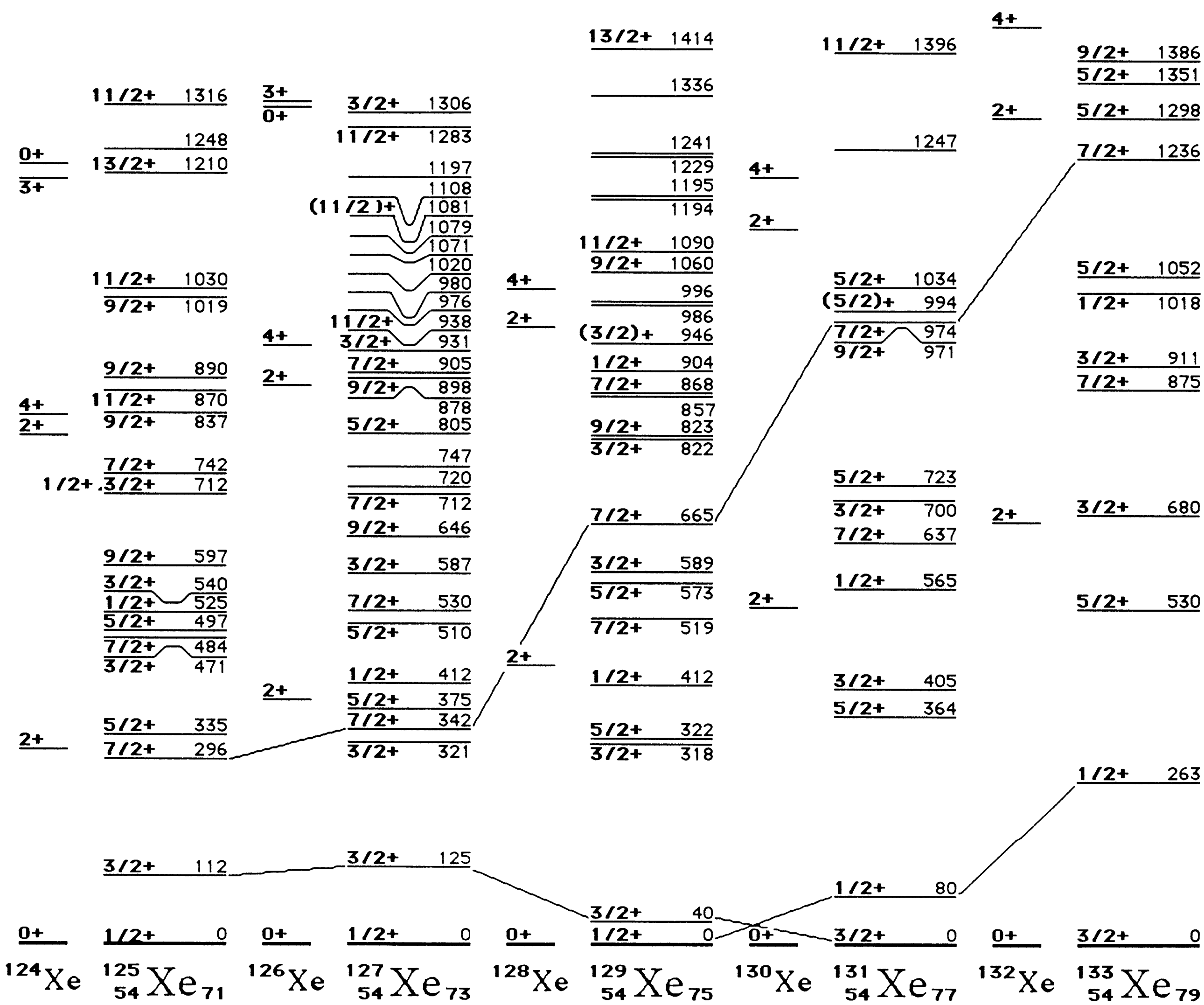

FIG. 2. Systematics of the positive-parity levels in the odd-mass Xe nuclides.

wish to examine the evolution of the weak coupling structure of the odd-mass Xe nuclides as neutrons are removed from the closed shell at $N=82$. To do so, we start with the structure of ^{135}Xe which lies near the $N=82$ shell closure.

1. ^{135}*Xe*

In Fig. 4 are shown the levels of the odd-neutron $N=81$ isotones along with the closed neutron core structures for the $N=82$ closed shell. The single neutron hole states are identified in ^{131}Sn where the energy of the adjacent core excitation lies at 4 MeV. It is important to note that the energy of the core 2^+ levels, whose structures are almost entirely two-proton configurations, in the $N=82$ isotones lies in the same position as the $d_{5/2}$ orbital. Consequently, in ^{137}Ba, the lightest of the $N=81$ nuclides where pickup reaction strength can be measured, the $d_{5/2}$ single particle strength is found to be widely split. The $g_{7/2}$ orbital lies at a higher energy where the level density is greater and is also split and admixed among several levels. In the heavier $N=81$ isotones where the 4^+ core level has moved to a higher energy, six (hole plus 2^+) levels can be identified, a $\frac{3}{2}^+$ and $\frac{5}{2}^+$ doublet arising from the $s_{1/2}+2^+$ configuration, and a $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$, and $\frac{7}{2}^+$ quartet arising from the $d_{3/2}+2^+$ configuration. Owing to the narrow splitting of the 4^+ and 6^+ levels in the ^{136}Xe core, the single neutron (hole plus 2^+)

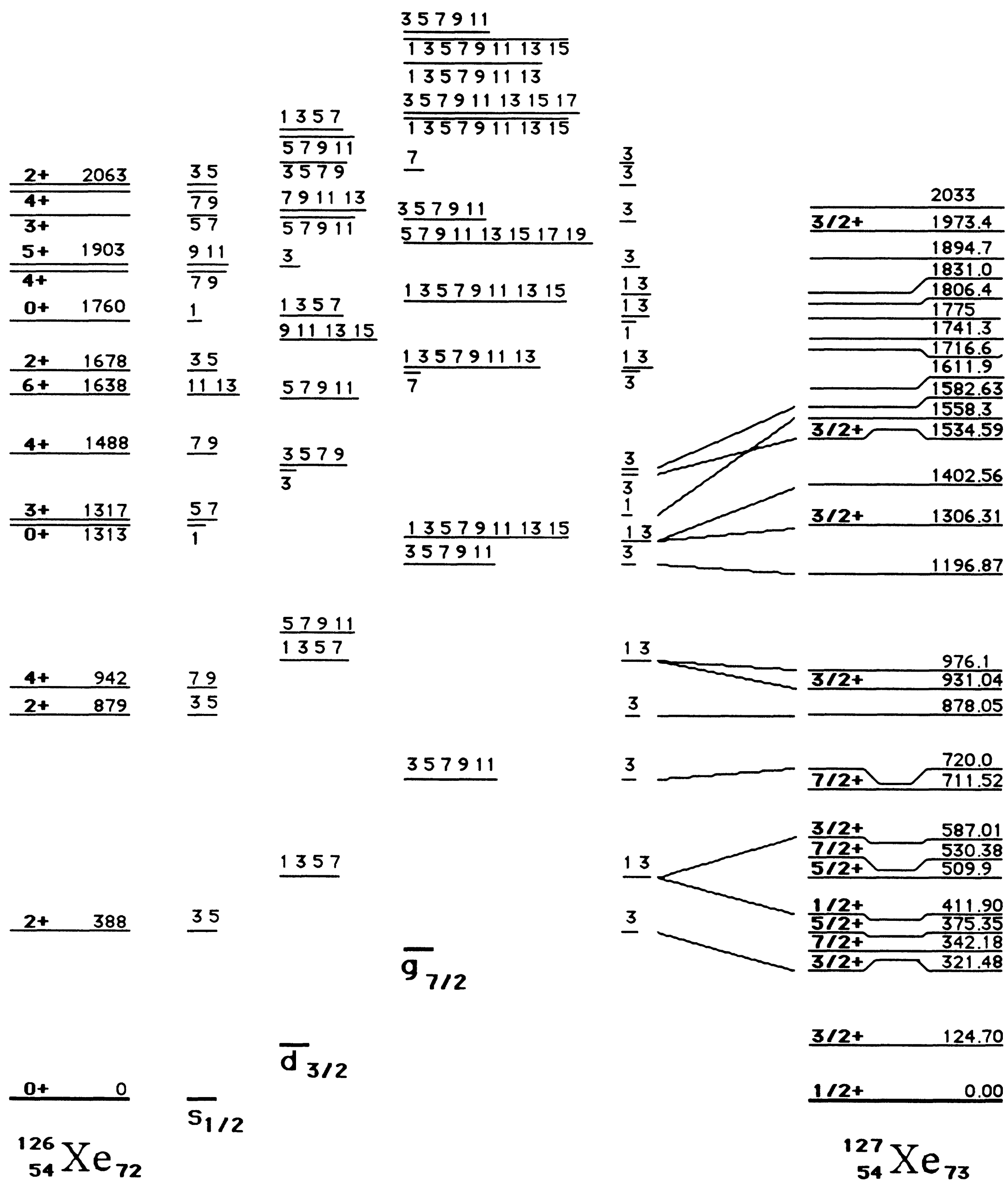

FIG. 3. Weak coupling multiplet structure in ^{127}Xe.

configurations are mixed with the couplings to the higher-spin levels. In a detailed experimental and theoretical study of the structure of ^{135}Xe below 2.5 MeV, only one of the three $\frac{1}{2}^+$ and one of the three $\frac{3}{2}^+$ predicted excited levels were observed, but five of the six $\frac{5}{2}^+$ levels, five of the six $\frac{7}{2}^+$ levels, and four of four $\frac{9}{2}^+$ levels were observed with little disagreement as to positions. In that study, the $d_{5/2}$ calculated single particle strength was found to be split between the lowest calculated $\frac{5}{2}^+$ level at 1147 keV (probably equivalent to the observed level at 1260 keV) and the fourth $\frac{5}{2}^+$ level at 2028 keV (probably equivalent to the observed level at 2045 keV).[57] Note that the average of these two energies compares closely with the position of the $\frac{5}{2}^+$ level in ^{131}Sn. As protons are added, it can be seen that the $d_{5/2}$ single particle strength moves slowly lower in energy relative to the $d_{3/2}$ and $s_{1/2}$ orbitals. Thus, the centroid of the $d_{5/2}$ hole strength probably lies somewhat lower in ^{135}Xe than its position at 1624 keV in ^{131}Sn, and with little change for the position of the $g_{7/2}$ centroid which appears to remain widely split among a number of levels between 2 and 3 MeV.

2. ^{133}Xe

There have been some difficulties with the firm establishment of the excited levels in ^{133}Xe. In a detailed study of the decay of $\frac{7}{2}^+$ 20.8-hr ^{133}I to levels of ^{133}Xe using the Lawrence Livermore National Laboratory Compton-suppression system, five of the six levels arising from the $d_{3/2}+2_1^+$ and $s_{1/2}+2_1^+$ multiplets were identified.[58] Owing to the large separation between the $d_{3/2}$ and $s_{1/2}$ levels, the levels at 530, 680, and 875 keV can be identified with the former configuration and the levels at 911 and 1052 keV with the latter. The observed γ-ray branching ratios support these identifications. A clear energy gap separates the (hole plus 2_1^+) levels from the higher-energy levels associated with the coupling to the 2_2^+ and 4_1^+ levels that lie at 1298 and 1440 keV, respectively.

In subsequent in-beam studies by Lönnroth *et al.*,[33] those five levels were identified, along with two additional proposed levels, a $\frac{5}{2}^+$ level at 607.9 keV, and a $\frac{7}{2}^+$ level at 1071 keV.[7] We have not shown these levels as it is not easy to understand how they could have been missed in the radioactivity study by Meyer *et al.* inasmuch as the

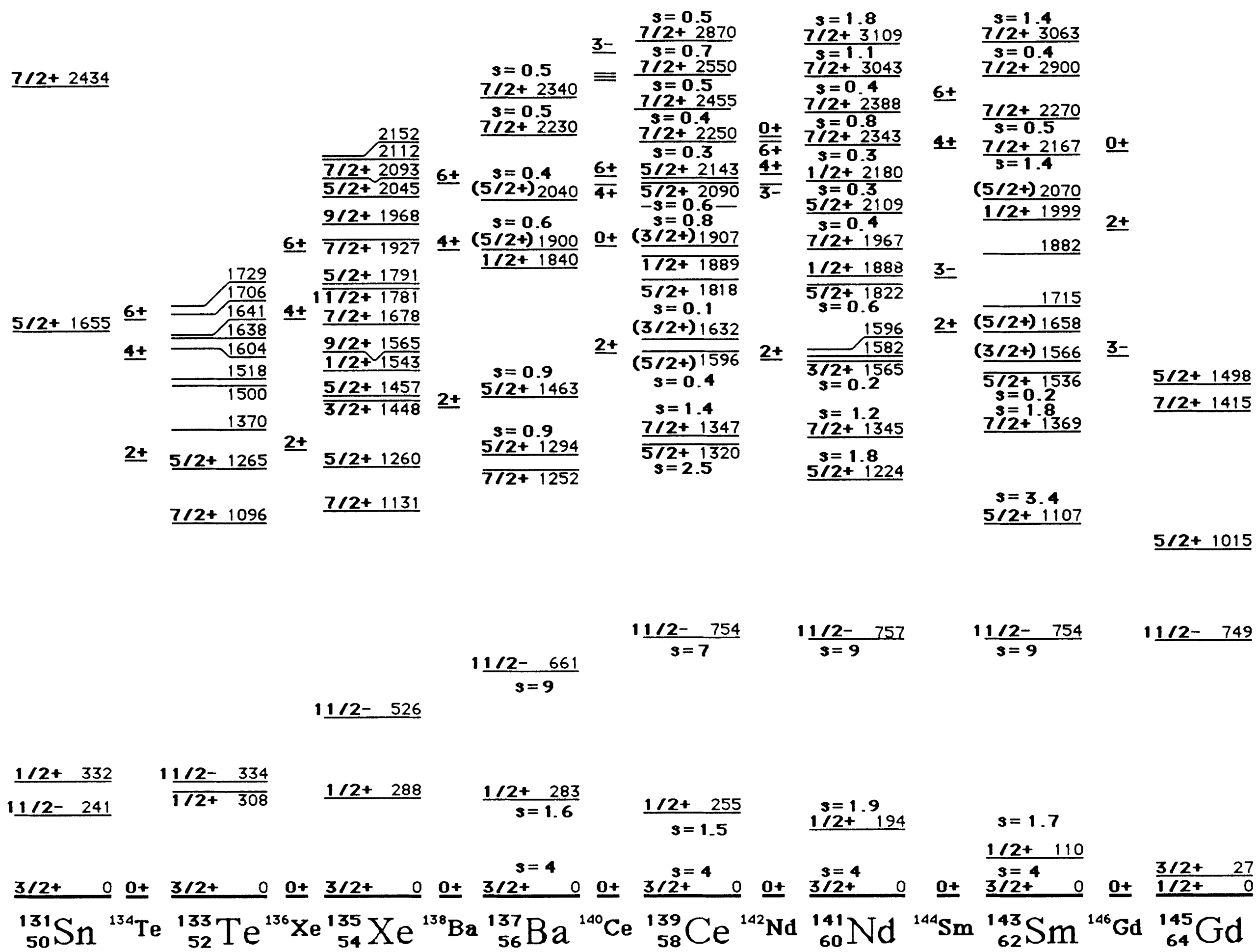

FIG. 4. Systematics of the levels of the $N=81$ isotones.

spin and parity of the beta decay parent ^{133}I is $\frac{7}{2}^+$. In that radioactivity study, other gamma rays with intensities as small as four parts in 100 000 were identified. They would have surely observed the members of this band if their spins and parities are $\frac{5}{2}^+$ and $\frac{7}{2}^+$. New measurements by Meyer, Henry, and Michailova[59] have set the limits even lower for population of such levels and led to the conclusion that this band must populate the $h_{11/2}$ isomer. Lönnroth *et al.* placed two other bands, also without interconnections, as populating the $h_{11/2}$ isomer. The cluster-vibration model calculations for ^{131}Xe by Paar and Koene[60] are quite reasonable. Since those calculations were reported, additional $\frac{3}{2}^+$ and $\frac{1}{2}^+$ levels near 1 MeV have been identified near the predicted positions.[60] New calculations by Meyer, Henry, and Michailova using a spinor symmetry approach have yielded particularly good fits for ^{133}Xe and other $N=79$ isotones.

The five negative-parity levels shown in Fig. 5 are of particular interest. The $\frac{15}{2}^-$, $\frac{13}{2}^-$, $\frac{7}{2}^-$, and $\frac{9}{2}^-$ levels lie above the $h_{11/2}$ single particle level in a nearly degenerate cluster around the 667-keV energy of the 2^+ phonon in ^{132}Xe. In contrast, the $\frac{11}{2}^-$ level would appear to have interacted rather strongly with the $h_{11/2}$ single particle orbital and been driven nearly 300 keV upwards in energy. The $\frac{9}{2}^-$ level has been slightly depressed as a consequence of admixtures of the $(h_{11/2})^{-3}$ structure. The depression is much larger in ^{131}Xe where there are certainly three full holes in the $h_{11/2}$ orbital. In ^{133}Xe, there are only three total holes in the $N=82$ closed shell and a significant portion of the vacancy lies in the $d_{3/2}$ and $s_{1/2}$ orbitals, leaving the $h_{11/2}$ orbital with vacancy less than three.[61]

3. ^{131}Xe

In ^{131}Xe, all six of the positive-parity (hole plus 2^+) levels have been identified in a narrow energy range around the 536-keV energy of the 2^+ level in ^{130}Xe. Owing to the close proximity of the $d_{3/2}$ and $s_{1/2}$ single particle levels, the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ members of the two particle-plus-phonon multiplets appear to have mixed in view of the strong branching of the $\frac{3}{2}^+$ level at 404 keV to both of the single particle levels. A gap of 250 keV separates these six levels from levels associated with coupling of the single-particle levels to the 2_2^+ and 4_1^+ levels. The IBFM

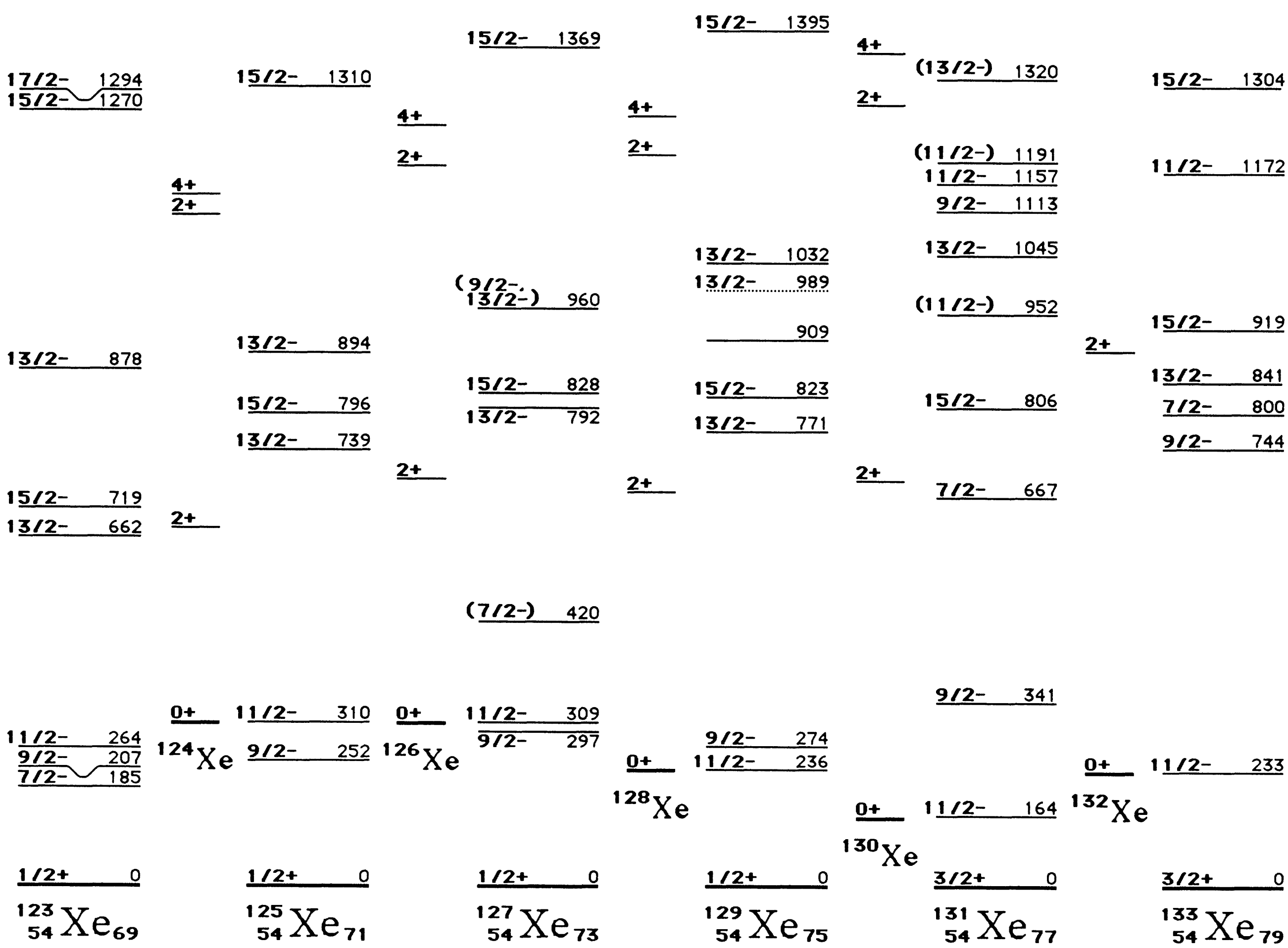

FIG. 5. Systematics of the negative-parity levels in the odd-mass Xe nuclides.

calculations reported by Cunningham fit these levels particularly well.[38]

Only four of the five $h_{11/2}$ plus 2^+ levels have been identified in ^{131}Xe and no longer give the appearance of a nearly degenerate cluster near the energy of the phonon in ^{130}Xe. In this nuclide, the $\frac{9}{2}^-$ level is significantly depressed while the $\frac{7}{2}^-$ level continues to move slowly below the energy of the phonon. For the other levels, the $\frac{15}{2}^-$ level lies closest to the phonon energy, while the $\frac{11}{2}^-$ level remains 250 keV above the $\frac{15}{2}^-$ level. The $\frac{13}{2}^-$ level at 1045 keV is unlikely to be a member of this multiplet, and would appear to be a part of the cluster of levels associated with coupling to the 2_2^+ and 4_1^+ levels. Unfortunately, Cunningham did not show his results for the negative-parity levels of ^{131}Xe.

4. ^{129}*Xe*

Our studies of the decay of ^{129}Cs were stimulated by the uncertainty that remains about the low-energy level structure of ^{129}Xe. As a consequence of several experiments on the decay of $\frac{1}{2}^+$ ^{129}Cs direct beta population of a $\frac{1}{2}^+$ level at 412 keV and $\frac{3}{2}^+$ levels at 318 and 589 keV is established as is the population of higher-energy $\frac{1}{2}^+$ and $\frac{3}{2}^+$ levels at 904 and 946 keV. Indirect population of $\frac{5}{2}^+$ levels 322 and 573 keV and a possible $\frac{7}{2}^+$ level at 624 keV is also observed. The same $\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{5}{2}^+$ low-energy levels were observed in Coulomb excitation and $(\alpha,n\gamma)$ reactions[33] and additional $\frac{7}{2}^+$ levels were proposed at 519 and 665 keV.[62] Again there is a gap and additional excited levels are observed at 822 and 857 keV along with the 904- and 946-keV levels mentioned earlier. In contrast, results from another $(\alpha,n\gamma)$ study did not provide evidence for the 519-keV level, but proposed $\frac{7}{2}^+$ levels at 624 and 665 keV and additional $\frac{5}{2}^+$ levels at 442 and 525 keV. The latter two levels are marked by an absence of branching and could belong in another placement. In a recent study using the OSIRIS system, the levels at 318, 322, 412, 573, and 589 keV found in the radioactive decay and Coulomb excitation studies were identified, along with proposed $\frac{7}{2}^+$ levels at 519 and 665 keV as well as higher-energy levels starting at 822 keV.[63] They also identified interconnecting cascades involving possible $\frac{5}{2}^+$ levels at 442, 525, and 693 keV. They note, however, that these levels were not interconnected by other gamma transitions to other known levels and cascades. The gamma transitions associated with these levels were also observed in the ^{130}Te(^{3}He,$4n\gamma$) reaction, but because of the absence of interconnecting gamma rays they were only tentatively placed. Inasmuch as neither we nor the previous investigations of radioactivity[64] could find any indication of any of these gamma rays in our spectra, while at the same time observing indirect population of the other $\frac{5}{2}^+$ levels in that energy region, we have omitted these levels from our systematic compilation. We have also omitted the $\frac{7}{2}^+$ level proposed at 624 keV as the 302-keV transition is more likely associated with deexcitation of a $\frac{3}{2}^+$ level at 823 keV and the 585-keV transition is more likely associated with depopulation of a low-spin level at 996 keV that depopulates to the $\frac{1}{2}^+$ level at 412 keV. Population of both of these levels would certainly be possible following the beta decay of $\frac{1}{2}^+$ ^{129}Cs.

General agreement appears to exist as to the presence of a $\frac{1}{2}^+$ level at 412 keV, $\frac{3}{2}^+$ levels at 318 and 589 keV, $\frac{5}{2}^+$ levels at 322 and 573 keV, and $\frac{7}{2}^+$ levels at 519 and 665 keV, and to a gap between these levels and higher-energy levels beginning at 822 keV.[26] The IBFM fits reported by Cunningham for these levels are not as good as in ^{131}Xe, and do not predict any additional $\frac{5}{2}^+$ levels in the 500-keV region. A particularly attractive feature of these calculations is the fit for the $g_{7/2}$ neutron hole level at 665 keV.

The data for the negative-parity levels[62] come entirely from the OSIRIS study. It may be seen that all three high-spin levels lie well above the 422-keV energy of the 2^+ phonon ^{128}Xe. The fit by Cunningham for these levels was made before the low-energy $\frac{9}{2}^-$ was identified. For the low-energy $\frac{9}{2}^-$ and $\frac{7}{2}^-$ levels, the $\frac{7}{2}^-$ is predicted to lie near the $\frac{11}{2}^-$ level and the $\frac{9}{2}^-$ about 200 keV higher. We note that inclusion of the $f_{7/2}$ and $h_{9/2}$ single particle levels from across the $N=82$ and shell gap was required in order to depress these two levels. The $f_{7/2}$nd $h_{9/2}$ single particle energy values of 3.0 and 3.12 MeV, respectively, are somewhat low and the separation between the two levels far below the approximately 1.4-MeV separation reported for these levels in ^{133}Sn. The depression of the $\frac{9}{2}^-$ and $\frac{7}{2}^-$ levels in many odd-neutron nuclides[65] in this mass region is well known and usually attributed to an $(h_{11/2})^3$ configuration.[66] As that feature may not be well developed in the IBFM, the rather large admixture of the $h_{9/2}$ level from across the $N=82$ closed shell may have been required to depress the $\frac{9}{2}^-$ levels.

5. ^{127}*Xe*

The discord in ^{129}Xe may be contrasted with the general agreement for the structures of ^{127}Xe and ^{131}Xe. The moment and lifetime measurements[34] leave little doubt about the $g_{7/2}$ hole character of the 34-ns 342-keV level. The strong population of the levels at 321, 412, and 587 keV in the decay of $\frac{1}{2}^+$ ^{127}Cs indicates spins and parities of either $\frac{1}{2}^+$ or $\frac{3}{2}^+$ for these levels and weak population indicates higher-spin levels at 375 and 510 keV. These three levels as well as proposed $\frac{5}{2}^+$ levels at 375 and 510 keV are observed in ^{127}I$(p,n\gamma)$ reaction studies.[33] In ^{125}Te$(\alpha,2n\gamma)$ studies, the 321-, 375-, and 510-keV levels are observed and a $\frac{7}{2}^+$ level is proposed at 530 keV.[28] Although the gap has narrowed as neutrons are removed, still the lowest energy of the next band members begins at 646 keV.

Among the negative-parity levels, the $\frac{9}{2}^-$ level has been depressed below the $h_{11/2}$ single particle level, while the $\frac{13}{2}^-$ and $\frac{15}{2}^-$ levels remain above the energy of the adjacent 2^+ energy.

6. ^{125}*Xe*

The levels of ^{125}Xe appear quite similar to those of ^{127}Xe, the $g_{7/2}$ hole state has been further depressed, and the six levels associated with the (particle plus 2^+) configurations remain easily identified with good estimates for spins and parities derived from population either in the beta decay of $\frac{1}{2}^+$ ^{125}Cs (525 and 540 keV) or from in-beam studies (335, 471, 484, and 497 keV).[31] We have also shown the negative-parity levels of ^{123}Xe to demonstrate that the continued depression of the $\frac{7}{2}^-$ level to the position of lowest negative-parity level in that nucleus.[51]

7. Summary

Based on this systematic examination of the positive-parity levels, two features stand out. First is the systematic association of the four $d_{3/2}+2^+$ and two $s_{1/2}+2^+$ hole-plus-phonon levels from the closed shell ^{135}Xe through ^{125}Xe with the position of the 2^+ phonon level in the adjacent even-even Xe core. Through all of these nuclides, these six levels can be identified and are separated by a discernable gap from the levels with configurations involving the coupling to the 2_2^+ and 4_1^+ core levels.

Second, these nuclides show the very rapid drop in the position of the $g_{7/2}$ single neutron hole brought about, at least in part, by the monopole interaction. The $g_{7/2}$ hole is found to be 800 keV deeper than the $d_{5/2}$ hole in ^{131}Sn with $N=81$, whereas at the beginning of the filing of the $N=50-82$ shell the $d_{5/2}$ orbital probably lies somewhat lower than the $g_{7/2}$ orbital. For ^{91}Zr with $N=51$, the $d_{5/2}$ orbital is the ground state and the $g_{7/2}$ orbital lies near 2230 keV. The strong interaction of the $g_{7/2}$ neutrons with their spin-orbit partner $g_{9/2}$ proton orbitals produces a drastic drop in the $g_{7/2}$ orbitals as protons are added to ^{91}Zr. Consequently, the position of the $g_{7/2}$ level drops to 1362, 946, and 686 keV in ^{93}Mo, ^{95}Ru, and ^{97}Pd, respectively. The data presented here suggest that in ^{127}Xe the two orbitals have already crossed with the $g_{7/2}$ orbital concentrated below the widely admixed $d_{5/2}$ orbital. Surprisingly, this single hole level does not appear to mix strongly with the adjacent collective $\frac{7}{2}^+$ levels. Moreover, the entire pentuplet arising from the $g_{7/2}$ plus 2^+ coupling can also be identified in ^{127}Xe. This behavior may be contrasted with that of the $d_{5/2}$ orbital which appears to be admixed with the many collective $\frac{5}{2}^+$ levels to a point that no particular level has been identified as the $d_{5/2}$ neutron hole.

The negative-parity levels are marked by the depression of the $j-1$ $\frac{9}{2}^-$ level and $j-2$ $\frac{7}{2}^-$ level as neutrons are removed while the $\frac{15}{2}^-$ and $\frac{13}{2}^-$ $j+2$ and $j+1$ levels are slightly elevated relative to the position of the 2^+ level in the adjacent even-even nuclide. The $\frac{15}{2}^-$ and $\frac{13}{2}^-$ levels remain quite close to each other across this series of nuclides. This slight elevation could arise from the blocking of some of the collectivity of the core when the single neutron is in the $h_{11/2}$ orbital. These features of the structure have been particularly difficult to fit. Hagemann *et al.*[67] attempted to fit the similar structures in the odd-N Te nuclides with both a rigid triaxial and a soft rotor core. While both models were able to fit the higher-spin levels, it was not possible to lower both the $\frac{9}{2}^-$ and $\frac{7}{2}^-$ levels at the same time. But, Meyer[68] has shown in his Fig. 12 parts C and D that in cluster-vibration model calculations for unique parity orbitals, the levels with spin $j-1$ and $j-2$ both are depressed as a function of coupling strength for particles, while for holes, *only the $j-1$ level is depressed.*[69] Consequently, the rapid depression of the $\frac{9}{2}^-$ level in the heavier odd-mass Xe nuclides is consistent with their hole character, whereas the depression of the $\frac{7}{2}^-$ level develops more slowly as the occupancy of the $h_{11/2}$ level is reduced. Finally, when the occupancy of the $h_{11/2}$ level is below 0.5, the $\frac{7}{2}^-$ level moves below the $\frac{11}{2}^-$ and $\frac{9}{2}^-$ levels in ^{123}Te$_{71}$.

VI. CONCLUSION

^{127}Xe is the heaviest odd-mass Xe nuclide for which beta decay population of the low-spin levels in the 1–2-MeV range is possible. Consequently, it has been possible to use these new data for low-spin levels to examine various interpretations of the level structure of these Xe nuclides. The levels observed are consistent with particle-core coupling of weak to intermediate strength with clusters of levels in the correct numbers associated with particle or hole coupling to the first, second, and third phonon. While the levels are hardly degenerate, the mixing is not so strong as to obscure the boundaries between the three groups. There is no evidence for rotational bands and their parent Nilsson orbitals that would arise if these nuclides possessed a strongly deformed prolate shape.

In none of these structures at low energies does there appear to be strong evidence for the degree of deformation (β approaching 0.3) deduced from the radius differences or used in some of the calculations that are designed to fit the structure of the nucleus at higher energies. The interpretation of the changes in mean square charge radii are admittedly quite model dependent and the conclusion that the neutron deficient Xe and Ba nuclides are more deformed than the neutron rich Xe and Ba nuclides would appear to merit closer examination, particularly in view of the much more rapid drop in the energy of the first 2^+ levels on the neutron rich side of $N=82$. In these nuclides with $N<82$ there is little evidence for the steady movement of the Fermi level through the various Nilsson orbitals associated with the deformation of the $h_{11/2}$ single particle orbital. These nuclides would appear to be particularly fertile ground for additional testing of IBFM calculations using the new core parameters inasmuch as the core Xe nuclides appear to have features that are reasonably well described by the O(6) limiting IBM symmetry. In view of the simplicity of the description of the core structures, the reasonably well established positive-parity single particle orbitals, and the excited levels associated with the single j shell $h_{11/2}$ negative-parity orbital, such calculations should be of particular interest.

The depression of the $j-1$ $\frac{9}{2}^-$ and $j-2$ $\frac{7}{2}^-$ levels below the $h_{11/2}$ single particle level is well described by the cluster-vibration model and shown to vary with cluster core interaction strength and occupation of the unique parity orbital. In view of the possible satisfactory cluster-vibration model description of the unique parity orbitals and the absence of any indication for strong coupling in the positive parity levels, there is, therefore, little need to invoke triaxial calculations in which β values of near 0.25 have been used along with γ values of near 26° to account for the negative-parity structures.[70]

Another perspective on the systematic changes in the low-energy positive-parity levels has been presented in the fermion dynamic symmetry model (FDSM) that has been proposed by Wu, Feng, Guidry, and others.[71,72] The slowly varying structure of the odd-mass Xe nuclides as a function of neutron number in the range $73 \leq N \leq 79$ where the $h_{11/2}$ orbitals are filling would appear to support their contention that nuclear structure is driven by interactions among like parity orbitals and that the unique parity orbital (the $h_{11/2}$ neutron orbital in this case) plays a much smaller role in determining the shape of the nucleus.

The presence of these large quantities of systematic data also make it possible to test any set of wave functions that are to be used in the calculation of ^{127}I neutrino cross sections for the production of ^{127}Xe. Whatever wave functions are used should be those that are derived from a fit to all of these odd-mass Xe nuclides, rather than just a fit to the isolated ^{127}Xe levels.

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