$E0$ transitions and 0^+ levels in ^{136}Xe

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The β^- decay of ^{136}I isomers to levels in ^{136}Xe was studied using sources isolated at the on-line mass separator TRISTAN. Conversion-electron and gamma-ray singles data have been collected. Evidence for excited 0^+ states at 2582.4 and 4320 keV has been obtained. A shell-model study elucidating the salient features related to the first excited 0^+ state in the $N=82$ nuclei has been carried out. Comparing two-particle, four-particle exact shell-model and two-quasiparticle shell-model calculations using both a Gaussian and surface-delta interaction in the latter case, an explanation could be given for the Z dependence in the $E_x(0_2{}^+)$ excitation energy. We also calculate the $E0$ reduced matrix elements for ^{134}Te.

I. INTRODUCTION

In recent studies on the beta/electron-capture decay of ^{120,122,124,126}Cs, high-energy $E0$ transitions were identified in the daughter even-even ^{120,122,124,126}Xe nuclei, respectively, with decay energies of approximately 2500 keV.[1,2] Only in ^{120,122}Xe does gamma emission compete with the $E0$ transition. In ^{124,126}Xe these levels have been identified on the basis of the presence of an $E0$ transition in the conversion-electron spectra and peaks in the two-proton transfer spectra.[3] Decay of ^{128,130}Cs (1^+ parent ground states) to levels of ^{128,130}Xe also populates 0^+ levels near 2500 keV. These levels depopulate by gamma emission, but are not populated in the two-proton transfer reactions, and conversion-electron measurements have not shown $E0$ branches to the ground state or other well-known 0^+ levels lying at lower energies.

The presence of 0^+ levels that depopulate by strong $E0$ transitions in the 2–2.5-MeV energy range has also been established in the even-even $N=82$ isotones.[4,5] Some of these levels have been identified in two-neutron transfer reactions [both (t,p) and (p,t)]. For ^{138}Ba, such a level has been found to lie at 3.61 MeV and at successively lower energies in ^{140}Ce (3.23 MeV), ^{142}Nd (2.97 MeV),[6] ^{144}Sm (2.827 and 3.142 MeV), and ^{146}Gd (3.016 MeV).[7] Other 0^+ levels have also been identified and attributed to proton excitations owing to their population in $(^3\text{He},n)$ two-proton transfer reactions. Six such 0^+ levels have been identified in ^{138}Ba and one or two 0^+ levels in the higher-Z $N=82$ isotones.[8]

The presence of these $E0$ transitions in the $N=82$ isotones raised the question as to the positions of 0^+ levels in the lower-Z $N=82$ isotone ^{136}Xe and whether the 0^+ levels that lie at a nearly constant energy of 2.5 MeV in the lower-mass Xe nuclei could represent proton configurations as already indicated from the two-proton transfer strength. Shell-model and two-quasiparticle calculations in the even-even $N=82$ nuclei have long been known to produce an excited 0^+ state in the energy region $1.5 \le E_x \le 2.5$ MeV. Therefore, and in order to test the shell-model predictions relating to the precise position of the noncoherent 0^+ excitation that mainly originates from the $(1g_{7/2})^2_{0^+}$ and $(2d_{5/2})^2_{0^+}$ configurations (see also Sec. IV and Table II), search for 0^+ excited states and their subsequent $E0$ decay is of considerable importance. If all 0^+ levels would be described within a ($1g_{7/2}$, $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$) model space, $E0$ transitions would all disappear since these $N=4$ orbitals all have the same radial value $\langle nlj|r^2|nlj\rangle$. It is only the admixture of the $N=5$ $1h_{11/2}$ orbital in both the excited and ground states that causes nonvanishing $E0$ transitions to result. To that end, we have investigated the decay of the isomers of ^{136}I to levels in ^{136}Xe.

Several studies of the decay of ^{136}I to levels of ^{136}Xe have been reported, and the existence of two isomers with half-lives of 83 and 47 s in ^{136}I is well established.[9] The results have been compiled in the Nuclear Data sheets by Burrows.[10] The decay scheme reported therein was taken mostly from the work of Western *et al.*[11] and includes levels proposed in ^{136}Xe up to an energy of 6600 keV. Inelastic proton scattering has also been used[12] to study the levels of ^{136}Xe, with the population of many particle-hole states in ^{136}Xe above 3 MeV. Conversion coefficients have also been measured[13] for several transitions in ^{136}Xe below 400 keV. Multipolarities were assigned as $E2$ for the 197-keV gamma-ray transition and $M1/E2$ for the 381-keV transition. The K conversion for the gamma-ray transitions of 345 and 371 keV were also observed, with conversion coefficients reported as corresponding to $E3(+M2)$ multipolarity for both transitions (those authors did not report any actual values for these conversion coefficients, however). The levels below 3.2 MeV populated in the decay of ^{136}I isomers are shown in Figs. 1 and 2. In each figure we have shown, at the side, the other levels that lie below 2650 keV not populated in the decay of that isomer, but populated in the decay of the other isomer.

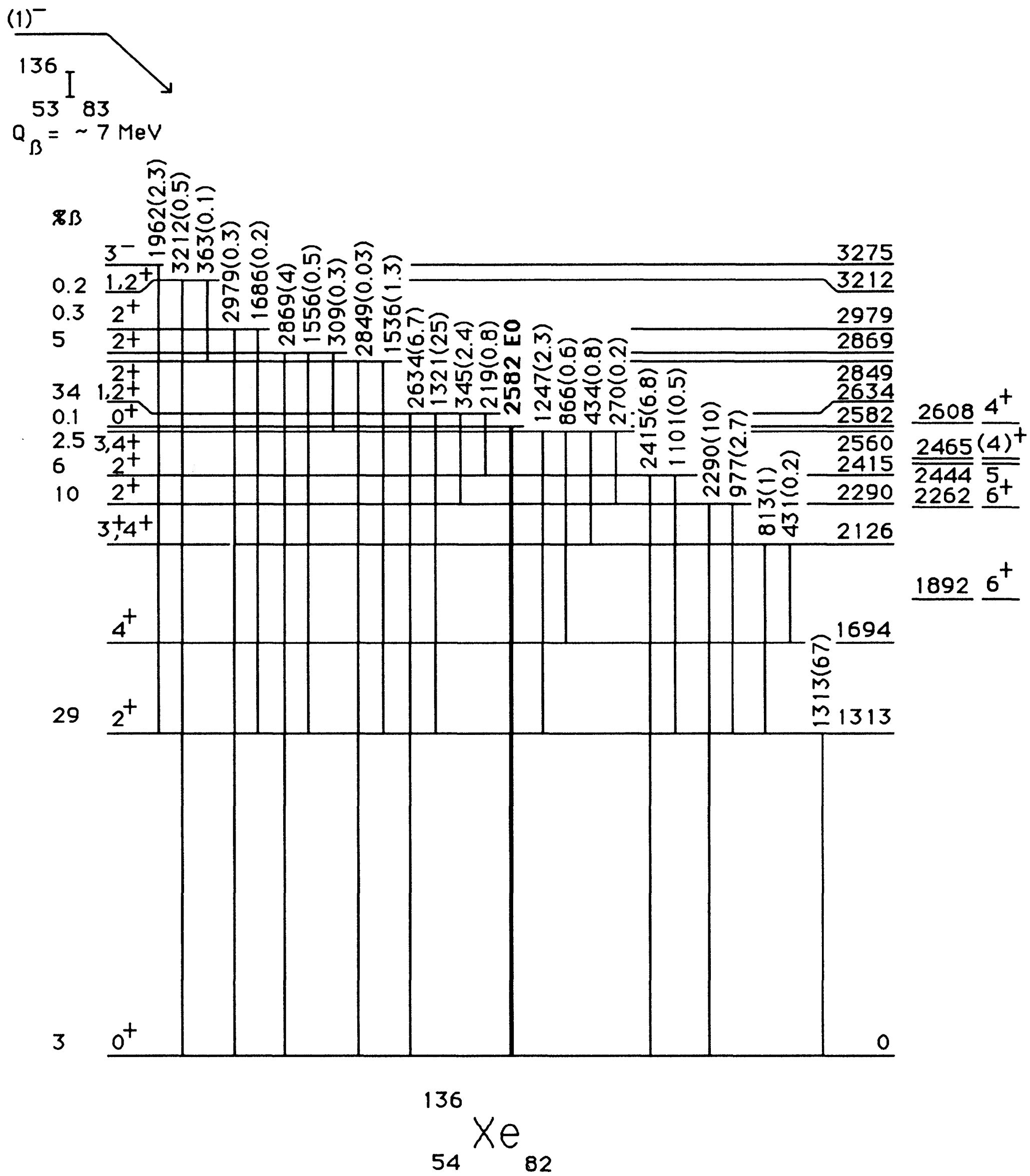

FIG. 1. Decay scheme for the low-spin isomer of ^{136}I showing only the levels populated below 3.3 MeV. For comparison, the additional levels known below 2.65 MeV that are populated by the decay of the high-spin isomer are also shown. The next higher level in ^{136}Xe populated by the low-spin isomer is at 3873 keV.

II. EXPERIMENTAL PROCEDURES AND RESULTS

This study of the levels of ^{136}Xe fed in the β^- decay of ^{136}I was performed at the on-line mass separator TRISTAN associated with the 60-MW high flux beam reactor at Brookhaven National Laboratory. Fission products were produced inside a thermal ion source by the neutron-induced fission of a ^{235}UC target. The ionized fission products were mass separated and the desired $A=136$ products directed toward the conversion-electron experimental station. As the ion beam reached the experimental area, it passed through a lead collimator and was then deposited into an aluminized tape. The detectors were located around the point of beam deposit and the tape was positioned at a 45° angle with respect to the beam. The tape was not moved, however, during this experiment as the daughter ^{136}Xe is stable.

Conversion-electron and gamma-ray singles data were collected at a rate of 40 000 s^{-1} at the position of the gamma detector. The gamma detector was a 28% Ge detector with a full width at half-maximum (FWHM) of 2.2 keV at the 1332-keV ^{60}Co transition, and the detector was placed 2 cm from the point of deposit. The conversion-electron detector was a lithium-drifted silicon detector Si(Li) with a 200-mm^2 active area and a depletion depth of 3 mm. The electron detector had a

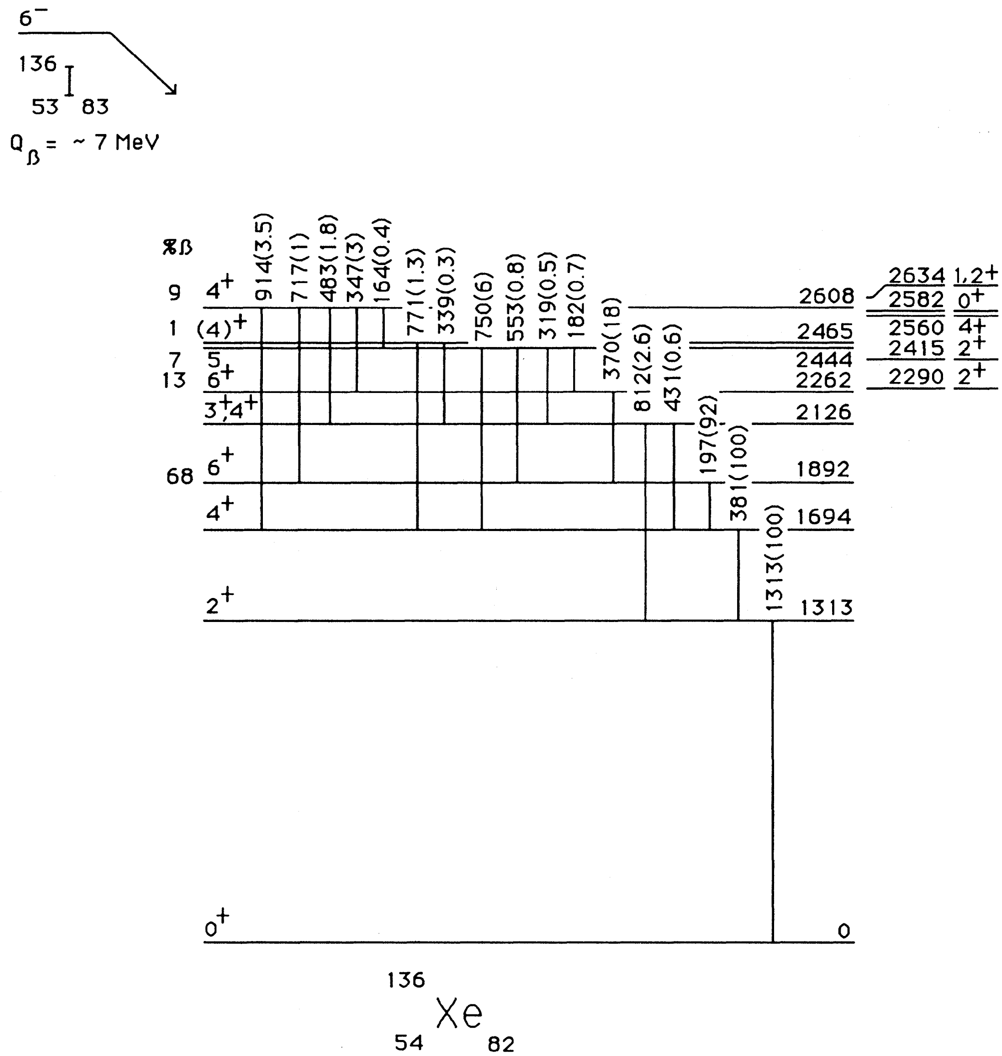

FIG. 2. Decay scheme for the high-spin isomer of ^{136}I showing only the levels populated below 3.3 MeV. For comparison, the additional levels known below 2.65 MeV that are populated by the decay of the low-spin isomer are also shown. The next higher level in ^{136}Xe populated by the high-spin isomer is at 3830 keV.

FWHM of 2.5 keV for the 975-keV ^{207}Bi electron transition. The detector was placed 1.5 cm from the point of deposit at an angle of 45° to the tape. Gamma-ray and conversion-electron singles data were collected at two separate gain settings for both detectors, one with a full energy range of 3 MeV and a second with a full energy range of 6 MeV. The singles electron spectrum in the range from 2 to 3 MeV is shown in Fig. 3 and from 3.5 to 5 MeV in Fig. 4.

Energy calibration spectra for both detectors were collected from a source of ^{133}Ba and for the gamma detector from a ^{60}Co source. The relative efficiency curve constructed for the gamma detector used gamma transition intensity values from the decay of the 83-s isomer of ^{136}I as compiled by Burrows.[10] The relative efficiency curve for the conversion-electron detector was completed using the three well-established $E2$ transitions of 197, 381, and 1313 keV in the decay of both ^{136}I isomers. The energy calibration of the Si(Li) detector was determined by a plot of the gamma-ray energies of transitions in ^{136}Xe less the K-electron binding energy for Xe versus the corresponding peak position of the K-electron peak.

The results of the conversion coefficient measurements for transitions in ^{136}Xe are shown in Table I. The conversion coefficients were normalized to the 1313.0-keV 2^+ to 0^+ transition K-conversion coefficient theoretical $E2$ value of 0.781×10^{-3} from Rösel *et al.*[14] Included in Table I are transitions of 2582.4 and 4320 keV, which are labeled as $E0$ transitions. Conversion-electron peaks are observed in the electron spectrum at transition energies of 2582.4 and 4320 keV, with no corresponding transitions seen in the gamma-ray singles spectrum. Consequently, these transitions have been assigned as having $E0$ multipolarity. From the intensities of the conversion-electron peaks, it is possible to estimate that the beta branching to the level at 2582 keV is ~0.1%.

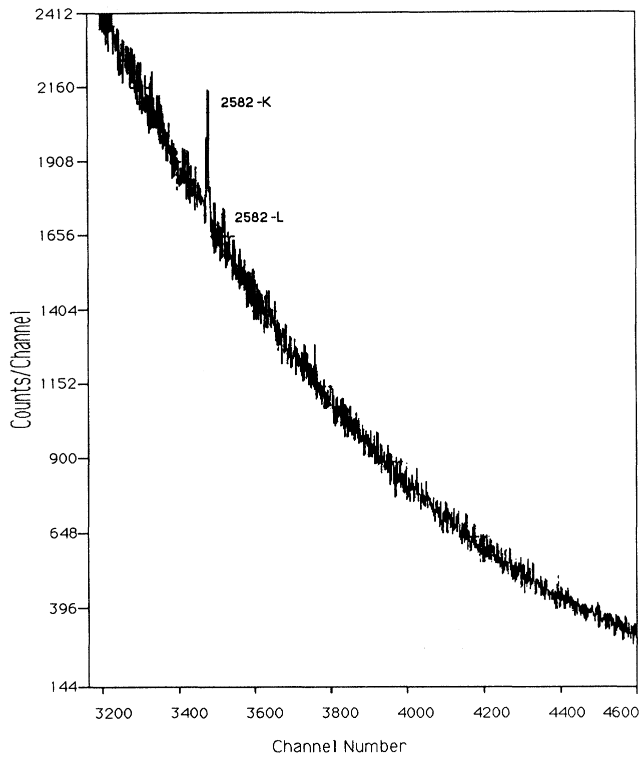

FIG. 3. Electron spectrum in the energy range 2200–2700 keV for the decay of ^{136}I isomers to levels of ^{136}Xe.

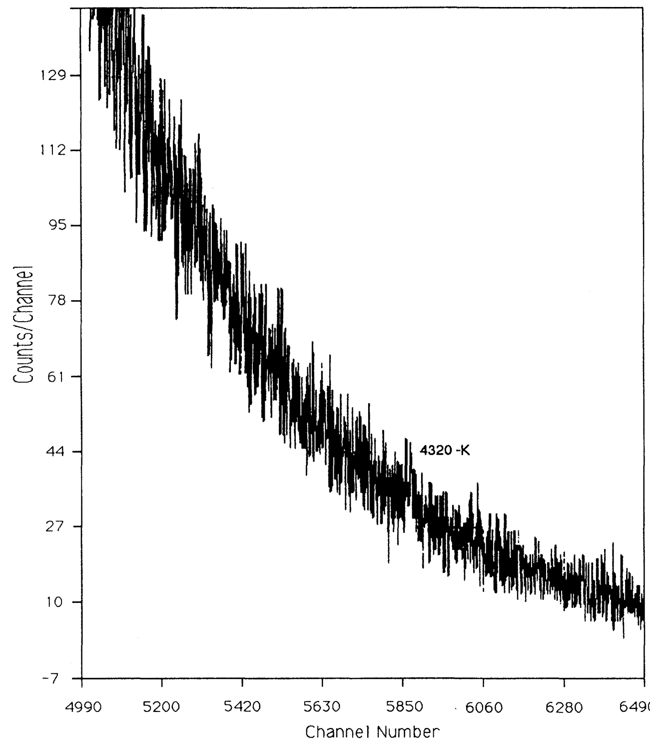

FIG. 4. Electron spectrum in the energy range 3800–4500 keV for the decay of ^{136}I isomers to levels of ^{136}Xe.

TABLE I. Experimental conversion coefficients for transitions following the beta decay of ^{136}I isomers.

Transition energy (keV)		Electron intensity	Conversion coefficient ($\times 10^3$)[a]	Theoretical K conversion ($\times 10^3$)[b] $M1$	$E2$	$E1$
197.3	−K	64.9	137(25)	110	137	27.9
	−L	16.0	35(6)			
	−M	7.90	17(3)			
219.3	−K	1.80	174(44)	81.3	94.3	20.6
344.7	−K	0.90	22(4)	25.0	22.1	6.29
370.1	−K	1.72	19(4)	20.9	17.9	5.29
	−L	0.25	2.8(5)			
381.4	−K	8.57	16(3)	19.4	16.3	4.91
	−L	1.58	3.0(6)			
	−M	0.97	1.9(4)			
482.8	−K	0.15	17(6)	10.7	8.22	2.79
1313.0	−K	1.00	0.78(15)	1.03	0.781	0.364
1321.1	−K	0.30	0.97(22)	1.01	0.773	0.360
2582.4	−K	0.20	$E0$			
	−L	0.04	$E0$			
4320	−K	c	$E0$			

[a]Conversion coefficients normalized to 1313.0-keV transition K-conversion coefficient theoretical $E2$ value of 0.781×10^{-3} from Rösel *et al.* (Ref. 14). The number(s) in parentheses is the error in the last digit(s) of the value for the experimental conversion coefficient. The electron intensities used in the computation of the conversion coefficient were determined using an electron efficiency curve based on the well-known $E2$ transitions of 197.3, 381.4, and 1313.0 keV in ^{136}Xe.

[b]Calculated from Rösel *et al.* (Ref. 14).

[c]We observe 60 counts in this peak compared to 12 700 in the 2582-keV K-electron peak. If efficiency is estimated to decline by a factor of 2, the relative intensity would be 0.0004.

The 2582-keV $E0$ transition has been included in the level scheme for the decay of the low-spin isomer of ^{136}I in Fig. 1. In earlier studies, Achterberg *et al.*[13] reported conversion coefficients for the 344.7- and 370.1-keV gamma-ray transitions sufficiently larger than would be expected for $M1/E2$ multipolarity as to suggest $M2/E3$ multipolarity or complex peak structure. Other investigations have not indicated complex peaks, and our conversion coefficient data are consistent with $M1/E2$ transitions within the 20% uncertainties that our data show.

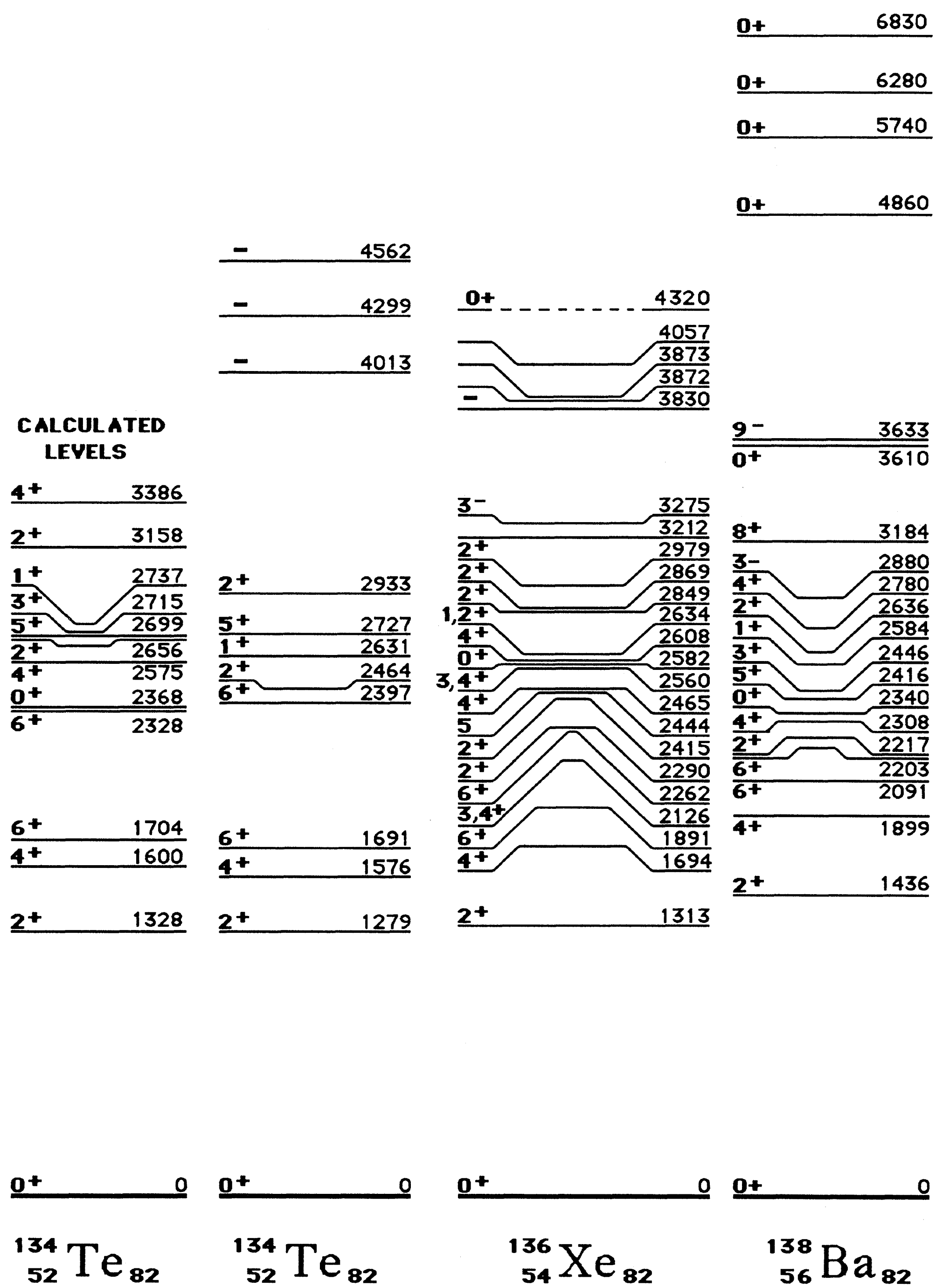

FIG. 5. Systematics of the known energy levels of ^{134}Te up through 4600 keV, ^{136}Xe up through 4400 keV, and ^{138}Ba through 3700 keV. In ^{138}Ba, the higher-energy 0^+ levels are populated in transfer reactions. The calculated levels for ^{134}Te are taken from the work of Lane (Ref. 24).

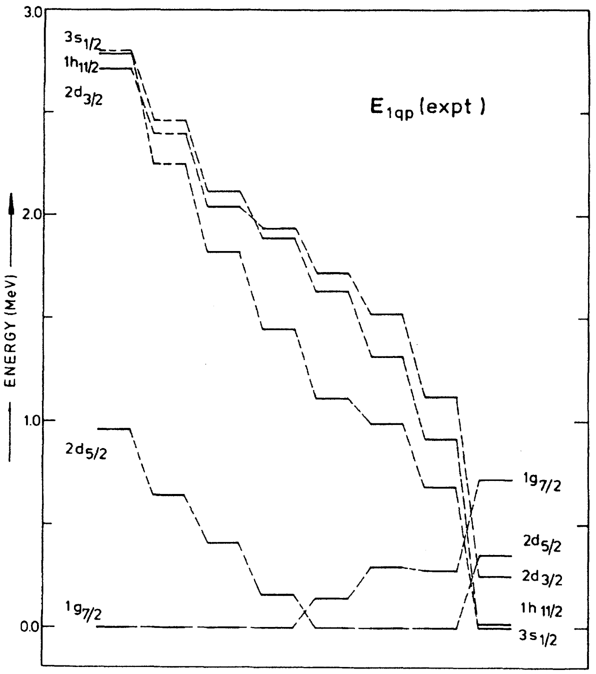

FIG. 6. Proton one-quasiparticle energies for the $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, and $1h_{11/2}$ states for the odd-mass $N=82$ nuclei, ^{133}Sb-^{147}Tb. Dashed lines indicate interpolated and/or extrapolated values. In ^{147}Tb, the $1h_{11/2}$ level lies 50.6 keV above the $3s_{1/2}$ level.

Hithertofore, none of the investigations of the structure of the levels of ^{136}Xe has shown any evidence for the presence of a level in the uncertainty range of the 0^+ levels that we propose. Such a search for a 1269-keV transition from the 2582-keV level to the 2_1^+ level at 1313 keV is considerably hindered by the presence of the double-escape peak from the intense 2289.6-keV gamma-ray transition. We have normalized our observed gamma-ray intensities to 37 intensity units for the 1321-keV gamma ray intensity, the value reported by Western *et al.*[11] who derived that value by setting the intensity for the 1313-keV gamma-ray transition to 100 for decay of the 85-s low-spin isomer. In that system we observe an intensity of 170 for the 1313-keV gamma-ray transition, indicating that the 85-s low-spin isomer constitutes 60% of our activity and the other 40% originates from the 45-s high-spin isomer. We measure an intensity of 3.1(6) for the 1247-keV gamma ray which compares to 3.4(2) reported by Western *et al.*[11] The intensity of the 1269-keV double-escape peak is 1.0(2). We should have expected to observe a peak at 1267 keV if its intensity were 0.3 units. In view of the factor of 3 lower uncertainty reported by Western *et al.*, it appears that they had about 10 times the data that we have and would have observed this peak if it were as large as 0.3 units. In fact, they do observe a peak at 1179 keV whose intensity is 0.33(5). Other possible decay branches would be to the 2^+ levels at 2290 and 2415 keV by gamma rays with energies of 292 and 167 keV, respectively. We observe transitions at 163 and 270 keV with intensities of 0.6(1) and 0.24(5), respectively, and can set upper limits of 0.2 and 0.1, respectively, for

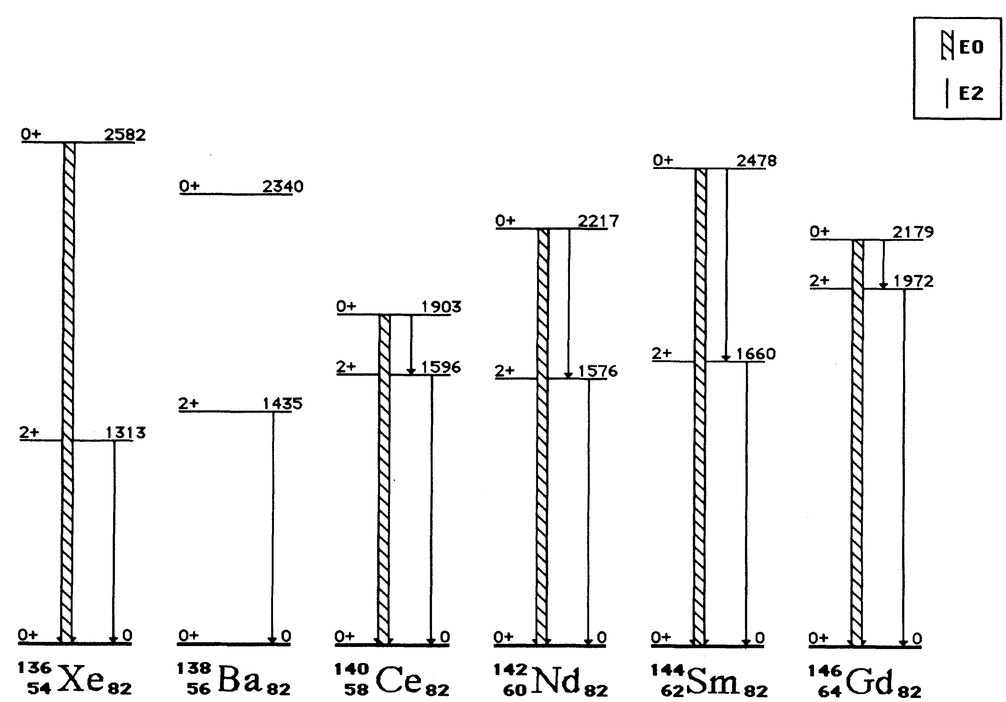

FIG. 7. Lowest excited 2^+ (2_1^+) and 0^+ (0_2^+) levels in ^{136}Xe-^{146}Gd. The $E0$ and $E2$ transitions are indicated.

TABLE II. Amplitudes of $|(j_k)^2 0^+\rangle$ configurations in $|0_i^+\rangle_{(i=1,\ldots,5)}$ states for ^{134}Te.

	0_1^+	0_2^+	0_3^+	0_4^+	0_5^+
$(1g_{7/2})^2$	0.917	−0.359	0.169	0.008	−0.001
$(2d_{5/2})^2$	0.309	0.914	0.261	0.012	−0.001
$(3s_{1/2})^2$	0.082	0.062	−0.301	−0.168	0.933
$(2d_{3/2})^2$	0.120	0.091	−0.500	0.853	−0.024
$(1h_{11/2})^2$	−0.202	−0.152	0.750	0.494	0.359

the possible 167- and 292-keV transitions. No gamma rays have been reported at those energies in any of the highly detailed investigations of the level structure of ^{136}Xe. Decay of the 4320-keV level to the 1313-keV level would be by a transition at 3007 keV. Western *et al.* observe transitions at 2979 and 3195 keV with intensities of 0.46(4) and 0.25(3). We also observe these transitions, but our uncertainties are significantly larger, and about 25% for the latter transition. A limit of 0.2 for the transition at 3007 keV could be set from our data, and probably a lower limit can be inferred from the absence of such a transition in the paper by Western *et al.*

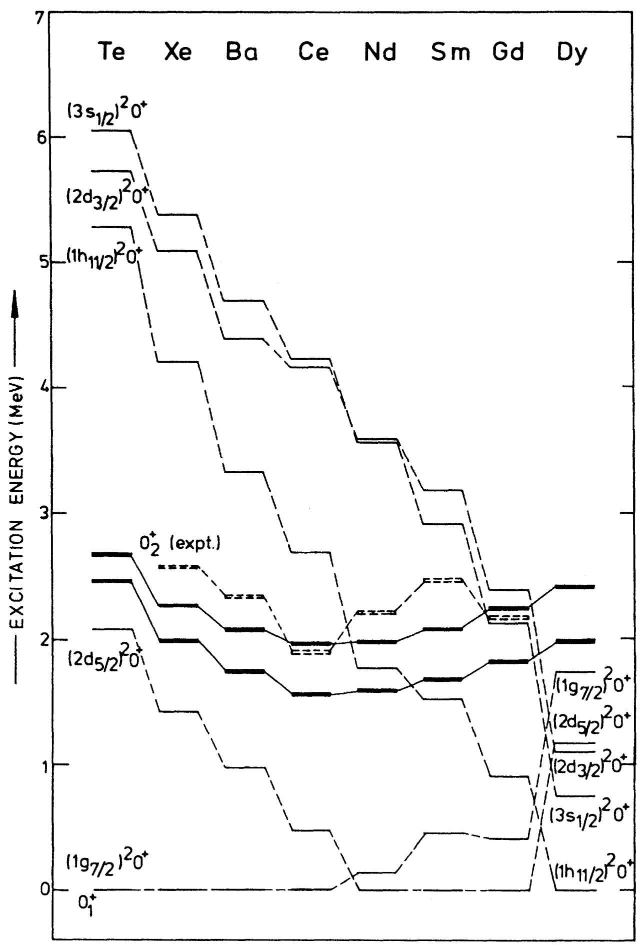

FIG. 8. Two-quasiparticle spectra for ^{134}Te to ^{148}Dy for the $0_1^+, \ldots, 0_5^+$ levels, obtained in the $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, and $1h_{11/2}$ model space. The light, full lines give the unperturbed energy to which diagonal pairing matrix elements, using $g=20/A$ MeV, are added. The lower and upper thick lines (the 0_2^+ level) correspond to the calculation using $g=20/A$ and $25/A$ MeV, respectively. The double-dashed line presents the experimental 0_2^+ excitation energy.

III. SPIN AND PARITY OF THE ^{136}I ISOMERS

There have been a variety of spin and parity assignments proposed for the isomers of ^{136}I. Lundán and Siivola identified two isomers and suggested 2^- for the 83-s isomer and 6^- or 7^- for the 40-s isomer.[9] Later Lundán suggested the presence of three isomers. From his data, he proposed a spin of 1^- or 2^- for the 83-s isomer, 3^- or 4^- for a 100-s isomer, and 5^- or 6^- for a 48-s isomer.[15] Carraz *et al.* subsequently reported data for the decay of these isomers, but could only identify the decay of two isomers.[16] Then, Erten, Coryell, and Walters reported results that indicated the presence of only two isomers and supported the 2^- suggestion for the 83-s isomer and suggested 5^- for the 42-s isomer.[17] Subsequently, Western *et al.* used mass-separated sources to produce the most detailed level scheme for the decay of the two isomers.[11] They showed that there was almost no beta population of the 4^+ levels in ^{136}Xe from the high-spin isomer and suggested either 5^- or 6^- for its spin and parity. For the low-spin isomer, they discovered that nearly all of the levels populated in its decay also populate the ground state. They did observe a possible low log ft for beta population of a level at 6624 keV that is proposed to depopulate to the 3^- level at 3275 keV and the 4^+ level at 1694 keV. On the basis of these data, they concluded that the 6624-keV level has spin 2, 3, or 4. As the strong beta decay dictates negative parity, the population of the 4^+ level sets a minimum spin of 3^-. Consequently, Burrows assigned 3^- as the spin and parity for the 6624-keV level and indicated a firm 2^- assignment for the low-spin ^{136}I isomer that is a direct result of this 3^- assignment. We note, however, that this is the only level above 3 MeV that is assigned as depopulating to the 4^+ level at 1694 keV and that there is no coincidence support for this assignment. We also note that there is no direct beta decay to the well-known 3^- level at 3275 keV, and that nearly all of the other levels directly populated in beta decay of the low-spin isomer show direct depopulation to the 0^+ ground state. This behavior is to be contrasted with the decay of the 2^- ground state of ^{142}La that has been extensively studied.[18] In the decay of that nuclide, whose ground-state configuration would be comparable to that of a 2^- ground state of ^{136}I, there is direct population of the 3^- level and many fewer of the levels populated show direct decay to the 0^+ ground state.[19]

Data for the structure of ^{136}I were provided by the study of the decay of 20-s ^{136}Te to levels of ^{136}I by Schussler *et al.*[20] From their data, it was possible to suggest spin and parity of 1^- for the low-spin isomer of ^{136}I. Walters *et al.* recently examined the systematic behavior of the structure of the odd-odd $N=83$ isomers.[21] In that work it was shown that the structure of the low-energy levels of ^{136}I would be most consistent with the theoretical analysis of multiplets in odd-odd nuclides as described by Paar[22] if the ground-state spin and parity are 1^-. The beta decay by the low-spin isomer of ^{136}I to two excited 0^+ levels in ^{136}Xe proposed in this work offers strong support for the assignment of 1^- for the low-spin isomer of ^{136}I. While indirect cascades or first-forbidden unique direct beta decay could be postulated for population of the 2582-keV 0^+ level, neither of those two modes is likely for the 0^+ level at 4320 keV. While the absence of significant beta decay to the ground state of ^{136}Xe would appear to be contrary to the 1^- assignment for the low-spin isomer, it is consistent with the proposed configuration of the 1^- isomer.

The proposed configuration of that isomer is largely $(\nu 2f_{7/2}\pi 2d_{5/2})_{1^-}$. Inasmuch as the decay of the isomer involves the conversion of the $2f_{7/2}$ neutron into a proton, the decay should lead to configurations in ^{136}Xe that involve the existing $2d_{5/2}$ proton coupled to the newly formed proton, either in a $2d_{5/2}$ orbital or in the lower-energy $1g_{7/2}$ orbital. The ground state of ^{136}Xe is largely composed of $1g_{7/2}$ protons with some occupancy of the $2d_{5/2}$ orbitals. Consequently, the beta decay of the $(\nu 2f_{7/2}\pi 2d_{5/2})_{1^-}$ isomer of ^{136}I to the ground state of ^{136}Xe would reflect the $2d_{5/2}$ occupancy of that ground state. In a recent study of the decay of the 0^- isomer of ^{134}Sb whose configuration is $(\nu 2f_{7/2}\pi 1g_{7/2})_{0^-}$ to levels of ^{134}Te, Fogelberg *et al.* have observed weak population by first-forbidden unique beta decay of 2^+ levels in ^{134}Te$_{82}$ at 2464 and 2933 keV and much stronger population of a 1^+ level at 2631 keV.[23] The levels of ^{134}Te are shown in Fig. 5 along with those of ^{136}Xe and ^{138}Ba. That 1^+ level has a nearly pure $\pi 1g_{7/2}\pi 2d_{5/2}$ configuration and lies quite close to the 2737-keV position calculated by Lane using a large-scale shell-model calculation.[24] Fogelberg *et al.* have set an upper limit of $\sim 0.1\%$ for any electron peak above 2 MeV that might originate with an $E0$ transition from a 0^+ level in ^{134}Te comparable to the one we observe in ^{136}Xe. Inasmuch as the 0^- ground state of ^{134}Sb is exclusively $(\nu 2f_{7/2}\pi 1g_{7/2})_{0^-}$, it is not surprising that population of the excited 0^+ level whose configuration is largely $(\pi 2d_{5/2})^2$ would be severely hindered. The contrast between the decays of these two nuclei serves to support the proposal that the configuration of the low-spin isomer in ^{136}I could have considerable $(\nu 2f_{7/2}\pi 2d_{5/2})$ character.

IV. STRUCTURE OF ^{136}Xe

The 12 calculated excited levels shown in Fig. 5 for ^{134}Te are all of the possible two-particle levels that can lie

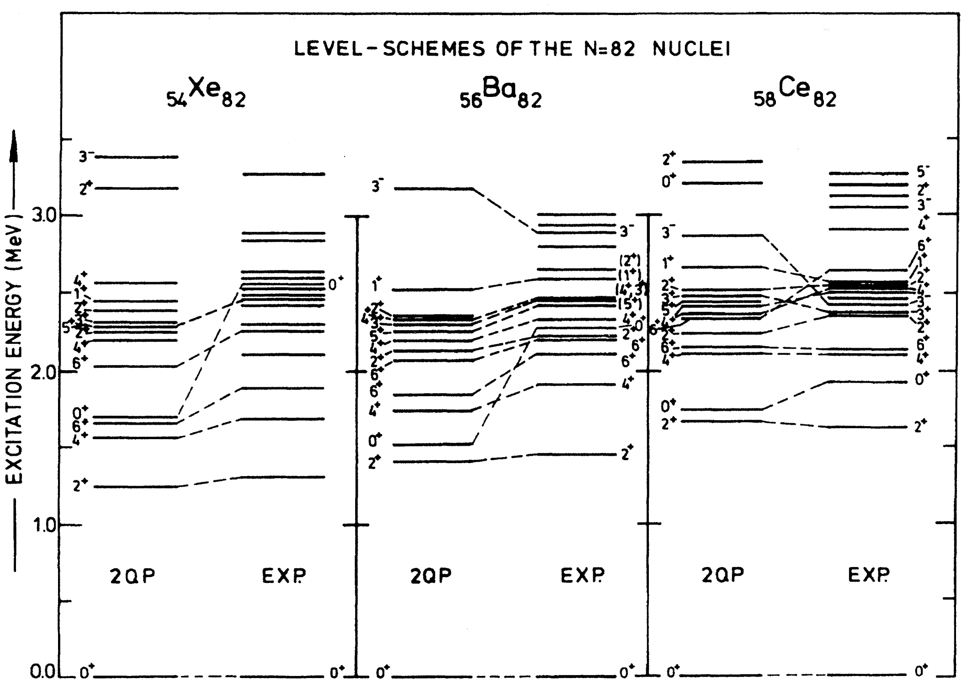

FIG. 9. Comparison between a two-quasiparticle Tamm-Dancoff approximation (TDA) calculation, using a Gaussian two-body force (Ref. 29) and the experimental data for the even-even $N=82$ nuclei, ^{136}Xe, ^{138}Ba, and ^{140}Ce nuclei.

below about 4 MeV made from combinations of two protons in either the $1g_{7/2}$ and/or $2d_{5/2}$ orbitals. The lower-energy 2^+, 4^+, and 6^+ levels have configurations that are largely $(1g_{7/2})^2$, and upper 2^+ and 4^+ along with the 0^+ at 2368 have configurations that are largely $(2d_{5/2})^2$, while the 1^+, 2^+, 3^+, 4^+, 5^+, and 6^+ levels in the middle have configurations that are largely $(1g_{7/2}-2d_{5/2})$ levels. In fact, the 1^+, 3^+, and 5^+ levels have very pure $(1g_{7/2}-2d_{5/2})$ configurations. These same 12 levels should be found in both ^{136}Xe and ^{138}Ba. In the latter nuclei, however, four-quasiparticle levels with combinations of four protons in the $1g_{7/2}$ and/or

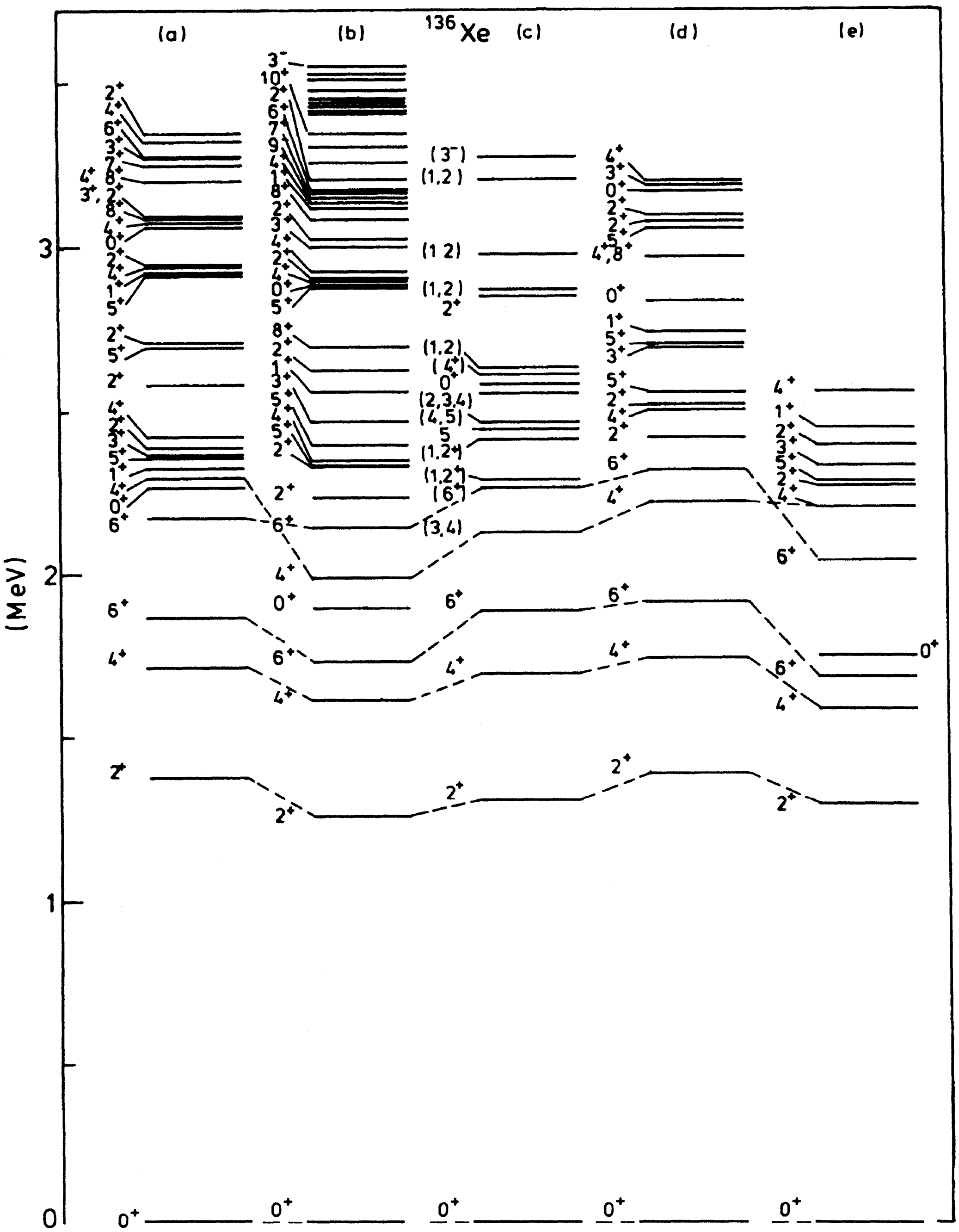

FIG. 10. Comparison of an exact four-particle shell-model calculation, carried out using the (b) method of Ref. 30 and a Gaussian residual interaction, (c) with the data from Ref. 19 and this work, and with other calculations, such as (a) the shell-model calculation of Baldridge (Ref. 33), (d) the shell-model calculations of Wildenthal and Larsson (Ref. 34), and (e) the two-quasiparticle calculations of Waroquier and Heyde (Ref. 29).

$2d_{5/2}$ orbitals will begin to appear near 3 MeV. The 8^+ level in ^{138}Ba is certainly one such level, and the 2^+ levels in ^{136}Xe near 2800 keV are also likely to have such configurations.

Several general features of the structure of these three nuclei stand out. The proton one-quasiparticle levels are shown in Fig. 6. Thus, as the gap in the one-quasiparticle $2d_{5/2}$ and $1g_{7/2}$ narrows with increasing Z, the gap between the two 6^+ levels narrows also. There is only one 5^+ level possible, and in ^{136}Xe it likely lies at 2445 keV where spin 5 was established by the angular correlation measurements reported by Berant *et al.*[25] Moreover, the positions of the pure 1^+ and 5^+ levels also move comparably lower. In like manner, the two-quasiparticle negative-parity levels also move to lower energies along with the $1h_{11/2}$ one-quasiparticle level as does the more collective 3^- level.

The total number of the possible positive-parity levels is 12. In stable ^{138}Ba that has been studied by a variety of methods including in-beam gamma-ray identification of a number of high-spin levels,[26] precisely 12 levels are found below 2800 keV. Above that point, the next three levels all have more complex configurations. The 3^- level is surely quite collective and involves the $1h_{11/2}$ orbital as well. The 0^+ level at 3610 MeV has been identified in two-neutron transfer and surely arises from a complex particle-hole configuration. And the 8^+ level is likely a four-quasiparticle configuration involving the $2d_{5/2}$ and $1g_{7/2}$ protons. Since the lowest negative-parity level with a $1h_{11/2}$-$1g_{7/2}$ simple configuration lies at 3633 keV, a $(1h_{11/2})^2$ configuration for the 8^+ level is unlikely.

In ^{134}Te, where the ^{134}Sb beta-decay parents have spins and parities of 0^- and 7^-, 8 of the 12 possible levels have been identified, namely, those with low and high spins. Missing are two 4^+ levels, the 3^+ level, and the 0^+ level. In ^{136}Xe, where the isomer spins are 1^- or 2^- and 6^-, 13 levels have been proposed below 2650 keV. We suspect that the proposed $1^+,2^+$ level at 2634 keV is actually the 1^+ level in view of its intense beta population and the absence of any transitions to the lower-energy 4^+ levels, and that the proposed $3^+,4^+$ level at 2560 keV is most likely the 3^+ level in view of the absence of indirect population in the decay of the high-spin ^{136}I isomer. The 13th level could be a somewhat depressed four-quasiparticle level.

V. EXCITED 0^+ STATES IN THE $N=82$ NUCLEI

In Fig. 7 are shown the systematics of the 2_1^+ and 0_2^+ levels in the $N=82$ isotones from $Z=54$(Xe) to the subshell closure at $Z=64$ (Gd). The data presented for the isotones from ^{140}Ce to ^{146}Gd are from the work of Julin *et al.*,[4,5] and the 0_2^+ level identified in ^{138}Ba was taken from a ^{136}Xe(^{3}He,n)^{138}Ba study of Alford *et al.*[8] The new data make clear that there is a minimum 0^+ energy at ^{140}Ce, the point where, in a most naive shell-model picture, the $1g_{7/2}$ proton orbital would be full and where the $2d_{5/2}$ orbital would start filling. Because of smearing out of the proton distribution, this shell-model discontinuity will become smoothed out somewhat. The sharpness of the filling has been discussed by Faller *et al.*[27] who noted the absence of a second low-energy $\frac{5}{2}^+$ level in ^{139}La$_{82}$ as contrasted with adjacent odd-Z $N=82$ isotones ^{137}Cs and ^{135}I. Inasmuch as that extra $\frac{5}{2}^+$ level in ^{135}I and ^{137}Cs has a $(1g_{7/2})^{\pm 3}_{5/2}$ configuration, its absence in ^{139}La serves as an indication that the $1g_{7/2}$ orbital becomes largely filled by $Z=57$ and that three holes are not present to form this configuration in ^{139}La. Subsequently, Losano *et al.* in a series of calculations reproduced the sharp differences between ^{137}Cs and ^{139}La.[28]

To understand the 0_2^+ behavior, starting from the one-quasiparticle experimental energies as deduced from the experimental data for ^{133}Sb through ^{147}Tb (shown in Fig. 6), we have carried out a simple calculation. Using the experimental energies for the $1g_{7/2}$, $2d_{5/2}$, $1h_{11/2}$, $2d_{3/2}$, and $3s_{1/2}$ orbitals, a pairing interaction was diagonalized within a two-particle basis. Using extreme values of $g=20/A$ and $25/A$ MeV as reasonable values, and the pairing matrix element $\langle (j_a)^2 0^+ | V | (j_c)^2 0^+ \rangle = -g(-1)^{la+lc}[(j_a+\frac{1}{2})(j_c+\frac{1}{2})]^{1/2}$, the spectrum of Fig.

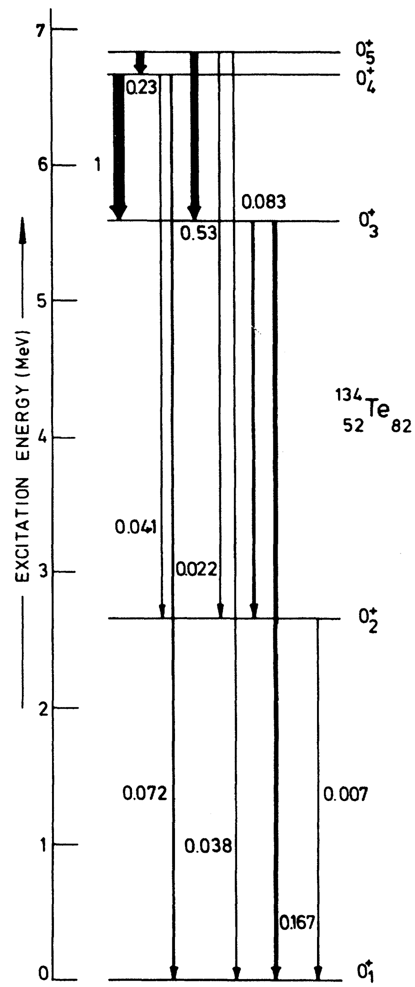

FIG. 11. Relative $E0$ reduced matrix elements $|\langle 0_f^+|M(E0)|0_i^+\rangle|^2$ in ^{134}Te for all possible $E0$ transitions as calculated in the two-particle shell-model calculations discussed in Sec. IV.

TABLE III. Reduced $E0$ transition probabilities between the 0_i^+ ($i=1,\ldots,5$) levels in ^{134}Te. Both the absolute values [in units $(\hbar/m\omega)^2$] and relative rates are presented.

$\lvert\langle 0_f^+ \lvert M(E0) \rvert 0_i^+ \rangle\rvert^2$	Absolute values $(\hbar/m\omega)^2$	Relative units
$0_2^+ \to 0_1^+$	0.0038	0.007
$0_3^+ \to 0_1^+$	0.0918	0.167
$0_4^+ \to 0_1^+$	0.0396	0.072
$0_5^+ \to 0_1^+$	0.0210	0.038
$0_3^+ \to 0_2^+$	0.0453	0.083
$0_4^+ \to 0_2^+$	0.0225	0.041
$0_5^+ \to 0_2^+$	0.0119	0.022
$0_4^+ \to 0_3^+$	0.5490	1
$0_5^+ \to 0_3^+$	0.2899	0.530
$0_5^+ \to 0_4^+$	0.1257	0.230

8 results with wave functions shown in Table II. The upper value for the position of the 0_2^+ level corresponds to the larger pairing strength. The initial drop in energy is indeed related to the drop in the quasiparticle energy for the $2d_{5/2}$ orbital. By diagonalizing the residual interaction, mainly acting amongst the $1g_{7/2}$, $2d_{5/2}$, and $1h_{11/2}$ orbitials, the unperturbed picture is modified in an important way. The 0_2^+ energy variation is quite smooth, but still goes through a minimum at ^{140}Ce. The subsequent slight increase is a consequence of the crossing of the $2d_{5/2}$ and $1g_{7/2}$ one-quasiparticle excitations. At ^{148}Dy, the $1h_{11/2}$ orbital takes over and starts dominating the 0^+ ground-state wave function. Because of the particularly large pairing matrix element for the $1h_{11/2}$ orbital, the 0_2^+ level will rise up again in excitation energy. This simple calculation reproduces rather well the 0_2^+ excitation energy in ^{146}Gd $[(1h_{11/2})^2_{0^+}]$ that is found at 2.165 MeV.

More extensive two-quasiparticle BCS calculations as performed by Waroquier and Heyde[29] have some problems with the reproduction of the 0_2^+ level, especially in the Xe and Ba nuclides as shown in Fig. 9. There is an overall indication that these calculated 0^+ energies are too low in energy. This is not so when using a surface-delta interaction (SDI) in the same two-quasiparticle calculation. Most probably, use of a finite range force is a critical facet in producing the incoherent 0^+ pair distribution for the 0_2^+ state. Moreover, the two-quasiparticle BCS calculation only conserves particle number in an average way as compared to particle number projected calculations or exact shell-model calculations.

In the case of ^{134}Te (where the two-particle space almost coincides with the two-quasiparticle space), the calculation should do quite well as is shown in Fig. 5. For ^{136}Xe, which is a nucleus with four particles outside the (50,82) double closed shell, exact shell-model calculations have been performed[30] (Fig. 10), and we compare them with the two-quasiparticle (BCS calculations of Fig. 9 and some other theoretical studies. In this case, the approximation inherent in a two-quasiparticle calculation can be tested by comparing both calculations. There, using a Gaussian force as was used in this mass region and in the two-quasiparticle calculations shown in Fig. 9, the experimental level scheme for ^{136}Xe is rather well reproduced. There, too, the 0_2^+ energy is somewhat too low in excitaion energy compared with the data and is consistent with the Gaussian force used by Waroquier and Heyde. This seems to be a general conclusion that, independent of the approximation made, a finite-range force gives the exciation of the 0_2^+ at too low an energy.

The $E0$ transition rates in these $N=82$ nuclides, where protons are filling orbitals that have $\langle r^2 \rangle_{N,l}$ values that in the harmonic-oscillator sense are identical $(1g_{7/2}, 2d_{5/2}, 2d_{3/2}, 3s_{1/2})$, will be non-negligible only when admixtures of the $1h_{11/2}$ orbital are present. Any admixture of the former four orbitals, i.e.,

$$|0_i^+\rangle = \sum a_{ik} |(j_k)^2;0^+\rangle ,$$

$$|0_f^+\rangle = \sum a_{fk} |(j_k)^2;0^+\rangle ,$$

gives the matrix element

$$\langle 0_f^+ | M(E0) | 0_i^+ \rangle = \sum_k a_{fk} a_{ik} \langle (j_k)^2 0^+ | M(E0) | (j_k)^2 0^+ \rangle ,$$

and a vanishing value results since

$$\langle (j_k)^2 0^+ | M(E0) | (j_k)^2 \rangle = 2 \langle r^2 \rangle_{N,l} ,$$

where N,l are the major oscillator and orbital quantum numbers for the orbital j_k. For ^{134}Te, using the pairing interaction of the calculation as discussed for Fig. 9, we obtain the 0^+ spectrum as shown in Fig. 11 and $E0$ transition rates as tabulated in Table III. These results should still closely resemble the case of ^{136}Xe where a two-quasiparticle calculation is to be carried out and where data have been obtained. The $0_2^+ \to 0_1^+$ transition has a small transition rate since the $(1h_{11/2})^2_{0^+}$ admixture is small and nearly equal in both configurations. [The 0_2^+ level is largely built from the $(2d_{5/2})^2$ configuration.] The $0_3^+ \to 0_1^+$ $E0$ rate is 25 times larger than the $0_2^+ \to 0_1^+$ transition rate since the 0_3^+ state contains a very large $(1h_{11/2})^2_{0^+}$ amplitude (0.75) and a non-negligible $(2d_{3/2})^2_{0^+}$ amplitude (-0.500) and is largely composed of proton excitations. This calculated enhancement is supported by its experimental observation of $E0$ decay of the 4320-keV 0^+ level as some considerable enhancement must be present for the $E0$ to be observed in view of the speed of the possible $M1$ and $E2$ transitions derived from the E_γ^3 and E_γ^5 factors.

One measure of $E0$ transition strength is the X factor defined as

$$X_{ijk} = B(E0;0_i^+ \to 0_j^+)/B(E2;0_i^+ \to 2_k^+) .$$

The systematics of these X factors have been discussed by Kantele[31] and by Colvin and Shreckenbach.[32] Using the upper limits for the gamma-ray transitions mentioned above, lower limits for X values for the decay of the 2582-keV level can be established as $X_{211} > 0.13$, $X_{213} > 0.004$, and $X_{213} > 0.003$. These are lower values that would rise if even lower limits could be established for the unobserved gamma-ray transitions. Even so, they are well within the range that would be expected, especially in view of the low $B(E2)$ values expected in this closed-shell nuclide. For example, the lower limit for X_{211} in isotonic ^{146}Gd is given by Kantele as 0.02. For the 4320-keV level, $X_{311} > 0.016$, again a value in line with observed X values in other nuclides.

Returning to the motivation for this study, namely, the nature of the 0^+ levels that lie at a nearly constant energy of 2500 keV in the even-even Xe nuclei, it would appear likely that the important components of these states must involve the $(1h_{11/2})^2_{0^+}$ configuration. Inasmuch as the $2d_{5/2}$ and $1g_{7/2}$ single-particle states invert as N decreases from 82 to 50 in the Sb nuclides, while the $1h_{11/2}$ state remains at a relatively high energy, it is this latter configuration that will provide the $E0$ strength necessary to compete with the alternate $M1$ and/or $E2$ transitions that become increasingly collective near midshell. In ^{122}Xe, where the strong $E0$ is observed from a level at 2520 keV, the $X_{212}=0.35$. In view of the much larger collectivity in these midshell nuclides, a considerably enhanced $E0$ strength must be present to compete with the enhanced $E2$ decay rates.

VI. CONCLUSION

New conversion-electron data for the decay of ^{136}I isomers have permitted the placement of a new 0^+ level in ^{136}Xe at 2582 keV and a tentative placement of a second 0^+ level at 4320 keV. The population of these 0^+ levels in beta decay gives support to the possibility of a 1^- spin and parity assignment for the low-spin isomer of ^{136}I. The new 0^+ levels have permitted a reevaluation of calculations of the structure of the $N=82$ nuclei including ^{136}Xe, where the 0_2^+ level has been found to be higher than most of previous theoretical calculations. The systematic changes in the position of the 0^+ levels in the $N=82$ nuclei are now relatively well understood as moving up and down with the crossing, first of the $2d_{5/2}$ and $1g_{7/2}$ one-quasi-particle levels and, at higher Z, the crossing of the $1h_{11/2}$ one-quasiparticle level. The observed strength of the $E0$ transitions has been identified with the admixture of $(1h_{11/2})^2$ configuration. It is possible to suggest that the $E0$ transitions that are observed for the series of 0^+ levels in the lower-mass Xe nuclei that lie near 2500 keV also arise from the admixture of the $(1h_{11/2})^2$ configuration present in those levels.

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