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^{136}Xe$(p, p')^{136}$Xe and ^{136}Xe$(p, d)^{135}$Xe Reactions*

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Low-lying states of ^{136}Xe with excitation energies up to 3.3 MeV are investigated via inelastic scattering of 13.982-MeV protons. Spin, parity, and deformation parameters are extracted for 13 excited states through distorted-wave Born-approximation (DWBA) analysis using a collective-model form factor. The results obtained indicate that ^{136}Xe is not a typical vibrational nucleus. A microscopic calculation for the level spectrum and the inelastic form factor, based on the quasiparticle random-phase approximation, is performed. DWBA angular distributions are calculated using a microscopic form factor. The level spectrum and the absolute magnitudes of the cross sections for most of the 4^+, 6^+, and 3^- observed states are reasonably well reproduced through these calculations. For the 2^+ states, however, the predicted level density and the distribution of the inelastic strengths disagree with the observed data. In addition, three deuteron groups leading to states of ^{135}Xe are observed. The orbital-angular-momentum-transfer values and the spectroscopic factors for these states are obtained through DWBA analysis of the data.

I. INTROUDCTION

The inelastic scattering of protons is a useful spectroscopic tool for the investigation of nuclear energy levels. Analysis of experimental data is usually carried out in the framework of the distorted-wave Born approximation (DWBA) using a collective-model form factor. The angular distribution of a particular excited state is characteristic of the orbital angular momentum transfer, which gives information on the spin and parity of the state. From the absolute magnitude of the cross section, one can extract information on the nuclear correlations in a particular excited state. For many even-even nuclei the inelastic scattering cross sections, particularly of the low-lying first 2^+ and 3^- collective states, have rather large magnitudes, indicating that the coupling between these states and the ground state is strong and consequently that the DWBA theory is not sufficiently accurate. In such cases one may improve the analysis by making use of the coupled-channel (C.C.) approximation instead of the DWBA. On the other hand, there are many cases where the low-lying spectra do not show typical vibrational character and where the inelastic cross sections are of rather small magnitudes. In such cases the description of the scattering in terms of a collective-model form factor is questionable and the use of a microscopic form factor would be more appropriate.

In this paper we report the results of a study of the ^{136}Xe$(p, p')^{136}$Xe and ^{136}Xe$(p, d)^{135}$Xe reactions. The low-lying states of ^{136}Xe have been the subject of considerable theoretical investigation,[1-4] but have received little experimental attention compared with the other stable $N = 82$ even-even nuclei.

Moore, Riley, Jones, Mancusi, and Foster,[5] in a study of the (p, p') reaction through isobaric analog resonances (IAR), measured angular distributions of excited states of ^{136}Xe, nearly all of which were above 3.5 MeV in excitation. These high-lying states were interpreted as excitations of the closed neutron core, i.e., neutron-particle-hole states formed by lifting a neutron in the closed core into an orbit in the next major shell. Moore *et al.*,[5] however, made tentative spin and parity assignments to two states below 3.5 MeV excitation, namely 2^+ for the 1.31-MeV state and 3^- for the 3.26-MeV state. β-decay studies of ^{136}I isomers have been reported by Carraz, Blachot, Monnand, and Moussa[6] and by Lundan.[7] The spin assignments made in these studies were not unique, except for the few lowest states. The present ^{136}Xe(p, p') experiment was thus carried out in order to study the structure of the low-lying states of ^{136}Xe. The measurements were carried out at an incident proton energy of ~14.0 MeV. Because of the low (p, n) threshold (~0.9 MeV), it is reasonable to expect that the low-lying inelastic states would be populated predominantly through direct reaction processes. Since ^{136}Xe has a ground-state spin 0^+ (even-even), the transferred orbital angular momentum in a (p, p') reaction is equal to J of the final state and an unambiguous spin assignment to the inelastic states should thus be possible.

II. EXPERIMENTAL PROCEDURE AND Q-VALUE DETERMINATION

The target gas of ^{136}Xe, isotopically enriched to 91%, was contained in a 3-in.-diam gas cell with 120-μin.-thick walls and rectangular $\frac{5}{16}$ in. × $\frac{7}{16}$ in. nickel beam entrance and exit windows 10 and 25 μin. thick, respectively. The gas pressure was approximately 0.025 atm corresponding to a target thickness of approximately $(300/\sin\theta_{\text{lab}})$ μg/cm^2. Further experimental details are given in Hollas *et al.*[8] The angular distribution data were taken at 20 laboratory angles between 30 and 160°, at an incident center-of-target proton energy of 13.982 MeV. The proton beam was provided by The University of Texas EN tandem Van de Graaff accelerator injected by the CN Van de Graaff accelerator. The over-all experimental proton resolution was approximately 38 keV. Proton groups leading to 24 excited states in ^{136}Xe with excitation energy up to 5.22 MeV were identified. In addition, three states of ^{135}Xe, the ground state and two excited states, populated via the reaction ^{136}Xe$(p, d)^{135}$Xe, have been identified in the spectra. A representative spectrum taken at the laboratory angle of 75° is shown in Fig. 1. The excitation energies are shown in the figure. The spectrum also indicated the presence of contaminants attributed to ^{134}Xe, oxygen, nitrogen, and carbon. The over-all uncertainty in the measured cross section is of the order of ±5% (standard deviation).

The Q values of all the observed inelastic proton groups and of the deuteron groups were obtained by means of a least-squares-fitting code, using the peak locations of (1) ^{136}Xe, ^{16}O, ^{14}N, and ^{12}C elastic states, and (2) the ^{12}C first excited state. Corrections were applied for loss of energy of reaction particles in passing through the exit gas and Mylar walls using the tables of Williamson and Boujot.[9] A quadratic fit was employed to compensate for the nonlinearity of the energy loss and possible nonlinearity introduced by the electronics. The procedure was repeated for 10 different observation angles. The Q-value determinations for a given group were checked for consistency and averaged. The absolute uncertainty in the Q-value (hence excitation energy) determinations is believed to be ±15 keV.

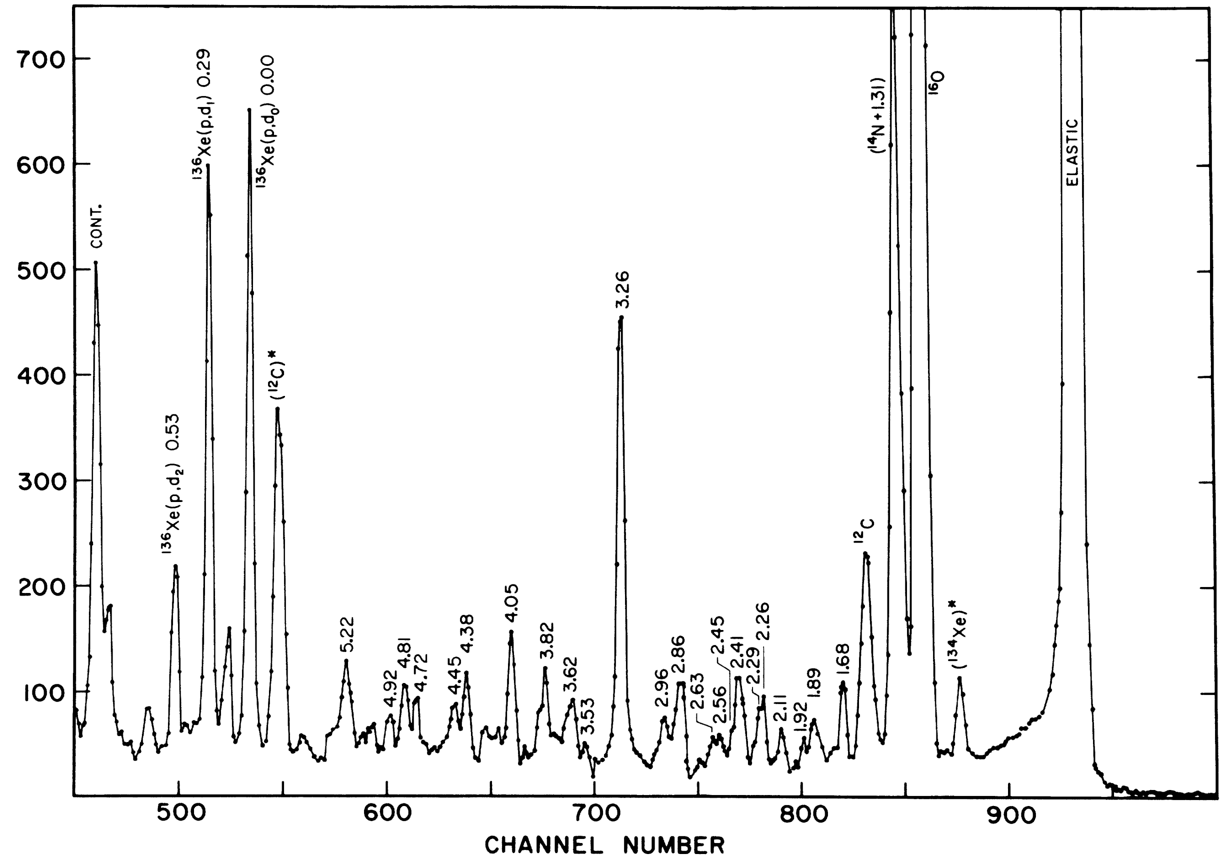

FIG. 1. ^{136}Xe$(p,p')^{136}$Xe pulse-height spectrum at an incident proton energy of 13.982 MeV and laboratory angle of 75.0°.

TABLE I. Proton-optical-model-potential parameters describing ^{136}Xe$(p, p)^{136}$Xe elastic scattering angular distribution at 13.973 c.m. proton energy.

Set	V (MeV)	r_0 (fm)	a_r (fm)	W_D (MeV)	r_i (fm)	a_i (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_c (fm)
P	52.46	1.26	0.69	11.08	1.26	0.65	8.0	1.24	0.65	1.25
BG	57.18	1.77	0.77	9.49	1.30	0.70	6.2	1.01	0.75	1.30

III. ELASTIC ANALYSIS

The elastic scattering cross sections were analyzed in terms of the optical model. The following conventional form of the potential with a surface-absorption term and a real Thomas-type spin-orbit term was used:

$$V(r) = -V(1+e^{x})^{-1} + 4iW_D \frac{d}{dx'}(1+e^{x'})^{-1} \quad \text{(central)}$$

$$+V_{so}\left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{|\vec{s}|}\frac{1}{r}\frac{d}{dr}(1+e^{x''})^{-1}\vec{l}\cdot\vec{s} \quad \text{(spin-orbit)}$$

$$+V_c(r) \quad \text{(Coulomb)},$$

where

$$V_c(r) = (Ze^2/2r_c)(3 - r^2/r_c^2), \quad r \le r_c$$

$$= Ze^2/r, \quad r > r_c,$$

$$x = (r - r_0 A^{1/3})/a_r;$$

$$x' = (r - r_i A^{1/3})/a_i,$$

$$x'' = (r - r_{so} A^{1/3})/a_{so}.$$

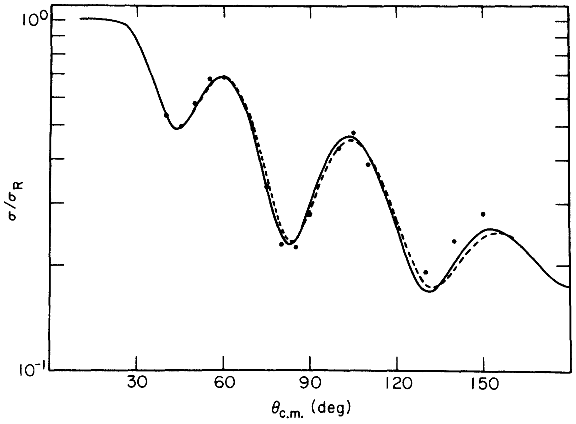

FIG. 2. Optical-model fit to the ^{136}Xe$(p, p)^{136}$Xe elastic scattering data. The cross section is shown as ratio to the corresponding Rutherford cross section. $E_{c.m.} = 13.877$ MeV. The solid line represents the optical-model fit and the dashed line, the C.C. fit.

The potential parameters were searched using a code written by Perey,[10] and starting with two sets of average parameters of Perey[11] and of Becchetti and Greenlees.[12] Correspondingly, two sets of potential parameters designated as P and BG that each gave an equally good fit to the elastic scattering data (approximately same χ^2) were obtained. The final values of the parameters are listed in Table I. These two sets can also reproduce the observed inelastic angular distributions equally well. The set P was arbitrarily chosen for the inelastic analysis described in the following sections. The optical-model fit to the elastic data generated by set P is shown by the solid line in Fig. 2.

IV. ANALYSIS OF THE INELASTIC ANGULAR DISTRIBUTIONS

The present investigation concerns the analysis of the 14 low-lying states in ^{136}Xe with excitation energies below 3.3 MeV. The inelastic angular distribution data have been analyzed in the DWBA using a collective-model complex form factor to obtain information on the spins, parities, and deformation parameters of these states. The level spectrum thus obtained and the absolute magnitude of the cross sections will be compared with the predictions of a microscopic calculation discussed in the next section.

The optical-potential parameters for the entrance channel were chosen as those of set P of the previous section. For the exit channel, the same set of geometrical parameters were used but the real and imaginary well depths were varied with the energy of the outgoing particle according to the expressions, $V = V_0 - 0.32E$ and $W = W_0 + 0.25E$.[12] Numerical calculations were carried out using the code DWUCK.[13]

The experimental angular-distribution data together with the DWBA fits are displayed in Fig. 3 (solid lines) and Fig. 4. The errors shown are statistical; where the error bars are not used, the size of the data points indicates the approximate statistical errors. In Fig. 4, fits generated using a real, collective-model form factor have been included for comparison in some cases.

The deformation parameters (β_l) were obtained by normalizing the calculated cross sections to the experimental data at forward angles.

The excitation energies, spins, parities, and the β_l values obtained from the analysis are listed in Table II. Comparisons with the spin-parity assignments deduced from the β decay of ^{136}I isomers by Carraz *et al.*[6] are also shown.

A. Collective 2^+ and 3^- States

The states with excitation energies 1.305 and 3.263 MeV are the most strongly excited of the low-lying states of ^{136}Xe and are believed to be the collective one-phonon quadrupole and octupole states, respectively. They are fitted with $l = 2$ and $l = 3$ transfers, respectively, as shown in Fig. 3. The extracted β_2 value (=0.06), which is about two times the single particle value, is rather small compared with the β_2 values (~0.2) of typical vibrational nuclei. This is probably due to the fact that ^{136}Xe has only four protons outside a doubly-magic core. Thus the β_2 value may be better compared, for instance, with that of ^{204}Pb ($\beta_2 = 0.057$),[14] which has just four neutron holes outside a doubly-magic core.

Even though the collectivities are rather small, the above two states are most strongly excited. It may thus be interesting to reanalyze the data by using the C.C. method, which takes into account the coupling between the elastic and inelastic channels exactly. Such a calculation has been performed using the code JUPITOR [15] with the same potential parameters as before except that W_D was reduced by 10% following the suggestion of Tam-

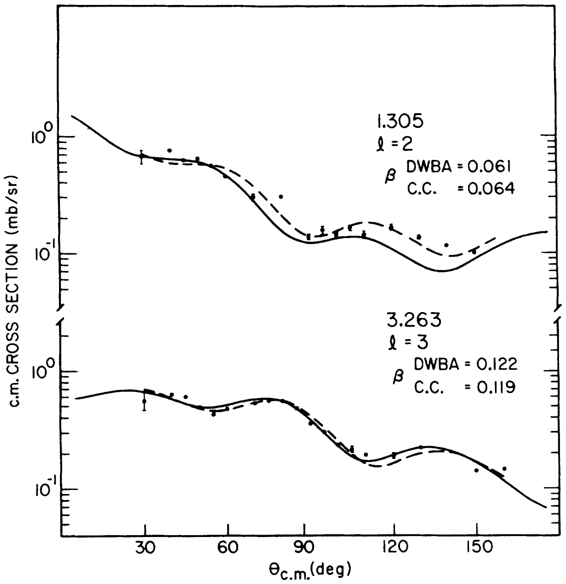

FIG. 3. DWBA (——) and C.C. (---) fits to the angular distribution data for the 1.305- and 3.263-MeV states of ^{136}Xe from the reaction $^{136}\mathrm{Xe}(p,p')^{136}\mathrm{Xe}$. Where error bars are not used, the size of the data point indicates the approximate statistical error in the cross section. $E_{\mathrm{c.m.}} = 13.877$ MeV.

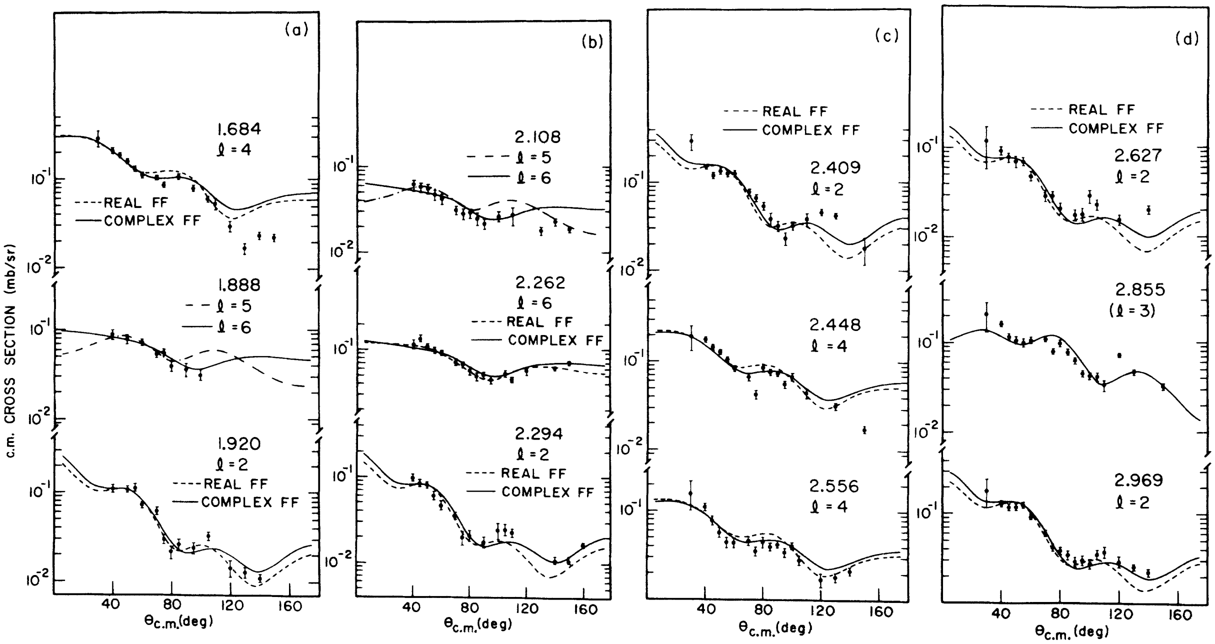

FIG. 4. DWBA fits to the $^{136}\mathrm{Xe}(p,p')^{136}\mathrm{Xe}$ angular distribution data using collective-model form factor. The l-value transfers and the excitation energies in MeV are indicated. $E_p(\mathrm{c.m.}) = 13.877$ MeV.

ura.[16] The C.C. fits to the 0^+ ground state and the 2^+ and 3^- collective states are shown by dashed lines in Figs. 2 and 3. The β_l values determined by the C.C. method are found to be almost the same as those obtained from DWBA.

B. Other Low-Lying Excited States

Except for the 1.305- and the 3.263-MeV states, the low-lying states below 3.3 MeV are all weakly excited. DWBA analysis of these states using a collective-model form factor, however, provides almost uniquely the l value, which in turn enables the spin and parity assignments to be made to these states.

The angular distribution of the states with excitation energies 1.684, 2.448, and 2.556 MeV are all fitted reasonably well assuming an $l = 4$ transfer, implying $J^\pi = 4^+$ for these states. Carraz *et al.*[6] have assigned $J^\pi = 4^+$ to the 1.684-MeV state. A J value of either 3 or 4 was also suggested for this level in a recent report on the conversion-coefficient measurements of transitions between low-lying levels of ^{136}Xe by Achterberg *et al.*[17] These are consistent with the present assignment of $J^\pi = 4^+$. From the systematics of the other $N = 82$ isotones, one also expects to observe a 4^+ state around this excitation energy. The 2.444-MeV state has not been previously reported. For the 2.556-MeV state, a probable spin-parity assignment of $(2, 3)^\pm$ was made by Erten[18] from the β-decay studies in ^{136}I, which is inconsistent with the $l = 4$ observed in the present work. The extracted β_l values for all these $l = 4$ states are relatively small; the values on the average, are approximately 1.7 times the single-particle estimate.

The angular distributions of the 1.888- and 2.108-MeV states are equally well reproduced by either $l = 5$ or $l = 6$ transfer. The 2.262-MeV state is better fitted with $l = 6$ than with $l = 5$ transfer. We have, therefore, assigned $J^\pi = 6^+$ to the 2.262-MeV state. The 1.888-MeV state is partially masked in the spectra by a contaminant believed to be due to inelastic scattering from ^{134}Xe, present as an 8.6% impurity in the target gas. The angular-distribution data for this state could be extracted only for a few angles by comparison with auxiliary spectra from natural xenon. At backward angles, the statistics were too poor for reliable cross section extraction. Achterberg *et al.*[17] suggest a positive parity for the 1.888-MeV state. We have, therefore, assigned $J^\pi = 6^+$ to this state. The 6^+ assignment is also in agreement with the systematics of the level scheme of neighboring $N = 82$ isotones. We have also assigned 6^+ to the 2.108-MeV state; this assignment should, however, be regarded as tentative. The extracted β_l values for the 1.888-, 2.108-, and 2.262-MeV states are all rather small and are on the average two times the single-particle estimate.

States with excitation energies 2.294, 2.627, and 2.969 MeV have all been fitted with an $l = 2$ transfer and consequently, have been assigned

TABLE II. Summary of results of DWBA and C.C. analysis of the states of ^{136}Xe via ^{136}Xe(p, p')^{136}Xe using a collective-model form factor. E_x is the excitation energy, l is the orbital angular momentum transfer, J^π is the final state spin-parity, and β_l is the deformation parameter.

	Present work					Carraz *et al.* (Ref. 6)	
Level No.	E_x (MeV)	l	J^π	β_l (DWBA)	β_l (C.C.)	E_x (MeV)	J^π
1	1.305	2	2^+	0.061	0.064	1.3133	2^+
2	1.684	4	4^+	0.054		1.6948	(4^+)
3	1.888	6(5)	$6^+(5^-)$	0.053		1.8923	$(5^-, 6^+)$
4	1.920	2	2^+	0.026			
5	2.108	6(5)	$6^+(5^-)$	0.045			
6	2.262	6	6^+	0.064		2.2628	(7^-)
7	2.294	2	2^+	0.025		2.289	$(1, 2)^\pm$
8	2.409	2	2^+	0.033		2.415	$(1, 2)^\pm$
9	2.448	4	4^+	0.050			
10	2.556	4	4^+	0.036			
11	2.627	2	2^+	0.025		2.6346	(2^+)
12						2.849	$(3, 4)^\pm$
13	2.855					2.854	$(2, 3, 4)^\pm$
14						2.869	$(1, 2)^\pm$
15	2.969	2	2^+	0.035			
16	3.263	3	3^-	0.122	0.119	3.276	(3^-)

$J^\pi = 2^+$. One other observed state at 1.920 MeV has not been previously reported. This state is partially masked by a heavy contaminant peak, permitting data extraction for a limited number of angles. The limited data are, however, reasonably well reproduced by $l = 2$ transfer and this state is also assigned $J^\pi = 2^+$. For these four 2^+ states, the extracted β_l values are rather small and are of the order of single-particle estimates.

The proton peak corresponding to the excitation energy 2.855 MeV is broad and is believed to be a doublet or higher multiplet. In fact, Carraz *et al.*[6] observed three states with excitation energies 2.849, 2.854, and 2.869 MeV in this energy neighborhood. Consequently, data with better experimental resolution is necessary for a more meaningful spin assignment, and the $l = 3$ fit shown in Fig. 3(d) should not be taken seriously.

C. Discussion

The above analysis clearly shows that the level structure of ^{136}Xe is not of typical vibrational character. For example, the 4^+ and 6^+ states are observed well below twice the excitation energy of the first excited 2^+ state. The nonvibrational (or noncollective) character can also be seen in the present observations that (i) the extracted deformation parameters for the first 2^+ and 3^- excited states are rather small compared to those found in typical vibrational nuclei and that (ii) the inelastic scattering strength is distributed over a number of levels.

The low-lying excited states observed in the present experiment are expected to consist mainly of proton-single-particle (two-quasiparticle) excitations, since the neutron shell is closed. In the next section, the observed spectra and the absolute magnitudes of the cross sections are compared with the theoretical predictions obtained from a microscopic calculation.

TABLE III. Single-particle states used in the microscopic calculation.

Proton orbitals	Energy relative to $1g_{7/2}$ orbit (MeV)	Neutron orbitals	Energy relative to closed $N = 82$ core (MeV)
$1f_{5/2}$	−7.50	$2d_{5/2}$	−3.65
$2p_{3/2}$	−6.90	$1g_{7/2}$	−2.90
$2p_{1/2}$	−5.80	$1h_{11/2}$	−2.60
$1g_{9/2}$	−4.80	$3s_{1/2}$	−2.36
$1g_{7/2}$	0.00	$2d_{3/2}$	−2.07
$2d_{5/2}$	+0.74	$2f_{7/2}$	+1.81
$1h_{11/2}$	+2.18	$1i_{13/2}$	+2.41
$2d_{3/2}$	+2.88	$3p_{3/2}$	+2.93
$3s_{1/2}$	+3.20	$2f_{5/2}$	+3.20
		$3p_{1/2}$	+3.44
		$1h_{9/2}$	+3.71

V. MICROSCOPIC CALCULATIONS

The excitation energies of the levels observed in the present experiment are very close to or little higher than twice the energy gap. One may, therefore, consider that these states are essentially two-quasiparticle states. The theoretical calculations are thus performed in the framework of the quasiparticle random-phase approximation (QRPA).[19-22] The simple model assumed is that the residual nuclear interaction consists of pairing and multipole-multipole interactions.[22] Higher-order multipole components of the pairing force were also included. The single-particle states considered in the present calculation and the single-particle energies are summarized in Table III. (The energies were taken from Ref. 22.) The pairing-interaction strengths G_n and G_p and the multipole-multipole interaction strengths F_{nn}, F_{pp}, and F_{np} were adjusted so that the calculated energy of the lowest state for a given spin and parity is close to that of the lowest observed state. This criterion was, however, not applied to the 3^- state, because the energies chosen give an unperturbed 3^- state with excitation energy close to the collective 3^- state. In this case, values which are consistent with a systematic calculation of 3^- states[23] were used and are listed in Table IV. The F and G parameters for the 2^+, 4^+, and 6^+ states are in good agreement with those used in other works.[22, 24, 25] The predicted energy eigenvalues, the dominant configurations of these states, and the excitation energies of the corresponding observed states are also given in Table IV.

The inelastic form factors were calculated using a Gaussian two-body force depth of 30.0 MeV and range 1.85 fm. The DWBA calculations were performed using the code VENUS.[26] The fits to the angular-distribution data are shown in Fig. 5. The calculated cross sections have been normalized to the data to illustrate better the agreement in shapes. The normalization constants are listed in Table IV.

A. 2^+ States

The present calculation predicts the lowest 2^+ state to be at 1.306 MeV, which is a collective one-phonon state. In addition to the main configuration of $\pi[(g_{7/2})^2]$ (two-proton-quasiparticle state), this state contains about a 20% admixture of other two-quasiparticle configurations which contribute coherently to the inelastic scattering processes. This explains the observed enhancement of the cross section to the lowest 2^+ state at 1.305 MeV. The DWBA calculation using the microscopic form factor reproduces well the shape of the observed angular distribution but the predicted enhancement is found to be too large by about a factor of 3 with the present choice of parameters.

The calculation predicts two additional 2^+ states below 3.3 MeV, at 2.137 and 2.410 MeV, respectively, while five additional 2^+ levels were identified experimentally. In addition to this discrepancy, the calculation cannot explain the fairly large fractionation of the 2^+ transition strength. Each of the five observed transitions have cross sections close to one half of that of the collective state; the sum of their cross sections exceeds that of the collective 2^+ state. The calculated cross sections of the predicted 2.137- and 2.410-MeV states are, respectively, ~1/200th and ~1/7th of that of the 1.306-MeV collective state. (The predicted 2.410-MeV state has approximately the same strength and angular distribution as the experimentally observed 2.409-MeV state, as is shown in Fig. 5.) The summed strength of the 2.137- and 2.410-MeV states is thus only 15% that of the 1.306-MeV state.

Due to the above discrepancies, a detailed analysis of the cross sections for individual 2^+ levels is not meaningful. The discrepancies may be due to the fact that in the present calculation we have included only two-quasiparticle states. In fact, four-quasiparticle states are expected to occur starting around 2.6 MeV, i.e., twice the energy of the lowest 2^+ state. The inclusion of four-quasiparticle states as well as the mixing between the two- and four-quasiparticle states would explain the above discrepancy of the level density. Another

TABLE IV. Summary of the results obtained from the microscopic calculation. E_{th} is the predicted energy.

Spin parity	G_n	G_p	F_{nn}	F_{pp}	F_{np}	E_{th} (MeV)	Dominant configurations[a] π: proton ν: neutron	E_x (MeV)	Normalization
2^+	0.045	0.044	0.050	0.050	0.045	1.306	$\pi[81\%(g_{7/2})^2]$	1.305	2.85
								1.920	
						2.137	$\pi[86\%(g_{7/2}d_{5/2})]$		
								2.294	
								2.409	
						2.410	$\pi[80\%(d_{5/2})^2]$		
								2.627	
								2.969	
						3.588			
						4.099			
						4.357			
4^+	0.024	0.024	0.024	0.024	0.024	1.688	$\pi[99\%(g_{7/2})^2]$	1.684	2.3
						2.141	$\pi[99\%(g_{7/2}d_{5/2})]$	2.448	0.12
						2.562	$\pi[99\%(d_{5/2})^2]$	2.556	1.1
						4.022			
						4.276			
						4.364			
6^+	0.020	0.020	0.020	0.020	0.020	1.732	$\pi[99\%(g_{7/2})^2]$	1.888	0.75
						2.098	$\pi[99\%(g_{7/2}d_{5/2})]$	2.108	0.35
								2.262	
						4.353			
						4.460			
						4.773			
3^-	0.000	0.000	0.004 75	0.004 75	0.004 75	2.855	$\pi[10\%(h_{11/2}g_{7/2}),\ 18\%\ (h_{11/2}d_{5/2})];\ \nu[18\%\ (f_{7/2}s_{1/2}^{-1}),\ 10\%\ (f_{7/2}d_{3/2}^{-1}),\ 17\%\ (i_{13/2}h_{11/2}^{-1})]$	3.263	0.64
						3.342			
						3.794			
						3.957			
						4.421			

[a] Shown for low-lying predicted states only.

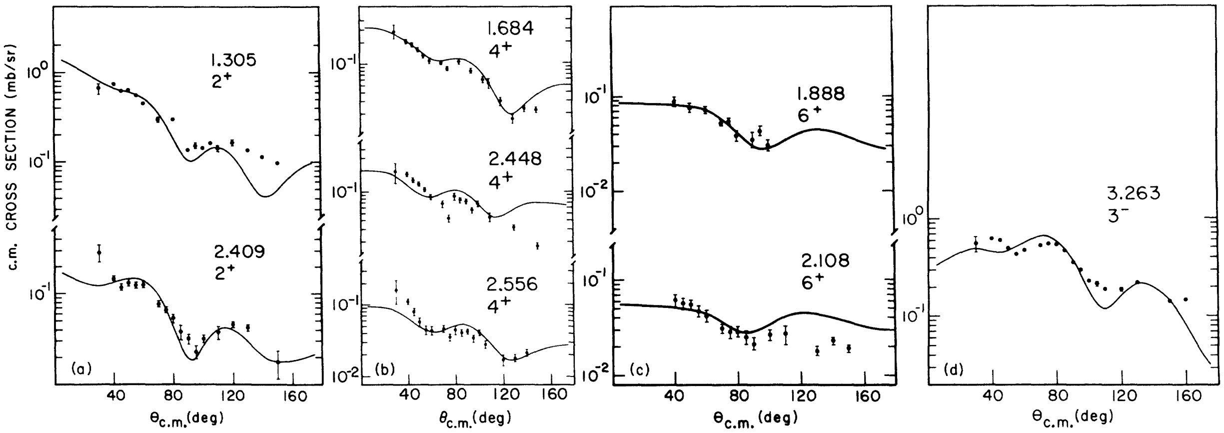

FIG. 5. DWBA fits to the ^{136}Xe$(p,p')^{136}$Xe angular-distribution data using microscopic form factor. The spin-parity and the experimental excitation energy in MeV are indicated. E_p(c.m.) = 13.877 MeV.

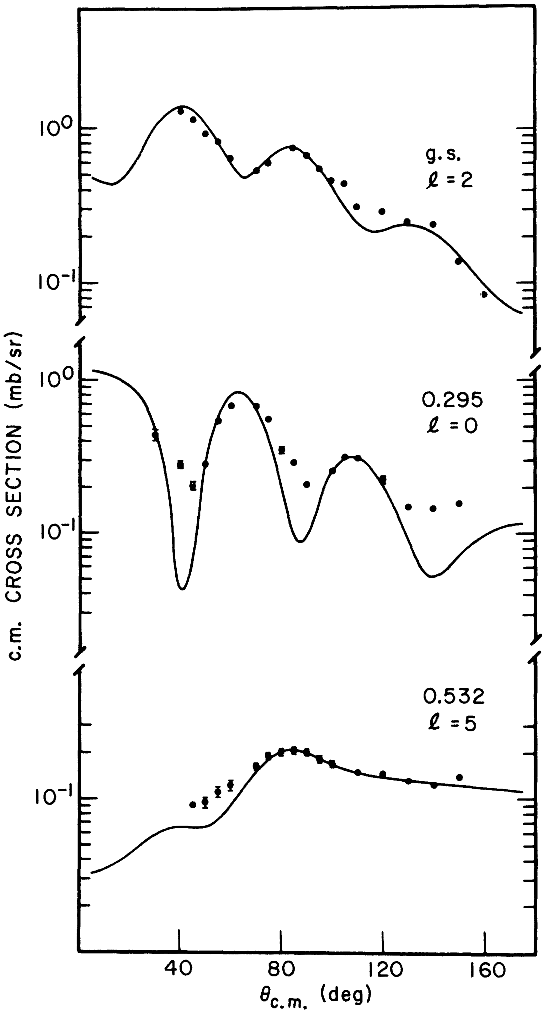

FIG. 6. DWBA fits to the ^{136}Xe$(p,d)^{135}$Xe angular distribution data. The excitation energies in MeV and the l-value transfers are indicated. E_p(c.m.) = 13.877 MeV.

source of disagreement between experiment and theory could be the use of a simple model of pairing plus multipole-multipole force as the residual interaction.

Beyond 3.3 MeV excitation the calculation predicts a number of 2^+ states, but the calculated cross sections are found to be from two to three orders of magnitude smaller than the cross sections of the observed low-lying states.

B. 4^+ States

The calculation predicts three states below 3.3 MeV, at 1.688, 2.141, and 2.562 MeV. These can be well compared with the observed states with excitation energies 1.684, 2.448, and 2.556 MeV, respectively. The calculated cross sections for the 1.688-MeV states are about twice the observed cross sections for the 1.684-MeV state. The predicted cross sections of the 2.562-MeV state are in good agreement with the cross sections of the corresponding observed state at 2.556 MeV. The calculated cross sections for the 2.141 state are, however, an order of magnitude smaller than those of the corresponding experimental state. The rest of the predicted 4^+ states lie above 4.0 MeV. Some of these states have cross sections comparable to those of low-lying states and have considerable neutron-particle-hole admixtures. The observation of these states through direct inelastic scattering is difficult and they were more clearly seen in (p,p') reaction through IAR's.

C. 6^+ States

Two 6^+ states at 1.732 and 2.098 MeV are predicted below 3.3 MeV and can be compared with the 1.888- and 2.108-MeV observed states, respectively. The calculated cross sections of the 1.732-

TABLE V. Summary of the results of DWBA analysis of the ^{136}Xe(p, d)^{135}Xe angular distribution. S_J is the spectroscopic factor.

	Present work ^{136}Xe(p, d)^{135}Xe				Heyde *et al.* (Ref. 31)			Moore *et al.* (Ref. 32) ^{136}Xe(d, t)^{135}Xe		
E_x (MeV)	l	J^π	S_J	E_x ^{a} (MeV)	J^π	S_J	E_x (MeV)		J^π	S_J
0.00	2	$\frac{3}{2}^+$	3.86	0.00	$\frac{3}{2}^+$	3.6	0.00	2	$\frac{3}{2}^+$	3.96
0.295	0	$\frac{1}{2}^+$	1.65	0.30	$\frac{1}{2}^+$	1.6	0.28	0	$\frac{1}{2}^+$	1.86
0.532	5	$\frac{11}{2}^-$	11.31	0.53	$\frac{11}{2}^-$	11.2	0.51	5	$\frac{11}{2}^-$	9.83

^{a} Extracted from graph.

MeV state are in reasonable agreement with those of the observed 1.888-MeV state. The calculated cross sections of the 2.098-MeV state are, however, a factor of three lower than those of the corresponding observed state. The rest of the 6^+ states are predicted above 4.0 MeV and have small cross sections, at most two orders of magnitude smaller than those observed experimentally.

D. 3^- States

The predicted 3^-, 2.855-MeV state has been assumed to correspond to the experimental 3.263-MeV state, since this state is the only observed strong 3^- state having cross sections close to the predicted cross sections. The rest of the predicted 3^- states have cross sections from one to two orders of magnitude smaller.

In addition to the 2^+, 4^+, 6^+, and 3^- states discussed above, calculations were also performed for the 5^- states. It was found that the predicted energies were rather high and above the region of interest in the present investigation.

VI. ^{136}Xe(p, d)^{135}Xe REACTION

In addition to the inelastic proton groups, three relatively strong deuteron groups leading to states in ^{135}Xe via the reaction ^{136}Xe(p, d)^{135}Xe have been observed in the present work and are identified as the ground state, the 0.295-MeV state, and the 0.532-MeV state of ^{135}Xe. The angular-distribution data have been analyzed using the zero-range code VENUS[26] modified to include a correction for nonlocality of the optical potential.[27] The nonlocality lengths $\beta(p)$ and $\beta(d)$ for the proton and deuteron channels were chosen to be[28]

$$\beta(p) = 0.85 \text{ fm}, \quad \beta(d) = 0.54 \text{ fm}.$$

The proton-optical-potential parameters used are those of set P. The deuteron parameters[29] are slightly different from the average deuteron potential parameters in this mass neighborhood.[30]

The bound-state neutron wave functions were calculated using the code NEPTUNE.[26] A Woods-Saxon well having a standard geometry of $r = 1.25$ fm, $a = 0.65$ fm, and a spin-orbit depth of 6.2 MeV was used. A search was made on the Woods-Saxon well depth to reproduce the experimental separation energies. All DWBA calculations were performed with no radial cutoff and using the normalization constant

$$D_0^2 = 1.65 \times 10^4 \text{ MeV}^2 \text{ fm}^3.$$

The magnitude of the spectroscopic factor, S_J, was obtained by normalizing the calculated cross section at forward angles to the experimental data.

The experimental angular distributions together with the DWBA fits are displayed in Fig. 6. Fits to the data were obtained assuming l-value transfers of 2, 0, and 5 for the ground state, 0.295-, and 0.532-MeV states, respectively. The spin assignments of $\frac{3}{2}$ for the ground state and $\frac{11}{2}$ for the 0.532-MeV state are on the basis of the conventional shell-model ordering of states. The spin-parity assignments and the deduced spectroscopic factors are in good agreement with recent calculations[31] and earlier (d, t) work[32] and are listed in Table V. The pickup sum rule $\sum S_J^{(i)} = 2J+1$ is nearly satisfied for each of the three states. Thus the observed cross sections probably account for the total expected cross sections for these states.

VII. SUMMARY

24 states in ^{136}Xe with excitation energy up to 5.223 MeV via the ^{136}Xe(p, p')^{136}Xe reaction have been identified. Attention is focused on the analysis of the 14 low-lying states with excitation energies up to 3.263 MeV. Spin and parity assignments have been made and the deformation parameters have been extracted through DWBA calculations using a collective-model form factor. The magnitudes of the deformation parameters indicate

that ^{136}Xe is not very collective. The low-lying spectra do not show vibrational character and the inelastic strength is distributed over a number of levels. The level spectrum obtained is compared with the results of a microscopic calculation in the framework of the QRPA. The absolute magnitudes of the cross sections are compared with the DWBA cross sections obtained by using the calculated microscopic form factor. The level spectrum and the absolute magnitude of the cross sections for the 4^+, 6^+, and 3^- states are reasonably well reproduced through the calculation. The level density and the distribution of the inelastic strengths for the 2^+ states could not be predicted from the calculation. Inclusion of four-quasiparticle states and the consideration of mixing of the two- and four-quasiparticle states should remove some of the discrepancies between the calculated and observed results.

In addition to the proton groups, three strong deuteron groups leading to states in ^{135}Xe have been identified. The orbital angular momentum transfers have been obtained through DWBA analysis. Spin assignments have been made on the basis of the shell-model expectations. The J^π assignments and the extracted spectroscopic factors are in good agreement with recent calculations.

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