^{136}Xe(d,p) and ^{136}Xe(d,t) Reactions*

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States of ^{137}Xe and ^{135}Xe have been investigated via the ^{136}Xe(d,p) and ^{136}Xe(d,t) reactions with 13-MeV incident deuterons and an over-all energy resolution of 45 keV. Q values of 1.637 ± 0.020 and -1.723 ± 0.020 MeV have been obtained for the respective ground state ^{136}Xe$(d,p)^{137}$Xe and ^{136}Xe$(d,t)^{135}$Xe reactions. The angular distribution data have been analyzed using finite-range distorted-wave Born-approximation (DWBA) calculations corrected for nonlocality of the optical potential to extract spectroscopic information. Spin and parity assignments, excitation energies, and spectroscopic factors for most of the observed levels are presented. A ^{136}Xe(d,p) excitation function showed no significant evidence for an anomaly in the (d,p_0) cross section near the threshold of the (d,n) reaction to the corresponding isobaric analog state.

I. INTRODUCTION

STRIPPING and pickup reactions on nuclei with a "magic" neutron number are convenient for studying neutron shell structure in view of the simplicity of the final-state neutron configurations. In this paper we wish to report on the ^{136}Xe$(d,p)^{137}$Xe and ^{136}Xe$(d,t)^{135}$Xe reactions which have been studied in order to investigate neutron shell structure in the vicinity of the closed 82-neutron shell. Previous work[1–5] on the closed-shell nuclei ^{138}Ba, ^{140}Ce, ^{141}Pr, ^{142}Nd, ^{144}Sm, and ^{136}Xe has been done to investigate this same region. The measurements on ^{136}Xe were carried out by Schneid and Rosner[5] using xenon gas isotopically enriched to 80.5% ^{136}Xe in conjunction with a magnetic spectrograph, with an over-all experimental resolution of 80 keV. In the present work, xenon gas isotopically enriched to 99% ^{136}Xe was available, and the experimental resolution was 45 keV. The higher isotopic purity and better experimental resolution has allowed more accurate angular momentum and energy assignments and the identification of several more states in ^{137}Xe.

In addition, isobaric analogs of the low-lying states of ^{137}Xe have recently been studied by means of proton elastic and inelastic scattering measurements on ^{136}Xe at proton energies from 9.0 to 13.0 MeV.[6] A detailed comparison of analog states in ^{137}Cs observed in the proton elastic scattering measurements with the states in ^{137}Xe observed in the (d,p) work was therefore of interest.

II. EXPERIMENTAL PROCEDURE

^{136}Xe$(d,p)^{137}$Xe and ^{136}Xe$(d,t)^{135}$Xe cross sections were measured at 15 laboratory angles between 25° and 160° at an incident deuteron energy of 12.973 MeV. In addition, excitation function measurements were carried out between 12.335 and 12.973 MeV in order to search for anomalies in the ^{136}Xe(d,p_0) excitation function caused by charge-exchange effects. The target gas, isotopically enriched to 99% ^{136}Xe, was contained within a 3-in.-diam gas cell used in conjunction with the Oak Ridge National Laboratory precision gas scattering chamber.[7] The gas pressure was 0.022 atm, corresponding to a target thickness of approximately $(80/\sin\theta_{\rm lab})$ μg/cm^2. Beam entrance and exit windows were 5- and 25-μin. nickel foils, respectively. The cell walls were 0.00025-in.-thick aluminized Mylar. Four 2-mm-thick lithium-drifted-silicon solid-state detectors, cooled to dry-ice temperature, were used. Only one of the detectors was movable, the other being fixed at laboratory angles of 90°, 123.75°, and 146.25°. Each detector face was shielded by a 5-μin.-thick nickel foil to reduce oil contamination. The over-all experimental proton resolution was 45 keV. Proton groups leading to 23 states in ^{137}Xe, and triton groups leading to 3 states in ^{135}Xe were identified. Figure 1 shows typical spectra, taken at laboratory angles of 50° and 146.25°. The excitation

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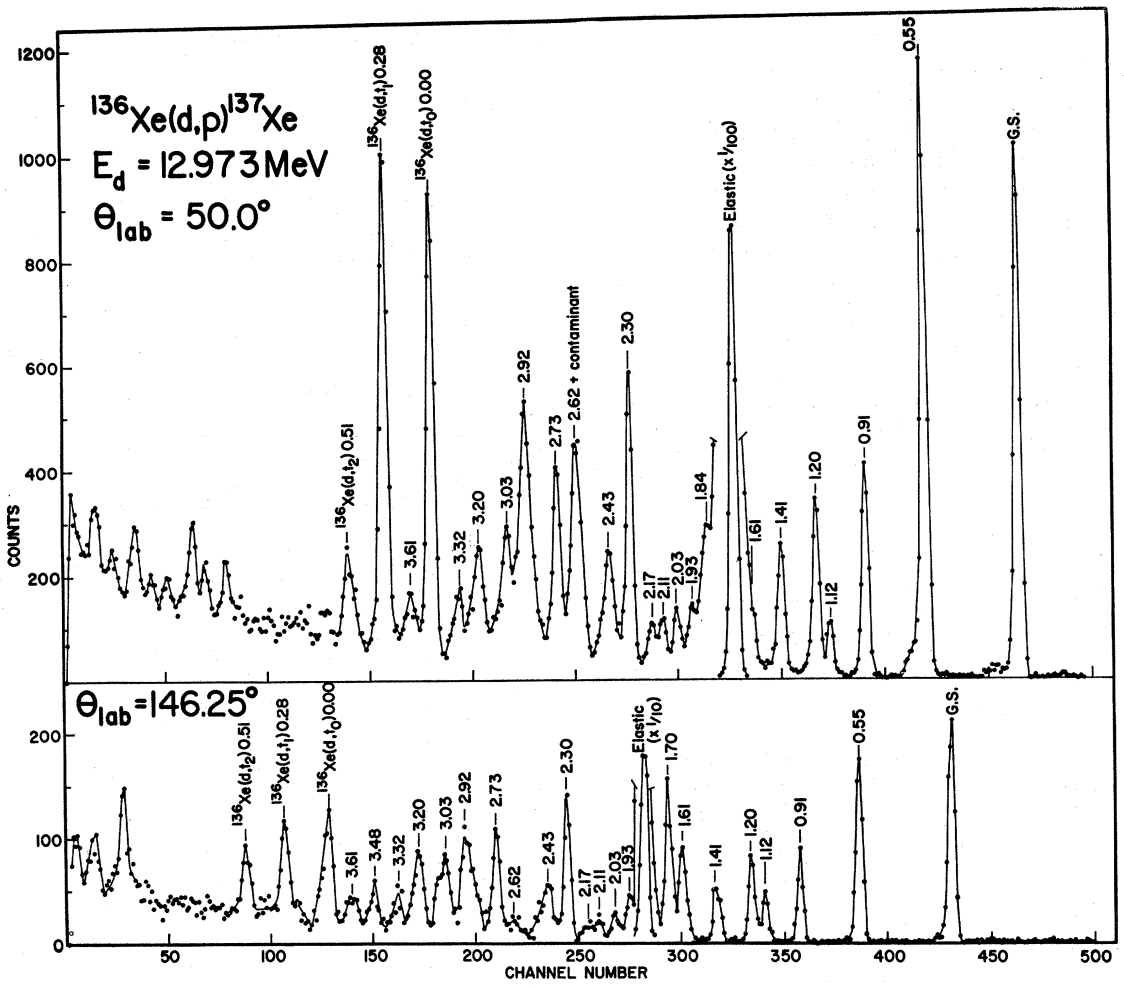

FIG. 1. ^{136}Xe(d,p)^{137}Xe pulse-height spectra, at a deuteron energy of 12.973 MeV and laboratory angles of 50.0° and 146.25°.

energies are indicated in the figure. Slight contamination was present, as the spectra indicate, and is attributed to oxygen, nitrogen, and carbon. The over-all experimental uncertainty in the measured absolute cross sections is of the order of ±6% (standard deviation).

III. Q-VALUE DETERMINATION

Q values for the observed transitions were determined using the following procedure. The positions of the elastic deuteron peak in the movable counter angular distribution pulse-height spectra were fitted with a linear least-squares fitting program to establish a single-energy–versus–channel-number calibration for these spectra. A code then evaluated the energy and Q value of each observed proton and triton group at each observed angle. The Q-value determinations for a given group were checked for consistency and averaged. For a given proton or triton group, the total maximum spread in Q-value determinations at different angles was approximately 20 keV. The Q values were corrected for the variation in energy loss (for different particles and energies) of the reaction particles in passing through the exit gas, Mylar cell wall, and nickel foil shielding the detector face. These corrections, of the order of 20 keV or less, were obtained from the tables of Williamson and Boujot.[8] The absolute uncertainty in the Q-value determinations is believed to be of the order of 20 keV. The ground-state Q value for the ^{136}Xe(d,p)^{137}Xe reaction obtained in the present experiment was 1.637 ±0.020 MeV, in slight disagreement with the value of 1.82±0.06 MeV obtained by Schneid and Rosner,[5] and in marked disagreement with the value of 2.235±0.100 MeV given by the Berkeley tabulation of Q values.[9] The ground-state Q value for the ^{136}Xe(d,t)^{135}Xe reaction obtained in this experiment was −1.723±0.020 MeV, in agreement with the value of −1.626±0.100 MeV given in the Berkeley tabulation of Q values.[9]

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IV. OPTICAL ANALYSIS

To obtain optical parameters with which to calculate the incoming deuteron and outgoing proton distorted waves in the DWBA calculations, optical-model fits, including a spin-orbit interaction, were made to 12.973-MeV deuteron elastic scattering and to 10.641-MeV proton elastic scattering from ^{136}Xe.[6] The proton energy represents an off-resonance region in the proton elastic excitation function. The deuteron fits were obtained with a code written by Smith[10]; the proton fits were made with a code written by Perey.[11]

The results of the deuteron optical-model analysis and the corresponding optical parameters are shown in Fig. 2. In both this and the proton analysis, fits were made using a potential with a surface-peaked imaginary part and a real spin-orbit part:

$$V(r)=-Vf(r,r_{0r},a_r)-i4a_iW_D\frac{d}{dr}f(r,r_{0i},a_i) \quad \text{central}$$

$$+\boldsymbol{\sigma}\cdot\mathbf{l}V_{s0}\left(\frac{\hbar}{m_\pi c}\right)^2\frac{1}{r}\frac{d}{dr}f(r,r_{0r},a_r) \quad \text{spin-orbit}$$

$$+(Ze^2/2r_c)(3-r^2/r_c^2), \quad \text{if } r\leq r_c$$

$$+Ze^2/r, \quad \text{if } r>r_c. \quad \text{Coulomb}$$

The function $f(r,r_0,a)$ is the usual Saxon-Woods shape:

$$f(r,r_0,a)=[1+\exp(r-r_0A^{1/3})/a]^{-1}.$$

The deuteron elastic scattering fits shown were obtained with two different sets of parameters. The best fits to both the elastic scattering data and to the (d,p) data were obtained using the deeper real well depth, and since, in addition, the finite-range correction to the DWBA analysis requires the use of the deeper well depth,[12] the parameters associated with the deeper real well depth were used in the analysis. The proton optical analysis, shown in Fig. 3, was made using Perey's[13] average parameters, with a search for V and W_D. Since the protons emitted in the (d,p) reaction have an energy different from that at which this fit was made, an energy extrapolation[13] of the real proton well depth was actually used in the DWBA analysis.

Since no triton elastic scattering data were available, the triton optical parameters were obtained[14] using a generalized, A-dependent formula for V and W_D de-

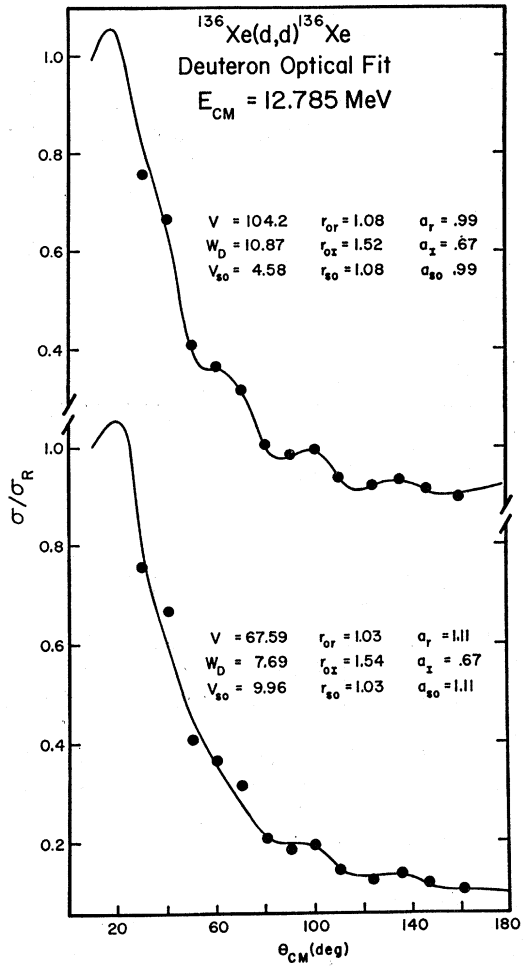

FIG. 2. Optical-model fits to ^{136}Xe(d,d) elastic scattering data. The cross section is shown as a ratio to the corresponding Rutherford cross section.

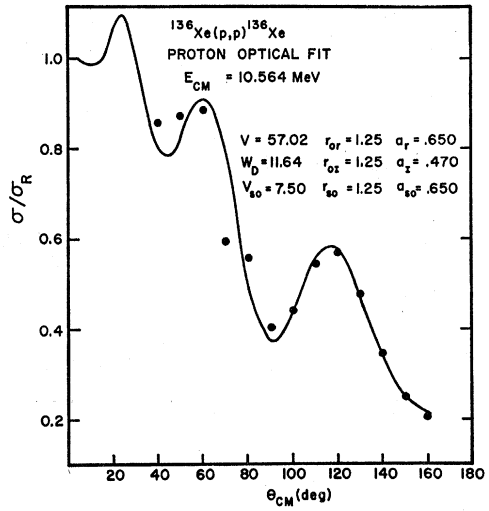

FIG. 3. Optical-model fit to ^{136}Xe(p,p) elastic scattering data. The cross section is shown as a ratio to the corresponding Rutherford cross section.

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duced by Hafele *et al.*[15] from the scattering of 20-MeV tritons from the tin isotopes.

V. DWBA ANALYSIS

A. ^{136}Xe$(d,p)^{137}$Xe Reaction

The (d,p) stripping data were fitted using a zero-range DWBA code VENUS, written by Tamura,[16] modified to include an approximation for the nonlocality[17,18] of the optical potential and a finite-range[12,19] correction. For the nonlocality correction, the local distorted waves in the entrance and exit channels $X_L(kr)$ were both replaced by[18]

$$X_{NL}(kr)=[1-(\mu\beta/2\hbar^2)U(r)]^{-1/2}X_L(kr),$$

where $U(r)$ is the central part of the usual local optical potential (excluding the spin-orbit term and the Coulomb potential) and β is the nonlocality length. Nonlocality lengths for the proton and deuteron channels were chosen as follows[20]:

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

The finite-range correction was made by including the factor $\Lambda(r)=1-y(r)$ in the overlap integral[12,19] where

$$Y(r)=\left[U_d(r)-U_n{}^l(r)-U_p\left(\frac{M_T}{M_R}\cdot r\right)-B_d\right]*\left[\frac{2\hbar^2}{mR^2}\frac{m_d}{m_pm_n}\right]^{-1}.$$

R is the range parameter, taken to be 1.25F,[12] $m=1$ amu, B_d is the deuteron binding energy, m_d, m_n, m_p are the deuteron, neutron, and proton masses, respectively, in amu, M_T is the mass of target, M_R is the mass of residual nucleus, $U_n{}^l$ is the bound neutron potential, and U_d, U_p are the central part of the deuteron and proton optical potentials. The finite-range correction was found to be negligible in all cases. The nonlocality correction increased the spectroscopic factor for the ground-state $f_{7/2}$ transition by about 15%, but was negligible for all other cases. The bound-state neutron wave functions needed for the analysis were calculated from code NEPTUNE, also by Tamura.[16] The Woods-Saxon well for the bound state was assumed to have the same geometry as the real part of the proton optical potential. The spin-orbit depth was taken to be 5.5 MeV, in agreement with the value obtained by Rosen[21] from analysis of proton elastic polarization data for a wide range of nuclei. The binding energy of each level was held fixed at the experimentally determined separation energy and a search was made for the Woods-Saxon well depth which predicted this binding energy.

The experimental angular distributions, and their comparison with DWBA predictions, are shown in Figs. 4(a) and 4(b). The agreement between the data and the DWBA predictions (with no radial cutoff) is quite good. Since ^{136}Xe is an even-even nucleus, the general relationship between the experimental absolute ^{136}Xe$(d,p)^{137}$Xe cross section and the theoretical cross section to a state with spin J is given by

$$\sigma(\text{expt})=(2J+1)\sigma_{\text{DWBA}}S_J.$$

In the present work, we have taken the absolute theoretical cross section, σ_J (theory), to be $(2J+1)\sigma_{\text{DWBA}}$, so that the spectroscopic factor S_J is defined by the ratio

$$S_J=\sigma(\text{expt})/\sigma_J(\text{theory}).$$

If the isotopic-spin formalism is preferred, S as tabulated here should be replaced by C^2S, where C^2 is the square of the usual isospin Clebsch-Gordan coupling coefficient.[22] Values of the spectroscopic factor were obtained by simply normalizing the theoretical cross sections at forward angles to the experimental data.

Table I shows a comparison of the present work with that of Schneid and Rosner. A disagreement in the excitation energies is evident. The $l_n=5$ state at 1.12-MeV excitation and several more highly excited states were not resolved in the earlier work. Both the present work and elastic scattering data[6] indicate an $l_n=3$ assignment instead of $l_n=1$ for the fourth excited state at 1.20 MeV. The state at an excitation of 2.73 MeV is also well fitted by $l_n=3$ instead of by $l_n=1$ as found by Schneid and Rosner. No evidence was found for any even-parity states in this work, in agreement with previous (d,p) measurements on 82-neutron shell nuclei.[1-5] It was not possible to obtain angular distribution data for the states at excitations of 1.70, 1.84, 1.93, 2.03, 2.11, and 2.17 MeV, due to the presence of the deuteron elastic scattering peak in the spectra. The states at excitation energies of 2.92, 3.03, and 3.61 MeV appear to be unresolved doublets, and because of this and also because of rather large uncertainty in the cross sections of the more highly excited states, DWBA fits were not attempted for states of excitation higher than 2.73 MeV. The spectroscopic factor for the ground state is 0.68, in fair agreement with the value of 0.58 found in the earlier work, and with the values of 0.58 and 0.77 obtained in the ^{144}Sm$(d,p)^3$ and the ^{138}Ba$(d,p)^4$ measurements, respectively.

Spin assignments to the states of ^{137}Xe were made on

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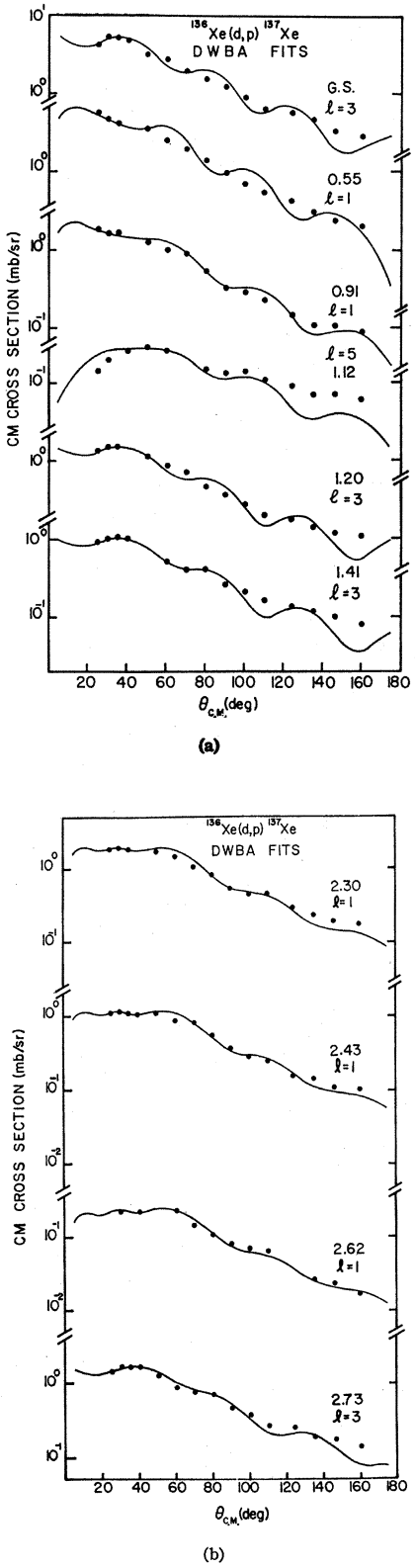

FIG. 4. DWBA fits to ^{136}Xe$(d,p)^{137}$Xe angular distribution data. The l_n values and excitation energies are as indicated. The experimental uncertainty is approximately the size of the data points.

the basis of the conventional shell-model ordering of states, and on the results of polarization measurements of proton elastic scattering at analog resonances in ^{139}La made by Veeser and Haeberli.[23] This work indicated that the ordering of states in the 83-neutron nucleus ^{139}Ba is $f_{7/2}$, $p_{3/2}$, $p_{1/2}$, $f_{5/2}$, and $f_{5/2}$, and it is expected that the ordering of states in ^{137}Xe should be approximately the same. In particular, the polarization measurements showed that the spin of the first excited state is $J=\frac{3}{2}$, and that of the second is $J=\frac{1}{2}$. The only known $p_{3/2}$ state, therefore, is the first excited state at 0.55 MeV, for which $S=0.49$. It would therefore appear very likely that some of the more highly excited $l_n=1$ states are $p_{3/2}$ states. In support of this, if we assume

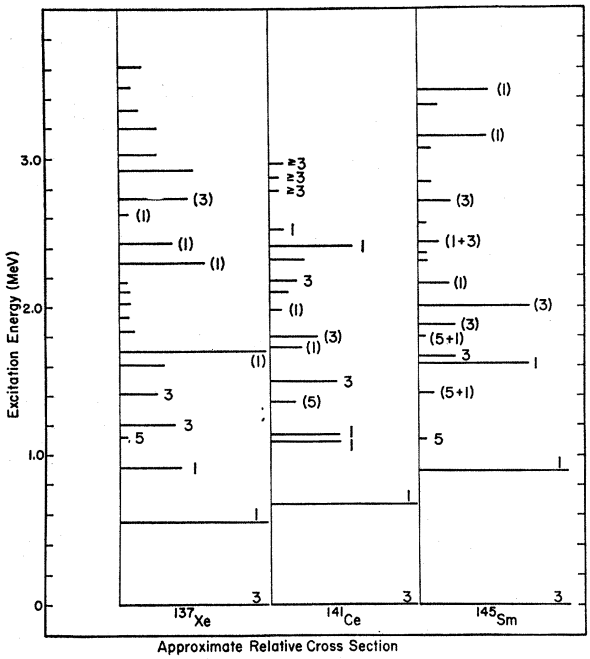

FIG. 5. A comparison of low-lying levels of ^{137}Xe, ^{141}Ce,[2] and ^{145}Sm.[3] The length of the horizontal lines representing levels indicates the approximate relative differential cross section observed in forward-angle (d,p) measurements. l_n values are indicated by the numerals.

that the states at excitations of 0.91, 1.70, 2.30, 2.43, and 2.62 MeV are all $p_{1/2}$ states, then the stripping sum rule for the spectroscopic factors, $\sum_i S_i^{(J)}=1$, is exceeded for $J=\frac{1}{2}$. The application of the sum rule also indicates that not all the $f_{5/2}$ or $h_{9/2}$ states are seen in the present work, since $\sum_i S_i^{(J)}=0.61$ for $f_{5/2}$ and 0.31 for $h_{9/2}$.

A comparison of the present work with the low-lying levels of 83-neutron nuclei ^{145}Sm and ^{141}Ce is given in Fig. 5. Xenon, with 54 protons, has four protons less than cerium, and eight protons less than samarium, and it is clear that the differences in proton number make

[23] L. Veeser, J. Ellis, and W. Haeberli, Phys. Rev. Letters 18, 1063 (1967).

TABLE I. Levels of ^{137}Xe from the ^{136}Xe$(d,p)^{137}$Xe reaction. E^* is the excitation energy of the observed levels in ^{137}Xe, l_n is the orbital angular momentum of the transferred neutron, J and π are the spin and parity of the observed levels in ^{137}Xe, $d\sigma/d\Omega$ is the laboratory differential cross section, and S is the calculated spectroscopic factor as defined in the text.

Present work					Reference 5				
E^*(MeV)	l_n	J^π	$d\sigma/d\Omega$ (30°) (mb/sr)	S	E^*(MeV)	l_n	J^π	$d\sigma/d\Omega$ (20°) (mb/sr)	S
0.00	3	$\frac{7}{2}^-$	5.35	0.68	0.00	3	$\frac{7}{2}^-$	3.52	0.58
0.55	1	$\frac{3}{2}^-$	4.81	0.49	0.61	1	$\frac{3}{2}^-$	4.60	0.37
0.91	1	$\frac{1}{2}^-$	1.64	0.34	1.01	1	$(\frac{3}{2}^-)$	1.68	0.13
1.12	5	$\frac{9}{2}^-$	0.20	0.31					
1.20	3	$\frac{5}{2}^-$	1.53	0.24	1.32	1	$(\frac{3}{2}^-)$	2.12	0.16
1.41	3	$\frac{5}{2}^-$	1.00	0.16	(1.56)				
1.61			0.18[a]						
1.70			0.32[a]		1.87	(1)		4.30	0.30
1.84			0.41[b]		(1.99)				
1.93			0.27[b]						
2.03			0.35[b]						
2.11			0.29[b]					2.10	
2.17			0.21[b]					1.38	
2.30	1	$(\frac{1}{2}^-)$	2.26	0.35	2.53	(1)			0.13
2.43	(1)	$(\frac{1}{2}^-)$	1.39	0.22	2.70	(1)			0.09
2.62	(1)	$(\frac{1}{2}^-)$	0.23	0.04					
2.73	(3)	$(\frac{5}{2}^-)$	1.82	0.21	3.00	(1)		1.89	0.11
2.92					(3.18)				
3.03					(3.32)				
3.20					(3.45)				
3.32									
3.48									
3.61									

[a] $d\sigma/d\Omega$ (135°) (mb/sr).
[b] $d\sigma/d\Omega$ (50°) (mb/sr).

an appreciable difference in the states of the 83rd neutron.

B. ^{136}Xe$(d,t)^{135}$Xe Reaction

Tritons leading to the ground and first two excited states of ^{135}Xe were observed in the present work. Good fits to the data were obtained with l_n assignments of 2, 0, and 5, respectively, as indicated in Fig. 6, in agreement with the work of Schneid and Rosner. The fits were obtained by assuming the same bound-state geometry and spin-orbit depth as in the (d,p) analysis. Again, a search was made for the Woods-Saxon well depth which produced the experimental separation energies. Finite-range and nonlocality corrections were not included in the DWBA analysis since their effect was found to be negligible. The (d,t) normalization suggested by Bassel[24] was used to obtain absolute theoretical cross sections σ_{DWBA}. Table II shows a comparison of the present work with that of Schneid and Rosner. The spectroscopic factors indicate that the observed cross sections probably account for the total expected cross section for these states, since the pickup sum rule, $\sum_i S_i^{(J)} = (2J+1)$, is satisfied for each of the three states.

TABLE II. Levels of ^{135}Xe from the ^{136}Xe$(d,t)^{135}$Xe reaction. E^* is the excitation energy of the observed levels in ^{135}Xe, l_n is the orbital angular momentum of the transferred neutron, J and π are the spin and parity of the observed levels in ^{135}Xe, $d\sigma/d\Omega$ is the laboratory differential cross section, and S is the calculated spectroscopic factor as defined in the text.

Present work					Reference 5			
E^*(MeV)	l_n	J^π	$d\sigma/d\Omega$ (30°) (mb/sr)	S	E^*(MeV)	l_n	J^π	$d\sigma/d\Omega$ (60°) (rel)
0.00	2	$\frac{3}{2}^+$	3.45	3.96	0.00	2	$\frac{3}{2}^+$	1.30
0.28	0	$\frac{1}{2}^+$	3.33	1.86	0.29	0	$\frac{1}{2}^+$	1.10
0.51	5	$\frac{11}{2}^-$	0.82	9.83	0.53	5	$\frac{11}{2}^-$	0.31
					1.28	(2)	$(\frac{5}{2}^+)$	0.26
					1.47	(2)	$(\frac{5}{2}^+)$	0.31
					(1.53)	(0+4)	$(\frac{1}{2}^+ + \frac{7}{2}^+)$	0.16
					1.83	2	$(\frac{5}{2}^+)$	0.24
					2.10	2	$(\frac{5}{2}^+)$	0.21

[24] R. H. Bassel, Phys. Rev. **149**, 791 (1966).

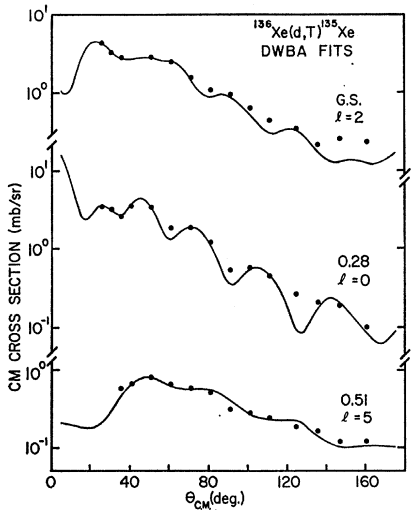

FIG. 6. DWBA fits to ^{136}Xe$(d,t)^{135}$Xe angular distribution data. The l_n values and excitation energies are as indicated. The experimental uncertainty is approximately the size of the data points.

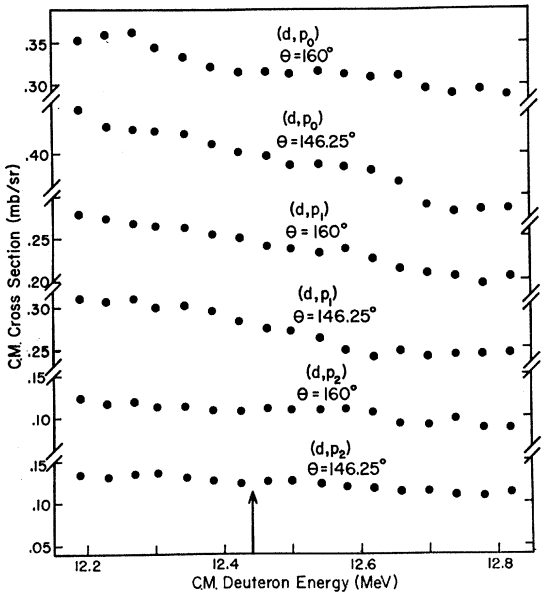

FIG. 7. ^{136}Xe$(d,p)^{137}$Xe excitation functions for the ground and first two excited states of ^{137}Xe at laboratory angles of 160.0° and 146.25°. The arrow indicates the approximate position of the expected anomaly.

VI. ^{136}Xe(d,p) EXCITATION FUNCTION

There has been considerable interest in the behavior of the (d,p) excitation function near the threshold of the (d,n) reaction channel to the analog of the state under investigation in the (d,p) reaction.[25,26] A ^{136}Xe-$(d,p)^{137}$Xe excitation function, measured in 40-keV steps at deuteron energies from 12.335 to 12.973 MeV to search for possible anomalies in the (d,p_0) cross sections, is shown in Fig. 7. Since the center-of-mass proton energy for excitation of the analog of the ground state of ^{137}Xe in the compound nucleus ^{137}Cs is 10.194 MeV,[6] the center-of-mass threshold energy of the (d,n) reaction to the corresponding isobaric analog state, given by $E_d = E_p + 2.226$ MeV, is 12.420 MeV, and is indicated in the figure.

If an anomaly is present, its effect is very small. The energy span of the data is insufficient to indicate clearly whether or not there is a slight change in the slope of the excitation function at the threshold energy, as was reported by Richard *et al.*, for the ^{140}Ce(d,p) excitation function.[27] That the anomalous effect, if any, is very weak may not be surprising because the deuteron energy (~12.4 MeV) is above the Coulomb barrier.[28]

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