Study of (d,p) and (d,t) Reaction on the Xe^{136} Isotope*

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Eight levels of Xe^{137} and seven of Xe^{135} were observed in the $Xe^{136}(d,p)$ and $Xe^{136}(d,t)$ reactions. The angular distributions of the proton and triton groups were analyzed using zero-range distorted-wave Born-approximation calculations to extract spectroscopic information. Spin and parity assignments for most of the observed states were attempted. Comparison with (d,p) and (d,t) reaction on Ba^{138}, Ce^{120}, and Nd^{142} reveals that the multiplicity of the hole states in the $N=81$ isotones is much lower than that of the particle states in the $N=83$ isotones.

INTRODUCTION

THE (d,p) and (d,t) reactions on target nuclei having a closed-neutron-shell configuration are very powerful tools for studying nuclear shell structure because of the simplicity of the final neutron and neutron-hole configurations. The multiplicity of levels in the final nucleus is rather low compared to neighboring isotopes, and therefore the protons and triton groups emitted as reaction products can be detected even with moderate resolution techniques.

The present study of the $Xe^{136}(d,p)$ and $Xe^{136}(d,t)$ reactions is part of a general investigation of $N=82$ isotones using (d,p) and (d,t) reactions and begun with similar studies performed on the Ba^{138}, Ce^{140}, Nd^{142}, and Sm^{144} isotopes.[1–3]

The investigation of (d,p) and (d,t) reactions on closed-shell even-even nuclei serves also as a check on the normalization of the cross sections by distorted-wave Born-approximation (DWBA) calculations. In these nuclei, the multiplicity of the levels with the same spin value is usually small and frequently the entire transition intensity goes to a single level. For a neutron stripping reaction, the general relation between the experimental absolute cross section for a transition from the ground state of an even-even nucleus to a state with spin j in a final nucleus is given by

$$\sigma_j(\text{expt})=(2j+1)\sigma(\text{DWBA})S_j, \qquad (1)$$

where S_j is the spectroscopic factor, and expresses the overlap between the initial and final nuclear states. The product $(2j+1)$ times the sum of the spectroscopic factors for the transitions leading to states with definite j is equal to the number of unoccupied spaces in that shell-model state. Therefore if the target nucleus is a closed-shell nucleus, and only one level with a spin j exists in the final nucleus we must have

$$S_j=1 \quad \text{and} \quad \sigma_j(\text{expt})=(2j+1)\sigma(\text{DWBA}) \qquad (2)$$

which is a simple relation between the experimental and predicted cross sections.

There exists up to the present time very little information on the nuclear properties of Xe^{135} and Xe^{137}, presumably because until recently isotopically enriched xenon isotopes were difficult to obtain. The little knowledge that does exist comes mainly from beta decay of the iodine isotopes produced by the fission process (I^{137} is a delayed neutron emitter), which establishes a very low separation energy of the last neutron of Xe^{137} and gives a $\frac{7}{2}^-$ assignment to the ground state of this nucleus. Two states of Xe^{135} are known from the decay of I^{135}, the ground state with a $\frac{3}{2}^+$ assignment and a state at 0.53-MeV excitation with $11/2^-$ spin assignment.[4]

EXPERIMENTAL PROCEDURE

The stripping and pick-up reactions in this experiment were induced by 15-MeV deuterons from the University of Pittsburgh cyclotron. The scattering chamber and gas cell have already been described in a previous paper[5] as have the horizontal magnetic spectrograph used as the proton detector from the $Xe^{136}(d,p)Xe^{137}$ reactions,[6] and the solid-state detectors used for the identification and detection of the tritons from the $Xe^{136}(d,t)$ reaction.[7]

The resolution of most detection systems for gas targets is worse than for solid targets of the same thickness. This is due to the following reasons: First, solid targets allow the "target-thickness compensation" which is obtained by aligning the solid target at an optimum angle with respect to the beam direction. Second, all reactions in a solid target can be considered as occuring on a plane, whereas for gas targets the detected reaction products originate in an "active volume" with a finite extension in the beam direction. Third, the straggling in energy of the incoming and outgoing particles in the gas cell windows and through

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[1] F. W. Brigham and M. B. Sampson, Phys. Rev. **129**, 1796 (1962).
[2] R. H. Fulmer, A. L. McCarthy, and B. L. Cohen, Phys. Rev. **128**, 1302 (1962).
[3] R. K. Jolly and C. F. Moore, Phys. Rev. **145**, 918 (1966).
[4] *Nuclear Data Sheets*, compiled by K. Way, *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C.).
[5] R. E. Sass, B. Rosner, and E. J. Schneid, Phys. Rev. **138** B399 (1965).
[6] B. L. Cohen, *et al.*, Phys. Rev. **118**, 499 (1960).
[7] R. H. Fulmer and W. W. Daehnick, Phys. Rev. **139**, B579 (1965).

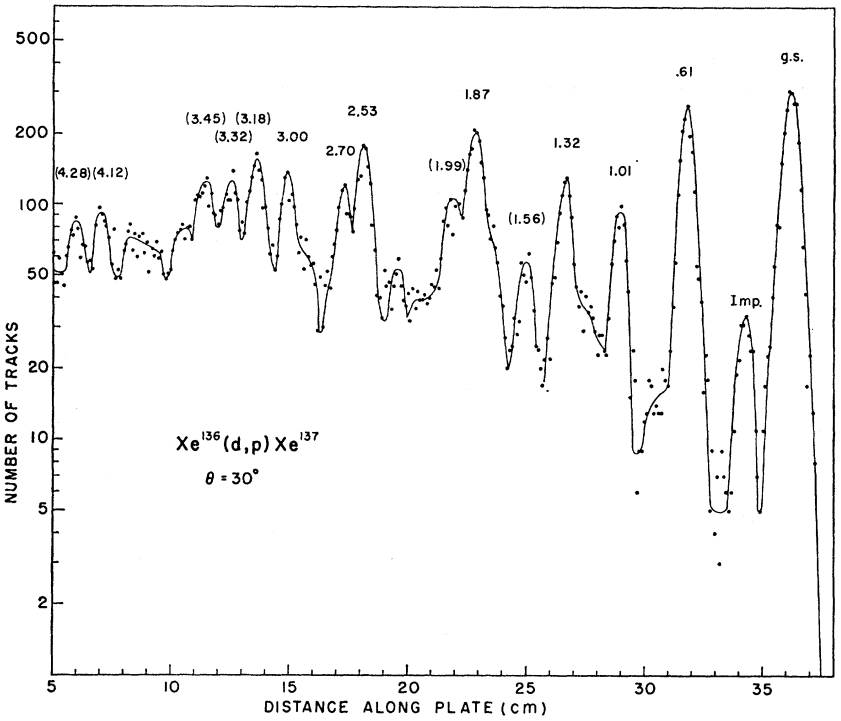

FIG. 1. Energy spectrum of protons from the $Xe^{136}(d,P)Xe^{137}$ reaction. The excitation energies of the final nucleus of the final nucleus are given in MeV. The relatively weak transitions whose energies are listed in parentheses may be due to the Xe^{134} impurity, and the peak labeled "Imp." is a light mass impurity.

the gas also contribute appreciably to worsen the over-all resolution. The best attainable resolution of the system for the gas target in the experiment was about 80 keV. Nevertheless, because of the expected very low Q value for the $Xe^{136}(d,p)$ reaction the magnetic analysis of the protons was preferred despite much loss in transmission of the reaction products.

A 10-ml sample of xenon gas, isotopically enriched to 80.48% of Xe^{136}, 16.48% of Xe^{134}, 2.34% of Xe^{132}, and 0.70% of Xe^{131}, was obtained from Mound Laboratories. The gas cell was filled to a pressure of 150 mm Hg corresponding to a density of 1.22 mg/cm³. To a good approximation the effective target thickness (t) is related to the laboratory scattering angle (θ) by the expression

$$t = 0.24 \csc\theta \text{ mg/cm}^2.$$

The uncertainty in the excitation energies of the final nuclei increases progressively since the energy loss of the protons and tritons at different energies in the xenon gas is not known accurately. The uncertainty in excitation energy is estimated to be ±30 keV at 1.5-MeV excitation and ±50 keV at 3.MeV excitation energy. The errors in the absolute cross section are small and are given by the error bars on the relevant figures.

TABLE I. Summary of results of the $Xe^{136}(d,p)Xe^{137}$ reactions. The levels with the excitation energies listed in parentheses may be due to Xe^{134} impurities.

E^* (MeV)	l_n	J^π	$(d\sigma/d\Omega)_{abs}$ (22°) mb/sr	$(2J+1)S$
0.0	3	7/2⁻	3.52	4.65
0.61	1	3/2⁻	4.60	1.48
1.01	1	(3/2⁻)	1.68	0.52
1.32	1	(3/2⁻)	2.12	0.64
(1.56)			...	...
1.87	(1)		4.30	1.20
(1.99)	...		...	...
2.53	(1)		2.10	0.55
2.70	(1)		1.38	0.36
3.00	(1)		1.89	0.45
(3.18)	...		...	5.20
(3.32)	...		...	...
(3.45)	...		...	...
(4.12)	...		...	...
(4.28)	...		...	...

RESULTS AND DISCUSSION

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

The results of the stripping reaction on Xe^{136} are listed in Table I. This table gives the excitation energies, the assigned l_n values, the absolute cross sections obtained at 22° laboratory angle, and the transition strength $(2j+1)S$ where S is the spectroscopic factor, as calculated using Eq. (1). The energy spectra of the proton groups from the $Xe^{136}(d,p)Xe^{137}$ were recorded at 6 angles between 13° and 30° using the magnetic spectrograph, and then extended up to 60° using solid-state detectors. A typical spectrum obtained at 30° with the magnetic spectrograph is shown in Fig. 1. In Fig. 2, the experimental angular distributions are

compared to those predicted by DWBA[8] calculations in order to make l_n assignments for each transition.

The transition leading to the ground state of Xe^{137} is the only $l_n=3$ transition observed. Since the $f_{7/2}$ shell-model orbit should be empty in Xe^{136}, having a closed-shell $N=82$ configuration, the spectroscopic factor for this transition should have the value of unity. The value of 0.58 obtained experimentally is lower than expected, but consistent with the values of 0.58 and 0.77 obtained for the ground-state transitions for the $Sm^{144}(d,p)$ and $Ba^{138}(d,p)$ transitions, respectively, by Jolly[3] and by Rapaport.[9] This low value for the spectroscopic factor may result from the following: First, the ground state is not the only $\frac{7}{2}^-$ state of the final nucleus and the remaining intensity of transitions to the $f_{\frac{7}{2}}$ shell is to unobserved levels. Second, the absolute cross sections predicted by the DWBA calculation may be too large. Third, the $f_{7/2}$ shell may be filling for the $N=82$ nuclei[10] and therefore the spectroscopic factor would be less than unity. The third reason alone is not adequate to explain the low value. Other $l_n=3$ transitions at excitation energies of about 1.5 MeV were observed in the (d,p) reactions on Ba^{138}, Ce^{140}, and Sm^{144}; however, no $l_n=3$ transitions were observed in this study, most probably owing to the lack of good resolution.

The angular momentum transferred in the transitions to the 0.61-, 1.01-, 1.32-, 1.87-, 2.53-, 2.70-, and 3.00-MeV states is probably $l_n=1$ as shown in Fig. 3. If these assignments are correct then the total transition strength, $\sum(2j+1)S=5.20$, a value which is in good agreement with the expected value of 6 for the $3p_{3/2}$ and $3p_{1/2}$ neutron subshells. But it should be stressed again that not only $l_n=3$ or higher transitions may be mixed in the transition assigned as pure $l_n=1$ transitions but also the 16% Xe^{134} isotope in the gas sample could contribute to the strength of the levels of Xe^{135} with excitation energies above 3 MeV.

The Q Value for the $Xe^{136}(d,p)$ Reaction

The separation energy of the last neutron from Xe^{137} is expected to be small for two reasons: First, the separation energy of a single nucleon outside a closed shell is known to be of the order of 2 MeV lower than normal. Second, the Xe^{136} isotope is located well off the valley of stability, towards the neutron-rich isotopes. In effect, only the closed-neutron-shell configuration is responsible for its occuring naturally with such a surprisingly high abundance.

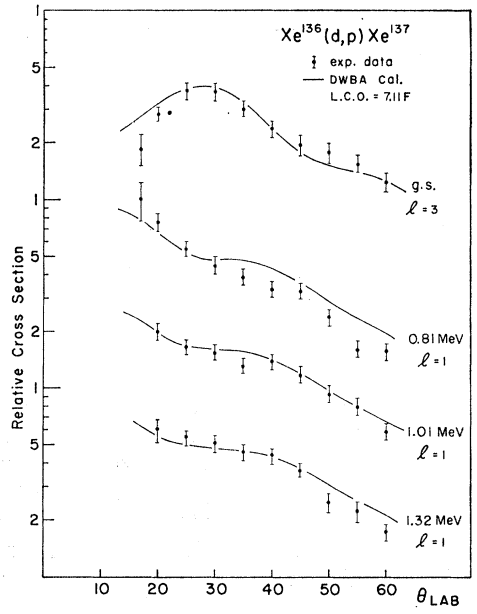

FIG. 2. Angular distributions of protons from $Xe^{136}(d,p)Xe^{137}$ reaction for the first four levels are shown along with the DWBA predicted angular distribution. To the right of these distributions the excitation energies and values of angular momentum transfer are indicated. A lower cutoff (L.C.O.) was used in the calculated distribution.

The Q value for the $Xe^{136}(d,p)$ reaction was measured relative to the well-known low Q value of the $O^{16}(d,p)$ reaction. The proton spectra for the two reactions were taken in two consecutive runs on two nearby strips of the same nuclear-emulsion plate. For the exposure taken at $\theta_{lab}=22°$, the protons leading to the ground state in both reactions were found to be within 1 cm of each other on the photographic plate.

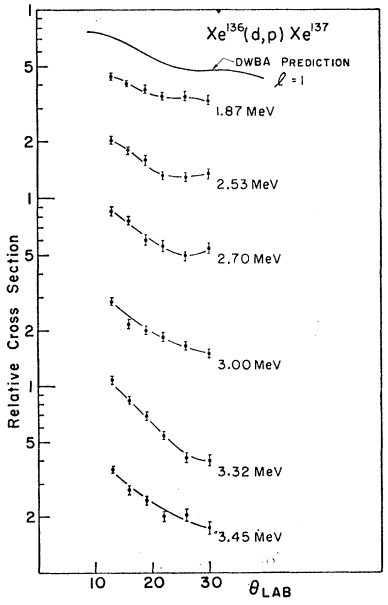

FIG. 3. Angular distributions of protons from the $Xe^{136}(d,p)Xe^{137}$ reaction for several excited states are shown. Also shown is a DWBA predicted angular distribution for an angular momentum transfer of $l_n=1$, for an excitation energy of 2 MeV. The lines drawn through the experimental points are only to aid the reader and are not DWBA predictions.

[8] DWBA parameters used in this work are: deuterons: $V=97.2$ MeV, $r_0=1.15$ F, $a=0.81$ F, $r_0'=1.34$ F, $a'=0.68$ F, $W=64$ MeV; protons: $V=52.3$ MeV, $r_0'=1.25$ F, $a'=0.47$ F, $W=14$ MeV; tritons: $V=106$ MeV, $r_0=1.07$ F, $a=0.854$ F, $r_0'=1.7$ F, $a'=0.754$ F, $W=14$ MeV. The optical potentials of Saxon form surface derivative absorption for the deuterons and volume absorption for the protons and tritons.

[9] Y. Rapaport and W. W. Buechner, Phys. Letters **18**, 299 299 (1965).

[10] R. K. Jolly, Phys. Rev. **136**, B683 (1964).

TABLE II. Summary of results for the $Xe^{136}(d,t)Xe^{135}$ reaction and the $Xe^{134}(d,t)Xe^{133}$ reaction. The quantities in parentheses are suggested or tentative assignments. The method used to determine the relative cross sections is discussed in the text.

$Xe^{136}(d,t)Xe^{135}$				$Xe^{134}(d,t)Xe^{133}$			
E^* (MeV)	l_n	J^π	$(d\sigma/d\Omega)_{rel}(60°)$	E^* (MeV)	l_n	J^π	$(d\sigma/d\Omega)_{rel}(60°)$
0.0	2	$3/2^+$	1.30	0.0	2	$3/2^+$	0.73
0.29	0	$1/2^+$	1.10	{0.23 / 0.25}	{(5) / (0)}	{$11/2^-$ / $1/2^+$}	1.44
0.53	5	$11/2^-$	0.31				
1.28	(2)	$(5/2^+)$	0.26				
1.47	(2)	$(5/2^+)$	0.31				
(1.53)	(0+4)	$(1/2^+,7/2^+)$	0.16				
1.83	2	$(5/2^+)$	0.24				
2.10	2	$(5/2^+)$	0.21				

The errors entering the comparison method which are to be taken into consideration using the characteristics of the University of Pittsburgh cyclotron are given by Cohen[11] and add up to approximately 20–30 keV. However, in our measurements, the main source of error comes from the large difference in the specific energy loss for the deuterons and protons traversing the oxygen and xenon volumes. Moreover, the exact values of the energy loss of charged particles in xenon are not known and interpolated values were used in the calculations.

Using the values:

$$\left(\frac{dE}{dx}\right)_d^{O_2}=48\ \frac{\text{keV cm}^2}{\text{mg}},\quad \left(\frac{dE}{dx}\right)_p^{O_2}=27\ \frac{\text{keV cm}^2}{\text{mg}},$$

$$\left(\frac{dE}{dx}\right)_d^{Xe}=28\ \frac{\text{keV cm}^2}{\text{mg}},\quad \left(\frac{dE}{dX}\right)_p^{Xe}=16\ \frac{\text{keV cm}^2}{\text{mg}},$$

the Q value for the reaction $Xe^{136}(d,p)Xe^{137}$ was found to be 1.82 ± 0.06 MeV.

In Fig. 4, the separation energies (S_n) of the 83rd neutron in five even-odd isotopes are plotted together with the separation energies of the 81st neutron. This comparison shows that the separation energy drops approximately 2.3 MeV just beyond the $N=82$ closed shell. It is also notable that the S_n values for all five $N=83$ nuclei as well as for the $N=81$ nuclei are on straight lines. This behavior, which is also expected from the semiempirical mass formula, predicts that the still unknown Sn^{133} isotope is a bound nucleus.

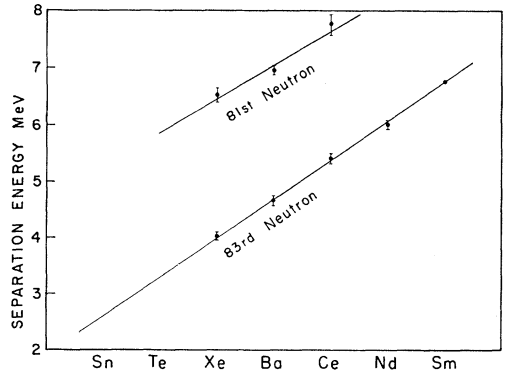

FIG. 4. Separation energies of the 83rd and 81st neutrons from Xe, Ba, Ce, Nd, and Sn targets.

[11] B. L. Cohen, R. Patell, A. Prakash, and E. J. Schneid, Phys. Rev. **135**, B383 (1964).

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

The results for the pick-up reaction on the enriched Xe^{136} targets are given in Table II. This table lists the excitation energies, assigned l_n values, the assigned values of spins and parity, and the relative cross sections at 60°. Also listed are the results for two levels attributed to Xe^{133}. The triton spectra were recorded at eleven angles between 20° and 70° with 80-keV resolution. Figure 5 shows a typical spectrum taken at a lab angle of 45°. Nine strong peaks are observed and

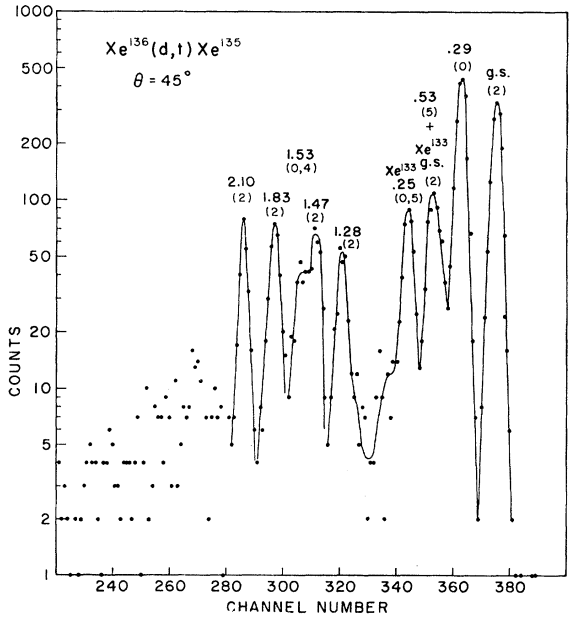

FIG. 5. A typical energy spectrum of triton groups from $Xe^{136}(d,t)Xe^{135}$ and $Xe^{134}(d,t)Xe^{133}$. The excitation energies in units of MeV and assigned values of angular-momentum transfer are listed above the peaks.

identified as belonging to Xe^{135} or Xe^{133}. The angular distributions of the nine triton groups leading to the excited states of Xe^{135} and Xe^{133} are given in Fig. 6.

The transition to the ground state of Xe^{135} has an $l_n=2$ angular distribution which agrees very well with the known assignment of $\frac{3}{2}^+$. The transition to the first excited state at 0.29 MeV has an $l_n=0$ angular distribution, and is assigned $\frac{1}{2}^+$. From the decay studies of I^{135},[4] the $11/2^-$ state is known to have an excitation energy of 0.523 MeV. A triton group at 0.53 MeV was observed and the angular distribution was found to contain an $l_n=5$ component when compared to the DWBA prediction. The angular distribution for this triton group could be reasonably well fitted with combinations of either $l_n=0$ plus $l_n=5$ or $l_n=2$ plus $l_n=5$ curves calculated by DWBA. The $l_n=2$ plus $l_n=5$ combination gives a slightly better fit and the $l_n=2$ component of the peak does correspond to the $\frac{3}{2}^+$ ground state of Xe^{133}. The assignments for the 1.28- and 1.47-MeV states are not as clear as the assignment for the first three states. The DWBA prediction indicates that these peaks may be $l_n=2$. Tentative spin and parity assignments of $\frac{5}{2}^+$ were made for both these states. Two other $l_n=2$ states have been identified at 1.83 and 2.10 MeV and these have also been assigned $J^\pi=\frac{5}{2}^+$. The total cross section for these transitions almost accounts for the total expected cross section of the $\frac{5}{2}^+$ state. Taking the center of gravity of these four peaks as the energy of the $\frac{5}{2}^+$ single-hole state in Xe^{135}, it is found to be 1.70 MeV, which is lower than the results of Fulmer *et al.*[2] for Ba^{137} and Ce^{139}, >2.0 and >1.8 MeV, respectively.

The state at 1.53 MeV appears to be a multiplet having $l_n=0$ and $l_n=4$ distributions. This $l_n=4$ level is the only level which is assigned to the $\frac{7}{2}^+$ single-hole state. One expects another $\frac{7}{2}^+$ state from ($d_{3/2}$+one phonon) in this energy region so the strength of the $g_{7/2}$ state should be split among more than one state. It is possible that angular distributions for the states assigned to $l_n=2$ may have some weak $l_n=4$ admixture in them from nearby $\frac{7}{2}^+$ states. The DWBA calculation for the ground-state $l_n=2$ distribution predicts higher cross sections than experimentally observed for angles greater than 30°. If this is true for all the DWBA predictions for $l_n=2$, the good fit to the 1.80- and 2.10-MeV states may be explained by some $l_n=4$ admixture in the angular distributions. However, since this is not certain, these states have been assigned as $l_n=2$ transitions.

Absolute cross sections were not obtained for the (*d*,*t*) reaction, however relative cross sections taken at 60° are given in Table II. The relative cross-section scale should be a reasonable approximation to the absolute cross sections for these peaks. If the assumption is made that the spectroscopic factor for the $d_{3/2}$ ground-state transition should be unity, the DWBA calculation predicts an absolute cross section of 1.30 mb/sr. The remaining levels are normalized relative to the ground-state transition. The resultant cross sections are in very good agreement with the experimentally determined cross sections of Fulmer[2] for Ce^{139} and Ba^{137}. This rather remarkable agreement seems to indicate that, for at least the $l_n=2$ cases, the normalization of the DWBA (*d*,*t*) calculations is very good. Very similar relative cross sections can be obtained if we normalized to the 0.29-MeV, $l_n=0$ state using the same method as described for the ground state.

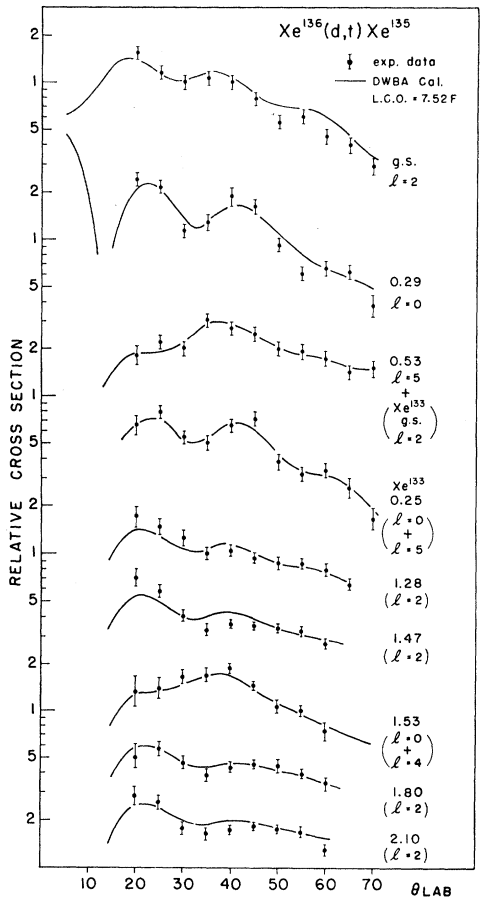

FIG. 6. Angular distributions of the triton groups leading to the excited states of Xe^{135} and Xe^{133} are shown along with the DWBA predicted angular distributions. To the right of these distributions the excitation energies and values of angular momentum are indicated.

The $Xe^{134}(d,t)Xe^{133}$ Reaction

Since Xe^{134} was present as an impurity in our target gas, triton groups appeared in our spectra which could be assigned to levels belonging to Xe^{133}. The results for Xe^{133} are also listed in Table II and the angular distributions for the Xe^{133} states are shown in Fig. 5. The ground-state transition has a *Q* value very close to that of the 0.53-MeV $11/2^-$ state of Xe^{135} so that the two levels could not be resolved and the angular distribution indicates $l_n=2$ and $l_n=5$ admixture. An $l_n=0$ peak was

observed which could be an excited state of either Xe^{135} and Xe^{133}. This $\frac{1}{2}^+$ level was assigned to the 0.25-MeV state of Xe^{133} for the following reasons:

(1) In Ba^{137} and Ce^{139} only one $\frac{1}{2}^+$ state is observed. The 0.29-MeV $\frac{1}{2}^+$ state of Xe^{135} seems to have nearly the same cross section and energy as the $\frac{1}{2}^+$ states in Ba^{137} and Ce^{139}. This fact suggests that only one $\frac{1}{2}^+$ state may be expected in Xe^{135}.

(2) The cross section of this level has the correct intensity for the $\frac{1}{2}^+$ state in Xe^{133}.

(3) The $\frac{1}{2}^+$–$\frac{3}{2}^+$ energy spacing is roughly the same as that for the two neighboring even-odd isotones, Te^{131} and Ba^{135}, with 0.29 and 0.22 MeV, respectively.

The excitation energy of the $11/2^-$ state in Xe^{133} is known from the decay of I^{133} to be 0.23 MeV, and contributes an $l_n=5$ component to the angular distribution of the 0.25-MeV state.

The relative cross sections for the levels of Xe^{133} are calculated from the same normalizations used for Xe^{135}, however they are increased by a factor proportional to the enrichment of Xe^{134} relative to that of Xe^{136}. The relative cross section for the $\frac{3}{2}^+$ state of Xe^{133} is approximately 55% of the cross section for the corresponding state in Xe^{135}. This is expected from shell-model theory since in Xe^{134} the $d_{3/2}$ shell-model state should be half empty, i.e., have a spectroscopic factor $S=0.5$. The relative cross section of the $\frac{1}{2}^+$ state in Xe^{133} is roughly the same as that for the $\frac{1}{2}^+$ state in Xe^{135}, and again one would expect the cross sections to be the same since the spectroscopic factor for the $\frac{1}{2}^+$ shell-model state for both target nuclei should be unity.

ACKNOWLEDGMENTS

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Errata

Measurement of the Spins of Some States in Fe^{55}, D. S. GEMMELL, L. L. LEE, JR., A. MARINOV, AND J. P. SCHIFFER [Phys. Rev. **144**, 923 (1966)]. The last sentence of the figure caption on Fig. 5 should be deleted. The 1.322-MeV state in Fe^{55} is in fact populated in the $Fe^{56}(n,d)Fe^{55}$ reaction, as was observed in the references cited earlier in this caption. The conclusions reached in the rest of the paper remain unchanged. We are indebted to Dr. C. A. Whitten for calling this error to our attention.

Elastic Electron Scattering from the Magnetic Multipole Distributions of Li^6, Li^7, Be^9, B^{10}, B^{11} and N^{14}, R. E. RAND, R. FROSCH AND M. R. YEARIAN [Phys. Rev. **144**, 859 (1966)]. In the analysis of the Li^7 data (Sec. VIII) there is an error in the independent particle value of the $E2$ part of the inelastic (0.478-MeV level) form factor. This form factor $F_{E2'}(q^2)$ should be increased by a factor of 2.

This change implies that one should then choose $S_2=0.75\pm0.10$ (instead of 0.50) as a reasonable guess at the actual inelastic $E2$ contribution. The new numerical results are as follows:

In Tables VIII and XIV, the ratio of the magnetic octupole moment to the dipole moment of Li^7 is reduced from 2.83 to 2.30 ± 0.50 (±0.15 in Table VIII) for $a_0=1.70$ F. Similar changes apply for other possible values of a_0. Experimental values of the parameter R_2 are reduced accordingly. The predicted value for the parameter C should now be 1.89 for the independent-particle model.

Conclusions regarding the preferred coupling scheme are unchanged, i.e., the independent-particle model is still favored by the experimental data (although not so strongly as before), while the L-S coupling scheme is incompatible with the experitmenal results. (Note that the parameter most sensitive to the coupling scheme is B. This is unchanged.)