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Study of 83-Neutron Nuclei by Deuteron Stripping Reactions*

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A study of the 83-neutron nuclei Ba^{138}, La^{139}, and Pr^{141} was made by the (d,p) stripping reaction with 11-MeV deuterons. The outgoing protons were analyzed with a magnetic spectrometer, and angular distributions were measured for the well-resolved states. Excited levels, with spins and parities indicated in parentheses, were found at 0 (7/2-), 0.59 (3/2-), 1.07, 1.39, 1.67 (5/2-), 1.20 (1/2-), 2.44 (1/2-) MeV in Ba^{139}; at 0 $(g_{7/2}f_{7/2})$, 0.25 $(g_{7/2}f_{7/2})$, 0.60 $(g_{7/2}p_{3/2})$, 0.71 $(g_{7/2}p_{3/2})$, 1.02, 1.31, 1.37, 1.46, 1.80, 1.88, 1.95, and 2.13 MeV in La^{140} $(d_{5/2}f_{7/2})$, 0.62 $(d_{5/2}p_{3/2})$, 1.02 $(d_{5/2}p_{3/2})$, 1.38 $(d_{5/2}p_{3/2})$, and 2.12 MeV in Pr^{142}. The angular distributions were fitted with a distorted-wave Born approximation calculation to determine the angular momentum transfer. The absolute Q values obtained agree with previous measurements. A comparison is made with earlier measurements on the 83-neutron nucleus Ce^{141}.

INTRODUCTION

Recent developments in nuclear theory have led to an increased interest in the study of heavy nuclei in which either the protons or the neutrons are in a major closed shell. An especially promising advance has been the introduction of a pairing force which, combined with a long-range force, furnishes a representation of the nuclear two-body interaction.[1] Using this representation in an actual calculation of the properties of single closed-shell nuclei, Kisslinger and Sorensen[2] have demonstrated that the properties of such nuclei are amenable to theoretical computation. The success of these calculations has suggested that nuclei which possess one nucleon outside a major closed shell may also be of interest for theoretical and experimental investigation.

There are several naturally occurring isotones which possess the neutron shell closed with the eighty-second neutron; deuteron stripping on these isotones is an ideal way to make nuclei with a single neutron outside this shell. Furthermore, experiments have shown the deuteron stripping reaction to be useful for investigating heavy nuclei.[3–5] When the bombarding deuteron energy is below the Coulomb barrier of the target nucleus (as it is in this experiment), the proton angular distributions are distorted from the shapes predicted by the Butler theory because of nuclear and Coulomb effects. Nevertheless, the distributions still possess features characteristic of the angular momentum transfer involved, and the distorted-wave Born approximation (DWBA) stripping formulation has been successful in interpreting them.[5,6]

The deuteron stripping study of the 83-neutron nuclei was begun by Holm and Martin[4] with the reaction $Ce^{140}(d,p)Ce^{141}$. The work reported in this paper is a continuation of this study and involves the reactions $Ba^{138}(d,p)Ba^{139}$, $La^{139}(d,p)La^{140}$, and $Pr^{141}(d,p)Pr^{142}$. In Ba^{139}, as in Ce^{141}, there are an even number of protons in addition to the closed neutron shell. Accordingly, Ba^{139} is expected to exhibit properties similar to those observed in Ce^{141}, e.g., well-separated levels which are interpretable in terms of single-particle states. In La^{140} and Pr^{142} there is an unpaired proton which is expected to interact with the neutron added by the stripping reaction; a more complex level scheme is, therefore, to be expected in these two nuclei.

1. EXPERIMENTAL PROCEDURES

The deuterons which initiated the (d,p) reactions in this experiment were furnished by the Indiana University cyclotron. Because of repairs made on the machine between data runs, the beam energy was slightly different for each of the three reactions studied: 11.0 MeV for the La^{140} run, 11.3 MeV for the Pr^{142} run, and 11.2 MeV for the Ba^{139} run. The proton groups emerging from the (d,p) reactions were analyzed with a double-focusing magnetic spectrometer. The arrangement of the experimental apparatus has been described in other papers.[3,7]

The targets were prepared by vacuum evaporation. The lanthanum (1.38 mg/cm^2) and praseodymium (2.28 mg/cm^2) targets were self-supporting. Because barium oxidizes very readily, the evaporation of the barium target was performed inside the reaction chamber. The barium target therefore required a backing; after several thin backing materials had proved too weak to withstand the evaporation, a 0.000003-in.-thick nickel foil was found satisfactory. This foil was supplied by the manufacturer[8] on copper backing, which was removed by dipping the nickel-plus-copper foil (glued to a target frame) into a solution of 17 g of trichloracetic acid in 100 ml of $3N$ NH_4OH. The handling

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* Work supported in part by the Office of Naval Research.

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[1] S. T. Belyaev, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **31**, No. 11 (1959).

[2] L. S. Kisslinger and R. A. Sorensen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **32**, No. 9 (1960).

[3] M. T. McEllistrem, H. J. Martin, D. W. Miller, and M. B. Sampson, Phys. Rev. **111**, 1636 (1958).

[4] G. B. Holm and H. J. Martin, Jr., Phys. Rev. **122**, 1537 (1961).

[5] D. W. Miller, H. E. Wegner, and W. S. Hall, Phys. Rev. **125**, 2054 (1962).

[6] W. Tobocman, Phys. Rev. **115**, 98 (1959).

[7] G. B. Holm, J. R. Burwell, and D. W. Miller, Phys. Rev. **118**, 1247 (1960).

[8] Chromium Corporation of America, Waterbury, Connecticut.

of the foil during the dipping followed the procedure used by Sellschop.[9] The thickness of the barium layer deposited on the nickel foil was 1.16 mg/cm^2.

In spite of the precautions taken to eliminate oxidation of the barium target, an oxygen contaminant was present in it. This contaminant contributed proton groups from the $O^{16}(d,p)O^{17}$ reaction; these groups interfered severely with some of the groups being studied in the experiment. The contributions of the oxygen contaminant were subtracted from the data by the methods described in reference 4, but the subtractions were so uncertain that large errors were indicated for some cross sections. The subtraction was made especially difficult by the fact that the amount of oxygen in the target increased during the time that the data were taken; a further correction, with accompanying uncertainty, was therefore necessary.

Typical spectra from the three reactions studied are shown in Figs. 1, 7, and 12. These spectra were taken at 7.5-deg intervals starting from 12.5°, the smallest angle obtainable. Q values and cross sections were extracted from these spectra. The parameters involved in the absolute cross section calculations were measured by the methods of Holm and Martin; the energy measurements also followed the procedures described in earlier papers.[3,7] The momentum resolution of the spectrometer was set at 0.32% for the barium run. A better resolution was desired for the more closely spaced groups expected in lanthanum and praseodymium. In the latter case, a resolution of 0.21% was employed. For lanthanum the resolution was 0.25% although 0.18% was employed for one portion of the spectrum.

The error in the absolute cross sections is $\pm 30\%$. Error in relative cross sections is shown by error bars on the angular distribution figures. The error in Q values is ± 30 keV in the Ba^{139} and La^{140} cases; the two lowest lying groups in Pr^{142} are uncertain by ± 33 keV; the other Pr^{142} Q values have an error of ± 38 keV.

2. THEORETICAL CALCULATIONS

The distorted-wave Born approximation predictions of the stripping cross sections measured in this experiment were calculated with the code of Gibbs and Tobocman, as modified by Blair, Swartz, and Hall. After some minor program modifications to adapt the code to the facilities available, the calculations were performed on the IBM 709 computer of the Indiana University Research Computing Center. In general, a comparison of theoretical predictions with experimental distributions indicated unambiguously the orbital angular momentum transfers involved; the distributions and assignments are discussed individually below.

It should be emphasized that no effort was made to obtain the best possible fit to the experimental data. The shapes of the angular distributions, rather than their magnitudes, were considered the primary criteria in assigning orbital angular momentum transfers. Accordingly, the theoretical distributions, which, in general, underestimated the cross sections, were normalized only roughly to the experimental data. No special effort was made to adjust the DWBA optical model parameters to get a precise fit. The optical model parameters used in the computer calculation were those used by Tobocman[10] in calculating the distributions for Ce^{141}. Better fits than those shown in this paper could probably be obtained by a careful variation of the DWBA parameters and a more precise normalization to the experimental data.

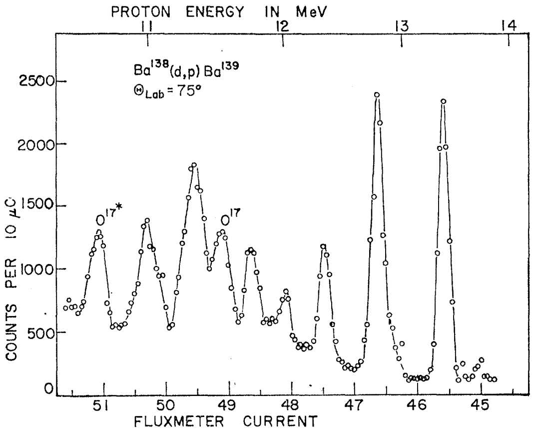

FIG. 1. A proton momentum spectrum for a natural barium target on thin nickel backing. All the strongly excited states are considered as leading to states in Ba^{139} except for the two groups marked O^{17} and O^{17*}, which result from deuteron stripping on the O^{16} contaminant present in the target.

3. $Ba^{138}(d,p)Ba^{139}$ REACTION

The particular spectrum shown in Fig. 1 was chosen because it displays the two oxygen contaminant peaks in addition to all seven of the proton groups attributed to the stripping on Ba^{138}. At other angles the oxygen groups osbcured one or more of the barium groups.

Natural barium consists of 71.7% Ba^{138} and 11.3% Ba^{137} with the remaining percentage distributed among five other isotopes. The Q value for the $Ba^{137}(d,p)Ba^{138}$ ground-state reaction is so large (6.4 MeV) that it

TABLE I. Ba^{139} and Ce^{141} level schemes.

	Ba^{139}			Ce^{141}	
Excitation (MeV)	Q (MeV)	Spin and parity	Excitation (MeV)	Q (MeV)	Spin and parity
0	2.50	7/2−	0	3.21	7/2−
0.59	1.91	3/2−	0.65	2.56	3/2−
1.07	1.43		1.12	2.09	3/2−
1.39	1.11		1.35	1.86	
			1.47	1.74	
1.67	0.83	5/2−	1.77	1.44	5/2−
2.10	0.40	1/2−	2.15	1.06	
2.44	0.06	1/2−	2.41	0.80	1/2−

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[9] J. P. F. Sellshop, Phys. Rev. **119**, 251 (1960).

[10] W. Tobocman (private communication to H. J. Martin, Jr).

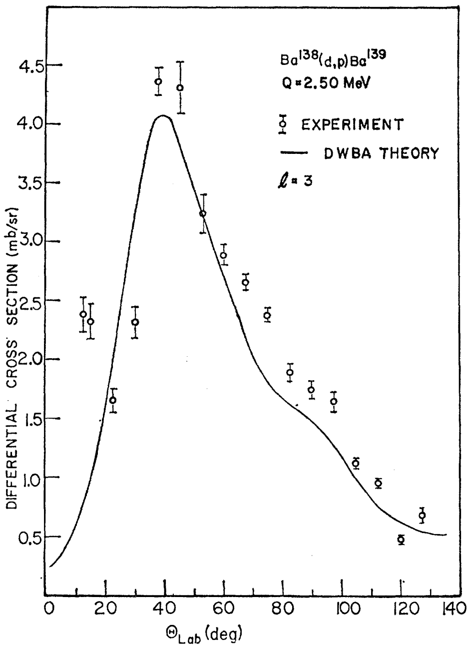

FIG. 2. Angular distribution of the proton group leading to the ground state of Ba^{139}. The agreement with the distorted wave Born approximation theoretical curve indicates that three units of orbital angular momentum l have been transferred to the residual nucleus. An f-wave neutron capture is therefore assumed.

was felt that proton groups from this reaction would lie at too high an energy to interfere badly with the protons from Ba^{139} levels. Any interfering groups leading to states in Ba^{138} would be formed at high excitation and high level density; they should accordingly form a roughly level (and subtractable) background beneath the Ba^{139} peaks. Therefore, all the strongly excited groups observed in the reaction were attributed to the formation of Ba^{139}.

The Q values measured for the seven Ba^{139} levels are given in Table I, where they are compared with the Ce^{141} levels. The two lowest-lying states in Ba^{139} have been observed in previous (d,p) work[11]; the Q values measured there agree with the values measured in this experiment. These states have also been observed in the beta decay of Cs^{139}.[12]

Ground State: $Q=2.50$ MeV

The spin of Ba^{139} has been previously assumed to be 7/2− because of the measurements of the ground-state spin of Ce^{141}.[13] As shown in Fig. 2 the angular distribution of this state indicates f-wave neutron capture, in agreement with the shell-model assignment of $2f_{7/2}$ for the eighty-third neutron. A similar distribution was obtained for the Ce^{141} ground state in the work of Holm and Martin.

The normalization factor applied to the theoretical DWBA curve to get the curve in Fig. 2 was 1.5.

The 0.59-MeV Level: $Q=1.91$ MeV

The injurious effects of the oxygen contaminant are evident in the angular distribution for this state (Fig. 3). At the three most forward angles the oxygen ground state group interfered severely with the barium group; large errors were accordingly placed on the barium cross sections taken there. Unfortunately, the cross section at these angles still seems to be falling rather than rising, in contradiction to any distribution expected for this state. However, the rest of the distribution agrees with the p-wave theoretical distribution. Since, furthermore, the corresponding state in Ce^{141} yielded an unmistakable p-wave distribution, it seems reasonable to assign a $p_{3/2}$ configuration to this state; the $3p_{3/2}$ neutron state is expected near this excitation.

A normalization factor of 1.5 was required for the DWBA curve in Fig. 3.

The 1.07-MeV Level: $Q=1.43$ MeV

The distribution for this state was ruined by the oxygen contaminant. Although it resembles a p wave perhaps more than anything else, the data were not good enough to allow a definite assignment. The Ce^{141} state at about the same excitation had a p-wave angular distribution, and a $p_{3/2}$ state was assumed for the neutron.

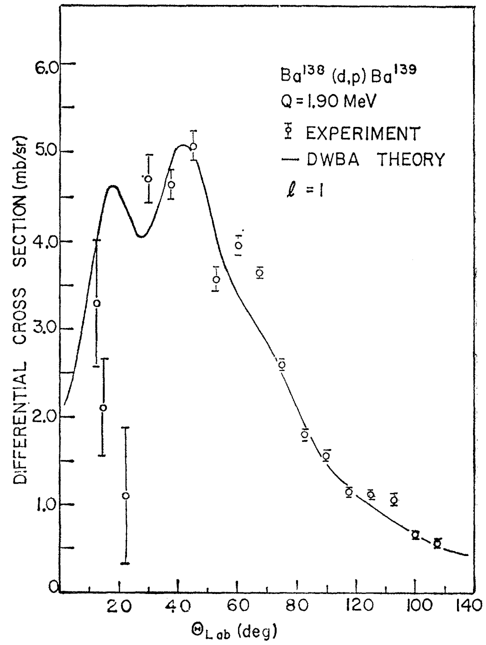

FIG. 3. Angular distribution for the 0.59-MeV level in Ba^{139}. The distribution indicates a p-wave neutron capture.

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[11] C. H. Paris, W. W. Buechner, and P. M. Endt, Phys. Rev. **100**, 1317 (1955).

[12] *Landolt-Börnstein, New Series*, edited by A. M. Hellwege and K. H. Hellwege (Springer-Verlag, Berlin, 1961), Vol. I, pp. 2–312.

[13] Reference 12, pp. 2–313.

The 1.39-Mev Level: $Q=1.10$ MeV

At three angles this level was badly obscured by the oxygen groups. Although its angular distribution did not appear to be either a *p* wave or an *f* wave, no unambiguous spin assignment could be made. The cross section of the state is quite small compared to the others observed in the experiment, indicating that this may be a high spin state. Indeed, the $h_{9/2}$ state is expected somewhere in this region, and a recent study[14] has suggested that one of the corresponding states in Ce^{141} possesses an angular distribution consistent with an $h_{9/2}$ assignment. Since the DWBA program is not capable of generating an *h*-wave distribution, no direct comparison with the present data could be made. However, the distribution for this state does seem to possess a rather broad peak that extends to angles greater than 60°, as one might expect from an *h*-wave neutron capture. As in the measurements by Holm and Martin of the corresponding Ce^{141} states, the possibility of an $h_{9/2}$ level cannot be ruled out, but in view of the large errors in the cross sections it would seem presumptuous to exclude the possibility that this state is formed by mixing of an *f* state with another nuclear state.

The 1.67-MeV Level: $Q=0.83$ MeV

The angular distribution for this state is shown in Fig. 4. Although there are difficulties with the oxygen subtraction, the distribution indicates an *f*-wave neutron capture. As for the corresponding Ce^{141} state, the assignment made is 5/2− ; the $3f_{5/2}$ state is expected around this excitation.

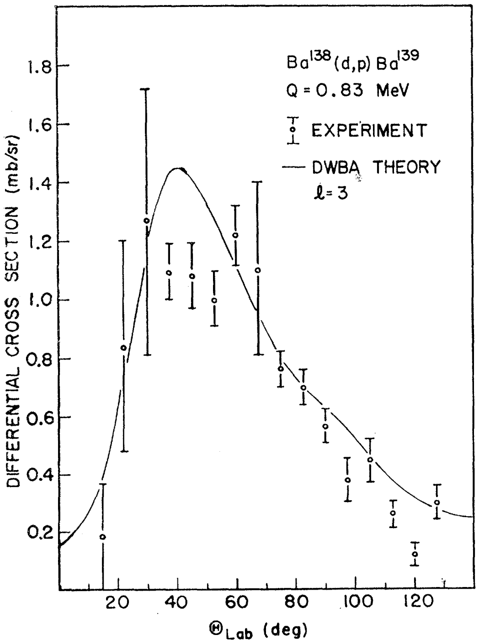

Fig. 4. Angular distribution for the 1.67-MeV state in Ba^{139}. An *f*-wave assignment is indicated.

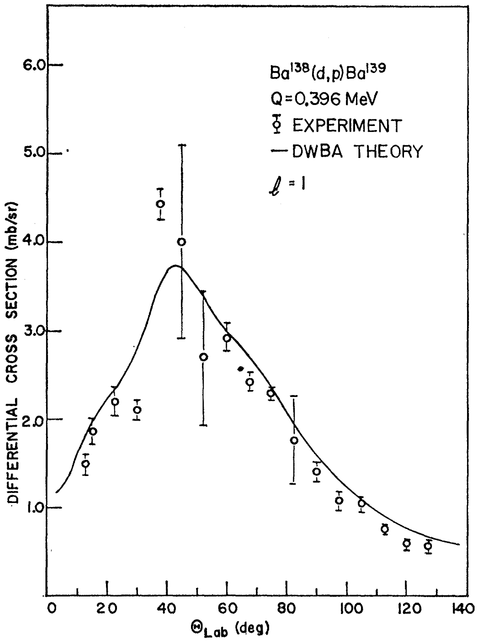

Fig. 5. Angular distribution for the 2.10-MeV state in Ba^{139}. A *p*-wave neutron capture is indicated.

There still remains a difficulty in the relation of this state to its Ce^{141} analog. Where the total cross sections for the cesium $f_{5/2}$ and $f_{7/2}$ states were in the ratio 0.7 (in agreement with the statistical factor in the Butler stripping theory), the corresponding ratio in the barium case is only 0.3. Apparently, there is a striking difference between the two very similar nuclei Ba^{139} and Ce^{141}, at least in the formation of these two *f* states.

The 2.10-MeV Level: $Q=0.396$ MeV

In Fig. 5 is displayed the angular distribution for the Ba^{139} fifth excited state. A *p*-wave neutron capture is indicated, and since the $3p_{1/2}$ state is expected in this region a 1/2− assignment has been made.

In Ce^{141} the corresponding state yielded cross sections that at the peak of the distribution were less than half as large as the cross sections in Fig. 5. No spin assignment was made in the cerium study.

The normalization factor for the DWBA curve of Fig. 5 was 1.5.

The 2.44-MeV Level: $Q=0.056$ MeV

The distribution in Fig. 6 indicates another *p*-wave distribution and another $p_{1/2}$ assignment. A possible explanation for the occurrence of two 1/2− states follows the lines of the suggestion made in the cerium study for the occurrence of two 3/2− states at lower excitation. A group of perturbing levels, consisting of $f_{7/2}$ plus two phonons, is expected to lie near 2.4 MeV;

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[14] R. H. Fulmer, A. L. McCarthy, and B. L. Cohen, Bull. Am. Phys. Soc. 7, 316 (1962).

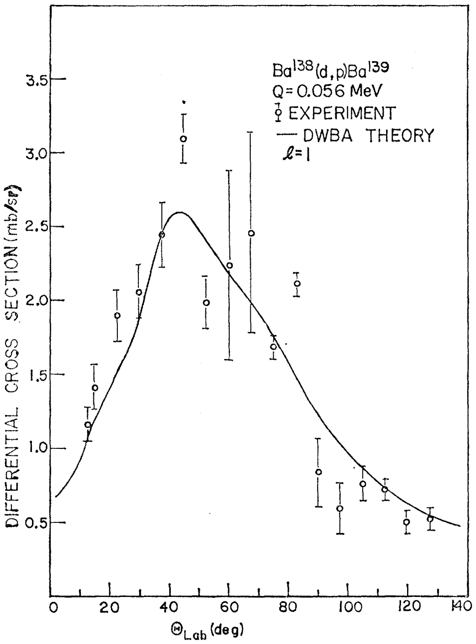

FIG. 6. Angular distribution for the 2.44-MeV state in Ba^{139}. The distribution indicates a p-wave neutron capture.

among these levels is a 1/2− state which might mix with the $3p_{1/2}$ state to produce the extra 1/2− level observed in Ba^{139}. Such an argument is, of course, rather conjectural. However, the width of the proton peak representing this state is greater than the width of the other peaks observed; this indicates that the 2.44-MeV level is probably not a single state. Moreover, the normalization factor for the DWBA curve of Fig. 6 was 1.0, somewhat less than the factor of 1.5 required for some other states. Since the DWBA calculations assume single-particle states, the fact that this factor is less than 1.5 may be further evidence that the 2.44-MeV level is not a pure single-particle state.

There is a discrepancy between the Ba^{139} and Ce^{141} data concerning the two highest states observed in each case. In the cerium data, the higher of these two states had the larger cross section, which was, at the peak of the distribution, about four times the smaller cross section. In barium, the situation is reversed; the lower lying state has a cross section about 1.3 times the cross section of the state at higher excitation. Furthermore, the sum of the $p_{1/2}$ cross sections in Ba^{139} is roughly equal to the sum of the $p_{1/2}$ cross sections in Ce^{141}. If it is true that the $p_{1/2}$ pairs are formed by mixing, then the mixing must be appreciably different in the two very similar nuclei.

A similar discrepancy occurs when the second and third excited states in the two nuclei are compared. The Ba^{139} data are too rough to allow a very accurate comparison, but they do indicate that in Ba^{139} the upper of these states is more strongly excited, relative to the lower state, than in Ce^{141}.

Levels at Higher Excitation

As in Ce^{141}, there lies above the highest state discussed here a long group of unresolved levels. Presumably these states are formed by configuration mixing; no single-particle states are expected in the region where they appear.

Conclusions

As expected, the two nuclei Ba^{139} and Ce^{141} possess similar level schemes. As shown in Table I, their excited states lie at roughly the same excitation; all the Ce^{141} states, except for the 2.41-MeV level, lie at slightly higher excitation than the corresponding Ba^{139} states. Although the spin assignments for the two nuclei agree, there are very noticeable differences in the cross sections of some of the corresponding states. The Ba^{139} data do, nevertheless, corroborate the conclusion drawn in the Ce^{141} experiment that mixing of the neutron levels with perturbing levels at excitations below 2.4 MeV is not a large effect; most of the levels found are interpretable on the assumption that they are single-particle states.

The simple Butler-Born approximation stripping theory is not expected to yield accurate predictions for this experiment. For comparison purposes, however, an attempt was made to use this theory to extract reduced widths from the barium angular distributions. Butler radii larger than 4 F could be obtained only for the f-wave states, i.e., the ground state and the 1.67-MeV state. These radii were 4.7 and 4.4 F, respectively, and the calculated reduced widths were 0.02 and 0.006.

4. $La^{139}(d,p)La^{140}$ REACTION

A typical spectrum for this reaction is shown in Fig. 7. Compared with the Ba^{139} spectrum, the levels observed here are rather closely spaced after the first two. A

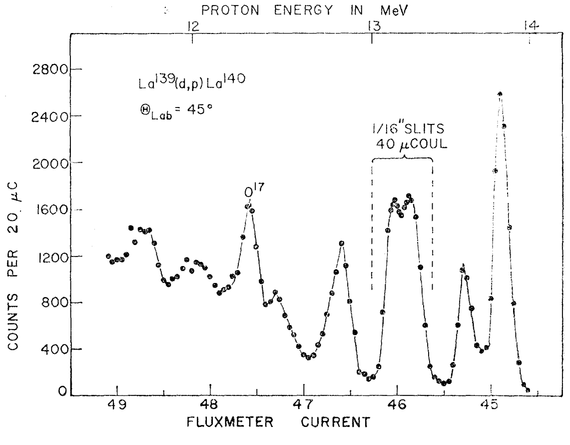

FIG. 7. A proton momentum spectrum for a metallic lanthanum target. The spectrometer acceptance slit was reduced from 1/8 in. to 1/16 in. over one portion of the spectrum in order to increase the resolution. Forty microcoulombs of charge were allowed to pass through the target during this part of the run. All the proton peaks have widths larger than the experimentally expected widths, indicating that each peak represents more than one nuclear state.

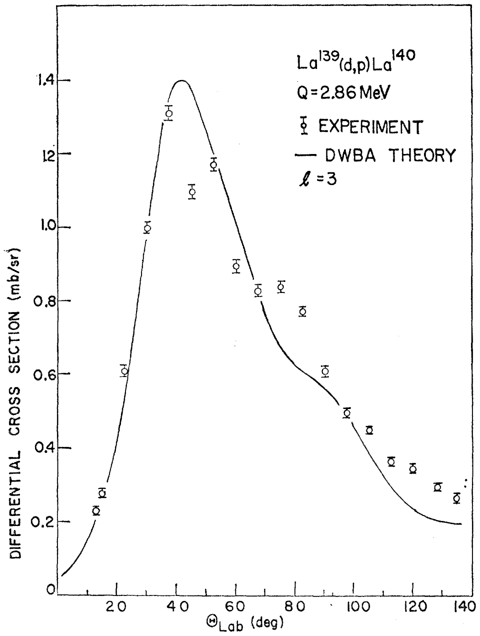

FIG. 8. Angular distribution for the La^{140} group at zero excitation. An f-wave assignment is indicated.

number of levels were not resolved well enough to permit the extraction of their cross sections; however, it was possible to measure their Q values. Three of these peaks could be identified at only a few angles; whether they really represent levels in La^{140} is subject to some question. These are the groups at 1.90-, 1.88-, and 1.95-MeV excitations.

Since natural lanthanum is 99.9% La^{139}, there was no difficulty in identifying the peaks leading to states in La^{140}. Moreover, there was little difficulty with oxygen contaminant in the target; a rather easy carbon subtraction was necessary at a few angles.

It is important to note that probably all the peaks in the lanthanum spectra represent the formation of more than one state; the widths are all larger than the experimental resolution. However, the groups observed do possess reasonable angular distribution shapes; each probably consists of states formed by the same angular momentum transfer.

The results of the measurements are shown in Table II.

Most of the previous information about the La^{140} nucleus has come from the beta decay of Ba^{140}.[15] One level at zero excitation was observed in the (d,p) work of Wall.[16]

Ground State: $Q=2.86$ MeV

The distribution for this level is shown in Fig. 8. An f-wave assignment is clearly indicated. Because the neutron deposited by the stripping reaction interacts with the unpaired proton in La^{140}, no unambiguous spin assignment can be made for this level. In fact, the states that make up this undoubtedly complex group certainly must have different spins. However, the spin of the odd proton has been known for some time to be $g_{7/2}$,[17,18] and the nuclear configuration indicated for this lowest group of states in La^{140} is $g_{7/2}f_{7/2}$.

TABLE II. La^{140} level scheme.

Excitation (MeV)	Q (MeV)	Nuclear configuration
0	2.86	$g_{7/2}f_{7/2}$
0.25	2.61	$g_{7/2}f_{7/2}$
0.60	2.26	$g_{7/2}p_{3}f_{2}$
0.71	2.15	$g_{7/2}p_{3/2}$
1.02	1.84	
1.31	1.55	
1.37	1.49	
1.46	1.40	
1.80(?)	1.06	
1.88(?)	0.98	
1.95(?)	0.91	
2.13	0.73	

The Q value for this group agrees with the earlier measurement.

The 0.25-MeV Level: $Q=2.61$ MeV

The angular distribution for this level (Fig. 9) is clearly the f-wave distribution, and a configuration of $g_{7/2}f_{7/2}$ is indicated.

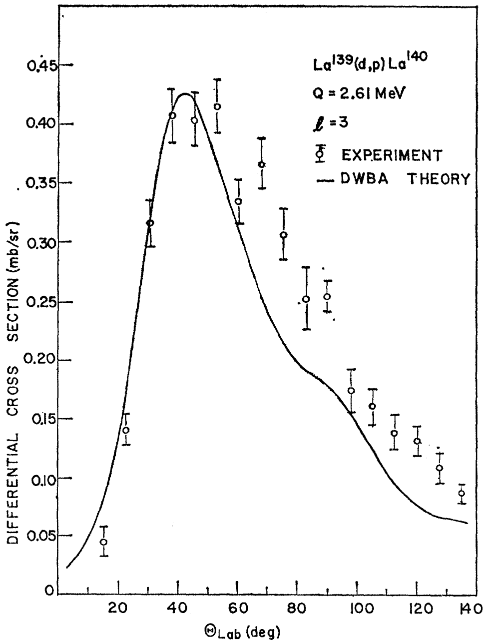

FIG. 9. Angular distribution for the 0.25-MeV level in La^{140}. An f-wave assignment is indicated.

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[15] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).

[16] N. S. Wall, Phys. Rev. **96**, 664 (1954).

[17] O. E. Anderson, Phys. Rev. **45**, 685 (1934).

[18] R. Sheriff and D. Williams, Phys. Rev. **82**, 651 (1951).

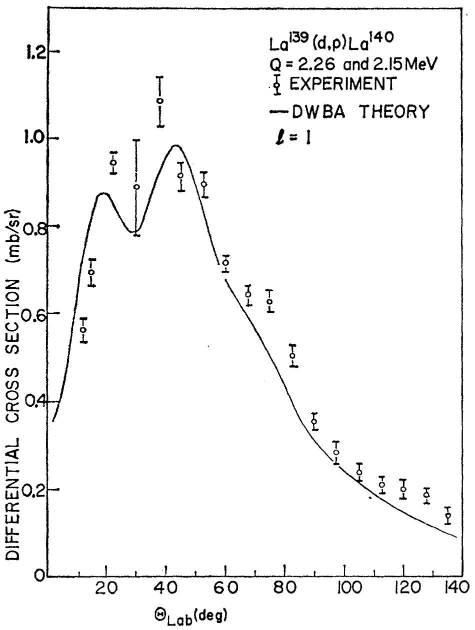

FIG. 10. Angular distribution for the 0.60- and 0.71-MeV levels in La^{140}. A *p*-wave neutron capture is indicated.

Kurath[19] has stated that when nucleons in different shell-model levels couple there tend to appear two groups of states of different J. The higher lying of these two groups is characterized as containing the levels for which the quantity (l_1+l_2+J) is odd; for the lower group this quantity is even. If the two $g_{7/2}f_{7/2}$ states seen here are following this rule, the upper group should possess about 40% of the total cross section for both groups. The experimental value is about 34%; it is subject to error because, as seen in the sample spectrum, the two peaks are joined at their bases and had to be separated by assuming a symmetrical shape for each of them.

The 0.60- and 0.71-MeV Levels: $Q=2.26$ and 2.15 MeV

These two groups are seen as a close doublet in Fig. 7 It was in the attempt to separate the two levels that the spectrometer resolution was improved when their portion of the spectrum was taken. Their combined distribution is shown in Fig. 10, and a *p* wave is indicated. The nuclear configuration adopted for the two levels is, therefore, $g_{7/2}p_{3/2}$.

The 1.02-MeV Level: $Q=1.84$ MeV

The angular distribution for this level (Fig. 11) is inconclusive. Because of the presence of contaminants in the target, data could not be taken for this group at the most forward angles, and in their absence the angular distribution does not permit a clear cut orbital angular momentum transfer assignment. The incomplete distribution obtained indicates an *f*-wave capture more than a *p* wave, although the single-particle *f*-wave states found in Ba^{139} and Ce^{141} appear at excitations rather far from the excitation of this state.

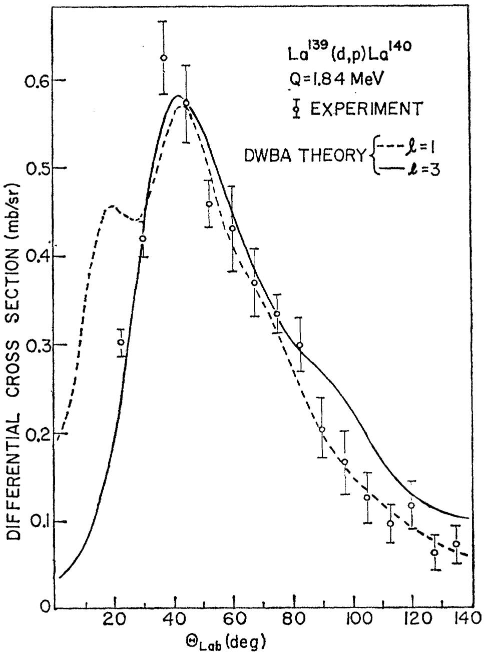

FIG. 11. Angular distribution for the 1.02-MeV group in La^{140}. The angular momentum transfer is not conclusively indicated by the fit to the theoretical curve because the experimental distribution is incomplete at low angles. The fit favors an *f*-wave assignment, although this assignment is not the one to be expected on the basis of the excitation energy of this group.

5. $Pr^{141}(d,p)Pr^{142}$ REACTION

In the sample spectrum shown in Fig. 12 the peaks are all wider than the experimental resolution, and the levels observed in Pr^{142} are probably all complex. All

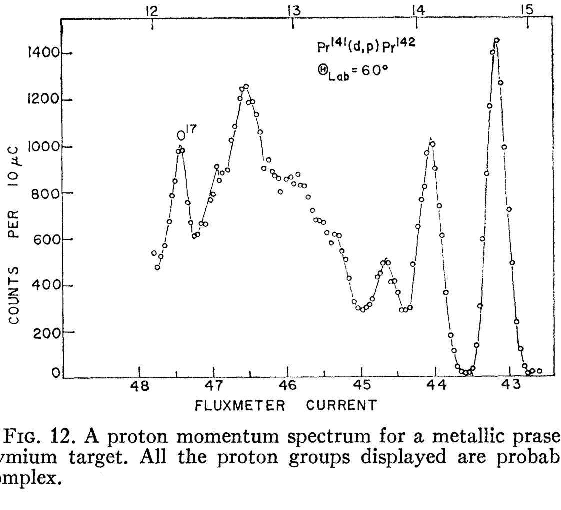

FIG. 12. A proton momentum spectrum for a metallic praseodymium target. All the proton groups displayed are probably complex.

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[19] D. Kurath, *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York and London, 1960), p. 983.

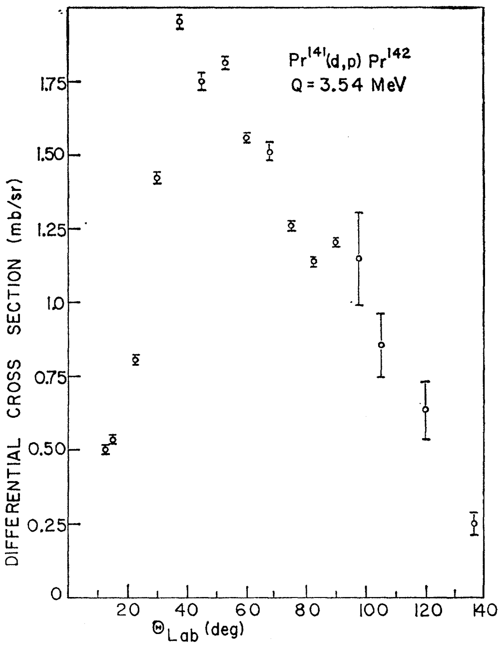

FIG. 13. Angular distribution for the Pr^{142} group at zero excitation. An *f*-wave assignment is indicated.

TABLE III. Pr^{142} level scheme.

Excitation (MeV)	Q (MeV)	Nuclear configuration
0	3.54	$d_{5/2}f_{7/2}$
0.62	2.92	$d_{5/2}p_{3/2}$
1.02	2.52	$d_{5/2}p_{3/2}$
1.38[a]	2.16	$d_{5/2}p_{3/2}$
2.12	1.40	

[a] A group of unresolved levels extends from this state to an excitation of about 2.5 MeV.

the proton groups in Fig. 12 are attributed to stripping on Pr^{141}, which is 100% of natural praseodymium. Table III summarizes these data.

A feature of the Pr^{142} spectrum is the appearance of a long group of unresolved states extending from about 1.4-MeV excitation to about 2.5 MeV. Only one peak in this smear stood out clearly enough to permit a Q-value measurement; its angular distribution could not be measured.

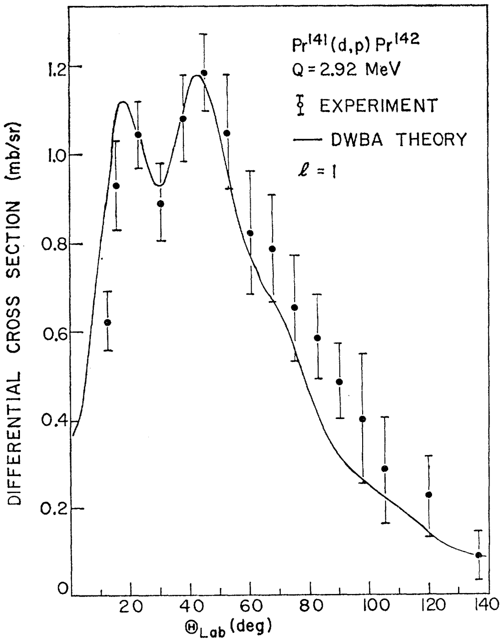

FIG. 14. Angular distribution for the 0.62-MeV level in Pr^{142}. A *p*-wave assignment is indicated.

The Q values for the first two groups observed in Pr^{142} agree with the previously measured values.[16] Some other levels in Pr^{142} have been observed in (n,γ) work.[20]

Ground State: $Q=3.54$ MeV

The angular distribution shown in Fig. 13 represents *f*-wave neutron capture. As in the La^{140} analysis, no unambiguous spin can be assigned to the states represented by the proton group observed here. However, the unpaired proton in Pr^{142} is in a $d_{5/2}$ state[21,22]; the nuclear configuration for the zero excitation group is accordingly taken as $d_{5/2}f_{7/2}$.

Two low-lying *f*-wave states were observed in La^{140} and only one in Pr^{142}. It, therefore, seems reasonable that

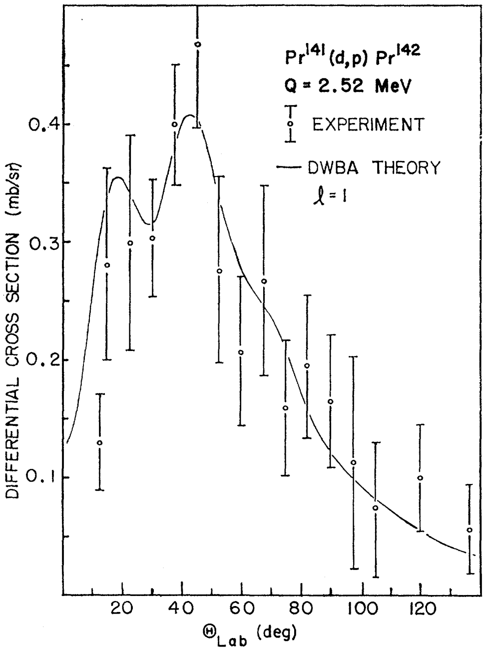

FIG. 15. Angular distribution for the 1.02-MeV level in Pr^{142}. A *p*-wave assignment is indicated.

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[20] G. Bartholomew and B. Kinsey, Can. J. Phys. **31**, 1025 (1953).

[21] H. E. White, Phys. Rev. **34**, 1397 (1929).

[22] P. Brix, Phys. Rev. **89**, 1245 (1953).

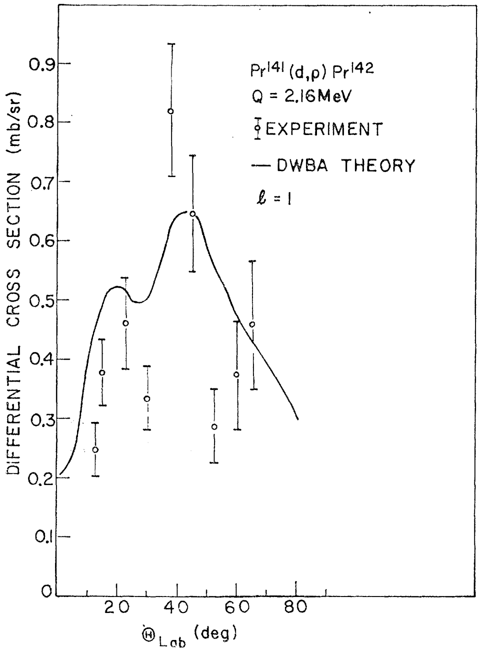

FIG. 16. Angular distribution for the 1.38-MeV level in Pr^{142}. The angular momentum transfer assignment is not clearly indicated, but the p-wave distribution fits the data better than any other.

the width of this group is larger than the width of the lowest-lying group in La^{140}. The reason that the $d_{5/2}f_{7/2}$ states do not fall into two clearly defined groups in Pr^{142} may be simply that there are less states possible from the $d_{5/2}f_{7/2}$ configuration.

The 0.62-MeV Level: $Q=2.92$ MeV

The states within this complex group are predominantly formed by p-wave neutron capture, as shown by the angular distribution in Fig. 14. The nuclear configuration is taken as $d_{5/2}p_{3/2}$.

The 1.02-MeV Level: $Q=2.52$ MeV

The cross section for this state is small, and large percentage errors make the distribution shown in Fig. 15 less precise than others extracted in the experiment. However, the agreement with the theoretical p-wave distribution is better than with any other distribution, and a $d_{5/2}p_{3/2}$ configuration is indicated.

The 1.38-MeV Level: $Q=2.16$ MeV

The cross section for this state could be measured at only a few angles. The proton group is situated at the beginning of the smear of unresolved levels that characterized the praseodymium data; at angles larger than 60°, it merged into the smear. However, the partial distribution seems to resemble a p wave (Fig. 16). The configuration is taken with some uncertainty as $d_{5/2}p_{3/2}$.

6. COMPARISON OF THE NUCLEI STUDIED

In Fig. 17 are shown the levels observed in all four of the nuclei studied in this and the cerium experiment.

The data show reasonable agreement among the energy levels and spins. The lowest-lying groups are all formed by f-wave neutron capture, and about 0.6 MeV higher in excitation occur the first of the states involving $p_{3/2}$ capture. Most of the levels lie at the same excitations at levels in at least some of the other three nuclei; there are, in each nucleus, levels at, roughly, 0.6, 1.7, 1.4, and 2.1 MeV.

It was thought that the total $f_{7/2}$ cross sections might be equal in the four nuclei because f-wave cross sections are not strongly dependent on Q. This conjecture is not at all verified by this experiment. The sum of the cross sections for all the observed $f_{7/2}$ neutron states in La^{140} or Pr^{142} is less than the $f_{7/2}$ cross section measured in Ce^{141} or Ba^{139}. If the $f_{7/2}$ state is able to mix with other states over excitation differences greater than 1 MeV, some of the total $f_{7/2}$ cross section for La^{140} or Pr^{142} might appear in some of the unresolved states and hence go unmeasured.

As expected, there are more states observed in the two odd-proton nuclei because the neutron-proton interaction splits the single-particle neutron levels. Also as expected, the neutron interacts with the $d_{5/2}$ proton differently from the $g_{7/2}$ proton, as evidenced by the somewhat dissimilar level schemes for La^{140} and Pr^{142}.

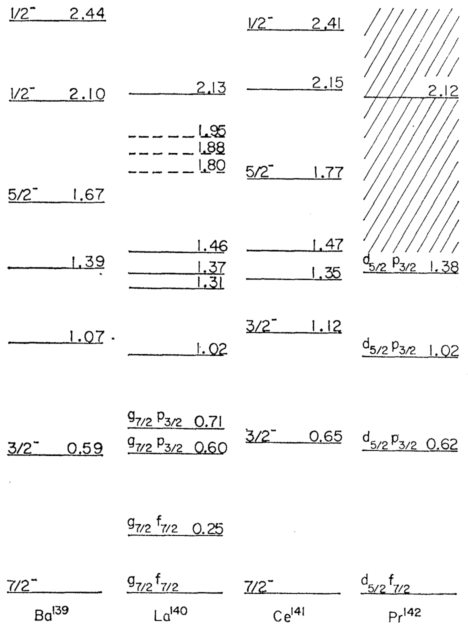

FIG. 17. Summary of the levels excited in this (d,p) work, compared with the levels in Ce^{141} studied by Holm and Martin. Energies are in MeV. Spins and parities are given for the Ba^{139} and Ce^{141} levels; the configurations of the unpaired proton and neutron are listed for the La^{140} and Pr^{142} levels.

The levels in Pr^{142} are more closely grouped above 1.4-MeV excitation; only one $f_{7/2}$ group appears in Pr^{142}; the La^{140} doublet has no easily visible analog in Pr^{142}.

In summary, the level and spin assignments made in the experiment are internally consistent. The behavior of the cross section magnitudes is not always what might be expected, but the angular distributions are, for the most part, readily interpretable in terms of stripping theory.

ACKNOWLEDGMENTS

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Optical-Model Analysis of the Energy Dependence of Neutron Polarization near 1 MeV

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An optical-model analysis is made of the energy dependence of the polarization of neutrons elastically scattered from a number of medium-weight nuclei near 1 MeV. Attention is also paid to the energy variation of the total and reaction cross sections, so that the optical parameters chosen represent the average scattering over a range of nuclei and a range of energies in a meaningful fashion. Some angular distributions at 1 MeV are also plotted. The effect of compound-elastic scattering on these angular distributions and on the polarization near 1 MeV is found from a Hauser-Feshbach calculation.

1. INTRODUCTION

RECENTLY, Brown, Ferguson, and White[1] have measured the polarization of neutrons elastically scattered from Cu, Zn, Mo, and Cd as a function of energy in the range 300–1500 keV. The experimental resolution was ~40 keV, and the measurements revealed very marked fluctuations of the polarization with energy, with half-width of the order of 200 keV or less. At some energies there was evidence of possible sharp resonance effects of half-width ~50–100 keV.

The same authors have discussed the general trend of these observations, and attempted an optical-model fit to the polarization, using the Bjorklund-Fernbach potential. The present paper describes a more thorough investigation of the possibility of fitting the average neutron polarization and scattering data by the optical potential. It is clear that nothing more than the average trend of the data can be expected to follow from the optical model at energies near 1 MeV, if, indeed, that much is possible. However, any further discussion of the marked fluctuations and sharper resonance effects observed by Brown *et al.* will be the clearer if an idea is first got of the average strength of the single-particle amplitudes in the scattering, and this will be provided by the optical model.

With this purpose in view, a search has been made for optical parameters which will reproduce the energy variation of the polarization and the total and reaction cross sections near 1 MeV, as well as a number of angular distributions at various energies, over a range of nuclei from about $A=50$–100 for which the polarization data are available. This investigation is made in the early spirit of the optical model, in the expectation that any over-all fit that may be achieved—over a range of energy and of nuclei, as above—will be of some significance in regard to the relative strength of the single-particle amplitudes in the actual scattering process. It is not intended that a detailed A-by-A choice of parameters should be made, nor are the optical parameters finely adjusted as functions of energy. We are so near the credible limits of the optical model that such refinements would probably be illusory. As it is, the agreement with the average trend of the data which can be achieved is quite remarkable, and would appear to justify the intentions expressed above.

Peterson[2] has recently pointed out that the giant resonances observed in the total neutron cross sections, which have a typical width of many MeV, are the result of a nuclear Ramsauer effect, rather than of resonant single-particle excitations of the compound nucleus. Nevertheless, such single-particle resonances of the compound system may be present, and in certain circumstances may lead to fluctuations in the neutron total or reaction cross sections with a width of the order of as little as 100 keV. This idea has been put forward by

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[1] D. Brown, A. T. G. Ferguson, and R. E. White, in *Proceedings of the International Symposium on Polarization* [Helv. Phys. Acta. Suppl. **6**, 291 (1960)].

[2] J. M. Peterson, Phys. Rev. **125**, 955 (1962).