Nuclear Structure Studies of the 83-Neutron Species Nd^{143}†

CARSON L. NEALY AND RAYMOND K. SHELINE
The Florida State University, Tallahassee, Florida
(Received 19 September 1966)

Thirty-eight states have been observed in Nd^{143} between the ground state and 3576 keV utilizing 10-MeV deuterons and the reaction $Nd^{142}(d,p)Nd^{143}$. The ground-state Q value for this reaction was measured as 3902 ± 15 keV. Absolute cross sections of the proton groups were measured. Angular distributions of most of the protons populating the lower-lying states were obtained and the corresponding l values determined. Shell-model assignments of the states were attempted and the spectroscopic factors calculated. The centers of gravity of the fragmented shell-model states were then compared with those of other 83-neutron species and with theory.

I. INTRODUCTION

SINCE Kisslinger and Sorensen[1] demonstrated that the properties of single-closed-shell nuclei can be calculated theoretically, a number of workers[2–6] have studied the nuclear structure of 83-neutron nuclei. The work on neodymium[3] employed natural neodymium and only the ground and first excited states were observed. The purpose of the present paper is to investigate in detail the nuclear structure of Nd^{143} utilizing the reaction $Nd^{142}(d,p)Nd^{143}$.

II. EXPERIMENTAL PROCEDURE

Targets of Nd^{142} were prepared by vacuum evaporation of approximately 200 μg/cm^2 of the separated isotope as Nd_2O_3 onto thin ($\sim$30–50 μg/cm^2) carbon backings. They were bombarded with approximately 10-MeV deuterons produced with the Florida State University Tandem Van de Graaff accelerator.[7] The protons resulting from the (d,p) reaction on Nd^{142} were analyzed at a number of angles in a magnetic spectrograph and detected by means of nuclear track emulsions. Details of the experimental procedure have been described previously.[8]

Angular distributions of the proton groups were determined by utilizing the ratio of Rutherford to reaction cross section. Rutherford scattering cross sections were measured at 4 MeV and then, without changing the position of the target or spectrograph, the (d,p) exposure was taken at 10 MeV.

III. EXPERIMENTAL RESULTS AND THEIR INTERPRETATION

A typical proton spectrum is shown in Fig. 1. Identification of the proton groups populating levels in Nd^{143} was based on the following facts. First, the targets were enriched to 97.45% in Nd^{142}. Second, unusually high cross sections leading to most of the states in Nd^{143} (of the order of 1 mb) were observed. These facts exclude assignment of the intense proton groups to heavy impurities and, in particular, the other neodymium isotopes which were present in amounts of approximately 1% or less. Light impurities were identified by their kinematic shift. The last factor used to identify proton groups populating Nd^{143} levels was the great similarity of the relative intensities from two different targets for which exposures were taken at the same angle and field-strength setting of the magnetic spectrograph. Exposures were taken at 45° and 65° in this manner. These two targets contained the same amounts of the various neodymium isotopes, since they came from the same batch of Oak Ridge separated isotopes[9]; but since the targets were made at different times, we may expect the amounts of other impurities to be different. It has been observed in target preparation at this laboratory that most impurities are introduced during the target preparation procedure and that impurities vary considerably from one target preparation to another, even when the same lot of separated isotopes is used.

The energy levels deduced in this manner are listed in Table I. The measured ground state Q value is 3902 ±15 keV. In calculating this Q value, the incident deuteron energy was determined by utilizing the Q value for the reaction $C^{12}(d,p)C^{13}$ ($Q=2723.3$ keV). In previous (d,p) work by Wall,[10] the Q-value was determined to be 3790 ± 80 keV. Angular distributions were determined on proton groups corresponding to levels in Nd^{143} up to approximately 2300 keV of excitation energy. These angular distributions were analyzed by the distorted-wave Born-approximation (DWBA)

† Work supported in part by the U. S. Atomic Energy Commission.

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

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[3] R. H. Fulmer, A. L. McCarthy, and B. L. Cohen, Phys. Rev. **128**, 1302 (1962).

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[5] R. A. Kenefick and R. K. Sheline, Phys. Rev. **139**, B1479 (1965).

[6] R. K. Jolly and C. F. Moore, Phys. Rev. **145**, 918 (1966).

[7] Operation of the Florida State University Tandem Van de Graaff Accelerator is supported in part by the U. S. Air Force Office of Scientific Research, Office of Aerospace Research, U. S. Air Force under AFOSR Grant No. AF-AFOSR-440-66.

[8] R. A. Kenefick and R. K. Sheline, Phys. Rev. **133**, B25 (1964).

[9] The neodymium isotopic composition of the targets as given by the Separated Isotopes Division of Oak Ridge is: $Nd^{142}-97.45\%$, $Nd^{143}-1.04\%$, $Nd^{144}-0.89\%$, $Nd^{145}-0.21\%$, $Nd^{146}-0.26\%$, $Nd^{148}-0.08\%$, and $Nd^{150}-0.07\%$.

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

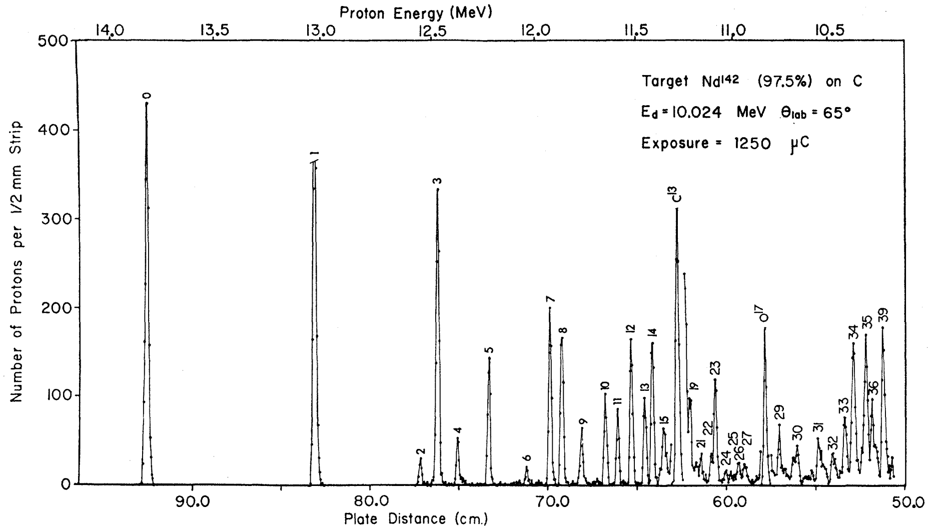

FIG. 1. Spectrum of the levels in Nd^{143} populated in the reaction $Nd^{142}(d,p)Nd^{143}$ at 65°.

theory utilizing the SALLY code.[11] The optical-model parameters used were not determined from elastic scattering data, but by the following procedure. Using initial guesses from the systematic study of Perey,[12,13] the optical-model parameters were varied until a fit was obtained for the $l=3$ transition to the ground state of Nd^{143}. The assumption of an $l=3$ ground-state transition is based on the $\frac{7}{2}$ spin determination[14–16] for the Nd^{143} ground state and on its interpretation as the $f_{7/2}$ shell-model state. The parameters determined in this manner (see Table II) were used to calculate the rest of the angular distributions. It was necessary to employ a lower cutoff radius of 4.2 F in the calculations. The experimental angular distributions compared with the theoretical calculations are shown in Figs. 2, 3, 4, and 5. In each case the theoretical values have been normalized to give the best fit to the experimental results.

The angular distributions of the two states at 1412 and 1743 keV were obscured by the strong proton peaks from the reactions $C^{12}(d,p)C^{13}$ and $O^{16}(d,p)O^{17}$ at more forward angles than 45° (see Fig. 5). Equally good fits with $l=4$, 5, or 6 can be obtained for the 1412-keV

TABLE I. Energy levels of Nd^{143}.

Group number	E_{ex} (keV)	σ (keV)	l
0	0		3
1	743	3	1
2	1236	3	5
3	1311	3	1
4	1412	4	4, 5, 6
5	1560	2	3
6	1743	6	5
7	1857	4	1
8	1916	2	3
9	2016	4	
10	2131	3	1
11	2192	4	3
12	2261	5	1
13	2328	4	1
14	2367	4	1
15	2423	5	
16	2463	4	
17	2505	5	
18	2535	4	
19	2558	3	
20	2592	6	
21	2618	5	
22	2666	4	
23	2688	3	
24	2743	4	
25	2777	7	
26	2811	4	
27	2842	4	
28	2927	3	
29	3021	5	
30	3114	3	
31	3228	4	
32	3303	5	
33	3373	7	
34	3412	3	
35	3480	2	
36	3515	4	
37	3576	6	

TABLE II. The optical-model parameters used in the DWBA calculations of the cross sections for the reaction $Nd^{142}(d,p)Nd^{143}$. The notation is as follows: V and W refer to the depth of the real and imaginary wells, respectively, r_0 and a are the radius and diffuseness, respectively, for the real well, while their primed counterparts are for the imaginary well, and r_c is the Coulomb radius.

	V (MeV)	r_0 (F)	a (F)	r_c (F)	W (MeV)	r_0' (F)	a' (F)
10-MeV deuterons	75	1.15	0.87	1.15	48	1.37	0.70
13-MeV protons	57	1.18	0.65	1.18	56	1.25	0.47

[11] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL-3240, 1962 (unpublished).

[12] F. G. Perey, Phys. Rev. **131**, 745 (1963).

[13] C. M. Perey and F. G. Perey, Phys. Rev. **132**, 755 (1963).

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[15] K. Murakawa and J. S. Ross, Phys. Rev. **82**, 967 (1951).

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state; although $l=5$ fits best for the 1743-keV state, $l=4$ and 6 cannot be ruled out entirely. However, shell-model considerations suggest that it is very unlikely that an $l=4$ transition exists in this energy region. It is therefore ruled out as a possibility for either of these states. The angular distribution of the 2016-keV state did not give a distribution typical of any l value and is probably a doublet.

Since the target nucleus, Nd^{142}, has a ground-state spin and parity of 0^+, the spin assignments from the experimentally determined l values for various states in Nd^{143} are limited to two values, $j=l\pm s$. This ambiguity is common to the type of measurement reported here. There are, however, a number of factors which place severe constraints on the final assignments of spins. These are: (1) the fact that in general the $j=l+s$ shell-model state lies lower in energy than the $j=l-s$ state and that the splitting[17,18] between these states can be estimated fairly accurately; (2) the fact that the sum of all spectroscopic factors of the fragmented states making up the single shell-model state must equal unity, i.e., $\sum_m S_j^m=1$; and (3) the fact that the final assignments can be compared with experimental determinations on other 83-neutron species and theoretical calculations for both Nd^{143} and other 83-neutron nuclei. In practice we have used the first two criteria to make the spin assignments, and then have compared them with calculations which are still largely incomplete.

The spectroscopic factor for each individual state is given by[19]

$$S=\frac{1}{(2j+1)}\frac{(d\sigma/dw)_{\text{expt}}}{(d\sigma/dw)_{\text{sp}}},$$

where j is the spin of the state; $(d\sigma/dw)_{\text{expt}}$ and $(d\sigma/dw)_{\text{sp}}$ are the experimental differential cross section and calculated single-particle cross sections, respectively. Table III contains the spectroscopic factors which were experimentally determined for the various states, assuming both possible spins whenever there was any ambiguity. The error quoted is derived from the reproducibility and is not the absolute error. Because of the uncertainty in the calculated single-particle cross sections, the absolute error cannot be determined; however, the error in the measured differential cross sections is $\pm 10\%$.

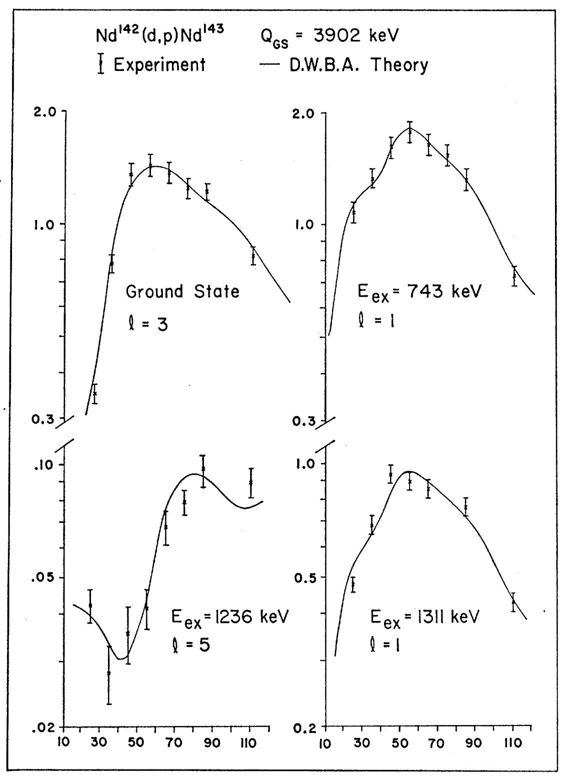

FIG. 2. Angular distributions of the ground state 743-, 1236-, and 1311-keV levels in Nd^{143}.

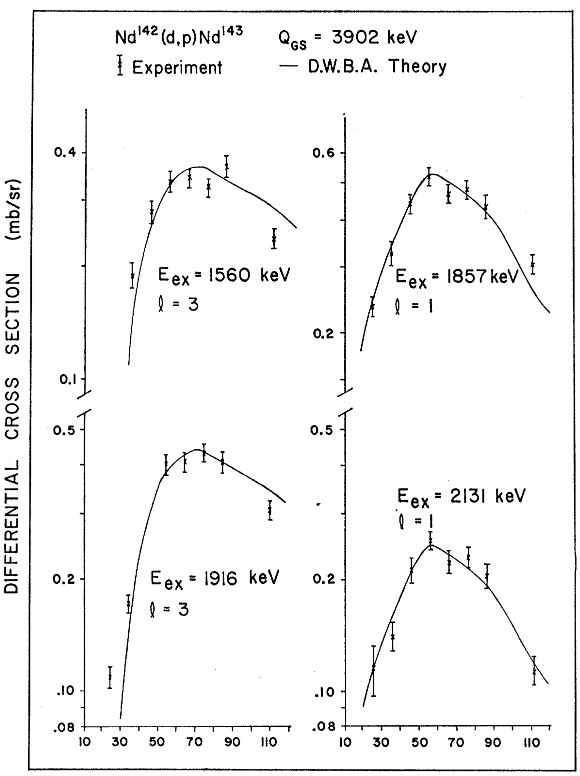

FIG. 3. Angular distributions of the 1560-, 1857-, 1916-, and 2131-keV levels in Nd^{143}.

[17] B. L. Cohen, P. Mukkerju, R. H. Fulmer, and A. J. McCarthy, Phys. Rev. **127**, 1678 (1962).

[18] B. L. Cohen, R. H. Fulmer, and A. J. McCarthy, Phys. Rev. **126**, 698 (1962).

[19] B. Cujec, Phys. Rev. **131**, 735 (1963).

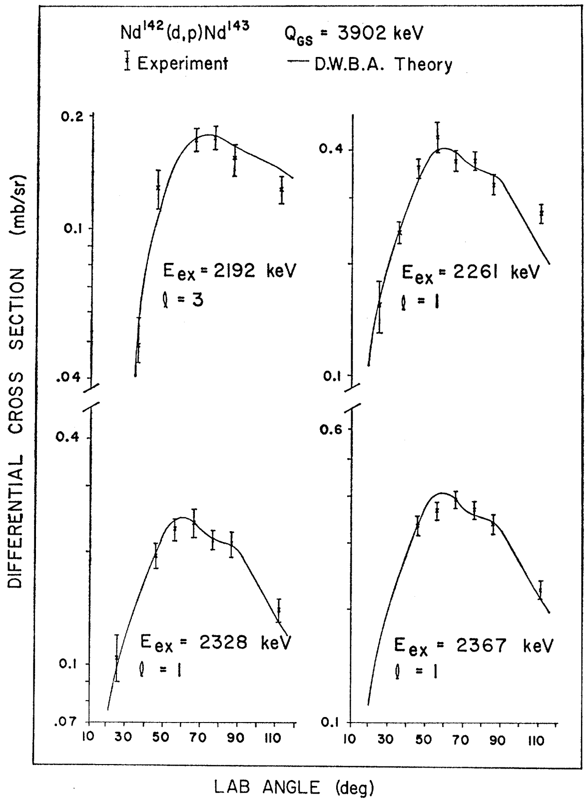

FIG. 4. Angular distributions of the 2192-, 2261-, 2328-, and 2367-keV levels in Nd^{143}.

The location of the single-particle states is assumed to be the center of gravity,

$$E_j = \frac{\sum_m E_j{}^m S_j{}^m}{\sum_m S_j{}^m},$$

of the states of the same spin. The location of these single-particle states is given in Table IV. Since the spins are only inferred for most of the states, there is no definite way to determine whether the two possible spin components are distributed correctly. Two equally reasonable distributions of the spin components of each l value are given in Table IV. Fortunately, the most reasonable assignments given in Table IV do not differ very much in the values obtained for centers of gravity of the shell-model states. All $l=5$ states are assigned to the $h_{9/2}$ state, which is the only single-particle state in this shell with an $l=5$ angular distribution. The inclusion or noninclusion of the 1412-keV state as $l=5$ does not appreciably affect the center of gravity of the $h_{9/2}$ state. The $l=3$ states are assigned as one $f_{7/2}$ state and three $f_{5/2}$ states. This distribution seems highly probable because of the wide energy separation and the high spectroscopic factor of the ground state ($f_{7/2}$) as compared with the other three states. In common with other experiments in which assignments are made with angular distribution

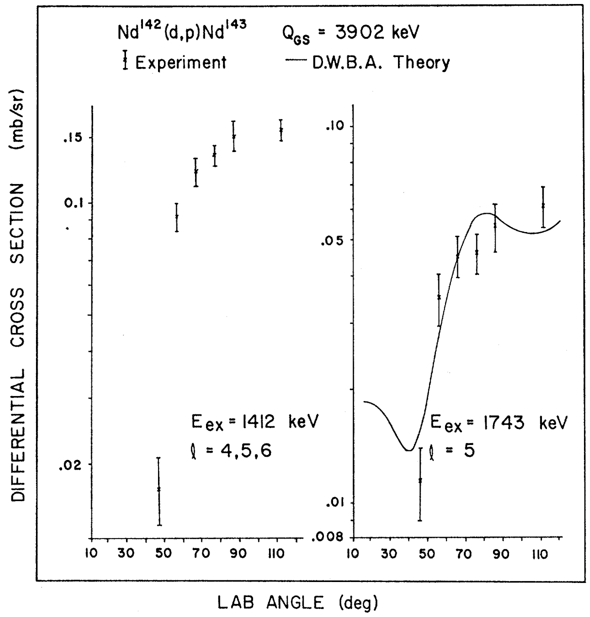

FIG. 5. Angular distributions of the 1412- and 1743-keV levels in Nd^{143}.

TABLE III. Calculated spectroscopic factors. Both of the possible spectroscopic factors are calculated when there is any possible ambiguity.

Energy	l	$S_j{}^m$ $l+\frac{1}{2}$	$S_j{}^m$ $l-\frac{1}{2}$
ground state	3	0.91±0.04	
743	1	0.05±0.02	
1236	5		0.31±0.04
1311	1	0.23±0.02	0.46±0.03
1412	5		0.53±0.08
1560	3	0.16±0.02	0.21±0.03
1743	5		0.19±0.04
1857	1	0.11±0.03	0.22±0.05
1916	3	0.18±0.01	0.25±0.02
2131	1	0.04±0.01	0.08±0.01
2192	3	0.06±0.01	0.08±0.01
2261	1	0.07±0.01	0.14±0.02
2328	1	0.04±0.01	0.09±0.01
2367	1	0.07±0.01	0.14±0.01

TABLE IV. Calculated "centers of gravity" for the shell-model states using two different sets of assignments.

Single particle	$\sum S_j{}^m$	E_j	States taken as belonging to the single-particle state
$f_{7/2}$	0.91±0.04	0.00	ground state
$p_{3/2}$	0.73±0.03	0.92	743, 1311
$i_{13/2}$	0.99±0.23	1.41	1412
$h_{9/2}$	0.50±0.06	1.43	1236, 1743
$f_{5/2}$	0.54±0.04	1.82	1560, 1916, 2192
$p_{1/2}$	0.67±0.06	2.12	1857, 2131, 2261, 2328, 2367
$f_{7/2}$	0.91±0.04	0.00	ground state
$p_{3/2}$	0.84±0.04	1.04	743, 1311, 1857
$h_{9/2}$	1.03±0.04	1.42	1236, 1412, 1743
$f_{5/2}$	0.54±0.04	1.82	1560, 1916, 2192
$p_{1/2}$	0.45±0.03	2.29	2131, 2261, 2328, 2367

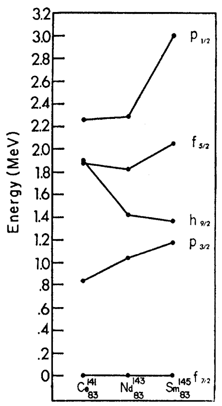

FIG. 6. Single-particle energies for odd-A 83-neutron nuclei. The single-particle energies are taken from the work of Fulmer *et al.* (see Ref. 3) for Ce^{144} and from Jolly and Moore (see Ref. 6) for Sm^{145}.

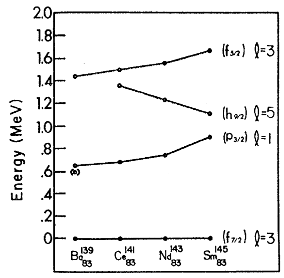

FIG. 7. Location of the first $l=1$, 3, and 5 states. Energy states in odd-A 83-neutron nuclei. The two points for $l=1$ for Ba^{139} result from two different experimental energies (see Refs. 3 and 4) whose errors do not quite overlap.

measurements, least confidence is placed in the distribution of the $l=1$ states. This results from the fact that the splitting between the $p_{3/2}$ and $p_{1/2}$ states is only about 1 MeV.[17] Considering the scatter of states around their center of gravity, there could be several states of each spin component which overlap. The distribution is further complicated by the fact that the 2016-keV state is probably a doublet whose components are not known. The one p state that can be assigned with considerable confidence ($p_{3/2}$ at 743 keV) is in disagreement with previous data. Ofer[20] measured the K-conversion coefficient of this transition to be $(6.5\pm1)\times10^{-3}$. This agrees with an assignment of $M1$ as the multipolarity of the transition. From this he deduced the spin to be $\frac{9}{2}$, $\frac{7}{2}$, or $\frac{5}{2}$. There can be little doubt about the present assignment, and supporting evidence for the $p_{3/2}$ assignment can be found in the systematics of the 83rd neutron. The first excited states in Ba^{139} at $\sim$600 keV,[3,4] in Ce^{141} at $\sim$660 keV,[2–4] and in Sm^{145} at $\sim$890 keV[6] have been assigned as $l=1$ angular distributions.

The inclusion of the 1412-keV state as the $i_{13/2}$ single-particle state is highly speculative; however, its angular distribution fits an $l=6$ equally as well as an $l=5$. Also its spectroscopic factor is 1 ($S=0.99\pm0.23$), as would be expected for the $i_{13/2}$ state.

The location of the single-particle states in odd-A 83-neutron nuclei is shown in Fig. 6. Since the exact location of these states is highly dependent upon the correct choice of the spin states involved, only general conclusions can be drawn from them. From Fig. 6 it can be seen that the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ single-particle states increase in energy relative to the $f_{7/2}$ ground state as the number of protons increases while the $h_{9/2}$ decreases in energy. These generalizations are borne out in greater detail in Fig. 7. In this figure the energies of the first $l=1$, 3, and 5 states relative to the ground state are shown as a function of the number of protons. It is particularly interesting to note in both Fig. 6 and Fig. 7 that the general energy sequence for the shell model states expected by Kisslinger and Sorensen[21] is observed. In particular, an $f_{7/2}$ ground state is followed by the sequence $p_{3/2}$, ($i_{13/2}$), $h_{9/2}$, $f_{5/2}$, and $p_{1/2}$. The only minor difference between experiment and theory is the fact that *both* the $p_{3/2}$ and the $p_{1/2}$ shell model states occur at somewhat higher energies than expected. This difference, however, cannot be ascribed to the division of the $l=1$ states between $p_{3/2}$ and $p_{1/2}$ assignments. Figures 6 and 7 also tend to emphasize the growing body of data on odd-A 83-neutron species available for comparison with theoretical calculations. We hope this experiment and the data from other experiments presented here will stimulate more detailed calculations.

ACKNOWLEDGMENTS

The authors wish to thank G. L. Struble, F. R. Rickey, and B. L. Lanier for their aid in data taking, and Mary Jones, Ella Jean Wehunt, and Sue Hipps for their accurate plate scanning.

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[21] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).