These data are shown in Table II and Fig. 1. Evidence of partially resolved resonance structure is seen. The value at 14.1 Mev agrees well with an earlier measurement[6] where the cross section for $S^{34}(n,\alpha)Si^{31}$ was determined to be 140±30 mb at 14.3 Mev.

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Angular Distribution of Protons from the $Ca^{40}(d,p)Ca^{41}$ Reaction*

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Proton groups emitted from a thin CaO target under 7-Mev deuteron bombardment were studied with a magnetic spectrograph. Their angular distributions were analyzed in terms of stripping theory to determine the orbital angular momenta and relative reduced widths for neutrons captured to form levels in Ca^{41} up to 4.2-Mev excitation. Capture gamma rays measured elsewhere can be fitted to a scheme comprised of levels strongly excited in the (d,p) reaction. Evidence is found for single-particle $f_{7/2}$, $p_{3/2}$, and $p_{1/2}$ states, but the expected $f_{5/2}$ level does not appear. Relative cross sections and reduced widths for (d,p) reactions forming states in Ca^{43} and Ca^{45} are also tabulated.

THIS paper is the third of a series reporting measurements of the angular distributions of proton groups produced by (d,p) reactions on calcium isotopes. The previous two papers[1,2] have been concerned with the reactions $Ca^{42}(d,p)Ca^{43}$ and $Ca^{44}(d,p)Ca^{45}$. The present publication presents results on the $Ca^{40}(d,p)Ca^{41}$ reaction and summarizes the relative intensities of the groups observed in each of the three reactions.

The present experiment supplements the work of Holt and Marsham,[3] who used the 8-Mev deuteron beam of the Liverpool cyclotron to study the angular distribution of protons emitted from a calcium target. The energy resolution of the Liverpool work was considerably lower than that of the work done by Braams,[4] whose experiment showed that certain of the proton groups observed by Holt and Marsham were composite and that a large number of low-intensity groups had been missed. In view of the importance of understanding the level structure of Ca^{41}, it appeared worth while to repeat the angular-distribution measurements using the high-resolution equipment available at this laboratory. In addition, the presence of groups from Ca^{40} in the Ca^{42} target used earlier[1] required a run on Ca^{40} to separate the effects of superimposed groups, as well as to check on the assignment of weak groups to impurities. As in the earlier reports from this laboratory on the calcium isotopes, the experiment described herein uses the results of Braams for identification of the proton groups and accepts his measurement of the energies of the excited states.

The previous communications of this series have outlined the experimental arrangements, with particular reference to the use of the broad-range magnetic spectrograph in measuring an angular distribution. The spectrograph itself and its use as a momentum analyzer have been described in detail.[5] Momentum analyses were obtained by deflecting the charged particles in a uniform magnetic field. The particles were detected in nuclear emulsions placed in the focal surface of the spectrograph, and plots were made of the number of particles against position on the plate. Polonium alpha particles afford a calibration of plate position against radius of curvature. Two such momentum plots are shown in Fig. 1. To simplify the plate counting, the emulsions were covered with sufficient aluminum foil to stop all particles heavier than protons.

The targets were prepared by Braams by vacuum evaporation of calcium metal onto Formvar backed with gold foil. The incident deuteron energy was 7.010 Mev. The proton groups, identified by numbers in Fig. 1, correspond to calcium levels identified by Braams,[4] and their energies are consistent with the measured Q values. A very intense peak produced by protons forming the ground state of C^{13} blocks out a portion of the spectrum. The obscured regions are graphed as a function of angle in Fig. 2. The unmarked peak to the right of group 7 in Fig. 1 is produced by the formation of the 1.902-Mev Ca^{45} level in the

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† Now at Yale University, New Haven, Connecticut.
1 Bockelman, Braams, Browne, Buechner, Sharp, and Sperduto, Phys. Rev. **107**, 176 (1957).
2 W. C. Cobb and D. B. Guthe, Phys. Rev. **107**, 181 (1957).
3 J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A46**, 565 (1953).
4 C. M. Braams, Phys. Rev. **103**, 1310 (1956).
5 Buechner, Mazari, and Sperduto, Phys. Rev. **101**, 188 (1956); and C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).

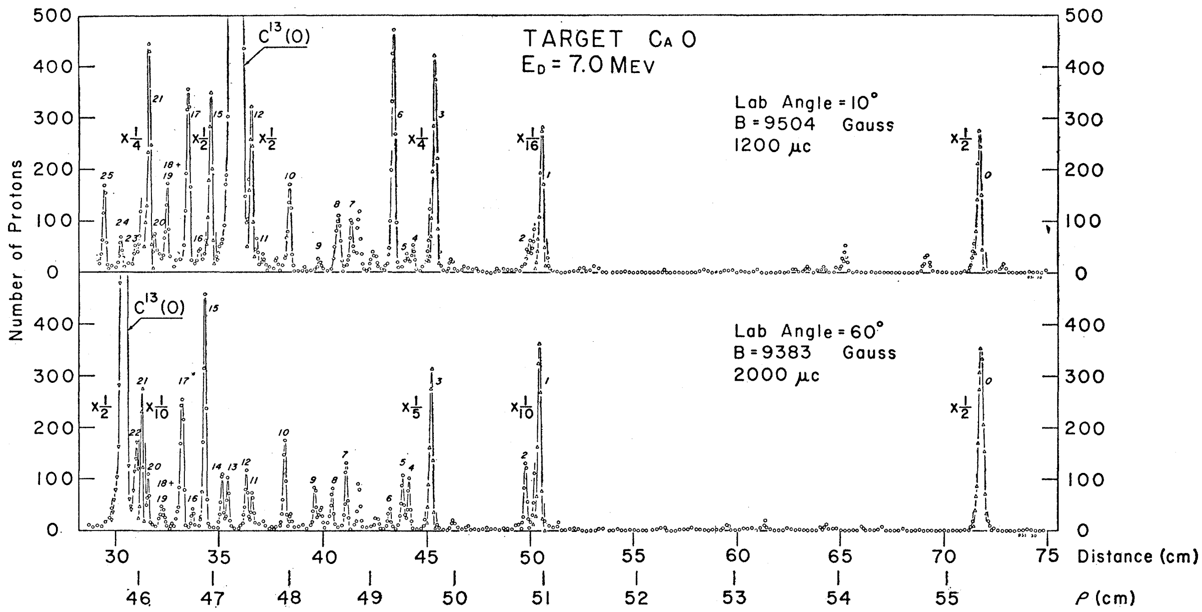


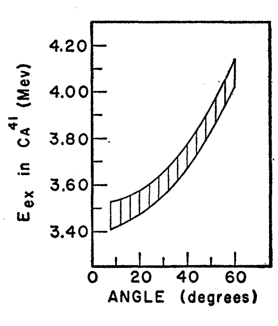
FIG. 1. Momentum analyses of protons emitted from a thin CaO target under deuteron bombardment. Results are shown for two laboratory angles. The numbered proton groups correspond to Ca^{41} levels reported in reference 4.

$Ca^{44}(d,p)Ca^{45}$ reaction.[6] For this group, the intensity observed relative to Ca^{41} and the angular distribution are consistent with the measured values and with the 2.1% abundance of Ca^{44} in natural calcium. The 1.432-Mev level in Ca^{45} is seen as a weak peak to the right of group 3. Groups corresponding to other levels in Ca^{45} are too low in intensity to be observed in Fig. 1. A number of other weak peaks is caused by impurities. Although the data were not sufficient to permit their identification in most cases, the fact that the observed intensity for the Ca^{40} targets was about the same as that seen with targets enriched in Ca^{42} and Ca^{44} prepared in the same way guarantees that these peaks cannot be associated with the formation of Ca^{41}, Ca^{43}, or Ca^{45}.

Angular distributions were obtained by summing at each angle the counts under the appropriate peak. The sums were normalized to the same deuteron bombardment as measured by a current integrator. Frequent repetition of standardizing runs demonstrated that the target did not change during the runs. Since the work of Braams[4] had shown the presence of closely spaced groups, the slits of the deuteron energy-defining magnet were narrowed to limit the energy spread to 10 kev, and the spectrograph aperture was narrowed to a half-angle of 2 degrees in order to guarantee that the groups would be well resolved. Figure 1 shows that this was accomplished except in the case of the closely spaced pair (18) and (19) which are separated by 18 kev at a proton energy of 8.8 Mev. The relatively high resolution used resulted in a low counting rate, necessitating longer runs; consequently, it was decided to investigate only angles of 60 degrees and less, where the previous calcium measurements appeared most instructive. In addition, a run was taken at 130 degrees, and, for the ground and first two excited states, it was possible to obtain data at intermediate angles from the measurement[1] on the Ca^{42} target which contained 35% Ca^{40}.

The results of these measurements are shown in Figs. 3 and 4. The observed yields of the individual groups from an arbitrary target was plotted as a function of laboratory angle. Actually, several targets were used, but the results were normalized so that Figs. 3 and 4 portray the relative intensity of the various groups without correction for the variation of solid angle with position in the focal surface. The data obtained from measurement with the Ca^{42} target for levels 0, 1, and 2 are indicated by triangles. The errors shown are the sum of the standard statistical error derived from the number of tracks observed in the peak and an estimated error in a background correction applied where appropriate. Also shown are stripping curves calculated with the aid of the tables prepared

FIG. 2. Range of excitation in Ca^{41} obscured by the intense proton group corresponding to the ground state of C^{13} as a function of laboratory angle.



[6] C. M. Braams, Ph.D. thesis, Utrecht, 1956 (unpublished).

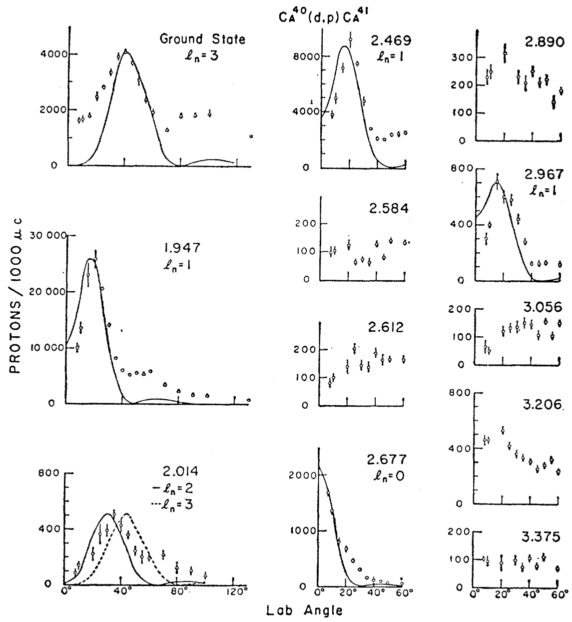


FIG. 3. Angular distributions in the laboratory system for proton groups corresponding to formation of Ca^{41} in the ground and excited states. Vertical bars indicate the standard statistical error. The stripping curves are computed for an interaction radius of 6.0×10^{-13} cm.

by Enge and Graue,[7] which are based on the theory as presented by Friedman and Tobocman.[8] The computed curves are sensitive to the value of the interaction radius employed. For the present work a radius of 6.0×10^{-13} cm was used, although it appears that a better fit may be obtained for the ground state by using a larger radius. The difficulties of applying a single r to all excited states are discussed in greater detail in reference 1, where it is pointed out that the lack of any attempt to account for the influence of Coulomb forces may be at the root of the trouble. The radius of 6.0 $\times10^{-13}$ cm used here appears to be the best compromise value for all three calcium angular distributions. In spite of the ambiguity in this parameter, it is felt that the values of orbital angular momentum of the captured neutron l_n can be assigned with confidence except for the Ca^{41} levels at 2.014, 3.619, 3.736, and 3.950 Mev. As shown in Fig. 3 for the 2.014-Mev level, the experimental points lie between the theoretical curves for $l_n=2$ and $l_n=3$. Likewise, for the levels at 3.619, 3.736, and 3.950 Mev, the $l_n=1$ curves drawn in Fig. 4 reach their peak at 15 degrees, but the experimental points show a maximum at 20 degrees. Curves for $l_n=2$ for these levels, not shown here, reach a maximum at about 30 degrees. Since inclusion of Coulomb effects appears to move the theoretical maxima to larger angles,[9] a preference is here expressed for the smaller of the two l_n values which bracket the experimental points in these doubtful cases. Further evidence in support of this preference is cited later.

The intensities of the individual proton groups relative to the ground-state group, all measured at the angle of maximum yield, are given in Table I, column 4. The value listed is obtained from Figs. 3 and 4 after correction for an experimentally determined variation of solid angle with position on the plate.[5] The values of the orbital angular momentum quantum number of the captured neutron l_n are also listed for those levels that display a stripping-type angular distribution. In column 7 are given the relative reduced widths, as deduced from the stripping calculations. In these calculations, it was assumed that the reaction proceeded entirely by stripping, even though the theory used cannot account for the relatively large isotropic components observed in certain of the distributions; an example is the case of the ground-state group. It should be emphasized that these reduced widths are sensitive to the radius used (6.0×10^{-13} cm) and also that they may be misleading because of the failure to include the effect of Coulomb forces. For $l_n>0$, the experiment does not distinguish between the two possible spin values. Therefore, a reduced width is cited for each spin, except for the ground and first excited states, which are presumed to have spins 7/2 and 3/2. The parity of the levels is even or odd as l_n is even or odd.

The variation in proton yield with angle, measured for the ground state and the first, third, and twenty-first excited states, is in excellent agreement with Holt and Marsham's results.[3] These authors obtain values of 1.0, 6.0, 2.6, and 1.6 for the relative maximum cross sections for production of the proton groups corresponding to these four levels. The present values given

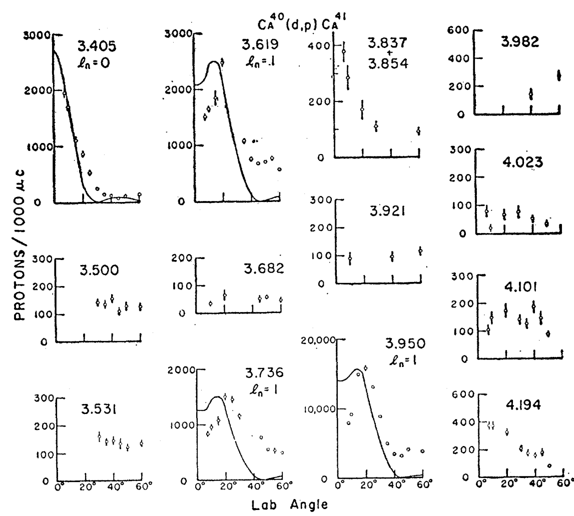


FIG. 4. Laboratory system angular distributions of proton groups corresponding to formation of Ca^{41} in excited states. Vertical bars indicate the standard statistical error. The stripping curves are calculated using an interaction radius of 6.0×10^{-13} cm.

[7] H. Enge and A. Graue, Universitetet i Bergen, Arbok, Naturvitenskapelig Rekke, Nr. 13 (1955).
[8] F. L. Friedman and W. L. Tobocman, Phys. Rev. **92**, 93 (1953).
[9] W. L. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).

in Table I differ by factors as large as 2. In view of the difference in deuteron energy, the variation may not indicate a disagreement. For the four levels, the l_n values selected by Holt and Marsham agree with Table I, except for level 21 at 3.950 Mev. As stated above, failure of the theory to account for Coulomb forces is here deemed reason to prefer $l_n=1$, although the Liverpool group assigned $l_n=2$ to their experimental angular distribution which appears identical with that in Fig. 4. Their assignment was based in part on an assumption that protons from a nearby C^{13} group known to show an $l_n=1$ distribution may have contributed to the observed angular distribution. Clearly this has not occurred in the present experiment. Since the other proton groups measured in the present experiment were not resolved by Holt and Marsham, no further comparison is possible. It should be noted that the $l_n=2$ assignments[3] to the 4.76-Mev and 5.72-Mev levels may be questioned, especially in view of the Coulomb effect.

In terms of the shell model, the ground state of Ca^{41} is predicted to be formed by a single neutron in an $f_{7/2}$ orbit about a doubly magic core. Because of the extreme stability of the Ca^{40} core (the first excited state is at 3.35 Mev), one might expect to find among the low excited states of Ca^{41} levels formed by the promotion of the extra neutron to the $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ orbits. The positive identification of such levels would give a direct measure of the magnitude of the spin-orbit splitting for this nucleus.

TABLE I. Relative yields and reduced widths for $Ca^{40}(d,p)Ca^{41}$ reaction.

Level[a]	Excitation[a] energy (Mev)	Angle of maximum yield	Relative yield at maximum	l_n	J	Relative reduced width
0	0	40°	1.0	3	7/2	1.0
1	1.947	15°	5.5	1	3/2	1.4
2	2.014	35°	0.11	2 or 3	5/2 3/2 7/2 5/2	0.056 0.084 0.098 0.13
3	2.469	20°	1.8	1	3/2 1/2	0.47 0.94
4	2.584	55°	0.029	...		
5	2.612	25°	0.041	...		
6	2.677	$\leq 7\frac{1}{2}°$	0.27 at 10°	0	1/2	0.44
7	2.890	20°	0.063	...		
8	2.967	15°	0.14	1	3/2 1/2	0.030 0.060
9	3.056	60°	0.031	...		
10	3.206	20°	0.10	...		
11	3.375	...	0.021	...		
12	3.405	$\leq 7\frac{1}{2}°$	0.33 at 10°	0	1/2	0.57
13	3.500	...	0.030	...		
14	3.531	...	0.030	...		
15	3.619	20°	0.47	1 or 2	3/2 1/2 5/2 3/2	0.090 0.18 0.20 0.30
16	3.682	...	0.012	...		
17	3.736	20°	0.29	1 or 2	3/2 1/2 5/2 3/2	0.056 0.11 0.12 0.18
18 19	3.837 3.854	$\leq 7\frac{1}{2}°$	0.054 at 10°	...		
20	3.921	...	0.022	...		
21	3.950	20°	3.00	1 or 2	3/2 1/2 5/2 3/2	0.56 1.1 1.3 1.9
22	3.982	60°	0.051	...		
23	4.023	$\leq 7\frac{1}{2}°$	0.014	...		
24	4.101	40°	0.032	...		
25	4.194	10°	0.070	...		

[a] See reference 4.

The work of Braams[4] and the present experiment offer considerable insight into the level structure of Ca^{41}, when examined together with the information available on gamma rays emitted after thermal neutron capture by Ca^{40}. The experiments of Kinsey *et al.*[10] on the high-energy radiation and of Braid[11] on the low-energy spectrum are consistent with, but less detailed than, the measurements of the Russian group at the Academy of Sciences, Moscow.[12] These workers have obtained energy and intensity measurements at good resolution over the gamma-ray energy range from 250 kev to 8.5 Mev. As pointed out by Lane and Wilkinson,[13] stripping may be expected to excite the same levels as does neutron capture, both processes favoring strongly those levels that are predominantly "single particle" in nature. In examining the angular distributions shown in Figs. 3 and 4, it is evident that all of the groups that do not show a strong stripping-type maximum are relatively low in yield. It appears that these groups may be associated with levels which are not "single particle" in nature. Of the ten groups that may be construed to display a stripping-type maximum, the four most intense show maxima in excess of 4000 in the arbitrary scales of Figs. 3 and 4. Holt and Marsham find evidence for $l_n=2$ groups of comparable intensity that correspond to levels at 4.76-Mev and 5.72-Mev excitation, a region not reached in the present experiment.

Using these six states, plus the two $l_n=0$ levels and the 2.014-level, presumed to be $l_n=2$, the scheme of states shown in Fig. 5 is obtained. The decay scheme differs in certain details from that proposed by the Russian workers.[12] It is interesting to note that, of the eighteen gamma rays that may be attributed to neutron capture by Ca^{40},[12] seventeen may be fitted to this level scheme. (The other gamma ray has an energy of 1.844 ± 0.015 Mev.) This assignment corroborates the prediction of Lane and Wilkinson and leads to the interpretation that the levels shown in Fig. 5 have large single-particle components.

The spins shown are consistent with the rough relative probabilities expected in the emission of electromagnetic radiation, although $M1$ transitions cannot occur in the

[10] Kinsey, Bartholomew, and Walker, Phys. Rev. **85**, 1012 (1952).
[11] T. H. Braid, Phys. Rev. **102**, 1109 (1956).
[12] Adyasevitch, Groshev, Demidov, and Lutsenko, J. Nuclear Energy **3**, 325 (1956) [translated from Soviet J. Atomic Energy **1**, No. 2 (1956)].
[13] A. M. Lane and D. H. Wilkinson, Phys. Rev. **97**, 1199 (1955).

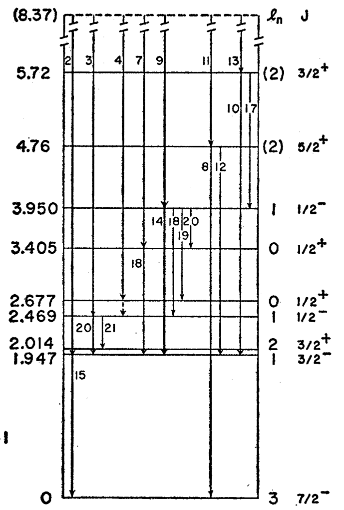


FIG. 5. Tentative scheme of certain Ca^{41} levels. The numbering of the gamma rays is that of reference 12. Excitation energies reported in references 3 and 4 are shown, as well as values of the orbital angular momentum number derived from the present experiment and the work of reference 3. The spins shown appear to be consistent with the assignments of the gamma-ray transitions but may not be unique. The other levels measured in the present experiment but not drawn in the figure are listed in Table I.

model of a neutron moving in a velocity-independent central potential.[14] It should be emphasized that the spin values shown in Fig. 5 cannot be claimed to be unique on the basis of the evidence presently available. In particular, if further studies indicate that the 4.76- and 5.72-Mev levels are formed by p rather than by d neutrons, assignments of $3/2^-$ and $1/2^-$, respectively, would appear to be satisfactory.

The most intense neutron-capture gamma rays are those labeled 2, 9, 14, and 15 in Fig. 5. While the experimental information does not permit a unique assignment in all cases, it seems clear that gamma rays 2 and 15 belong in the places assigned. This is consistent with an $f_{7/2}$ configuration for the ground state of Ca^{41} and a $p_{3/2}$ configuration for the first excited state, as has been suggested previously.[3] Gamma ray 9 is best accounted for as an initial transition to the 3.950-Mev level; the lack of a transition from this level to the ground state suggests spin 1/2. If gamma ray 14 is correctly located, the scheme suggests that the 3.950-Mev level rather than the 2.469-Mev level previously suggested[3] is the $p_{1/2}$ single-particle level. However, gamma ray 14 has an energy of 2.004 ± 0.010 Mev, and so energywise it may be a transition from the second excited state to ground. To make this placement consistent would require an interpretation of the angular distribution for the 2.014-Mev level as $l_n=3$ forming an $f_{5/2}$ state, in which case the 2.469-Mev level might be given spin $3/2^-$ to account for the reasonably strong gamma rays 20 and 21. The Russian group points out that such an assignment is rendered unlikely by the lack of a transition from the 2.469-Mev level to the ground state. The discussion could be continued; unfortunately, energy and intensity measurements alone do not allow construction of a unique level scheme.

Further light on the question of whether the 2.469-Mev or the 3.950-Mev level is the first single-particle $p_{1/2}$ state may be gained by noting that the reduced widths of the levels involved (Nos. 3 and 21) are nearly equal. However, as the doublet splitting increases, the reduced widths may be expected to change. An approximate calculation using square-well wave functions indicates that for two p levels bound by energies corresponding to levels 1 and 21, the reduced width of the upper level should be almost four times that of the lower. Table I shows that the observed reduced width of level 21 is smaller than that of level 1. On the other hand, for the 1.947–2.469 Mev pair, the relative reduced width of the upper level should be twice that observed for level 3 relative to level 1. From an extreme single-particle point of view, evidently neither level 3 nor level 21 supply a completely satisfactory $p_{1/2}$ level. Lane[15] has suggested that the single-particle picture should not be taken literally at an excitation of several Mev; both levels 3 and 21 may share the properties of a single-particle $p_{1/2}$ state.

TABLE II. Cross sections and reduced widths for $Ca^{42}(d,p)Ca^{43}$ reaction relative to $Ca^{40}(d,p)Ca^{41}$ ground-state reaction.

Level[a]	Excitation[a] energy (Mev)	Relative[b] σ at maximum	l_n[b]	J	Relative reduced width
0	0	0.69	3	7/2	0.72
2	0.593	0.25	1	3/2	0.080
				1/2	0.16
3	0.991	0.097	2	5/2	0.057
				3/2	0.085
			or 3	7/2	0.10
				5/2	0.14
8	1.957	0.69 at 10°	0	1/2	1.10
10	2.048	5.20	1	3/2	1.40
				1/2	2.80
18	2.607	0.58	1	3/2	0.14
				1/2	0.29
23	2.880	0.42	1	3/2	0.08
				1/2	0.17
24	2.947	0.42	1	3/2	0.09
				1/2	0.18
35	3.584	0.44	1	3/2	0.09
				1/2	0.17
			or 2	5/2	0.20
				3/2	0.30

[a] C. M. Braams, Phys. Rev. 105, 1023 (1957).
[b] See reference 1.

The calculations of French and Raz[16] on the level schemes of the calcium isotopes have made use of the relative intensities measured for the three $Ca(d,p)$ reactions. This measurement was possible because Ca^{41} groups were seen on all three targets. Using the observed intensities and the abundances for the calcium isotopes in the separate targets as given by Oak Ridge, the relative cross sections were obtained. For convenience

[14] S. A. Moskowski, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), pp. 390 and 392.

[15] A. M. Lane (private communication).

[16] J. B. French and B. J. Raz, Phys. Rev. 104, 1411 (1956).

TABLE III. Cross sections and reduced widths for $Ca^{44}(d,p)Ca^{45}$ reaction relative to $Ca^{40}(d,p)Ca^{41}$ ground-state reaction at 40°.

Level[a]	Excitation[a] energy (Mev)	Relative[b] σ at maximum	l_n[b]	J	Relative reduced width
0	0	0.39	3	7/2	0.39
3	1.432	0.78	1	3/2	0.20
				1/2	0.40
6	1.902	4.50	1	3/2	0.96
				1/2	1.90
8	2.249	0.74	1	3/2	0.17
				1/2	0.33
10	2.394	0.61 at 10°	0	1/2	1.0
14	2.844	0.83	1	3/2	0.16
				1/2	0.32
			or 2	5/2	0.35
				3/2	0.53
19	3.244	0.41	1	3/2	0.075
				1/2	0.15
			or 2	5/2	0.16
				3/2	0.24
22	3.419	1.68	1	3/2	0.32
				1/2	0.64
			or 2	5/2	0.70
				3/2	1.0

[a] See reference 6.
[b] See reference 2.

in reference, results from the previous work[1,2] have been presented in Tables II and III. The cross sections at the angle of maximum yield relative to the maximum cross section for formation of the ground state of Ca^{41} are given in columns 3. Also listed are reduced widths (relative to that for formation of the Ca^{41} ground state) appropriate to the l_n and J indicated. The significance of a comparison has been pointed out in the aforementioned work.[16] At the risk of some repetition, it is interesting to point out the following similarities in the data for the three nuclei. The ground-state angular distributions are consistent with the model of a $f_{7/2}$ neutron outside a core with zero spin. Further support for the picture is adduced from the fact that the cross sections for formation of the ground states of Ca^{41}, Ca^{43}, and Ca^{45} are in the ratio of $1:(0.69\pm0.05):(0.39\pm0.03)$; the model predicts 1:0.75:0.50. This was first pointed out by Endt and Braams[17] who cite 90-degree measurements in the same ratio (but with larger errors) as the 40-degree values given here. (Since the spins are the same and the Q values for the three reactions differ by less than an Mev, the reduced-width ratios are equal within 5% to the cross-section ratios.)

At 1.947 Mev in Ca^{41}, 2.048 Mev in Ca^{43}, and 1.902 Mev in Ca^{45} is a strong $l_n=1$ level which is probably the expected $p_{3/2}$ level. Positive parity levels indicating breakup of the core exist below 2.7 Mev for all three nuclei. The 2.014-Mev level in Ca^{41} and the 0.991-Mev level in Ca^{43} show the same angular distribution and relatively low yield. Although the difficulties in using the simple stripping theory with no account taken of Coulomb forces cast some uncertainty on the assignment of $l_n=2$, this choice is corroborated by beta-decay evidence in the Ca^{43} case.[18,19] Raz[20] suggests that these levels may be formed by promoting a $d_{3/2}$ core neutron to the $f_{7/2}$ orbit. On the other hand, these levels appear to be the only candidates for an expected $f_{5/2}$ single-particle classification. However, according to Table I, an $f_{5/2}$ assignment for level 2 of Ca^{41} is unsatisfactory because the reduced width compared to the ground state is too small by a factor of 10. The weight of the evidence appears to be against an $l_n=3$ assignment.

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[17] P. M. Endt and C. M. Braams, Physica 21, 839 (1955).
[18] T. Lindqvist and A. C. G. Mitchell, Phys. Rev. 95, 444 (1954).
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[20] B. J. Raz (private communication).