Angular Distributions of Protons from $Na^{23}(d,p)Na^{24}$ and $Ti^{47,48}(d,p)Ti^{48,49}$†

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Sodium and titanium targets were bombarded with 10-Mev deuterons, and angular distributions of protons from the stripping reaction were observed with arrays of nuclear emulsions. Absorbing foils in front of each emulsion were arranged so that the integrated flux of protons in a limited energy range could be determined. Distributions were found for each of the four most energetic proton groups from sodium, corresponding to Q values of 4.731 (ground state), 4.259, 4.167, and 3.390 Mev. The data were compared with the Butler theory, and l_n values of 2, 2, 0, and 0, respectively, were necessary to fit theory to data. With Ti^{47} targets, l_n values of 3, 1 (and 3?), 1, and 1, respectively, were determined for proton groups corresponding to Q values of 8.14, 6.81, 5.83, and 4.83 Mev. With Ti^{48} targets, l_n values of 3, 1, 1, and either 1 or 2 were determined for proton groups corresponding to Q values of 5.81 (ground state), 4.46, 4.11, and 3.40 Mev, respectively. From these data, parity and possible spin values for the various states of Na^{24}, Ti^{48}, and Ti^{49} are deduced.

INTRODUCTION

It has been shown by Butler[1] that stripping reactions, produced by deuterons of moderate energy, can be used to obtain information about the spins and parities of the initial and final nuclei involved. The angular distribution of the protons or neutrons shows a strong general preference for emission in the forward direction, which is characteristic of stripping reactions. In the small-angle region, however, the yield fluctuates violently as a function of the angle, and has a prominent maximum at or near the forward direction as well as subsidiary maxima at larger angles. The angular positions of these maxima depend rather sensitively on the orbital angular momentum, $l_p\hbar$ or $l_n\hbar$, carried into the nucleus by the captured nucleon. It is usually possible to determine l_p or l_n experimentally by locating the angular position of the prominent first maximum, and this information is sufficient (a) to decide whether or not the parity of the residual nucleus is the same as that of the target, and (b) to indicate possible values for the spin of one of the two nuclei if that of the other is known. The theory involves a radius parameter r_0 which is approximately the sum of the deuteron and nuclear radii. In our work we have used $r_0=(2.06+1.22A^{\frac{1}{3}})10^{-13}$ cm, where A is the mass number of the target nucleus.

Since the publication of Butler's results, a considerable amount of experimental work has been done on angular distributions for stripping reactions. The (d,p) process has received the most attention because fast protons are much easier to study than fast neutrons. Two principal experimental methods have been invoked. In one, nuclear emulsions are used to detect the protons, whose energies are determined by track-length measurements. In the other, one or more proportional counters serve as detector, and energy measurements are made by determining the range of the protons in suitable absorbers. The former method has also been used to investigate (d,n) reactions, by studying the head-on recoil protons produced in the emulsions. A survey of all published reports shows that (d,p) angular distributions have been investigated for targets of just about every abundant stable isotopic species in the mass range from $A=6$ to $A=40$, with occasional forays into even higher masses. This preoccupation with low-mass targets is owing to Butler's neglect of Coulombic effects in the interests of simplicity, so that his results as originally presented are expected to become increasingly less valid as the atomic number of the target rises.

It is the purpose of this paper to describe a slightly different experimental approach to this problem. The technique, which is outlined in detail in the next section, is a kind of hybrid in the sense that it combines some features from each of the methods previously mentioned. Nuclear plates are used as detectors, but proton energies are determined by range measurements with suitable absorbers. The new method has been used to investigate proton angular distributions from stripping reactions with targets of Na^{23}, Ti^{47}, and Ti^{48}.

EXPERIMENTAL PROCEDURE

The principal features of our experimental arrangements are outlined in Fig. 1. A portion of the 10-Mev deuteron beam from the Washington University cyclotron is concentrated by a pair of strong-focusing magnetic lenses[2] and is conducted through evacuated tubing to a circular scattering chamber of conventional design. The chamber is approximately five meters from the nearest corner of the cyclotron, and is shielded by 32 inches of concrete.

The target material is supported on a 0.2-mil polyethylene foil which is mounted perpendicular to the beam at the center of the chamber. A series of 13 nuclear plates in holders is arranged in a circular pattern around

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[1] S. T. Butler, Proc. Roy. Soc. (London) **208**, 559 (1951).

[2] Shull, MacFarland, and Bretscher, Rev. Sci. Instr. **25**, 364 (1954).

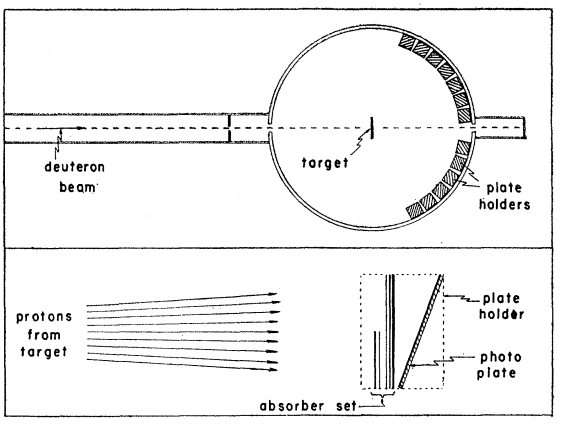

FIG. 1. Outline drawings of experimental arrangements.

the target and 20 cm from it; seven on one side of the beam cover the angular range 7.5° to 67.5° at 10° intervals; six on the other side similarly cover the 12.5° to 62.5° range. Each plate holder is machined with two pairs of slots. One pair accommodates a set of absorbing foils interposed between target and plate; the other pair supports the plate in a tilted position such that protons from the target enter the emulsion at approximately 20° from perpendicular (see Fig. 1).

The absorbing foils perform two functions: (1) they screen out deuterons, tritons, alpha particles, and low-energy protons, and (2) they act as a differential discriminator. The latter purpose is realized by assembling the upper and lower halves of each absorber set with different thicknesses, which cover different parts of a single nuclear plate one inch wide and 1.5 inches high. If the thinner half passes protons of incident energy E or higher, while the thicker half passes protons of energy $E+dE$ or higher, the difference between the fluxes of protons through the two halves is the flux of protons with energy between E and $E+dE$. Since only high-energy protons from the target can reach the emulsion, the microscopic analysis of the data is reduced to the very simple problem of counting the number of tracks per unit area in each half of each plate. This task is further simplified by the steep dip angle of the tracks, since a relatively dense concentration of tracks can be counted without undue confusion caused by overlapping.

With this technique, a prior knowledge of Q values for the reaction is necessary. The laboratory energy of each proton group must be computed for each angle of observation, and the absorber thicknesses must be selected accordingly. It is evident that only limited resolution of proton groups is possible; in view of the straggling of protons in the absorber, it seems unlikely that complete resolution can be obtained by this method if two adjacent proton groups differ in energy by less than 400 kev. A separate exposure is required to determine the angular distribution for each of the several proton groups from any target. Moreover, the method can be applied reliably only to the three or four most energetic proton groups, since at still lower energies one quickly encounters the difficulty of measuring the rather small difference between two comparatively large numbers. In spite of these drawbacks, the technique is an attractive one because of the enormously increased simplicity of the microscopic analysis required. It is not necessary to identify and reject the tracks of deuterons, alphas, and low-energy protons, and it is not necessary to measure track lengths. Moreover, the advantage of simultaneous collection of data at all angles is preserved, thus avoiding normalization difficulties.

By way of developing confidence in the method, it was first applied to a study of the $C^{12}(d,p)C^{13}$ reaction. Carbon was chosen because of the ease of preparing targets with polyethylene foil and because excellent earlier studies of this reaction have been made by Rotblat[3] using the conventional nuclear plate method, so that comparisons could be made. Our results were in excellent agreement with those of Rotblat for both the ground state and first excited state of C^{13}. The l_n values required for a good fit with Butler's theory are 1 and 0 respectively.

During the carbon experiments, it became apparent that the use of aluminum absorbers introduces a discrepancy at very small angles owing to bombardment of the aluminum foils by elastically scattered deuterons from the target. At very small angles, the flux of such deuterons is fairly high, and $Al^{27}(d,p)$ reactions in the absorbers lead to an extra component of protons appearing in the emulsions, over and above what comes directly from the target. To reduce this effect, we switched

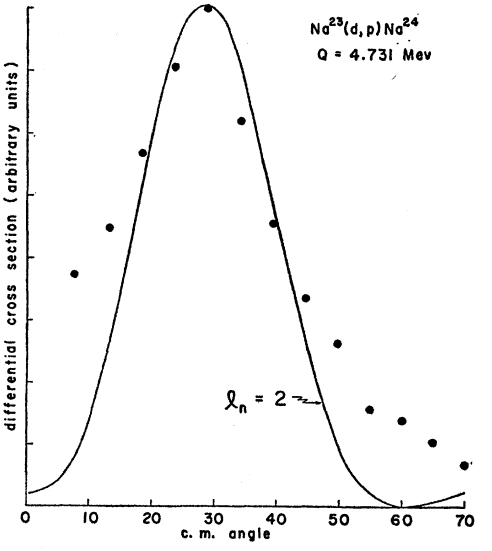

FIG. 2. Observed angular distribution of protons from deuteron bombardment of sodium, with Na^{24} formed in its ground state.

[3] J. Rotblat, Nature **167**, 1027 (1951).

to the use of Pb foil for the front layer of absorber in each set, the remainder being aluminum as before. The Pb layer was made thick enough to stop the scattered deuterons. This minimizes the extra proton component because of the relatively small cross section and high threshold for the (d,p) reaction in Pb. With this modification of technique, we then proceeded with the investigation of protons from sodium and titanium targets.

RESULTS

$Na^{23}(d,p)Na^{24}$

Targets were prepared for most runs by evaporating a solution of Na_2CO_3 to dryness on a polyethylene foil, although NaOH was similarly used in a few instances. The residual deposit was crystalline and hygroscopic, and tended to be crusty around the edges. The deposition area was made large so that the area of intersection with the beam would be clear of the crusty edges. New targets were prepared just before each bombardment, so that hygroscopic action would have minimal effect. Target thicknesses were about one or two milligrams per square centimeter.

Absorber thicknesses were computed at each angle for each state of Na^{24} using Q values reported by Sperduto and Buechner.[4] We limited our investigations to the four lowest states of Na^{24}, corresponding to Q values of 4.731 (ground state), 4.259, 4.167, and 3.390 Mev. The presence of abundant amounts of carbon and oxygen in our target and its supporting foil precluded any examination of more highly excited states. Since the first and second excited states are separated by only 92 kev, we lumped them together as if they were a single state, in the hope that their superimposed angular distributions could be disentangled later.

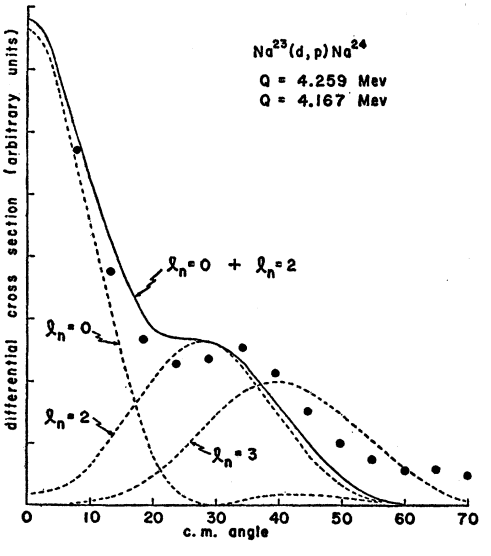

FIG. 3. Observed angular distribution of protons from deuteron bombardment of sodium, with Na^{24} formed in its first and second excited states.

[4] A. Sperduto and W. W. Buechner, Phys. Rev. 88, 574 (1952).

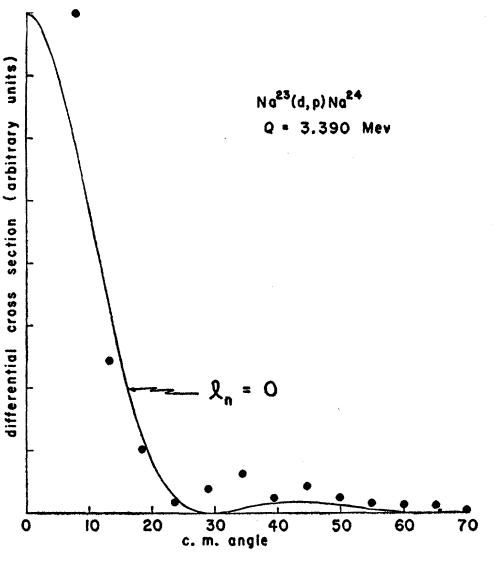

FIG. 4. Observed angular distribution of protons from deuteron bombardment of sodium, with Na^{24} formed in the third excited state.

The data are illustrated in Figs. 2–4, along with appropriate theoretical curves computed from Butler's theory. For the ground state and third excited state of Na^{24} the distributions can be unambiguously fitted by theoretical curves for $l_n=2$ and $l_n=0$, respectively. The lumped data for the first and second excited states in Fig. 3 show an abrupt rise near 0°, which indicates a strong $l_n=0$ component. The prominent subsidiary maximum at about 30° is probably a superposed component with higher l_n. We tried various combinations of $l_n=0$ with higher l_n, and conclude that the most promising combination is with $l_n=2$. We assume that the two l_n values are attributable to the two intermingled proton groups.

Kinsey, Bartholomew, and Walker[5] have measured the energies of gamma rays from Na^{24} which follow the capture of thermal neutrons by Na^{23}. Sperduto and Buechner[4] have fitted these gamma rays into a system of Na^{24} levels as determined from the $Na^{23}(d,p)Na^{24}$ reaction. No capture gamma-ray transitions directly to the ground state are observed; presumably this is because of the high spin ($I=4$) of the Na^{24} ground state compared with the initial capture state. In fact, the most energetic capture transition appears to go to the second excited state instead of to either the ground or first excited states. This suggests that the first excited state and the ground state are similar in that both have high spin, or at least that both have spins which differ by at least two units from that of the initial capture state. Moreover, the capture transitions to the second and third excited states occur with an 8

[5] Kinsey, Bartholomew, and Walker, Phys. Rev. 83, 519 (1951).

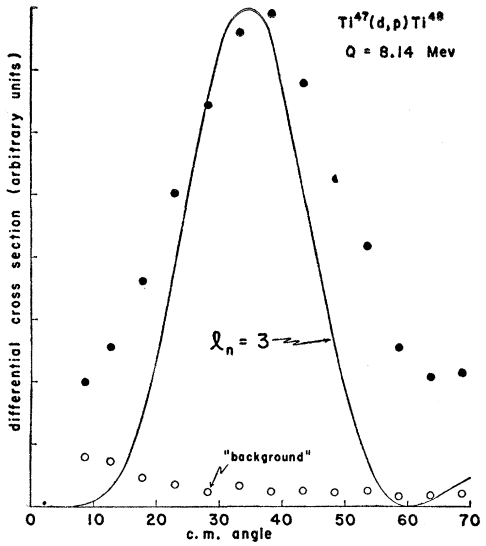

FIG. 5. Observed angular distribution of protons from deuteron bombardment of enriched Ti^{47} targets, with Ti^{48} formed in its ground (first excited?) state. The "background" represents the corresponding distribution of protons for which Q exceeds 8.35 Mev (approx.).

to 3 intensity ratio. This would be more or less consistent with the transition energies involved if both gammas were of the same multipole order and type. This behavior suggests that the second and third excited states of Na^{24} are quite similar, and may even have the same spin and parity. Combining these considerations with our own data leads us to conclude that the mixed $l_n=0$ and $l_n=2$ components in Fig. 3 are best identified with reactions leading to the second

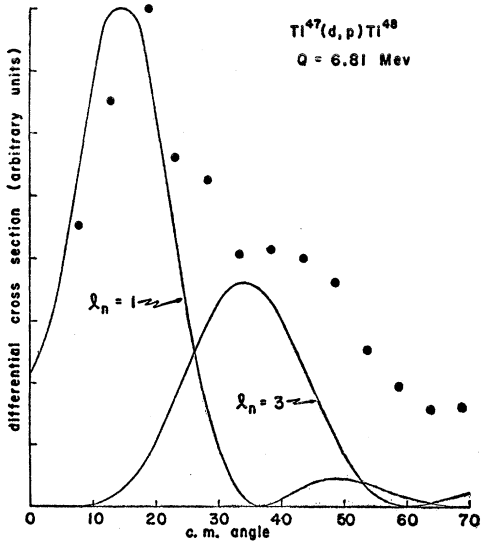

FIG. 6. Observed angular distribution of protons from deuteron bombardment of enriched Ti^{47} targets, with Ti^{48} formed in its first (second?) excited state. The data suggest that two different proton groups are involved, having similar Q values.

excited state ($Q=4.167$ Mev) and first excited state ($Q=4.259$ Mev), respectively, of Na^{24}.

The results for sodium targets are summarized in Table I, together with the parity and possible spin values for each corresponding level in Na^{24}. The spin of Na^{23} is $\frac{3}{2}$, and we assume that its parity is even, as predicted by the shell model. All of our conclusions are in agreement with those previously reported by Shapiro[6] and by Takemoto, Dazai, and Chiba.[7]

$$Ti^{47,48}(d,p)Ti^{48,49}$$

Three types of TiO_2 targets were used during this investigation:

(1) Those in natural form, in which the percentage abundances of the various titanium isotopes are 7.95 percent Ti^{46}, 7.75 percent Ti^{47}, 73.45 percent Ti^{48}, 5.51 percent Ti^{49}, and 5.34 percent Ti^{50}.

(2) Those enriched[8] in Ti^{47}, in which the percentage abundances of the titanium isotopes were 1.83 percent Ti^{46}, 82.05 percent Ti^{47}, 14.62 percent Ti^{48}, 0.81 percent Ti^{49}, and 0.69 percent Ti^{50}.

(3) Those enriched[8] in Ti^{48}, in which the percentage abundances of the titanium isotopes were 0.16 percent Ti^{46}, 0.32 percent Ti^{47}, 98.90 percent Ti^{48}, 0.48 percent Ti^{49}, and 0.14 percent Ti^{50}.

TABLE I. Summary of l_n values, together with the parity and possible spins for each level of the residual nuclei. The known ground-state spins are italicized.

Reaction	Q in Mev	Excit. energy of final nucleus (Mev)	l_n	Spin and parity of final nucleus
$Na^{23}(d,p)Na^{24}$	4.731	ground	2	0, 1, 2, 3, *4* even
	4.259	0.472	2	0, 1, 2, 3, 4 even
	4.167	0.564	0	1, 2 even
	3.390	1.341	0	1, 2 even
$Ti^{47}(d,p)Ti^{48}$	8.14	ground? 1.27?	3	*0*, 1, 2, 3, 4, 5, 6 even
	6.81	1.33? 2.60?	1 (and 3?)	1, 2, 3, 4 even
	5.83	2.31? 3.58?	1	1, 2, 3, 4 even
	4.83	3.31? 4.58?	1	1, 2, 3, 4 even
$Ti^{48}(d,p)Ti^{49}$	5.81	ground	3	*5/2, 7/2* odd
	4.46	1.35	1	1/2, 3/2 odd
	4.11	1.70	1	1/2, 3/2 odd
	3.40	2.41	(1 or 2)	???

The oxide was finely ground to form a semisuspension in amyl acetate, and a trace of a commercial coil dope was added to the liquid. The suspended oxide was allowed to settle out onto the supporting foil, after which the excess liquid was allowed to evaporate slowly. The trace of coil dope helped to hold the powdery oxide on the foil.

Absorber thicknesses were computed from Q values reported by Pieper[9] from a study of the (d,p) reactions. Again, only the more energetic proton groups were studied, so that the presence of carbon and oxygen in

[6] P. Shapiro, Phys. Rev. **93**, 290 (1954).
[7] Takemoto, Dazai, and Chiba, Phys. Rev. **91**, 1024 (1953).
[8] Enriched samples were loaned through the courtesy of the Isotopes Division of the U. S. Atomic Energy Commission.
[9] G. F. Pieper, Phys. Rev. **88**, 1299 (1952).

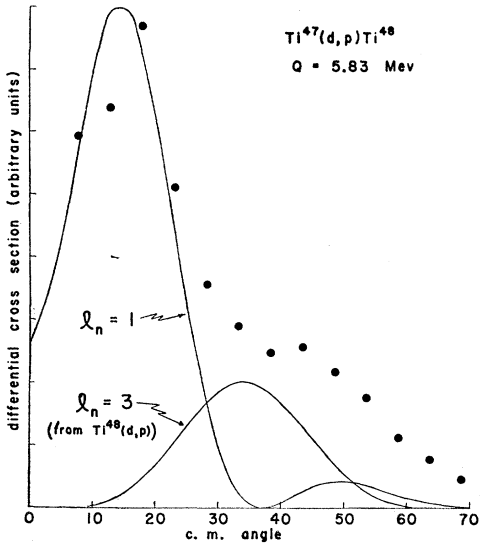

FIG. 7. Observed angular distribution of protons from deuteron bombardment of enriched Ti^{47} targets, with Ti^{48} formed in its second (third?) excited state. The presence of 14.6 percent Ti^{48} in the target is responsible for the $l_n=3$ contribution (compare with Fig. 9).

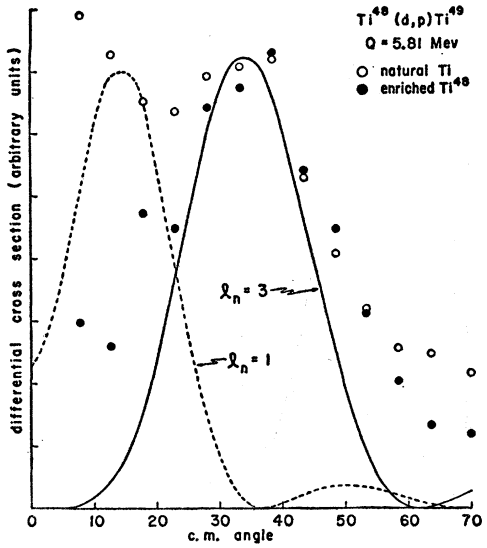

FIG. 9. Observed angular distribution of protons from deuteron bombardment of natural titanium and enriched Ti^{48} targets, with Ti^{49} formed in its ground state. The presence of 7.75 percent Ti^{47} in natural titanium is responsible for an $l_n=1$ contribution (compare with Fig. 7).

the target offered no difficulty. With the Ti^{47} target, proton groups for $Q=8.14$, 6.81, 5.83, and 4.83 Mev were investigated. With the natural titanium and enriched Ti^{48} targets, proton groups for $Q=5.81$ (ground state), 4.46, 4.11, and 3.40 Mev were investigated. The data are displayed in Figs. 5 through 12, together with appropriate Butler curves. In all but two cases, which are discussed below, the decision as to the value of l_n seems reasonably clear-cut. The results are tabulated in Table I, together with such deductions as can be made concerning parity and possible spin values for each state of a residual nucleus. The spins[10] of Ti^{47} and Ti^{49} are 5/2 and 7/2, respectively, while that of Ti^{48} is presumed to be zero because it is an even-even nuclide. The parity of Ti^{48} is assumed to be even for the same reason, while our own data on the $Ti^{47}(d,p)Ti^{48}$ reactions indicate that the Ti^{47} parity is odd, as expected from the shell model.

In $Ti^{47}(d,p)Ti^{48}$, the proton groups for Q values of 8.14 and 4.83 Mev show angular distributions for which

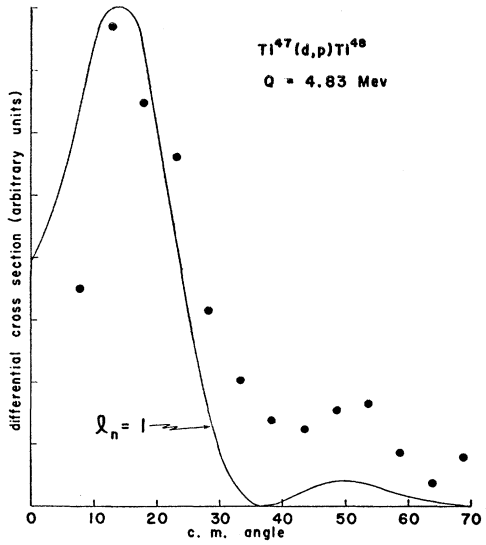

FIG. 8. Observed angular distribution of protons from deuteron bombardment of enriched Ti^{47} targets, with Ti^{48} formed in its third (fourth?) excited state.

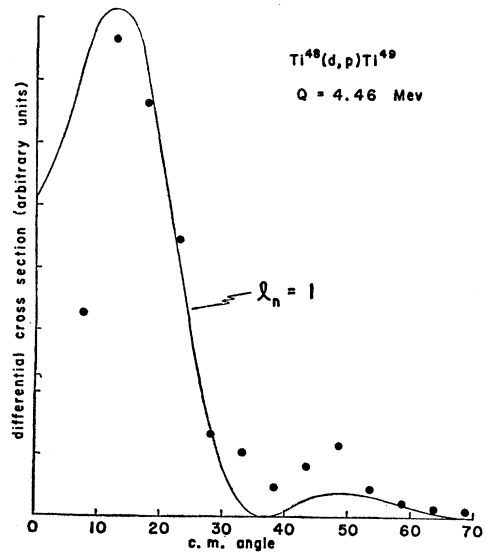

FIG. 10. Observed angular distribution of protons from deuteron bombardment of natural titanium targets, with Ti^{49} formed in its first excited state.

[10] C. D. Jeffries, Phys. Rev. **92**, 1262 (1953).

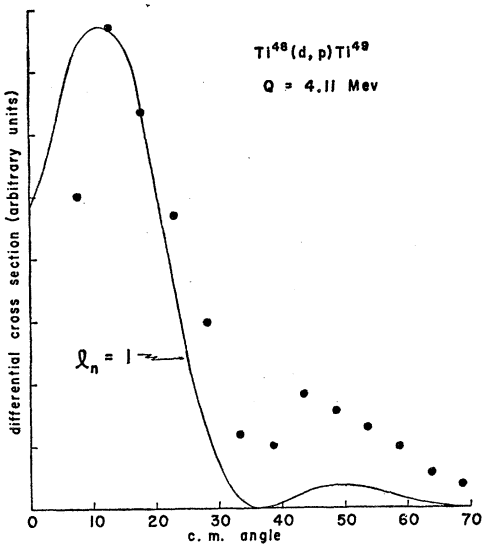

FIG. 11. Observed angular distribution of protons from deuteron bombardment of natural titanium, with Ti^{49} formed in its second excited state.

l_n values of 3 and 1 respectively can be identified unambiguously. The same is true also with the group for $Q=5.83$ Mev, for which $l_n=1$, but this appears with a small admixture of an $l_n=3$ component owing to the ground-state reaction with Ti^{48} in the target. When natural titanium is used, the two superposed groups show up with their relative intensities roughly reversed (see Figs. 7 and 9). The distribution for $Q=6.81$ Mev can be fitted by an $l_n=1$ curve, but in this case the unusually strong secondary component, which may also be fitted with $l_n=3$, cannot be attributed to the presence of other isotopes in the target. This may indicate another excited state in Ti^{48} with about the same excitation energy. If so, the new state probably has a Q value somewhat less than 6.81 Mev, since we specifically looked for a proton group having slightly higher Q with completely negative results.

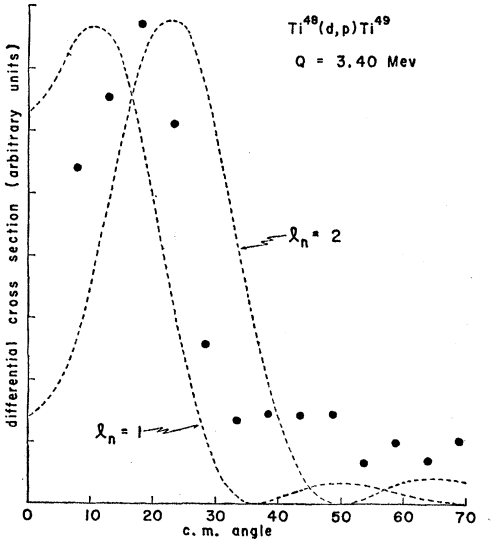

FIG. 12. Observed angular distribution of protons from deuteron bombardment of enriched Ti^{48} targets, with Ti^{49} formed in its third excited state.

In $Ti^{48}(d,p)Ti^{49}$, the first three groups have distributions which can be interpreted unambiguously. It should be pointed out, however, that the close spacing between the $Q=4.46$ and 4.11-Mev groups taxes the resolving power of our method. It is undoubtedly true that the latter group in particular is contaminated by degraded protons from the former. There is no indication of any component other than $l_n=1$ in either group, and we believe that our conclusions are correct in spite of the possible overlap. The yield of protons in the fourth group ($Q=3.40$ Mev) is relatively small, and our results are correspondingly unsatisfactory because of poor statistics. Figure 12 combines data from two separate trials, neither of which gave satisfactory data by itself. A peak at low angles is evident but it falls about halfway between the theoretical curves for $l_n=1$ and $l_n=2$. For this reason, we have listed no conclusions with respect to this state. For almost every other group, however, the experimental data seem to be shifted slightly toward larger angles relative to the Butler curve. For this reason it seems more likely that $l_n=1$ should be assigned in this questionable case. This opinion is strengthened by a comparison of the data points in Fig. 12 with the data points in Figs. 8, 10, and 11, where the assignments of $l_n=1$ seem to be correct.

There is some evidence, summarized by Pieper,[9] which indicates that $Q=8.14$ Mev does not correspond to the ground-state reaction in $Ti^{47}(d,p)Ti^{48}$. Collins, Nier, and Johnson[11] have measured the atomic masses of Ti^{47} and Ti^{48} with considerable precision, and the mass difference leads to an expected ground-state Q of 9.41 Mev. Moreover, their mass differences for Ti^{46}-Ti^{47}, Ti^{48}-Ti^{49}, and Ti^{49}-Ti^{50} all lead to expected Q values which agree satisfactorily with Pieper's conclusions for the related (d,p) reactions. In Fig. 5, where our data for $Q=8.14$ Mev are displayed, the "background" curve is a plot of the proton flux which passed the thicker halves of the absorber sets; it represents the yield of protons from the target with Q greater than about 8.35 Mev. We do not believe that the general shape of the "background" curve has any connection with the Butler theory. It seems more likely that the high "background" near 0° is the result of scattered deuterons which initiate (d,p) reactions in the absorber foils, an effect which we attempted to minimize by our use of Pb foil for the front layer in each set. If $Q=8.14$ Mev is not the ground-state transition, then the true ground-state group must be included in the "background"; moreover, its angular distribution should correspond to $l_n=3$ and thus resemble the $Q=8.14$-Mev distribution, because Ti^{47} and Ti^{48} (ground states) have different parities and their spins differ by 5/2. When we

[11] Collins, Nier, and Johnson, Phys. Rev. **86**, 408 (1952).

try to visualize an $l_n=3$ distribution buried in the "background" of Fig. 5, we conclude that, at best, this hypothetical proton group cannot amount to more than about 3 percent of the $Q=8.14$-Mev group in intensity. Even so, this may represent the proper identification of the proton groups from Ti^{47}, since it is difficult to gainsay the evidence for a ground-state Q greater than 8.14 Mev. We can find no reason to distrust the mass data, and so, in Table I, two alternatives have been listed in the column headed "excitation energy of final nucleus," one of which assumes $Q=8.14$ Mev is the ground state while the other assumes that it is the first excited state, with a very uncertain excitation energy of about 1.27 Mev. If $Q=8.14$ Mev is not the ground-state transition, we can only speculate about the failure to observe the true ground-state reaction. One argument, which can lead only to qualitative conclusions, has to do with the peculiar nature of Ti^{47}. By the independent-particle shell model, the Ti^{47} spin should be 7/2 instead of 5/2. Presumably spin 5/2 is the result of an unusual coupling of five neutrons in $f_{7/2}$ orbits. If another neutron is to be captured directly into an $f_{7/2}$ orbit to form ground state Ti^{48} with six $f_{7/2}$ neutrons and zero spin, some rearrangement of the angular momenta of the five original neutrons will be necessary in order to conserve total angular momentum. It is undoubtedly true that this necessity for rearrangement will reduce the cross section for the reaction, but it is not obvious that it can account for our complete failure to observe the corresponding proton group.

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Two-Step Cascades in Chlorine-36 and Cadmium-114 Neutron-Capture Gamma-Ray Spectra*

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Two NaI(Tl) crystals were used in conjunction with a twenty- and a single-channel pulse-height analyzer and a 5-microsecond coincidence circuit to determine cascade branches in the neutron-capture gamma-ray emission from Cl^{36} and Cd^{114}. Several two-step cascades in Cl^{36} and one in Cd^{114} have been verified by the present methods.

INTRODUCTION

THE use of NaI(Tl) crystals has provided a method of measuring photon energy values in the lower range of neutron-capture gamma-ray energies. The most prominent capture gamma energies in several elements have been determined by the use of such crystals.[1] Higher-energy photons have been measured accurately by the use of a pair spectrometer.[2]

A single neutron capture by an element X^A forms the isotope X^{A+1} in an excited state corresponding to the neutron binding energy for the element. In decaying to the ground state, intermediate states may be involved and the energy difference between each state then corresponds to the energy of the capture gamma rays emitted by the isotope. In a time on the order of 10^{-13} second the new nucleus is at the ground state unless an isomer is formed. In chlorine-36 several two-step cascades had been predicted according to the data collected by the use of NaI(Tl) crystals by Hamermesh and Hummel, and a pair spectrometer by Kinsey *et al.* The sum of the two gamma rays constituting each supposed cascade branch is in agreement with the neutron binding energy as shown in Table I.

The cadmium high-energy spectrum has been investigated by Kinsey *et al.*, and the neutron binding energy reported as corresponding to the highest-energy gamma ray of 9.046±0.008 Mev. Several other gamma rays have been determined including one at 8.48 Mev. The lower (50 kev to 5 Mev) energy range of the spectrum has been investigated in noncoincident runs with the NaI(Tl) crystal. The spectrum was found to be complicated and no lines other than the 0.558-Mev gamma ray were resolved. The sum of the 8.48-Mev and 0.558-Mev gamma rays equals the neutron binding energy, and a two-step cascade branch was also predicted here.

TABLE I. Combined pair-spectrometer and scintillation-spectrometer data on the capture γ rays from chlorine-36. Energies in Mev.

	Kinsey	Hamermesh	Sum (Neutron binding energy)
A	8.56±0.03	···	8.56±0.03
B	7.77±0.03	0.784±0.010	8.55±0.03
C	7.42±0.03	1.15 ±0.010	8.57±0.03
D	6.98±0.03	1.59 ±0.013	8.57±0.03
E	6.62±0.06	2.00 ±0.025	8.62±0.06

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[1] B. Hamermesh and V. Hummel, Phys. Rev. 88, 916 (1952).

[2] Kinsey, Bartholomew, and Walker, Phys. Rev. 85, 1012 (1952).