Reaction $Al^{27}(p,3pn)Na^{24}$†

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The cross section for the reaction $Al^{27}(p,3pn)Na^{24}$ has been measured as a function of proton energy between 32 and 350 Mev by comparison with the cross section of the reaction $C^{12}(p,pn)C^{11}$.

I. INTRODUCTION

THE reaction $Al^{27}(p,3pn)Na^{24}$ has been studied by a number of investigators,[1–3] and has proved useful in the measurement of proton beam intensities above 70 Mev. The proton energy regions covered by Hintz and Ramsey[1] and Marquez[2] were not adequate for experiments using the Berkeley 184-inch cyclotron. The data of Stevenson and Folger[3] were based on old values of the $C^{12}(p,pn)C^{11}$ cross sections by Aamodt, Peterson, and Phillips[4] which have since been revised by Crandall, Millburn, Pyle, and Birnbaum.[5] The remeasurement of the cross section of the reaction as a function of bombarding proton energy has been undertaken using better techniques.

II. EXPERIMENTAL PROCEDURE

Target Preparation and Bombardment

The reaction $Al^{27}(p,3pn)Na^{24}$ was studied using targets whose mass thicknesses were small with respect to the range of the bombarding particles. Such "thin target" experiments have several advantages over the stacked foil method. First, the bombarding particle energy may be selected by varying the radius at which the beam intercepts the target. The particle energy is not degraded appreciably by the target and therefore is known more precisely, particularly in the region below 150 Mev. Second, the reaction $Al^{27}(n,\alpha)Na^{24}$ from neutrons in the cyclotron tank contributes a negligible amount of Na^{24} compared to that formed by the proton beam. Third, Na^{24} produced by secondary particles is negligible because of the thin target.

However, the proton beam current must be measured in each bombardment; therefore, there must be a reaction whose cross section is known in the energy region of interest. A further requirement of the beam monitor is that the monitor foils and the target foils must intercept the same number of protons. The reaction $C^{12}(p,pn)C^{11}$ was chosen to monitor the beam.[5]

Targets consisted of polyethylene foils and aluminum foils arranged as shown schematically in Fig. 1. Both 0.005-inch and 0.001-inch aluminum foils were of commercial 2*S* aluminum, while the 0.001-inch polyethylene was commercial polyethylene sheet. Polyethylene was chosen as the source of carbon because of its relatively high melting point, vacuum stability, lack of elements of atomic number higher than carbon, and ease of fabrication. Guard foils on either side of each target and monitor foil were intended to compensate for the loss of reaction products by nuclear recoil and to protect the target foils from contamination. The foils were all cut precisely to the same area, $1\frac{1}{2}$ inches long $\times\frac{3}{8}$ inch wide, weighed, stacked in a jig, the holder clamped to the edge of the stack, and the alignment of all foils checked by inspection through a jeweler's loupe.

In preliminary experiments it was found that the amounts of activity induced in the two polyethylene monitor foils on opposite sides of the stack were not always comparable. (A similar effect has been noted in irradiations of other materials using aluminum foils as monitors.) It was concluded that for some unknown reason, possibly connected with the rapid evacuation to which the assembly was subjected on insertion into the cyclotron, the free edges of the foil stacks occasionally spread out, leading to improper alignment at the time of irradiation. This effect was completely eliminated by adding to the target assembly an aluminum foil (1 inch$\times\frac{3}{4}$ inch$\times$0.001 inch) folded over the free edge with both ends secured in the target holder, one end on each side of the stack. The ends of the foil stack which protruded beyond the enveloping foil were

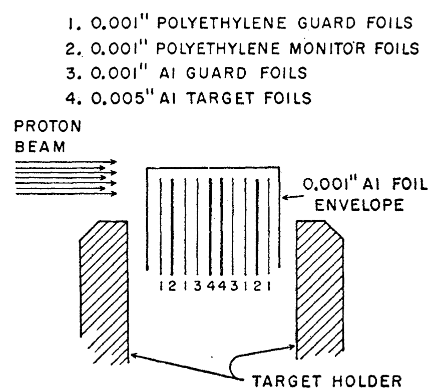

FIG. 1. Schematic target assembly for circulating cyclotron beam bombardments.

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[1] N. M. Hintz and N. F. Ramsey, Phys. Rev. **88**, 19 (1952).
[2] L. Marquez, Phys. Rev. **88**, 225 (1952).
[3] P. C. Stevenson and R. L. Folger (unpublished data).
[4] Aamodt, Peterson, and Phillips, Phys. Rev. **88**, 739 (1952).
[5] Crandall, Millburn, Pyle, and Birnbaum, Phys. Rev. **101**, 329 (1956).

then checked for alignment as before. All data here presented were obtained using this latter technique.

When targets were bombarded in the internal circulating beam of the 184-inch cyclotron, the gas flow to the ion source was reduced by one-half. The beam was pulsed 5 seconds on, 15 seconds off for two minutes, giving an average beam intensity of about 0.1 μa. There was no observable melting of the polyethylene targets after irradiation.

Independent measurements of the cross section of the reaction at 32 Mev and 350 Mev were made using a Faraday cup to measure proton beam intensities. Aluminum targets (1 inch diameter and 0.005 inch thick) were placed between 0.001-inch aluminum guard foils and fixed to the window of a Faraday cup for measurements using 32-Mev protons from the Berkeley linear accelerator[6] and 350-Mev protons from the external beam of the 184-inch cyclotron. The beam diameter in each case was about $\frac{1}{4}$ inch to give a well-defined counting sample.

Mounting and Counting of Samples

The target strips from internal beam targets were cut after irradiation to form two strips, $\frac{3}{4}$ inch$\times\frac{3}{8}$ inch, which were mounted side by side on a rigid backing. The irradiated edges were placed together to form a smaller source. The polyethylene foils were mounted on cardboard, and the aluminum foils on aluminum backings. Samples were counted using end-window methane-flow proportional counters. Coincidence corrections were less than one percent for counting rates below 10^5 counts per minute. It was not possible to use the same counter for all samples. The C^{11} was counted always on one counter, the Na^{24} always on another. The method of relating these counters is described in the next section. The solid angle intercepted by the counters was low (1–10%). All samples were counted for at least three half-lives of the desired product after the shorter lived products of the bombardment had decayed.

The Faraday cup targets were mounted without chemical separation of the Na^{24} on aluminum backing. The radiations were counted with a chlorine-quenched Geiger tube. The counting rates were all below one thousand counts per minute so coincidence correction was negligible. The number of disintegrations per count in the geometry and mounting conditions employed were determined independently with a 4π counter using the method of Batzel, Crane, and O'Kelley.[7]

Treatment of Data

The Na^{24} half-life was taken to be 15.05 hr and the C^{11} to be 20.50 min.[8] Individual counts on each counting sample were extrapolated analytically to the end of bombardment from the start of the count. Initial decay rates obtained from the various activity measurements on a given sample varied one percent or less from the mean in each sample from the internal circulating beam targets. Since the areas of all foils were equal, the weight of each individual foil was taken to be a measure of its thickness and hence of the number of atoms in the path of the proton beam. Specific activities of the various samples were calculated by dividing the average calculated initial activities by the foil weight. Specific activities of duplicate samples in general agreed to within one percent. The Na^{24} cross sections were then calculated by the following equation:

$$\sigma(\mathrm{Na}^{24})=k\cdot\frac{\text{specific activity aluminum}}{\text{specific activity polyethylene}}\cdot\sigma(\mathrm{C}^{11}).$$

The constant k includes the following factors: relative counting efficiencies including all scattering corrections, half-lives of Na^{24} and C^{11}, atomic weights of targets, decay of sample during counting interval (all counts were of 1.28-min duration for C^{11} and Na^{24}), and decay during bombardment (all bombardments were 2.00 min long). For each series of bombardments, k was determined by one or two bombardments at 350 Mev where both aluminum and carbon cross sections had been measured by using a Faraday cup to measure beam intensities (this work and that of Crandall *et al.*[5]).

TABLE I. Cross sections of the reaction $Al^{27}(p,3pn)Na^{24}$.

Proton energy Mev	$\sigma(C^{11})$[a] mb	$\sigma(Na^{24})/\sigma(C^{11})$	$\sigma(Na^{24})$ mb	Experimental technique
32			0.005[b]	Faraday cup
350	36.0	0.311	11.3 11.1[a]	Faraday cup
Run 1				Circulating beam
50	86.9	0.0175	1.52	
70	76.5	0.107	8.2	
80	70.4	0.146	10.3	
90	66.0	0.162	10.7	
125	51.7	0.201	10.4	
150	44.6	0.209	9.3	
200	36.3	0.248	9.0	
275	36.0	0.289	10.4	
340	36.0	0.319	11.5	
Run 2				Circulating beam
60	80.8	0.0668	5.4	
80	70.4	0.148	10.4	
175	38.7	0.230	8.9	
200	36.3	0.256	9.3	
225	36.0	0.258	9.3	
250	36.0	0.275	9.9	
300	36.0	0.311	11.2	
325	36.0	0.314	11.3	
Run 3				Circulating beam
110	57.2	0.185	10.6	
125	51.7	0.193	10.0	
125	51.7	0.193	10.0	
135	49.0	0.198	9.7	
150	44.6	0.204	9.1	

[a] See reference 5.
[b] See reference 6.

[6] R. S. Gilbert, private communication.
[7] Batzel, Crane, and O'Kelley, Phys. Rev. **91**, 939 (1953).
[8] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).

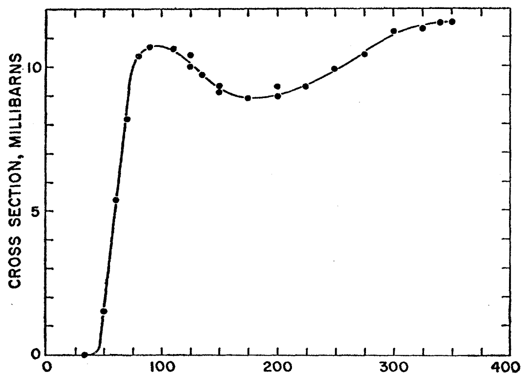

FIG. 2. Cross section of the reaction $Al^{27}(p,3pn)Na^{24}$.

Cross sections of the reaction $C^{12}(p,pn)C^{11}$ were obtained from the work of Crandall, Millburn, Pyle, and Birnbaum.[5] The results appear in Table I and Fig. 2.

III. DISCUSSION

The threshold of the reaction $Al^{27}(p,3pn)Na^{24}$ is calculated to be ~32 Mev if one disregards Coulomb barrier effects, and ~44 Mev if account is taken of the barrier. The cross section at 32 Mev was found to be 5×10^{-3} mb provided neutron background was negligible. This value disagrees with the value of ~0.5 mb given by Hintz and Ramsey.[1] The cross sections measured in this work from 50 to 125 Mev are consistently lower by about six millibarns than those of Hintz and Ramsey. The reaction $Al^{27}(p,pHe^3)Na^{24}$ has a threshold of 24 Mev if one disregards the Coulomb barrier, and one of 36 Mev if account is taken of the barrier. The present data indicate that the predominant reaction in the energy region studied is $Al^{27}(p,3pn)Na^{24}$.

IV. ACKNOWLEDGMENTS

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Pion Production by Inelastic Scattering of Electrons in Hydrogen*

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The ratios of the yield of electron-induced to photon-induced pion processes have been measured at an incident energy of 600 Mev. Measurements have been made at energies of 60 and 170 Mev for positive pions. The result is expressed in terms of "the equivalent radiation length" X_e defined so that the pion yield due to direct electron production is equal to the pion yield due to photons produced by electrons in a radiator of X_e radiation lengths. The results are $X_e=0.0191\pm0.0011$ for 60-Mev pions and $X_e=0.0178\pm0.0023$ for 170-Mev pions. At the lower pion energy the value is somewhat lower than the theoretical value if equal transverse and longitudinal interactions are assumed. If the contribution from the longitudinal matrix element is taken to be small or if the electron contribution from large angles of electron scattering is suppressed, then the value can be fitted. The value at 170 Mev is in agreement with predominantly magnetic-dipole absorption corresponding to the enhanced $P_{3/2,3/2}$ state of the final pion-nucleon system.

I. INTRODUCTION

A. General

In a previous paper,[1] we have discussed evidence for the direct production of positive pions by electron bombardment of lithium. Specifically, a measurement was carried out to establish the ratio of production by 500-Mev electrons to production by the corresponding photon bremsstrahlung of 60-Mev pions produced at 75° laboratory angle. Detailed interpretation of the lithium results is made difficult by the broadening effect of the initial momenta of the nucleons. For this reason, we have carried out further measurements using liquid hydrogen as a target. This paper covers measurements made only at one value of the incident electron energy (600 Mev), one pion laboratory production angle (75°), and two pion kinetic energies (60 and 170 Mev).

B. Kinematics and Description of the Process

Consider the inelastic collision between an electron and a proton resulting in pion formation. Figure 1 is a

* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
† On leave from the Laboratory for Nuclear Studies, Cornell University, Ithaca, New York.
[1] Panofsky, Newton, and Yodh, Phys. Rev. 98, 751 (1955).