A value for p_b in the laboratory system was then determined which was kinematically consistent with a mass of 500 Mev for the K-meson. This momentum turns out to be 0.56 Bev/c, which is well within the limits of error given for p_b.

The interpretation of the event as the simultaneous production of a K-meson and a hyperon is in accord with the predictions of Pais[4] and Gell-Mann[5] that heavy unstable particles are produced in pairs.

The authors wish to express their appreciation to Mr. M. Blevins of Duke University for aiding in the computations.

[4] A. Pais, Phys. Rev. **86**, 663 (1952).
[5] M. Gell-Mann, Phys. Rev. **92**, 833 (1953).

PHYSICAL REVIEW VOLUME 99, NUMBER 1 JULY 1, 1955

Disintegration of Aluminum by Protons in the Energy Range 0.4 to 3.0 Bev*

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Excitation functions for the production of Na^{24}, Na^{22}, F^{18}, O^{15}(?), N^{13}, C^{11}, and Be^7 in proton bombardments of Al have been measured from 0.4 to 3.0 Bev. The formation cross sections have strikingly small energy dependence, and this feature is discussed in the light of possible energy transfer mechanisms. The absolute cross-section values are based on a calibration method (suggested by A. Turkevich) which is discussed. It is based on measurements of gross radioactivity in copper irradiated at various energies and on the assumption that the fraction of inelastic collisions with copper nuclei that lead to radioactive products is independent of proton energy from 0.3 to 3 Bev. The validity of this assumption is examined.

WHEN proton beams with kinetic energies up to 3 Bev became available in the Brookhaven Cosmotron, it seemed desirable to extend radiochemical studies of nuclear reactions into this new range of bombarding energies. In an initial survey the yields of many radioactive products from the bombardment of a few selected target elements in different mass regions were measured at a given energy (usually 2.2 Bev) and compared with similar data at lower energies.[1-3] For target elements of medium[2] and high[3] Z the product yield distributions at 2.2-Bev bombarding energy were found to differ markedly from those observed with 300- to 400-Mev protons. For low-Z targets such as carbon[4] and aluminum[1] the most striking observation was the relatively slight difference between the cross sections in the two energy regions. In the present paper we report more detailed data on the excitation functions for the production of several radioactive nuclides in the bombardment of aluminum with protons in the energy range from 0.4 to 3.0 Bev.

The products studied include Na^{24}, Na^{22}, F^{18}, N^{13}, C^{11}, and Be^7. The production of all these nuclides from aluminum was investigated previously at lower proton energies. Hintz and Ramsey[5] published excitation functions for the formation of Na^{24}, Na^{22}, and F^{18} with protons of kinetic energies up to 120 Mev. Marquez and Perlman[6] and Marquez[7] reported cross sections for the production from aluminum of all six of the aforementioned nuclides by 335-Mev and 420-Mev protons, respectively.

EXPERIMENTAL

The irradiations were all carried out in the circulating beam of the Cosmotron. The proton energy was varied by variation of the turn-off time for the rf accelerating voltage. To prevent bombardment by stray protons of lower than the desired energy the targets were rammed into the bombardment position at the end of each acceleration cycle as previously described.[2] Circulating proton beams of about 10^{10} protons per pulse and a repetition rate of 12 pulses per minute were used in most of this work. Bombardments of one to two minutes' duration were found to produce adequate counting rates of the short-lived activities investigated: 15.0-hr Na^{24}, 112-min F^{18}, 20.5-min C^{11}, 10-min N^{13}, and some 2-min activity, probably largely O^{15}. The yields of 53-day Be^7 and 2.6-year Na^{22} were studied in aluminum samples irradiated up to a few hours.

Bombardments were carried out at a number of proton energies between 0.4 and 3.0 Bev. At each energy the yields of the various product activities were determined relative to the yield of Na^{24}. The excitation function for the $Al^{27}(p,3pn)Na^{24}$ reaction was measured in a separate set of experiments as described below.

* Research performed under the auspices of the U. S. Atomic Energy Commission.
[1] Wolfgang, Sugarman, and Friedlander, Phys. Rev. **94**, 775 (1954).
[2] Friedlander, Miller, Wolfgang, Hudis, and Baker, Phys. Rev. **94**, 727 (1954).
[3] Sugarman, Duffield, Friedlander, and Miller, Phys. Rev. **95**, 1704 (1954).
[4] R. L. Wolfgang and G. Friedlander, Phys. Rev. **96**, 190 (1954).
[5] N. M. Hintz and N. F. Ramsey, Phys. Rev. **88**, 19 (1952).
[6] L. Marquez and I. Perlman, Phys. Rev. **81**, 953 (1951).
[7] L. Marquez, Phys. Rev. **86**, 405 (1952).

The targets were made up of 0.00025-in. or 0.003-in. aluminum foils of purity >99.9 percent. Earlier experiments[8] had shown that recoil losses of Na^{24}, F^{18}, and C^{11} from 0.00025-in. aluminum foils are quite serious; but such losses were found to be negligible for all the nuclides investigated except for Be^7 if only the center two foils of a stack of six 0.00025-in. foils were used for the activity measurements. For the runs in which the Be^7 yields were studied, 0.003-in. target foils were used after Dr. N. Sugarman had shown in a preliminary irradiation of a stack of 0.003-in. foils that the recoil loss of Be^7 from such foils is less than a few percent.

The relative cross sections for the formation of Na^{24}, F^{18}, C^{11}, N^{13}, and "the 2-min activity" [O^{15}(?)] were determined by analysis of the gross decay curves of the irradiated 0.0005-inch aluminum foils (two 0.00025-inch layers) measured with end-window gas-flow proportional counters. The analysis into 15.0-hour, 112-minute and 20.5-minute components presented no difficulties and their relative intensities are thought to be known to ±5 percent. The intensities of the 10-minute N^{13} and 2-minute O^{15}(?) activities have somewhat larger uncertainties; checks between different runs and between duplicate decay curve analyses carried out by different individuals[9] indicate that these intensities may have probable errors of about ±20 percent. The effects of absorption in the 1.2 mg cm^{-2} counter window and of self-absorption and self-scattering in the 0.0005-inch (3.5 mg cm^{-2}) foils were thought to be sufficiently small to be taken as equal for the different β emitters. However, a correction had to be made for the different back-scattering of electrons and positrons[10] from the thick aluminum sample backings. Since the samples were counted in very nearly 2π geometry, Seliger's data for 2π geometry were used, and all β^+-counting rates were multiplied by $1.42/1.27=1.12$ to make them directly comparable with the Na^{24} counting rates. The over-all counting efficiency for Na^{24} in our standard arrangement was determined by Dr. J. B. Cumming by a $\beta-\gamma$ coincidence calibration of Na^{24} induced in aluminum foils by n,α reaction. For the 0.0005-inch foils this over-all counting efficiency was found to be 0.506, for the 0.003-inch foils it was 0.459.

The Na^{22}/Na^{24} ratios were determined in irradiated 0.003-inch aluminum foils by β-decay measurements over several months. In the proportional counters used the counting efficiency for Be^7 was found to be so low as to make the contribution of Be^7 activity to the measured counting rates negligible. Long-lived activities produced from impurities in the aluminum foil were found not to be a serious source of error. The counting efficiency for Na^{22} with the proportional counter arrangement used was established in a separate experiment, in which the absolute disintegration rate of a much stronger Na^{22} sample was determined by a $\beta-\gamma$ coincidence measurement. For this calibration measurement the Na^{22} was produced in a 0.003-inch aluminum foil by bombardment with 380-Mev protons at the Nevis cyclotron.

The Be^7 yields were determined with chemically separated beryllium samples. The target was dissolved in HCl and, after addition of Be and Na carriers, $Al(OH)_3$ and $Be(OH)_2$ were precipitated with NH_3. The hydroxides were dissolved in HCl, the bulk of the aluminum removed as $AlCl_3\times 6H_2O$ by the addition of HCl gas and ether, and $Be(OH)_2$ (and some $Al(OH)_3$) precipitated with NH_3. This precipitate was dissolved in glacial acetic acid, and beryllium was purified by repeated extractions of its basic acetate into chloroform, and finally ignited to BeO for mounting.

The radiochemical purity of the Be^7 samples was checked by decay measurements and by determination of the pulse height distribution with a grey-wedge scintillation spectrometer. The absence of β activity served as an additional criterion of purity. The Be^7 activities were counted with NaI scintillation counters calibrated as follows. A stronger Be^7 source was counted in the same geometry, and also intercompared with a calibrated Na^{22} standard by means of a scintillation spectrometer. This intercomparison involved measurement of the areas under the 0.48-Mev peak of Be^7 and the 0.51-Mev annihilation peak of Na^{22}. The small difference in counting efficiency at these two energies was neglected. The relative areas were converted to relative disintegration rates by means of published decay scheme information (11 percent abundance[11] of 0.48-Mev γ rays in Be^7; 90 percent β^+ emission[12] in Na^{22}).

In one run the relative yields of Be^7 and Na^{22} were checked by comparison of the γ activities of chemically separated samples with calibrated scintillation counters. For this purpose the sodium fraction was obtained by evaporation of the filtrate from the $Al(OH)_3+Be(OH)_2$ precipitate, followed by a NaCl precipitation.

RESULTS

For each bombardment, the disintegration rates of the nuclides measured were converted to relative formation cross sections by means of the appropriate corrections for length of bombardment and, where chemical separations were performed, for chemical yields.[13] In Table I these relative cross sections are given, normalized at each proton energy to the Na^{24} yield taken as unity. On the basis of estimates of the various sources of error in the experiments, the probable errors of the yields in Table I are thought to be about ±30 percent for N^{13} and "O^{15}," ±15 percent for Be^7, and ±10 percent for the others.

[8] R. Wolfgang and G. Friedlander, Phys. Rev. **94**, 775 (1954).
[9] Dr. F. S. Rowland kindly participated in these check analyses.
[10] H. H. Seliger, Phys. Rev. **88**, 408 (1952).
[11] R. M. Williamson and H. T. Richards, Phys. Rev. **76**, 614 (1949).
[12] R. Sherr and R. H. Miller, Phys. Rev. **93**, 1076 (1954).
[13] Dr. R. W. Stoenner kindly carried out the Na chemical-yield determination.

ABSOLUTE CROSS SECTION OF THE REACTION $Al^{27}(p,3pn)Na^{24}$

In order to convert the relative yields shown in Table I to absolute cross sections, it is necessary to know the formation cross section for at least one product as a function of bombarding energy. For convenience, the product chosen was Na^{24}; its activity is easily measured without chemical separation in irradiated aluminum foils, and its formation cross section has been the subject of several studies at synchrocyclotron energies.[5–7,14,15]

Since no external proton beam of sufficient intensity for activation experiments has been available at the Cosmotron, and since a direct, absolute determination of the number of protons striking an internal target is quite difficult, a somewhat indirect method was resorted to for the absolute cross section measurements. The technique was proposed and first applied with 2.2-Bev protons by Turkevich.[16] Since it has formed the basis of all the cross-section measurements made to date on proton-induced nuclear reactions at the Cosmotron, it is discussed here in some detail.

Turkevich's beam calibration method is based on the assumption that, for a target element of medium atomic weight such as copper, that fraction of all the inelastic collisions which leads to the formation of radioactive products stays approximately constant with bombarding energy over a wide energy range. Then, if the total inelastic cross section of, say, copper is known as a function of energy, the production of gross radioactivity in copper foils by protons of various energies serves as a measure of the relative beam intensities at these energies; furthermore, the measurements can be put on an absolute basis if the production of gross radioactivity in copper is determined at a proton energy of about 0.4 Bev where it may be calibrated directly against some known reaction cross section.

TABLE I. Product yields relative to the Na^{24} yield taken as unity at each proton energy.

Proton energy (Bev)	Na^{22}	F^{18}	O^{15} [a]	N^{13}	C^{11}	Be^{7}
0.39[b]	1.89					
0.41		0.65[c]		~0.07	0.27[c]	
0.6	1.78	0.64	0.6	~0.08	0.31	
1.0	1.59[c]	0.7[c]			0.5[c]	0.71
1.4	1.87	0.62	0.7	~0.15	0.52	0.77
1.6	1.38					
1.8	1.81					
2.2	1.37	0.66[c]	0.6[c]	~0.17[c]	0.57[c]	1.18[d]
3.0	1.66[c]	0.65	0.7	~0.11	0.61	1.08

[a] The 2-min activity observed is here considered to be O^{15}.
[b] Nevis cyclotron bombardment.
[c] Mean of two or more runs.
[d] In this run a Be^7/Na^{22} ratio of 0.88 was independently determined by scintillation spectrometry on the unseparated Al target. This corresponds to a Be^7 yield of 1.21 relative to Na^{24}. In another 2.2-Bev bombardment an approximate Be^7 yield of 0.85 (relative to Na^{24}) was found by comparison of chemically separated Be and Na samples.

[14] Birnbaum, Crandall, Millburn, and Pyle, Phys. Rev. (to be published).
[15] Stevenson, Hicks, and Folger (private communication).
[16] A. Turkevich, Phys. Rev. 94, 775 (1954).

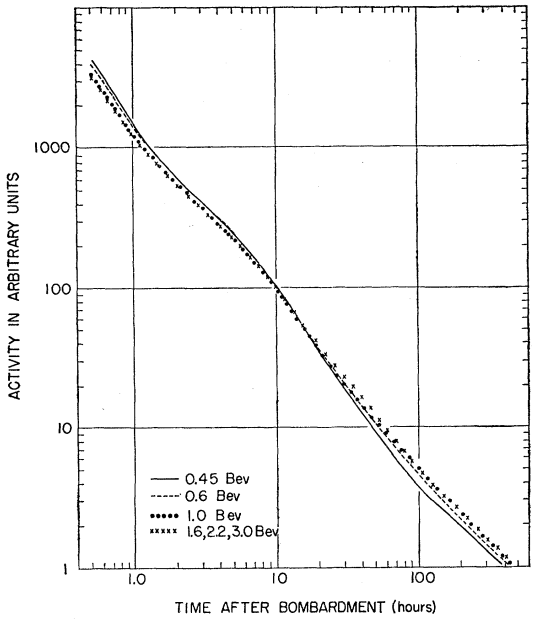

FIG. 1. Gross decay curves of copper foils bombarded with protons of various energies. The curves are normalized at 10 hours after bombardment.

The basic assumption that the ratio of the cross section for formation of radioactive products to the total inelastic cross section of copper is independent of proton energy in the range from about 0.3 to 3 Bev is plausible in view of the experimental data on the yield distributions of spallation products formed from copper. With respect to the stability line, the formation cross sections of the spallation products show very similar patterns at 2.2-Bev[2] and at 340-Mev[17] proton energy, the largest cross sections at both energies being near stability. The yield distribution as a function of mass number, on the other hand, changes quite strongly with bombarding energy,[2] so that the individual product cross sections can by no means be thought to remain constant. Yet the gross activity produced at each energy apparently represents a sufficiently large statistical assembly of half-lives that the gross decay curves of copper foils bombarded at various energies have very similar shapes. This is seen in Fig. 1 which shows on a log-log plot the decay curves of copper foils bombarded for 2 to 5 minutes with protons of various energies between 0.45 and 3.0 Bev. The foils were measured with β-proportional counters. The curves can all be represented approximately by a straight line on the log-log plot, corresponding to the equation $A_t = A_1 t^{-1.21}$, where A_t and A_1 are the activities t hours and 1 hour, respectively, after the end of bombardment. From $t=0.5$ hr to $t=400$ hr no experimental points deviate by more than $\pm$ 20 percent from this line. On the basis of the

[17] Batzel, Miller, and Seaborg, Phys. Rev. 84, 671 (1951).

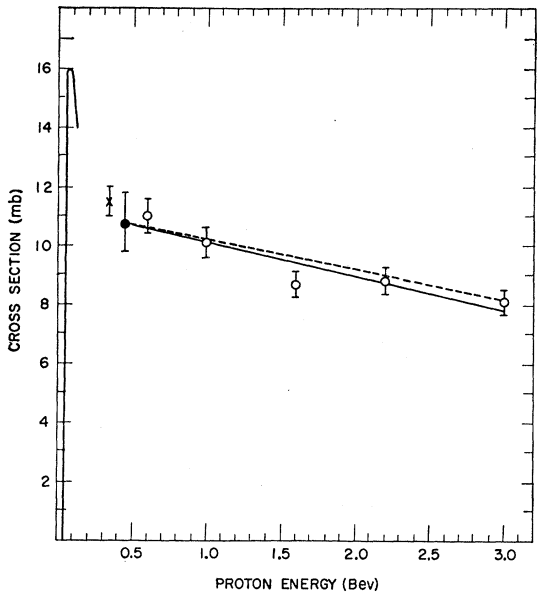

FIG. 2. Excitation function of the reaction $Al^{27}(p,3pn)Na^{24}$. The open circles are the cross sections determined in the present paper, the solid circle is from reference 7, the cross from reference 14, and the curve at low energies from reference 5. The solid line is a least squares fit to the points at $E_p \geqslant 0.45$ Bev. The dashed line has been the basis of the cross-section scale used for nuclear reactions studied with the Cosmotron.

similarity of all the gross decay curves the following additional assumption was considered reasonably justified: Not only the total number of active atoms formed (which would be hard to measure in practice), but the number N_{ac} of decays over a limited time, such as between 0.5 hr and 400 hr after bombardment, and observed in a β-proportional counter, is approximately proportional to the total number of inelastic events in the copper target. For each run, N_{ac} was determined by graphical integration under the decay curve (on linear scale!) between 0.5 and 400 hr. If a modified activation cross section, σ_{ac}, is defined as the cross section for production of these N_{ac} atoms and σ_{in} is the inelastic cross section for protons on copper, then the assumption may be stated in the form

$$\sigma_{ac}/\sigma_{in}=C, \tag{1}$$

where C is a constant independent of proton energy.

We now turn to the question of the energy dependence of σ_{in}. Actually, very few measurements are available. Kirschbaum[18] reported values of σ_{in} for copper of 746 $\pm$45, 667$\pm$31, and 608$\pm$22 mb with protons of 185, 240 and 305 Mev. A measurement[19] at a proton energy of 1.6 Bev gave a value of 680$\pm$50 mb, and an inelastic cross section of 674$\pm$34 mb has been reported for 1.4-Bev neutrons.[20] Both these direct measurements and the energy dependence of the elementary p-p and n-p cross sections[21] indicate that σ_{in} goes through a minimum in the vicinity of 400 Mev. For the present purpose it has been assumed that σ_{in} for copper stays essentially constant from 0.8 to 3 Bev (as do the total p-p and p-n cross sections[21]) and that

$$\sigma_{in}{}^{>0.8}=1.15\sigma_{in}{}^{0.45}=1.07\sigma_{in}{}^{0.6}, \tag{2}$$

where the superscripts are the proton energies in Bev. Any errors due to the assumptions of Eq. (2) are probably small compared with those introduced by the assumptions of the previous paragraph.

Experiments were carried out at 0.45, 0.60, 1.0, 1.6, 2.2, and 3.0 Bev. All bombardments were short compared with 0.5 hr. In each run a 0.003-inch aluminum foil and, downstream from it, three thicknesses of 0.001-inch copper foil were bombarded. After bombardment, an area of 1 or 2 cm^2 was cut out of the center of the foil stack. Only the middle Cu foil was used for the decay measurement and determination of N_{ac}; the other two foils served to compensate for the recoil losses of active nuclei from the middle foil. The Na^{24} activity in the Al foil was measured as described earlier and from it was deduced the number N_{Na} of Na^{24} atoms produced by the bombardment.

If the numbers of Al and Cu atoms in the foils are n_{Al} and n_{Cu}, respectively, and if σ_{Na} is the cross section for the production of Na^{24} from Al, then at each proton energy

$$\sigma_{ac}n_{Cu}/N_{ac}=\sigma_{Na}n_{Al}/N_{Na}. \tag{3}$$

N_{ac}, N_{Na}, n_{Cu}, and n_{Al} are measured quantities. At 0.45-Bev proton energy σ_{Na} is known from Marquez' work[7] as 10.8 mb; with the use of this value $\sigma_{ac}{}^{0.45}$ was calculated from the 0.45-Bev run to be 54.6 mb. Then, according to Eqs. (1) and (2), $\sigma_{ac}{}^{0.6}=58.5$ mb and $\sigma_{ac}{}^{>0.8}=62.8$ mb. Now σ_{Na} may be evaluated at each bombarding energy from Eq. (3). The values of σ_{Na} so obtained are shown in Table II and Fig. 2. In the figure the literature values for σ_{Na} at lower energies[5,7,14] are also shown. The solid line of Fig. 2 is a least-squares fit to the points for $E_p \geqslant 0.45$ Bev. It does not differ significantly from the dotted line drawn through Marquez's 0.45-Bev point and Turkevich's[16] value of 9.0 mb at 2.2 Bev. This dotted line has been the basis for all proton cross sections at Cosmotron energies reported to date and will continue to be used until a more reliable absolute determination of the cross-section scale is made.

The estimated probable errors of $\pm$5 percent shown

TABLE II. Cross section for the reaction $Al^{27}(p,3pn)Na^{24}$ as a function of proton energy (based on Marquez' value of 10.8 mb at 0.45 Bev).

E_p (Bev)	0.60	1.0	1.6	2.2	3.0
σ (mb)	11.0	10.1	8.7	8.8	8.1

[18] A. J. Kirschbaum, University of California Radiation Laboratory Report UCRL-1967, 1952 (unpublished).
[19] R. B. Duffield and G. Friedlander (unpublished).
[20] Coor, Hill, Hornyak, Smith, and Snow, Phys. Rev. **98**, 1369 (1955).
[21] Chen, Leavitt, and Shapiro (to be published).

on the points in Fig. 2 do not include any estimate of the error in the basic assumption of the method [Eq. (1)]. Such an estimate is difficult to make at this time. To date the only direct evidence on this point comes from the data on copper spallation by 2.2-Bev protons.[2] The cross sections for copper spallation products were based on the value 9.0 mb for the reaction Al(p,3pn)Na^{24} at 2.2 Bev. On this basis the sum of all the measured cross sections for radioactive products of $A>10$ is about 180 mb (the value for V^{49} in reference 2 should be lowered from 27 mb to about 15 mb on the basis of a recent redetermination[22] of the V^{49} half-life). The dependence of the formation cross sections on A and Z indicates that the measured values must represent about one-quarter of the total inelastic cross section, in good agreement with the measured values of σ_{in} ($\approx$675 mb)[19,20] based on transmission data. It is difficult to see how the estimate of 0.25 for the fraction of σ_{in} represented by the measured cross sections can be in error by more than $\pm$30 percent. This then may be assigned as the limit of error on the absolute values of the Al(p,3pn) cross sections in Table II and Fig. 2.

DISCUSSION

On the basis of the Al(p,3pn) cross section discussed in the preceding section, the relative yields of Table I may now be converted into production cross sections. The results are summarized in Figs. 3 and 4 together with the 0.42-Bev data of Marquez.[7] Except for their Be^7 point, the 0.34-Bev measurements of Marquez and Perlman[6] are not included because, according to Marquez,[7] the cross sections reported in reference 6 were calculated without proper corrections for β-ray absorption losses.

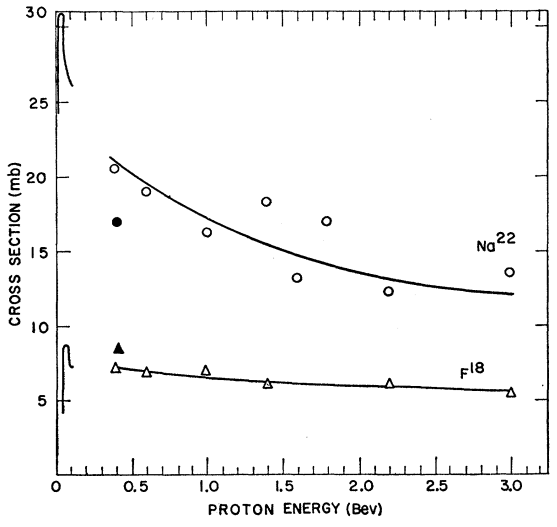

FIG. 3. Excitation functions for the formation of Na^{22} and F^{18} from Al. Data from reference 5 (curve for $E_p<0.12$ Bev) and reference 7 (solid points at 0.42 Bev) are included.

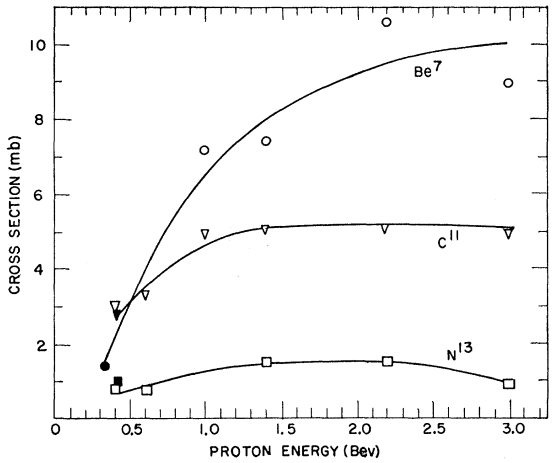

FIG. 4. Excitation functions for the formation of N^{13}, C^{11}, and Be^7 from Al. The solid points at 0.42 Bev are from Marquez (reference 7).

The main feature of the data is certainly the relatively slight energy dependence of the cross sections studied. If we assume that, with the possible exception of Be^7, the products observed are formed by evaporation processes following deposition of excitation energy, then the data indicate remarkably little change in the spectrum of these energy depositions with change in proton energy from 0.4 to 3 Bev. The gradual change in the shapes of the excitation functions from Na^{24} and Na^{22} through F^{18} and N^{13} to C^{11} indicates that, with increasing bombarding energy, the spectrum of excitation energies shifts slowly towards higher values. It is not clear whether the shape of the Be^7 excitation function should be ascribed entirely to this trend. Other mechanisms probably contribute to the formation of Be^7 as will be discussed below.

The rather high cross section for Be^7 formation above 1 Bev is of interest. In the spallation of copper[2] and of heavier elements[3] with 2.2-Bev protons a peak in the yield-*vs*-mass curve about 20 mass numbers below the target mass has been observed, and one might therefore be tempted to interpret the high yield of Be^7 as evidence for a similar peak in aluminum spallation. In the heavier elements the peak has been ascribed to a high probability for the transfer of hundreds of Mev to the struck nucleus by the reabsorption of π mesons produced in the same nucleus. This mechanism should be less important in aluminum than in copper because of the larger ratio of meson mean free path to nuclear radius. The absolute magnitude of the Be^7 cross section may thus be somewhat large to be accounted for in this manner. It is very likely that evaporation of Be^7 aggregates from excited nuclei (or perhaps some other direct ejection mechanism) makes at least some contribution to the Be^7 formation cross sections. This is indicated by the fact[23] that at Bev energies Be^7 is

[22] W. S. Lyon, Phys. Rev. **97**, 121 (1955).

[23] Hudis, Baker, and Friedlander, Phys. Rev. **95**, 612 (1954).

formed in high cross section from heavier target nuclei also, where it can hardly be a spallation residue.

It may be noted that, over the entire energy range, the N^{13} formation cross section is strikingly low compared to the other cross sections. In view of the similarity between C^{11}, N^{13}, O^{15}, and F^{18} as regards their positions relative to β stability and their β-decay energies, these low cross sections for N^{13} are, at first sight, surprising. Following a suggestion by Dr. D. H. Wilkinson, we attribute this apparent anomaly to the fact that all excited states of N^{13} are unstable with respect to heavy-particle emission[24] whereas each of the other nuclides observed has a number of excited states which can be de-excited by gamma emission only.

It is a pleasure to express our gratitude to the Cosmotron operating staff for carrying out the bombardments. Miss G. Vedder and Mrs. N. Hamilton helped with the activity measurements.

[24] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

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Elastic Photoproduction of π^0 Mesons from Deuterium*

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The average differential cross section for the reaction $\gamma+d=\pi^0+d$ has been measured for photons between 250 and 300 Mev at four angles. A difference measurement with deutero-paraffin and normal paraffin targets was employed. The recoil deuterons were detected by a counter telescope which discriminated against protons by recording the product of the energy and the specific ionization loss of the particles. The reaction was further identified by demanding a coincidence between the deuteron pulse and a pulse from a photon counter placed at an angle corresponding to the direction of the π^0. The values of the differential cross section for various angles of the π^0 in the laboratory system are as follows:

$\theta(\pi^0)$	$d\sigma/d\Omega$ (10^{-30} cm²/steradian)	$\theta(\pi^0)$	$d\sigma/d\Omega$ (10^{-30} cm²/steradian)
76°	4.2±0.6	110°	2.5±0.4
93°	3.2±0.5	130°	1.2±0.3

The stated errors are the standard statistical errors and apply to the relative cross sections at the various angles. The absolute cross-section scale is subject to an experimental error of 25 percent. The measured cross sections are in agreement with theoretical calculations based on the impulse approximation, with the assumption of equal amplitudes for π^0 production from the proton and neutron and constructive interference.

INTRODUCTION

NEUTRAL pi mesons can be produced by the photon bombardment of deuterium in either of two reactions, the elastic process

$$\gamma+d=\pi^0+d$$

in which the deuteron recoils as a unit, and the inelastic process

$$\gamma+d=\pi^0+p+n$$

in which the deuteron is broken up into its component nucleons. A study of these two reactions together with a knowledge of the π^0 production from hydrogen,

$$\gamma+p=\pi^0+p,$$

can lead to information about the relative properties of the photoproduction from protons and neutrons.

An exact theoretical calculation of meson photoproduction from deuterium is beyond the scope of present-day physics although some approximate calculations based on simplified meson theories have been made.[1,2] To simplify the problem, one can make use of the impulse approximation, which states that meson production in a nucleus may be treated as the sum of interactions with the individual nucleons.[3–6] By using this method it has been shown[5] that the cross section for the elastic production of a π^0 meson with a deuteron recoil of momentum D may be written, neglecting spin effects, as

$$\sigma_{el}=|A_n+A_p|^2\left(\int\psi_0^2\exp(\tfrac{1}{2}i\mathbf{D}\cdot\mathbf{R})d\mathbf{R}\right)^2, \quad (1)$$

where A_n is the amplitude for π^0 production from the neutron, A_p is the amplitude for π^0 production from the proton, $\psi_0(R)$ is the ground-state deuteron wave function, and $\mathbf{R}$ is the relative coordinate between neutron and proton. The quantity

$$\left|\int\psi_0^2\exp(\tfrac{1}{2}i\mathbf{D}\cdot\mathbf{R})d\mathbf{R}\right|^2$$

can be interpreted as the probability that the deuteron will stick together if one of the nucleons is given an impulse D. In the same notation, the cross section of a

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† Now at Eastman Kodak Company, Rochester, New York.

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