TABLE I. Relative number of events.

Excitation energy in Mev		150	200	250	300	300–150
Single protons	<20 Mev	256±64	⋯	⋯	170±20	−86±67
	>20 Mev	45±6	⋯	⋯	47±8	2±10
2 prongs	positive	20±3	⋯	⋯	47±6	27±7
	probable	11±2	⋯	⋯	46±7	35±7
3 or more prongs		32±4	42±4	93±13	100	68±4
Stars from which a meson comes out		∼0	⋯	⋯	5±2	5±2

3. The energy spectrum of the single protons as well as the protons from stars was obtained by determining the energy either from its range or gap density or grain density, depending on which one of the methods gives the most accurate value. The results are given roughly in Table II. The figures are relative to the number of stars of three or more prongs.

4. The angular distribution of protons from stars relative to the direction of the incident gamma-ray beam were studied at the excitation energy of 300 Mev. The protons of energy between 20 and 60 Mev have a strong forward asymmetry and have a peak between 30° and 60°. The protons above 60 Mev also show some forward asymmetry, which is not so conspicuous as in the case of protons between 20 and 60 Mev.

5. Discussion of results. The absolute value of the cross section is in agreement with the expected value, if the cross section for the production of stars for photons of energy above 150 Mev is proportional to $\sigma_m A$, where A is the atomic weight and σ_m is the cross section for the photomeson production by a nucleon including both the charged and neutral mesons. The percentage of the stars from which a meson is coming out is about twice as small as the value expected from the known data. This might be due to the fact that the mesons starting in the emulsion without being associated with a star were not taken into account in the figures given in Table I.

The forward asymmetry of the angular distribution of the protons of energy between 20 and 60 Mev in the case of 300-Mev excitation can be explained by assuming that they are mostly those protons which are knocked out by the primary process, in which a meson is produced by the interaction of a photon with a nucleon. If the high energy protons above 60 Mev are due to the absorption of a meson, their angular distribution should be more or less isotropic, contrary to the result. But the interpretation of the angular distribution of the protons of this group is expected to be fairly complicated. For the protons of this group might consist partly of protons knocked out by the meson producing process, partly of protons produced by the absorption of a meson, partly of the prongs confused with mesons, and finally of protons produced by electromagnetic photodissociation, if any.

These results, together with the excitation curve for star production obtained previously, indicate that most of the stars produced by the photons of energy between 150 and 300 Mev are due to the production and absorption of a meson inside the nucleus. The fact that the number of single protons is rather small compared with the number of protons from stars indicates that the high energy photoprotons excited by the high energy gamma-rays observed by other people[2] by counter methods are likely to have come from stars.

TABLE II. Energy distribution of protons.

Excitation energy in Mev	Single protons		Protons from stars	
	Between 20 and 60 Mev	Above 60 Mev	Between 20 and 60 Mev	Above 60 Mev
300	0.38±0.07	0.05±0.03	0.56±0.05	0.18±0.04
150	1.5±0.2 (>20 Mev)		0.45±0.08 (>20 Mev)	

Thanks are due to Professor R. R. Wilson, Professor H. A. Bethe, and Mr. S. Hayakawa and other members of the Laboratory for valuable discussions. Thanks are also due to the crews of the microscope laboratory for the scanning of plates.

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* This work was done under ONR contract.

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On the Angular Distribution and the Polarization of the Deuteron in the Reaction $p+p\rightarrow d+\pi^+$

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(Received July 27, 1951)

CROSS sections at several angles for the reaction $p+p\rightarrow\pi^++d$ have been measured.[1-3] For energies not too far above threshold (i.e., for those at which the cross sections have been measured) and in the center-of-mass frame of reference, there is reason to believe[4,5] that only orbital S- and P-states of the meson with respect to the deuteron contribute appreciably to the cross section.

There will be no S- and P-wave interference in the differential cross section, so for the moment we can restrict our considerations to just the contribution from meson P-waves. Combining the intrinsic angular momentum of the deuteron with the P-wave orbital motion, we obtain a total angular momentum $j=0, 2$ ($j=1$ is forbidden by parity considerations[6] if the meson is assumed to be pseudoscalar, in accord with present evidence). These values of j arise from the ${}^1S_0$ and ${}^1D_2$ states, respectively, of the initial $p-p$ system.

The wave functions for the orbital motion of the meson will then be described by the spherical harmonics $Y_1^\mu(\theta,\phi)$ (with the polar axis defined by the proton beam direction), and those of the internal coordinates of the deuteron by Σ_1^μ ($\mu=1, 0, -1$). Then the linear combinations of these, Q_0 and Q_2^0, which transform as a scalar and as the spherical harmonic Y_2^0, will arise from the ${}^1S_0$ and ${}^1D_2$ states, respectively, of the initial $p-p$ system.

The asymptotic form of the outgoing wave will be proportional to

$$(e^{iqr}/r)[Q_0+\eta Q_2^0], \tag{1}$$

where q is the meson momentum and η is a parameter. If one writes $\eta=\epsilon e^{i\sigma}$, the resulting angular distribution of the mesons will be

$$F(\theta)=1+\tfrac{1}{2}\epsilon^2+\sqrt{2}\epsilon\cos\sigma+3\cos^2\theta(\tfrac{1}{2}\epsilon^2-\sqrt{2}\epsilon\cos\sigma). \tag{2}$$

Including an arbitrary amount of contribution to the cross section from mesons in S-states, we arrive at the following generalization of the cross section given previously:[4]

$$d\sigma=\sigma_0(d\Omega/4\pi)[1+a(q^2/\mu^2c^2)F(\theta)], \tag{3}$$

where $F(\theta)$ is given by Eq. (2) and μ is the mass of the meson. Near threshold it is assumed that a is a constant and that σ_0 is just q (from the phase space factor) times a constant. Integrating, we obtain the total cross section

$$\sigma=\sigma_0[1+a(1+\epsilon^2)(q^2/\mu^2c^2)], \tag{4}$$

which is of the specific form given previously,[4] with $a(1+\epsilon^2)\equiv b$. We see that ϵ^2 represents the relative amounts of ${}^1S_0$ and ${}^1D_2$ contribution of the initial $p-p$ system to the P-wave partial cross section.

The approximate value, $b=8$, was deduced earlier.[4] This value is consistent with the observed angular distribution,[3] which however implies that b cannot be much less than 8. From the experimental cross sections,[3] it would then follow that at 340 Mev, $\sigma_0\simeq 5(10)^{-29}$ cm^2. The observed angular distributions are consistent with a pure $\cos^2\theta$ dependence from the meson P-states, which would imply $\cos\sigma=-1$, $\epsilon^2=2$ (the quoted experimental errors imply that these relations are also quite approximate). Of more positive significance is the conclusion from the observed angular asymmetry that the large contribution from the $^1D_2$ state of the initial protons implies, independently of a specific model, that noncentral interactions are involved[6] (since the deuteron is mostly in an S-state).

Equation (1) suggests that the deuterons observed at an angle (Θ, Φ) may be polarized.[7] Indeed, the direction of the polarization is given by the average values of the components of intrinsic angular momentum of the deuteron, which are $J_x=-R\sin\Phi$, $J_y=R\cos\Phi$, $J_z=0$ (i.e., at right angles to the plane defined by the direction of the protons and the deuterons).

The degree of polarization (considering just the P-wave component of the cross section), $R'(0<R'<1)$, is given by the numerical magnitude of

$$R=3\sqrt{2}\epsilon\sin\sigma\cos\Theta\sin\Theta[F(\Theta)]^{-1}, \tag{5}$$

where F is given by Eq. (2). R vanishes for a pure $\cos^2\theta$ angular distribution.

The detection of this polarization, if nonvanishing, would appear feasible. The beam of deuterons produced is more intense than the accompanying meson beam,[8] which has been used to study meson scattering.[9] A possible means of detection would be by means of (d, p) scattering, the polarization effects of which have been used by Wouters[10] to measure polarization in (n, p) scattering.

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* This work was performed under the auspices of the AEC.

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[7] The authors are indebted to Professor R. Serber for the suggestion that the deuterons should be polarized.

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Some Excitation Functions for Protons on Magnesium*

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(Received July 24, 1951)

In continuation of our study of proton-induced reactions on light and intermediate nuclei[1] we have determined the yield of Na^{22} as a function of energy for protons on Mg^{24}, Mg^{25}, and Mg^{26}. The experimental method has been previously described.[1,2]

Bombardments were made on natural MgO and on MgO enriched[3] in Mg^{25} and Mg^{26}, at initial energies of 100 and 70 Mev. Al metal foils were placed in the target stack with the MgO, and the Mg reactions were monitored by comparing them with the known excitation curve for $Al(p, 3pn)Na^{24}$ as measured by Hintz.[2] Bombardment times of approximately 12 hours were required to obtain sufficient activity for accurate counting. Since the half-life of Na^{24} is only 15 hours, some error may have been introduced by variations in the beam intensity during the bombardment.

The monitor foils were counted 24 hours after the end of the bombardment, when all activities with half-lives shorter than the 15-hour Na^{24} had disappeared. The MgO targets were counted after three weeks, when only the 2.6-year Na^{22} remained. The Al foils were also counted at this time, and the previous Na^{24} count was corrected for Na^{22} activity. All samples were counted, as nearly as possible, under the same geometry and mounting arrangements. Corrections were made for self-absorption and scattering and for absorption due to the air and counter window. The yield of Na^{22} from Mg^{24} was determined by subtracting the contributions of Mg^{25} and Mg^{26} from the yield obtained with the natural isotopic mixture. The results are shown in Fig. 1.

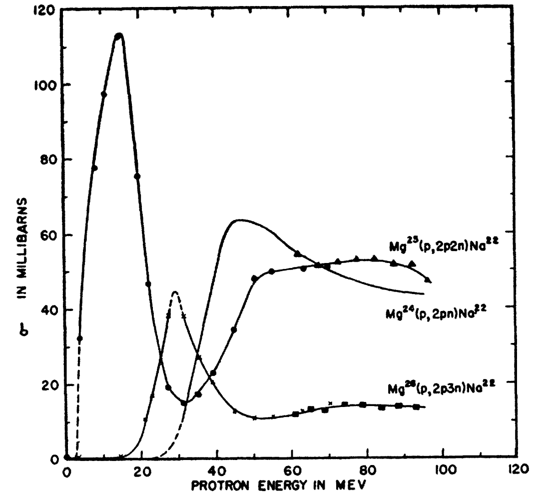

FIG. 1. Excitation function for protons on magnesium.

The thresholds to be expected, including the coulomb barrier heights, for the lowest energetically possible reaction and for single particle emission are shown in Table I. These lowest thresholds compare fairly well with the Mg^{25} and Mg^{26} excitation curves. However, accurate threshold energies cannot be determined by this method due to the thickness of the targets (20–30 mg/cm²) and the finite energy spread of the beam (0.5 Mev) on the target face.

It is evident that the emission of alpha-particles is a major mode of decay of these compound nuclei at low energies. It might be expected that the emission of other heavy fragments such as H^3 or He^3 would also be an important mode of decay. This does not seem to be the case. The observed threshold for $Mg(p, 2pn)Na^{22}$ at 20–25 Mev indicates a $(p, 2pn)$ or (p, dn) reaction rather than (p, He^3). Also if the emission of H^3 or He^3 were very probable, the minimum found in $Mg^{25}(p, 2p2n)Na^{22}$ at 30 Mev should not be so pronounced.

TABLE I. Thresholds in the laboratory system.

Reaction	$-Q$	$-Q+$barrier
$Mg^{24}(p, He^3)Na^{22}$	16.6 Mev	22.5 Mev
$(p, 2pn)$	24.4	32.2
$Mg^{25}(p, \alpha)Na^{22}$	2.3	8.2
$(p, 2p2n)$	31.6	39.2
$Mg^{26}(p, \alpha n)Na^{22}$	14.1	20.0
$(p, 2p3n)$	43.3	50.9

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* Assisted by the joint program of the ONR and AEC.

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[3] Obtained from Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Erratum: Non-Equilibrium Thermodynamics of Two-Fluid Models

[Phys. Rev. 81, 1070 (1951)]

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The line following Eq. (1) should read: "between the two effects (v is the specific volume). We can derive. . . ."