that α-particles constitute about 10 percent of the primary flux and that accordingly the ratio of α-particles to protons remains relatively constant over a large energy range. This seems to be in agreement with results previously reported,[2] which indicate a similar velocity spectrum for all components of the primary beam, and is not in agreement with the predictions of the simple Fermi[3] theory of acceleration of cosmic-ray primaries.

* This research was assisted by the AEC.

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[2] Kaplon, Peters, and Ritson, Phys. Rev. **85**, 900 (1952).

[3] E. Fermi, Phys. Rev. **75**, 1169 (1949). For an integral energy spectrum varying as $N = K/\epsilon^{\gamma}$, where ϵ is the kinetic energy in Bev/nucleon, Fermi gives $\gamma_p/\gamma_\alpha = \lambda_\alpha/\lambda_p$, where λ is the absorption mean free path. As $\lambda_\alpha \approx \frac{1}{2}\lambda_p$, we find $N_p/N_\alpha = (K_p/K_\alpha)\epsilon^{\gamma}$. For the energy region of this experiment one obtains $N_p/N_\alpha \approx 8\times 10^5$; $(K_p/K_\alpha \gtrsim 5)$. We believe therefore that our results are significant, notwithstanding the poor statistics.

Neutrons and Gamma-Rays from the Proton Bombardment of Beryllium

T. M. Hahn,* C. W. Snyder, H. B. Willard, J. K. Bair, E. D. Klema, J. D. Kington, and F. P. Green
Oak Ridge National Laboratory, Oak Ridge, Tennessee
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The neutron and gamma-ray yields in the forward direction resulting from the proton bombardment of beryllium have been extended to a maximum proton energy of 5.3 Mev. Voltage calibration of the electrostatic generator has been previously discussed.[1] Targets were thin (approximately 11 kev at threshold) foils obtained through the courtesy of Dr. Hugh Bradner. Neutron yields were measured with a "long" counter placed in the forward direction. Gamma-rays were detected with a large sodium iodide crystal also located along the beam axis. Pulses from the crystal were amplified and fed into two discriminators so that the yields of gamma-rays above approximately 2 and 6 Mev were obtained.

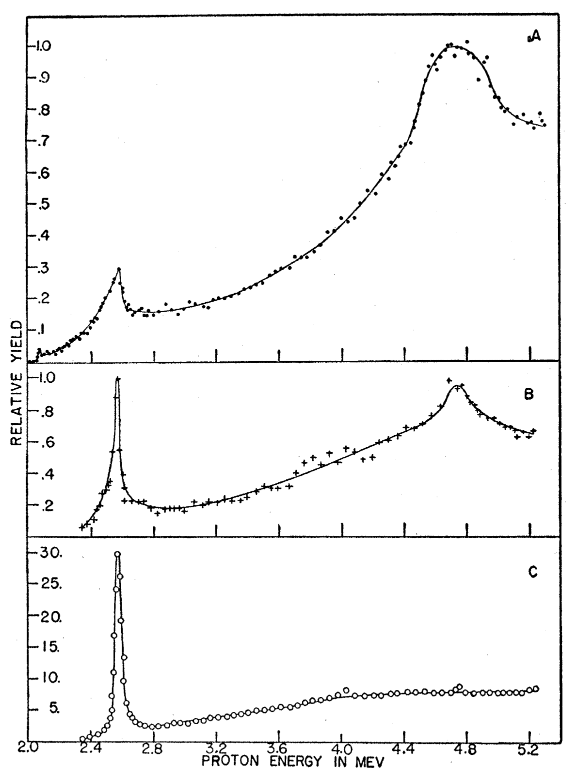

Fig. 1. Yield curves for neutrons and gamma-rays from beryllium bombarded by protons. Top curve, neutron yield; middle curve, gamma-rays of energy greater than approximately 6 Mev; lower curve, gamma-rays of energy greater than approximately 2 Mev. All yields are in arbitrary units.

The upper curve of Fig. 1 shows a typical neutron yield. In addition to the geometrical peak and the well-known rise at 2.56 Mev,[2] a third peak is obtained at a proton energy of 4.7 Mev. The existence of a level at high energy had been predicted from work done at the University of Wisconsin.[3] A run, not shown, using a low energy neutron counter similar to that described by Bonner and Butler[4] showed no obvious levels in the residual B^9 nucleus between 2- and 5.3-Mev proton energy.

The middle and lower curves of Fig. 1 show the yield of gamma-rays with energy greater than approximately 6 Mev and 2 Mev, respectively. The level at 2.57-Mev proton energy is observed in both the high and low energy gamma-ray yields. The level at 4.7 Mev does not appear in the low energy yield due to the relatively high intensity of the nonresonant, low energy gammas.

The gamma-ray yield curves are, in this particular case, essentially free of interferences from neutron reactions occurring in the NaI crystal. This is indicated by the considerably narrower resonance in the gamma-ray yield at 2.56 Mev as compared with the corresponding one in the neutron yield. Boron layers placed between the target and the crystal confirmed this hypothesis.

The new level occurs at a proton bombarding energy of 4.72 $\pm$0.01 Mev and has a full width at half-maximum of approximately 0.5 Mev. We find the lower energy level at 2.57$\pm$0.01 Mev. These energies are the averages obtained from several runs.

* Summer research participant on leave from the University of Kentucky.

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Total Cross Sections of Negative Pions in Hydrogen*

H. L. Anderson, E. Fermi, E. A. Long,† R. Martin,‡ and D. E. Nagle
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 21, 1952)

The interaction of negative pions and protons has been investigated by Steinberger and co-workers[1] for pions of 85-Mev energy by transmission measurements and by Shutt and co-workers[2] for pions of 55 Mev by direct observation of pion tracks in a Wilson chamber. Both measurements indicate a surprisingly low value for the cross section in this range of energies. We have undertaken to extend the total cross section measurements to higher energies.

The negative pions are produced in the large Chicago cyclotron by protons of 450 Mev striking a target which in some of the experiments was copper and in others beryllium. The negative pions are bent in the fringing field of the cyclotron and enter channels in a 6-foot steel shield which separates the cyclotron from the experimental room where the measurements are taken. Further monochromatization and purification of the pion beams are carried out by a deflecting magnet located in the experimental room. In this manner one obtains a sharply collimated beam containing pions with energy defined within $\pm$3 percent. In addition to the pions this beam contains some muons and electrons of the same momentum. Their number has been determined from a range curve. The muons amount to between 5 percent and 10 percent. The electrons are present in negligible numbers for beams above 100 Mev. Below this energy the electron contamination increases rapidly. For this reason low energy measurements have been taken by reducing with a beryllium absorber the energy of the 122-Mev beam.

By using various channels we have taken measurements over the energy range from about 80 to 230 Mev.

TABLE I. Total cross sections negative pions on hydrogen.

Energy band Mev	Cross section 10^{-27} cm²
89±8	21±8
112±6	31±9
135±6	52±6
176±6	66±6
217±6	60±6

The pion beam is monitored by two scintillation crystals of 1-inch-square cross section separated by a distance of about one meter. The coincidences of these two counters indicate the number of particles entering the equipment. Beyond the second crystal the pions enter the scattering chamber, which is a glass cylinder 3 inches in diameter and $7\frac{1}{2}$ inches long, closed by 0.005-inch copper windows. This chamber can be alternately filled with and emptied of liquid hydrogen. The particles which are not scattered out of the beam are recorded by the coincidences which they give in a pair of liquid scintillation counters, of which one has a 3-inch diameter and the other a 4-inch diameter. The double coincidence rate of the first two scintillators is recorded and at the same time the quadruple coincidence rate of all four scintillators. The attenuation of the beam is obtained from a comparison of the ratio of the quadruple to double coincidence counts with and without the hydrogen and is computed as a cross section.

A number of corrections have been applied to the results on account of the following effects:

(1) Background due to accidentals (usually 1 percent or less).

(2) Angular spread of the beam due to geometry, diffraction scattering, and pi–mu decay. In some experiments the multiple scattering was compensated by means of an equivalent aluminum foil; in others it was computed. This correction is important only at low energies.

(3) Muon and electron component in the original beam. It is assumed that muons and electrons suffer only Coulomb scattering and have no specific nuclear interaction.

(4) Correction for scattered particles recorded by the end counters. This correction was computed on the assumption of isotropic scattering in the center-of-mass system. It amounted to between 4 percent and 2 percent depending on whether the recoil protons are or are not recorded. The correction would be larger if the scattering were predominately forward but smaller if charge exchange scattering were important.[3] The results of the measurement are presented in Table I.

The data show that the cross section rises rather rapidly above 80 Mev until it reaches the "geometrical" value $\pi(\hbar/\mu c)^2$ at 150 Mev, where the cross section seems to level off, or perhaps to go through a maximum, although our measurements do not permit a decision between these two possibilities.

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† Institute for the Study of Metals, University of Chicago.
‡ AEC Predoctoral Fellow.
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[2] Shutt, Fowler, Miller, Thorndike, and Fowler, Phys. Rev. **84**, 1247 (1951).
[3] In view of the importance of the charge exchange process reported in the following Letter, it seems likely that the cross sections have been overcorrected by about 2 percent to 3 percent.

Ordinary and Exchange Scattering of Negative Pions by Hydrogen*

E. FERMI, H. L. ANDERSON, A. LUNDBY, D. E. NAGLE, AND G. B. YODH
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 21, 1952)

IN an accompanying letter some experiments on the total cross section of negative pions of various energies in liquid hydrogen have been described. Measurements of total cross sections, of course, do not give any indication as to the actual mechanism of the process. In particular, in the interaction of negative pions in hydrogen the following three processes are considered possible:

$$p+\pi^-\rightarrow p+\pi^- \quad (1)$$

$$p+\pi^-\rightarrow n+\pi^0\rightarrow n+2\gamma \quad (2)$$

$$p+\pi^-\rightarrow n+\gamma. \quad (3)$$

The first two are scattering without or with exchange of charge. The last is the inverse process of the photoproduction of pions by the action of gamma-rays on neutrons. Estimates of the cross section of this last process, based on the principle of detailed balancing, indicate that its cross section must be of the order of magnitude of a few millibarns and is therefore rather small compared to the total cross section, which is of the order of 40 millibarns for pions of 120 Mev.

We have started a series of scattering experiments in order to distinguish between the processes (1) and (2), as well as to give information as to the angular distribution of the scattered particles. We felt that the first results were of sufficient interest to be reported at this time.

The geometry used in this experiment is similar to the one adopted in the study of the total cross sections. The beam of pions enters the experimental space and is deflected by an analyzing magnet. After this, it is recorded by the coincidences of two 1-inch-square crystals and falls on the liquid hydrogen scattering chamber. The scattered products are observed by quadruple coincidences of these two counters with another pair of scintillators located directly under the scattering chamber in a direction at 90° to that of the incident pions. The latter two scintillators had diameters 4 inches and 3 inches and were placed, respectively, 8 inches and 11 inches below the center of the scattering chamber. The 118-Mev beam was chosen because of its high intensity. With 1-inch-square collimating crystals 10 inches apart, the coincidence counting rate was about 150,000 per minute. The count of the scattered particles was instead, of the order of only a few per minute. In order to increase the sensitivity of the scattering detectors to gamma-rays, a lead radiator $\frac{1}{4}$ inch thick was interposed in front of the third counter. A standard measurement involved the observation of the ratio between scattered and incident particles with and without hydrogen in the scattering chamber, and with and without the lead converter of the gamma-radiation. Typical results are given in Table I. The difference with and without liquid hydrogen is due to the scattered particles. With no radiator this difference is $(0.4\pm0.15)\times10^{-4}$; with the radiator it is $(1.02\pm0.11)\times10^{-4}$. The sensitivity of the detector to gamma-rays without lead radiator is small but not negligible, because the radiation goes through the walls of the chamber and part of the third scintillator where it may produce pairs and be recorded. An attempt has been made to separate the number of scattering events recorded due to scattered π^- from those due to gamma-rays. We find the following:

Scattered π^- in the accepted solid angle: $(0.34\pm0.12)\times10^{-4}$.

Photons in the accepted solid angle: $(1.41\pm0.32)\times10^{-4}$.

The conversion of these numbers to a scattering cross section depends on the assumptions made as to the angular distribution. It also depends on the assumption that we have made in this paper that all neutral pions decay immediately into two photons. For example, if we assume that the angular distribution is fairly isotropic in the center-of-mass system and that the gamma-rays are

TABLE I. Scattering of negative pions at 90°.

Liquid hydrogen	$\frac{1}{4}$-in. Pb radiator	Ratio quadruple to double coincidence
No	No	$(0.81\pm0.05)\times10^{-4}$
Yes	No	$(1.21\pm0.08)\times10^{-4}$
No	Yes	$(0.71\pm0.06)\times10^{-4}$
Yes	Yes	$(1.73\pm0.09)\times10^{-4}$