TABLE I. Total cross sections negative pions on hydrogen.

Energy band Mev	Cross section 10^{-27} cm^2
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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[1] Chedester, Isaacs, Sachd, and Steinberger, Phys. Rev. **82**, 958 (1951).
[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*

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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	$(1.73\pm0.09)\times10^{-4}$

produced in pairs by the decay of the neutral pions, the cross sections for the processes (1) and (2) would be $(10\pm4)\times10^{-27}$ and $(20\pm5)\times10^{-27}$ cm^2. The cross section obtained for the charge exchange process is not very sensitive to the angular distribution adopted. It would be $(29\pm7)\times10^{-27}$ cm^2 for a $\cos^2\theta$-distribution and $(18\pm4)\times10^{-27}$ cm^2 for a $\sin^2\theta$-distribution.

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Total Cross Sections of Positive Pions in Hydrogen*

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IN a previous letter,[1] measurements of the total cross sections of negative pions in hydrogen were reported. In the present letter, we report on similar experiments with positive pions.

The experimental method and the equipment used in this measurement was essentially the same as that used in the case of negative pions. The main difference was in the intensity, which for the positives was much less than for the negatives, the more so the higher the energy. This is due to the fact that the positive pions which escape out of the fringing field of the cyclotron magnet are those which are emitted in the backward direction with respect to the proton beam, whereas the negative pions are those emitted in the forward direction. The difficulty of the low intensity was in part compensated by the fact that the cross section for positive pions turned out to be appreciably larger than for negative pions. The results obtained thus far are summarized in Table I.

In Fig. 1 the total cross sections of positive and negative pions are collected. It is quite apparent that the cross section of the positive particles is much larger than that of the negative particles, at least in the energy range from 80 to 150 Mev.

In this letter and in the two preceding ones,[1,2] the three processes: (1) scattering of positive pions, (2) scattering of negative pions with exchange of charge, and (3) scattering of negative pions without exchange of charge have been investigated. It appears that over a rather wide range of energies, from about 80 to 150 Mev, the cross section for process (1) is the largest, for process (2) is intermediate, and for process (3) is the smallest. Furthermore, the cross sections of both positive and negative pions increase rather rapidly with the energy. Whether the cross sections level off at a high value or go through a maximum, as might be expected if there should be a resonance, is impossible to determine from our present experimental evidence.

Brueckner[3] has recently pointed out that the existence of a broad resonance level with spin 3/2 and isotopic spin 3/2 would give an approximate understanding of the ratios of the cross sections for the three processes (1), (2), and (3). We might point out in this connection that the experimental results obtained to date are also compatible with the more general assumption that in the energy interval in question the dominant interaction responsible for the scattering is through one or more intermediate states of isotopic spin 3/2, regardless of the spin. On this assumption, one finds that the ratio of the cross sections for the three processes should be (9:2:1), a set of values which is compatible with the experimental observations. It is more difficult, at present, to say anything specific as to the nature of the intermediate state or states. If there were one state of spin 3/2, the angular distribution for all three processes should be of the type $1+3\cos^2\theta$. If the dominant effect were due to a state of spin 1/2, the angular distribution should be isotropic. If states of higher spin or a mixture of several states were involved, more complicated angular distributions would be expected. We intend to explore further the angular distribution in an attempt to decide among the various possibilities.

TABLE I. Total cross sections of positive pions in hydrogen.

Energy (Mev)	Cross section (10^{-27} cm^2)
56 ± 8	20 ± 10
82 ± 7	50 ± 13
118 ± 6	91 ± 6
136 ± 6	152 ± 14

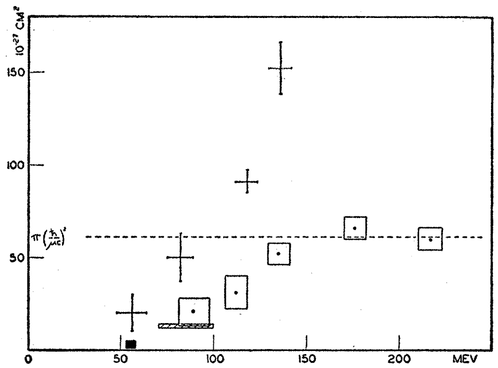

FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

Besides the angular distribution, another important factor is the energy dependence. Here the theoretical expectation is that, if there is only one dominant intermediate state of spin 3/2 and isotopic spin 3/2, the total cross section of negative pions should at all points be less than $(8/3)\pi\lambda\!\!\!^{-2}$. Apparently, the experimental cross section above 150 Mev is larger than this limit, which indicates that other states contribute appreciably at these energies. Naturally, if a single state were dominant, one could expect that the cross sections would go through a maximum at an energy not far from the energy of the state involved. Unfortunately, we have not been able to push our measurements to sufficiently high energies to check on this point.

Also very interesting is the behavior of the cross sections at low energies. Here the energy dependence should be approximately proportional to the 4th power of the velocity if only states of spin 1/2 and 3/2 and even parity are involved and if the pion is pseudoscalar. The experimental observations in this and other laboratories seem to be compatible with this assumption, but the cross section at low energy is so small that a precise measurement becomes difficult.

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[1] Anderson, Fermi, Long, Martin, and Nagle, Phys. Rev., this issue.
[2] Fermi, Anderson, Lundby, Nagle, and Yodh, preceding Letter, this issue, Phys. Rev.
[3] K. A. Brueckner (private communication).

Conductivity of Cold-Worked Metals*

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THE change in the electrical conductivity of a metal upon cold-working was first calculated by Koehler,[1] on the assumption that the change is primarily due to the dislocations themselves (rather than associated clusters of vacancies, for example). The scattering potential he used was the difference in