Letters to the Editor

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Cross Section for the Reaction $\pi^+ + d \rightarrow p + p$, and the Spin of the π^+ Meson*

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THE application of detailed balancing to the determination of the spin of the π^+ meson from the reaction $\pi^+ + d \rightarrow p + p$ and its inverse has been suggested by Marshak and Cheston[1] and independently by Johnson.[2] The detailed balancing argument requires the comparison of either differential or total cross sections of both the meson-producing and meson-absorbing reactions at the same energy in the center-of-mass system. The reaction $p + p \rightarrow \pi^+ + d$ has been studied for 340-Mev protons by Richman and others.[3] The best data are for the differential cross section at 0°, and other data are available at 18°, 30°, and 60°. From these data, limits on the angular distribution can be obtained and the total cross section computed. We have now measured the total cross section for the meson-absorbing reaction.

A beam of 40-Mev π^+ mesons was produced from an aluminum target bombarded by the 240-Mev proton beam of the Rochester cyclotron; the mesons were magnetically selected and focused by the fringing field. A threefold scintillation counter telescope[4] in the meson beam counts the mesons and discriminates against other particles by pulse-height measurements in one counter. The transmitted mesons, reduced to 33 Mev by the telescope, enter a D_2O target just thick enough to stop them. Protons produced in the D_2O are detected in coincidence by two large NaI scintillation counters. The ratio of 5-fold coincidences of mesons with protons to meson counts alone determines the cross section for the disintegration, averaged over energy and angle.

Backgrounds were assessed by replacing D_2O by H_2O. Scattering of mesons out of the target and purity of the meson beam were measured in auxiliary experiments. The meson beam was contaminated by not more than 2 percent protons or 6 percent deuterons. It was also shown that even much greater contamination would produce no significant difference between D_2O and H_2O targets.

To find the cross section at 22.7 Mev, which corresponds to 340 Mev in the production experiment, an auxiliary experiment was performed which showed that the average cross section from 23–33 Mev is the same as the average cross section from 0 to 23 Mev, within the statistical error of 10 percent. Since 33-Mev mesons are reduced to 23 Mev after half their range, we conclude that the yield at 23 Mev is equal to the yield averaged from 33 Mev to zero within 5 percent.

The coincidence rate as a function of proton pulse heights in the NaI counters corresponded to those expected for the reaction from the geometry of the apparatus. The NaI counters were calibrated with fast protons of known energy.

TABLE I. Predicted and observed total meson-absorption cross sections.

Angular dependence (c.m. system)	Predicted total cross section (mb) spin 0	spin 1	Measured total cross section (mb)
$\cos^2\theta$	2.55 ±0.6	0.85 ±0.2	5.0 ±0.9
$0.1+\cos^2\theta$	3.0 ±0.7	1.0 ±0.24	4.7 ±0.9
$0.5\pm\cos^2\theta$	4.2 ±1.0	1.4 ±0.35	4.2 ±0.8
$0.2\pm0.1+\cos^2\theta$	3.4 ±0.9	1.1 ±0.3	4.5 ±0.8

The detector solid-angle correction to the observed counting rate to obtain total cross section depends upon the angular distribution of the reaction products, and has been calculated assuming an angular dependence of the form $A+\cos^2\theta$ in the c.m. system. The latest data of Cartwright *et al.* (private communication) indicate $A=0.2\pm0.1$. Table I shows the value of the meson-absorption cross section predicted by detailed balancing, using the value 1.3×10^{-28} cm²/ster for the production cross section at 0° in the laboratory system, assuming different values for A. It also shows our observed values for comparison. We conclude that the spin of the π^+ meson is zero.

Kaplon has pointed out[5] that the principle of detailed balancing would not apply if the spin of the π^+ meson were 1, but for some reason only one polarization state appears in both the absorption and production reactions. A statistical weight of 1 would then be observed. For this effect to explain our results, the polarization would have to exceed 75 percent for both reactions, which we regard as very unlikely.

It would be highly desirable to verify further the detailed balancing predictions by a direct comparison of the differential cross sections at several angles. Our meson intensity is too low at present for this to be experimentally feasible.

From the indirect observation of the reaction $\pi^- + d \rightarrow n + n$ by Panofsky *et al.*,[6] Tamor and Marshak[7] have shown that if the π^- meson possesses spin zero, it cannot be scalar. If we assume that π^+ and π^- mesons possess the same spin and parity, we must conclude that the charged π-meson is pseudoscalar.

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2 M. H. Johnson, private communication.
3 Cartwright, Richman, Whitehead, and Wilcox, Phys. Rev. **81**, 652 (1951); Crawford, Crowe, and Stevenson, Phys. Rev. **82**, 97 (1951).
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5 M. Kaplon, private communication.
6 Panofsky, Aamodt, and Hadley, Phys. Rev. **82**, 97 (1951).
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Energy Distribution of the Primary Cosmic Radiation*

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THE primary cosmic-ray energy spectrum usually assumed, $N(E)=kE^{-n}$, where n has been assigned various values ranging from 2.5 to 2.9, by different writers obviously cannot hold for small values of the particle energy, E. To assume a cutoff of the primary radiation at an assigned value of, say, 3 or 4 Bev is also unsatisfactory, since a latitude effect at 30,000 ft,[1] as well as at balloon altitudes,[2,3] has been measured down to energies for protons to at least 1 Bev. It therefore appears (at least at the time these experiments were performed) that no definite cutoff occurs, although the energy brought in by these low energy particles must be relatively small.

The B-29 data of Biehl, Neher, and Roesch[3] taken at 310 g cm^{-2} from 64° geomagnetic north to the Equator, along longitude 80°W, has given a means of normalizing the balloon flight curves of Neher and Pickering[4] and of Biehl *et al.*[5] Further, by correlating counter telescope and ionization chamber data it is possible to make use of data at smaller latitude intervals than was possible with ionization chambers.[6] A further requirement is to know the minimum momentum *vs* geomagnetic latitude for the primary particles. This has been done with the help of Vallarta *et al.* by correlating the various geomagnetic effects.[7]

The resulting histogram obtained from the differences of the adjusted counter-telescope balloon curves is shown in Fig. 1. Block 5 is obtained from two high altitude points at 45°E over Peru, and a counts-*vs*-altitude curve is then constructed using the

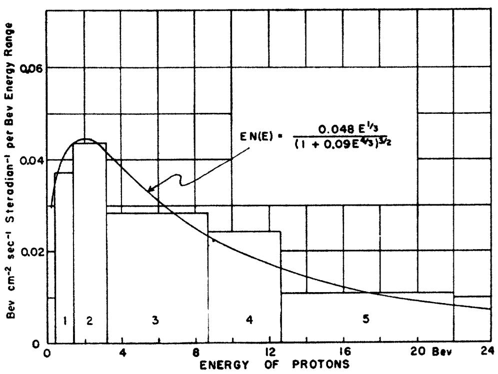

FIG. 1. Blocks 1, 2, 3, 4, and 5 result from differences in adjusted counter-telescope curves at various latitudes. The smoothed curve is a plot of an empirical relationship that fits the ionization data with experimental errors.

extrapolated behavior of known curves for lower minimum momenta of the primaries. This block is admittedly the least well determined of the set. The chief difference between the present results and those published by Bowen, Millikan, and Neher in 1938,[6] is in the abscissas.

An empirical expression that fits the experimental data is as follows:

$$EN(E)=0.048E^{1/3}/(1+0.09E^{4/3})^{3/2}, \tag{1}$$

where E is measured in units of 10^9 ev. $EN(E)dE$ is the energy in Bev cm^{-2} sec^{-1} steradian^{-1} brought to the earth by protons whose energy lies between E and $E+dE$. The differential number distribution is then

$$N(E)=0.048/[E^{2/3}(1+0.09E^{4/3})^{3/2}]. \tag{2}$$

The integral of this last equation, giving the numbers of primary particles with energies larger than E, is plotted in Fig. 2.

In justification of these expressions the following may be cited: (a) The expression (1) may be integrated directly and gives a total energy of 0.418×10^9 ev cm^{-2} sec^{-1} sterad^{-1} for all particles at the vertical in Peru. The experimental value is 0.413 in the same units. (b) A similar integration for Bangalore, India, yields 0.35 as against the experimental value 0.34. (c) From 0.4×10^9 ev to ∞, it gives 0.787 as compared with 0.774 for Saskatoon. (d) It gives a dependence on E of $E^{-2.67}$ for the differential number distribution at very large E. This is within the limits of the exponent found by Hilberry[8] to be necessary to explain extended showers. (e) It gives an effective dependence on E of $E^{-1.1}$ for the integral number spectrum in the range 2 to 12×10^9 ev. This is the distribution found necessary by Van Allen and Singer[9] to explain their results using rockets. (f) It gives a ratio in the total number of particles at 50°N and 30°N of 3.4, as compared with the value of 3.5 found for all primaries by Bradt and Peters.[10]

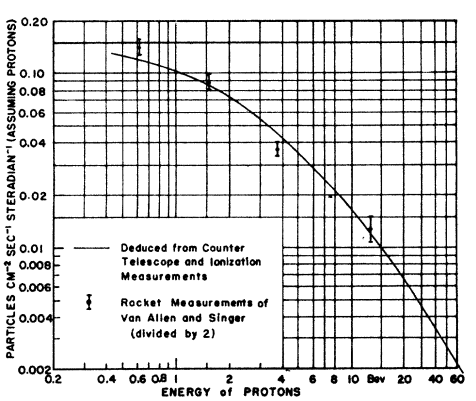

FIG. 2. The integral number distribution of the primary cosmic radiation deduced from the empirical relationship given in Fig. 1. For data of Van Allen and Singer, see reference 9.

The presence of particles heavier than protons in the primary radiation will affect only the constant in the numerator of Eqs. (1) and (2), provided the relative numbers of different particles are not dependent on the momentum, as it seems to be from the work of Bradt and Peters.[10]

The application of Liouville's theorem to be charged particles moving in the magnetic field of the earth implies that the found energy distribution of the primary cosmic-ray particles is also their distribution in space.

As has been pointed out by Van Allen and Singer,[9] and by Winckler *et al.*,[11] a discrepancy of about a factor of 2 exists between the numbers of primary particles determined directly near the top of the atmosphere and that found by taking the area under ionization curves. The, as yet undetermined, albedo effect will tend to make the directly measured value at high altitudes too large, while energy losses due to neutrinos will tend to make the numbers computed from ionization data too small. The small east-west effect measured at very high altitudes[9,11] is good evidence that the albedo, or general background, is important, at least at the Equator.

Further details are being published elsewhere.

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Observations of Zener Current in Germanium *p-n* Junctions*

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IN 1934 Zener[1] published a theory of excitation of electrons directly from the valence band to the conduction band under the influence of high electric fields. For this purpose the energy gap of width $\mathcal{E}_G$ is treated as a region of negative kinetic energy in which the wave function is attenuated, so that the probability of penetrating the gap is approximately

$$f=\exp[-(\pi^2/h)(2m)^{\frac{1}{2}}\mathcal{E}_G^{\frac{3}{2}}/eE], \tag{1}$$

where m is the effective mass and E the electric field; this formula differs from Zener's by being extended to larger energy gaps. The number of oscillations per second in the valence band is

$$\nu=eaE/h, \tag{2}$$

so that the current per unit cell, containing z/a^3 electrons, is $e\nu fz$. If the field is uniform over a certain region and produces a voltage drop V, then the Zener current per unit area is

$$\begin{aligned} I&=e^2Vzf/a^2h=V\exp[\alpha-(\beta/E)]\\ &=V10^{(11-10^7E)}\text{amp/cm}^2, \end{aligned} \tag{3}$$

the last form corresponding to the constants for germanium and an effective mass equal to the electron mass, V being expressed in volts, and E in volts/cm.

Measurements of the Zener current have been made across *p-n* junctions in germanium, formed in a single crystal by using arsenic as the donor impurity and gallium as the acceptor.[2–4] Figure 1 shows the reverse $i-e$ characteristic of the junction plotted on a log-log scale over five decades of current. The critical voltage gradient across the junction was measured by determining the behavior of the capacitance of the junction against the reverse bias voltage. The slope of the $\log V$ *versus* $\log C$ plot for the junc-