excitation of this state decreases compared to the excitation of the higher "resonances" as the momentum transfer increases. The momentum transfers in these experiments were ~0.1 $(\mathrm{Gev}/c)^2$. G. B. Chadwick, G. B. Collins, P. J. Duke, T. Fujii, N. C. Hien, and F. Turkot, International Conference on Elementary Particles, Aix-en-Provence, 1961 (unpublished). See also G. B. Chadwick, G. B. Collins, S. DeBenedetti, P. J. Duke, N. C. Hien, A. Roberts, and C. E. Swartz, Phys. Rev. Letters 4, 611 (1960).

π-MESON PRODUCTION IN 2.9-Bev p-p COLLISIONS*

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(Received November 29, 1961)

The momentum spectrum of charged π mesons produced in proton-proton collisions at an incident energy of 2.9 Bev has been measured by counter techniques. Related experiments have been recently performed in a 20-in. hydrogen bubble chamber[1,2] and the study of the recoil nucleons has been pursued with counters.[3] The present experiment, however, provides detailed momentum spectra of the π mesons as a function of angle. The shape of the momentum spectra at various angles, especially 0°, provides a crucial test for the most current theories on π production.[4]

The experiment was performed at Brookhaven's Cosmotron using the external proton beam III and a liquid H_2 target. The spectra were measured at 0°, 17°, and 32° in the laboratory and the setup is shown in Fig. 1; the circulating beam intensity ranged from 2×10^{10} to 2×10^{11} protons/pulse with 30% extraction efficiency to the second focus.

As seen in Fig. 1 all secondary beams were provided with focusing quadrupole doublets; however,

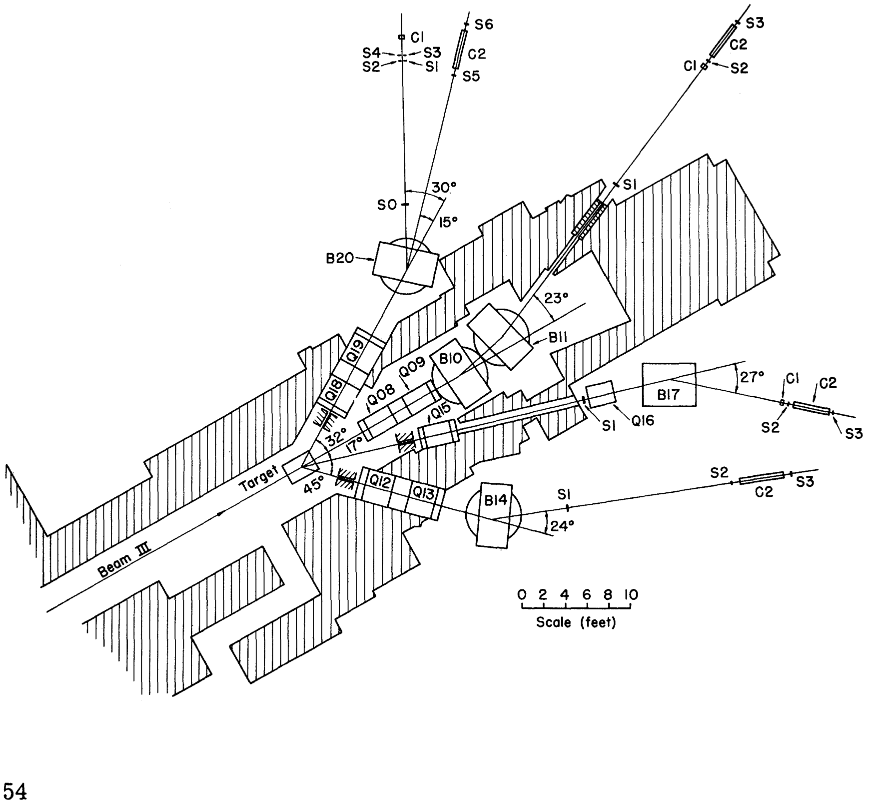

FIG. 1. The experimental setup.

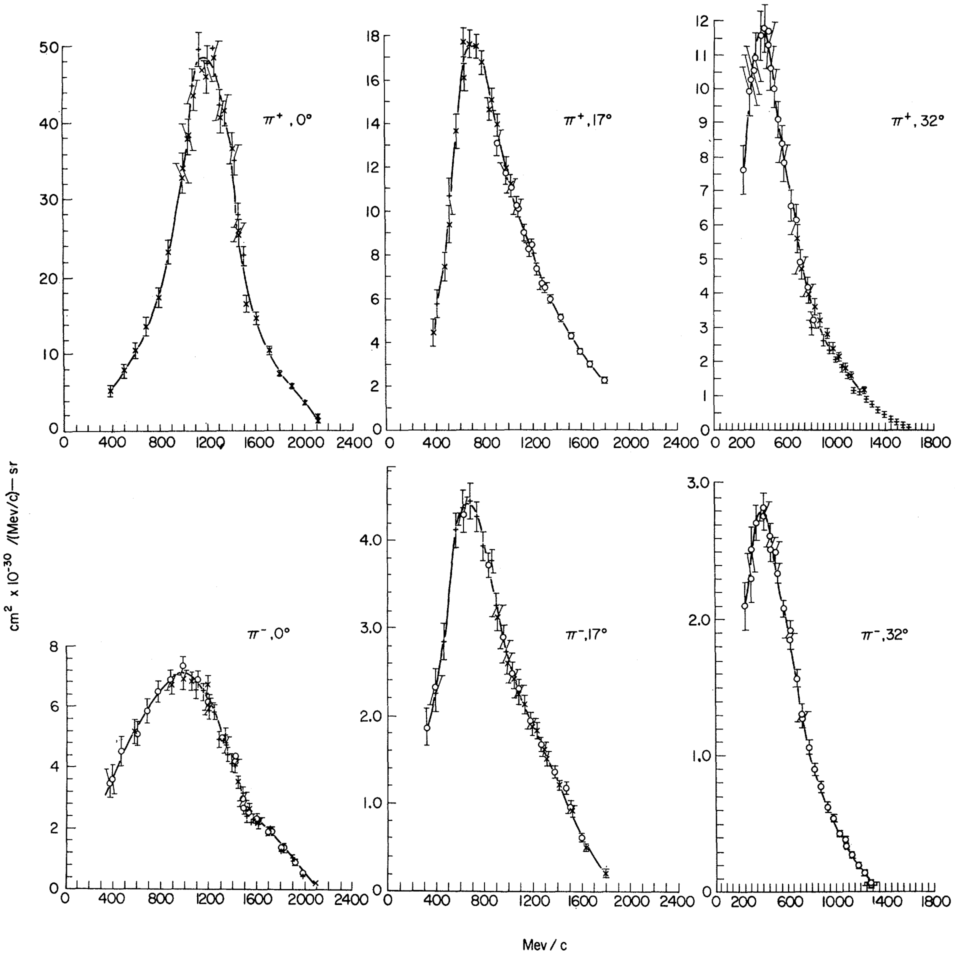

FIG. 2. The solid curves give the laboratory spectra for π^+ and π^- mesons at 0°, 17°, and 32°, after all corrections have been applied.

in the 17° and 32° case collimators were used to reduce the effective source width. With the quadrupoles "tuned" the magnification and momentum width (~2%) remain constant for all momenta. The absolute cross sections were obtained by measuring a few points of the spectrum with the quadrupoles turned off, so as to exclude any errors that may be introduced by the lens magnification or adjustment.

The π mesons were detected by a counter telescope consisting of plastic scintillators and a 4-ft long gas (SF_6) Čerenkov counter; a water Čerenkov counter was also used when required to complement time-of-flight identification in the lower momentum ranges. Corrections were applied to the data for nuclear absorption and multiple scattering in the telescope elements; such corrections were determined both experimentally and by calculation.[5]

The contamination of electrons ($e^{\pm}$) was determined experimentally over the whole spectrum by using the gas counter; the μ-meson contamination was measured at some points of the spectrum and then calculated for the remaining range. Finally the spectra had to be corrected for π-meson decay.

Figure 2 gives the momentum spectra for π^+ and π^- mesons in the laboratory at 0°, 17°, and 32°. The experimental points have been corrected for nuclear absorption, Coulomb scattering, empty target background, $\mu^{\pm}$ and $e^{\pm}$ contamination, and pion decay. The flags on the experimental points represent statistical and other estimated relative errors. The over-all reproducibility can be judged by the scatter of the points; in general the results of two or more completely different runs are shown on the same graph.

The analysis of the spectra has been performed in the c.m. system of the two incoming protons. The transformed c.m. spectra are shown in Figs. 3(a) and 3(b) and do exhibit a striking anisotropy both in shape and in their integrated (over momentum) values. A summary of the integrated cross sections is given in Table I; for comparison the

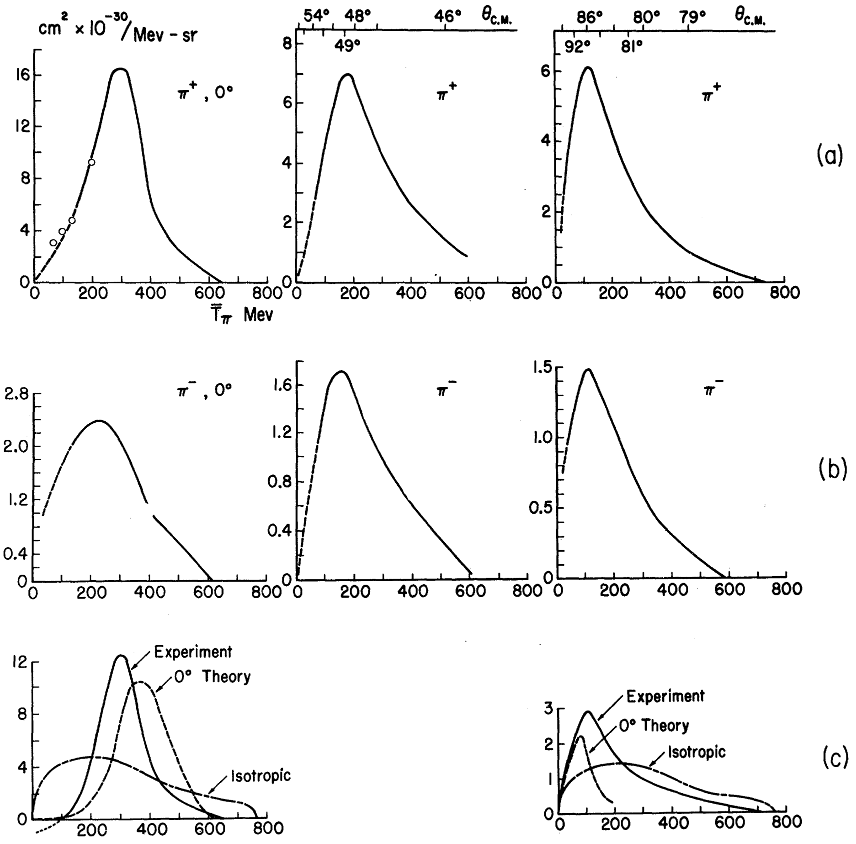

FIG. 3. The c.m. spectra for (a) π^+ mesons, (b) π^- mesons, (c) single production of π^+ mesons. In (c) the experimental spectrum is given by the solid curve and is obtained by subtraction, the dashed curve gives the 0° theory prediction, and the dot-dash curve gives the isotropic theory prediction. The 0° theory predictions have been normalized to fit the area under the experimental spectrum at 0°.

results of the bubble chamber work are also included and are in agreement. The c.m. spectra can now be used for a stringent test of any π-production theory. This is possible because each momentum spectrum is available at an almost fixed production angle and has been accurately determined in detail. In this communication we have tested only the "isobar model"[6] by assuming alternatively two extreme conditions: (a) that the isobars are produced isotropically in the p-p rest frame (isotropic theory); (b) that the isobars are produced in the p-p rest frame only at 0° and 180° (what we call the 0° theory). In both cases the isobars are assumed to decay isotropically in their own rest frame (no polarization). In Table II are compared the positions of the maxima of the experimental spectra, with the positions calculated according to these two extreme hypotheses.

It is evident from Table II that the predictions of the 0° theory are much closer to the experimental results for single pion production, and one may conclude that if the production of single π mesons proceeds through an intermediate isobaric state[1,3,6] then this state is produced (in the p-p rest frame) with an angular distribution ap-

Table I. Summary of integrated cross sections.

	$(d\sigma/d\Omega)_{\text{c.m.}}$ (mb/sr)					
	0°	47°	80°	Ang. distr.	σ_t	σ_t(bubble chamber)
π^+	3.92	2.25	1.53	$1+1.5\cos^4\theta$	25.0 ± 5.0 mb	24.9 ± 1.2 mb[a,b]
π^-	0.81	0.52	0.37	$1+1.2\cos^4\theta$	5.8 ± 1.5 mb	4.7 ± 0.7 mb[b]

[a] See reference 1.

[b] W. Willis et al. (private communication).

Table II. Position of maxima (in Mev) in pion spectra.

$\theta_{\text{c.m.}}$	π^+ singles spectrum Experiment	 Isotropic theory	 0° theory	π^- spectrum Experiment	 Isotropic theory
0°	310	225	370	220	150
47°	200	225	...	155	150
80°	115	225	80	115	150

proaching a δ function in the forward-backward direction.

For a more detailed and sensitive test of our results with theory we have attempted to isolate the spectra corresponding to different multiplicities. At 2.9-Bev proton energy, the π^+ spectrum contains single, double, and triple production:

$$p+p\rightarrow p+n+\pi^+\ (pn+),$$

$$p+p\rightarrow (pp+-)\ \text{or}\ (pn+0)\ \text{or}\ (nn++),$$

$$p+p\rightarrow (pp+-0)\ \text{or}\ (pn+00)\ \text{or}\ (nn++0)\ \text{or}\ (pn++-)$$

while the π^- spectrum includes only double and triple production:

$$p+p\rightarrow (pp+-),$$

$$p+p\rightarrow (pp+-0)\ \text{or}\ (pn++-).$$

The branching ratios for the various channels are known[1] or can be calculated using charge independence if one accepts a production mechanism through the $T=\frac{3}{2}$ and $T=\frac{1}{2}$ isobaric states ($p\pi$) of the nucleon.[6] It is then possible to subtract a fraction of the π^- spectrum from the π^+ spectrum and obtain the spectrum for single production at a given angle. These spectra for singles at 0° and 80° are shown in Fig. 3(c); on the same diagrams are given the predictions of the "isobar theory" under the simplified extreme assumptions of 0°-180°, or isotropic production. It is seen that the 0° spectrum is in complete disagreement with the "isotropic theory" and that a strong component of δ-function production is needed; on the contrary the 80° spectrum appears to be a composite of the two theoretical spectra. It is interesting to note that both the 0° and 80° spectra can be explained simultaneously if one assumes for the total cross section an almost equal mixture of isotropic and 0°-180° production.

Finally the contribution of the $T=\frac{1}{2}$ isobar cannot be clearly seen in the single production. The effects due to contributions from this isobar are more pronounced in the 0° spectrum for π^- mesons.

A detailed report of this work including the analysis of the spectra at all angles is being prepared for submittal to The Physical Review.

It is a pleasure to acknowledge the help of Mr. J. S. Weaver in the early stages of this experiment and of Mr. J. Robbins with some calculations. Also we thank the Cosmotron staff, operating crew, and experimental support group as well as the members of the University of Rochester 130-in. Cyclotron Laboratory for their generous cooperation. One of us (ACM) wants to thank R. Sugarman, R. Sternheimer, and G. Collins and his group for many helpful discussions.

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*This work was supported by the U. S. Atomic Energy Commission.

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