POSITIVE PION PRODUCTION IN p-p COLLISION AT 383 MEV *

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(presented by W. H. Evans)

The branching ratio between the two reactions $p + p \rightarrow \pi^+ + d$ ----- (1) the "bound" reaction and $p + p \rightarrow \pi^+ + n + p$ ----- (2) the "unbound" reaction, has been determined at 383 Mev using a hydrogen diffusion cloud chamber with an applied magnetic field. The ratio obtained $\frac{\sigma (\text{unbound})}{\sigma (\text{total})} = (47 \pm 8)\$, and the shape of the unbound spectrum do not agree with the predictions of the phenomenological theory. Agreement is possible in both cases if the theory is extended to allow for p-state final nucleons in reaction (2).

Previous to this work other experimenters had found disagreement between the experimental and predicted branching ratios.

The separation of the line spectrum from (1) and the continuum from (2) is only about 2 Mev in the centre of mass system. The energy resolution in most previous experiments was too poor for accurate division of the spectra and low-energy mesons were not detected.

In the present experiment a well-collimated beam of protons of intensity about 20,000 particles per picture passed through the diffusion chamber which was filled

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* A full account will be published shortly in the Proceedings of the Physical Society.
Typical cloud chamber photograph.

Beam profile taken with an X-ray film on beam entry window (actual size)

Fig. 2.
with 28 atmospheres of hydrogen and had a pulsed magnetic field of $11,200 \pm 200$ gauss (fig. 1). In this way all meson energies and production angles were observed in one experiment and the conversion to the centre of mass system was straightforward and reliable.

1,300 stereoscopic pairs of pictures were taken on 70 mm. film with a repetition rate of 2 min. Mesons were only accepted for analysis if the angle of dip was less than $20^\circ$. The origin of the meson track could not be seen and it was assumed to start in the centre of the collimated beam. Scanning was inefficient in the forward and backward directions due to the presence of the low energy “fan” around the main collimated beam, and the origin of the track was uncertain.

Fig. 2 shows a typical cloud chamber photograph the curvature (momentum) and production angle of 182 mesons with dip angle less than $20^\circ$ were measured.

Fig. 3 shows a plot of the measured curvature and production angle on a graph which also shows the corresponding c.m. angle and energy, calculated assuming an incident proton energy of 383 Mev.

Mesons at c.m. angles less than $40^\circ$ and above $160^\circ$ are not considered because of scanning difficulties. The total spectrum of the remaining 161 mesons is similar to that of fig. 4 and indicates a peak in the line spectrum at 41-42 Mev. This is slightly higher than the value (40.5 Mev) calculated for protons of 383 Mev. We place more reliance on the value of the magnetic field used than the quoted value for the proton energy and all subsequent calculations are based on this value.

The total spectrum is now divided at 38 Mev into “bound” and “unbound” respectively and the angular distributions are shown in fig. 4. The distribution for the “bound” reaction should be symmetrical about $90^\circ$ and there is a decrease in scanning efficiency below $80^\circ$, due to the presence of the low-energy “fan” around the proton beam.

We find:

$$\frac{d\sigma}{d\theta} \text{ (bound)} \big|_{80^\circ \text{ to } 180^\circ} = (0.19 \pm 0.06) + \cos^2\theta \quad (3)$$

and

$$\frac{d\sigma}{d\theta} \text{ (unbound)} \big|_{80^\circ \text{ to } 180^\circ} = (0.21 \pm 0.07) + \cos^2\theta \quad (4)$$

from a least squares fit of $A + \cos^2\theta$ to both distributions.

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**Fig. 3.** A plot of the accepted mesons.
The branching ratio

The spectrum of the remaining 109 mesons between 80° and 160° c.m. is shown in fig. 5. A Gaussian fitted to the mesons of energy above 38 Mev has a maximum at 41.8 Mev (τ = 0.83) and a standard deviation of 2 Mev and the upper limit of the unbound spectrum is calculated to be T_o = 39.8 Mev, τ_max = 0.807. A standard deviation of 2 Mev agrees closely with that calculated by considering uncertainties in the curvature measurements, angle measurements, magnetic field used and energy spread of the incident protons.

It is assumed that the experimental error of 2 Mev remains constant in the energy range 32-48 Mev, and this error is added on to the spectrum below 38 Mev. Mesons in the energy range 36-42 Mev are shared between the bound and unbound reactions in the ratio of the areas under the two curves.

Then \[
\frac{\sigma \text{ (unbound)}}{\sigma \text{ (total)}} \text{ 80° to 160°} = \frac{51 \pm 7}{109 \pm 11} = (47 \pm 8)%
\] (5)

Since the angular distributions are similar the branching ratio from 0° to 180° is assumed to be the same as (5).

This ratio can be compared with a "predicted" branching ratio R_1 obtained by Rosenfeld (1954) and Gell-Mann and Watson (1954).
\[ R_1 = \frac{\sigma \text{(unbound)}}{\sigma \text{(total)}} = \frac{\sigma_{10}^u (Ss + Sp)}{\sigma_{10}^u (Ss + Sp) + \sigma_{10}^s} = 30\% \] (6)

The notation is that adopted by Gell-Mann and Watson. The high value of the experimental branching ratio strongly suggests that a contribution of appreciable magnitude has been neglected in expression (6).

Possible cross-sections involved in the unbound reaction are \( \sigma_{10}^u (Ss) \), \( \sigma_{10}^u (Sp) \), \( \sigma_{10}^u (Pp) \), \( \sigma_{11}^u (Ss) \), \( \sigma_{11}^u (Pp) \), \( \sigma_{11}^u (Ps) \); \( \sigma_{10}^u (Sp) \) and \( \sigma_{10}^s (Ps) \) are excluded by considerations of spin and parity.

It is interesting to investigate if the shape of the "unbound" spectrum will enable us to determine which contribution has been neglected.

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**Fig. 5.** Spectrum of mesons between 80° and 160° in c.m. system

**Fig. 6.** Unbound spectrum of mesons between 80° and 160° in c.m. system
The unbound spectrum

This is shown in fig. (5) drawn in 8 Mev intervals. The contribution \( \sigma''_{10}(Ss + Sp) \) gives a spectrum which is sharply peaked at the high-energy end which does not agree with the measured spectrum. Division of the spectrum at a higher energy would reduce the discrepancy in the shape of the spectrum but would increase still further the measured branching ratio. Division at a lower energy would have the opposite effect.

The discrepancy in the measured branching ratio and in the shape of the measured unbound spectrum can both be explained by assuming in addition to \( \sigma''_{10}(Ss + Sp) \) and \( \sigma_{11} \) (which is known to be small) a contribution from \( \sigma''_{10}(Pp) \).

Little is known about the spectrum from \( \sigma_{11} \) since the predominant transitions could be (Pp) or (Ps). Since it is small we have assumed (Pp) transitions only.

The shape of the spectrum expected from (Pp) transitions is also shown in fig. (5). The measured spectrum is now assumed to be built up from the two contributions \( \sigma''_{10}(Ss + Sp) \) and \( \sigma''_{10}(Pp) + \sigma_{11}(Pp) \) and a least squares fit gives

\[
\frac{\sigma''_{10}(Pp)}{\sigma''_{10}(Pp) + \sigma_{11}(Ss + Sp)} = 0.38 \pm 0.30.
\]

Curve (1) New predicted ratio

\[
\frac{\sigma''_{10}(Ss + Sp) + \sigma''_{10}(Pp) + \sigma_{11}(Pp)}{\sigma'_{10} + \sigma''_{10}(Ss + Sp) + \sigma''_{10}(Pp) + \sigma_{11}(Pp)}
\]

Curve (2) Old predicted ratio

\[
\frac{\sigma''_{10}(Ss + Sp)}{\sigma'_{10} + \sigma''_{10}(Ss + Sp)}
\]

Results from reaction \( P^+ P \rightarrow \Pi^+ \) nucleons

Result from reaction \( N + P \rightarrow \Pi^0 \) nucleons

De Carvalho

Hildebrand

Rosenfeld

Peterson

Our result

Cartwright

(1)

(2)

\[ \eta_D = \text{Momentum of Pion from "Bound" reaction in } C \text{ of } M \text{ system in units of } \mu c \]

Fig. 7. Comparison of branching ratios \( \sigma \) (unbound)/\( \sigma \) (total)
The contribution $\sigma'(Pp)$ has an $\eta^8$ dependence and by normalizing to the calculated value of $\sigma_{10}(Ss + Sp)$ a value of $\sigma'(Pp)$ is obtained from the shape of the unbound spectrum

$$\sigma'(Pp) = (1.0 \pm 0.9) \eta^8_{\text{max}}$$

Another value of $\sigma'(Pp)$ is obtained from the measured branching ratios since

$$\frac{\sigma(\text{unbound})}{\sigma(\text{total})} = \frac{\sigma_{10}(Ss + Sp) + \sigma'(Pp)}{\sigma_{10}(Ss + Sp) + \sigma'(Pp) + \sigma_{10}}$$

and gives $\sigma'(Pp) = (1.8 \pm 0.8) \eta^8_{\text{max}}$

and the weighted mean is $\sigma'(Pp) = (1.4 \pm 0.6) \eta^8_{\text{max}}$

If we assume that $\sigma_{11} = 0.2 \eta^8_{\text{max}}$ we find $\sigma_{10}(Pp) = 1.2 \eta^8_{\text{max}}$.

Fig. (7) shows a comparison of the experimental branching ratios with the phenomenological theory both with and without the (Pp) contributions. It is seen that better agreement is obtained between theory and experiment if the (Pp) transitions in $\sigma_{10}$ are included in addition to $\sigma_{11}$.

**DISCUSSION**

*J. Ashkin* drew the attention to measurements done by T. Fields, J. Fox and R. Sutton of his Institute. At 437 Mev proton energy they measured the total inelastic $p$-$p$ cross-section by detecting the slow protons and deuterons (correcting for the fact that two final protons are detected in neutral pion production). They found $\sigma = 2.60 \pm 0.23$ mb. From this they subtract the known cross-sections for $p + p = \pi^+ + d$ $(1.23 \pm 0.07$ mb) and the cross-section for neutral pion production $(0.15 \pm 0.03$ mb). They obtain in this way the cross-section for the “unbound” reaction and find for the ratio unbound/total $0.5 \pm 0.1$.

*V. M. Sidorov* asked whether for the unbound reaction energy spectra at different angles had been measured.

*W. H. Evans*: “No, the statistics were too poor to make such a subdivision of the results meaningful”.