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Alston, M H; Crewe, A V; Evans, W H; Von Gierke, G O J

CERN-57-04

Published in: Proc. Phys. Soc. Lond.: 69 (1956) pp.691-704

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Dr Jill Membrey
Managing Editor, Copyright and Permissions
Institute of Physics Publishing
Dirac House, Temple Back,
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A Study of Positive Pion Production in p-p Collisions at 383 MeV

BY MARGARET H. ALSTON, A. V. CREWE†, W. H. EVANS
AND G. VON GIERKE‡

Nuclear Physics Research Laboratory, University of Liverpool

*Communicated by H. W. B. Skinner ; MS. received 2nd February 1956, and in
final form 8th May 1956*

Abstract. An 18 in. diffusion cloud chamber filled with 28 atmospheres of hydrogen and in a magnetic field of 11 200 gauss is used to investigate the production of π^+ -mesons in p-p collisions at 383 MeV. The energy resolution is of the order of 2 MeV and the spectrum obtained can be divided into mesons from the 'bound' and 'unbound' reactions. The angular distributions found are

$$\frac{d\sigma}{d\omega}(\text{bound}) \propto (0.19 \pm 0.06) + \cos^2 \theta' \quad \text{and} \quad \frac{d\sigma}{d\omega}(\text{unbound}) \propto (0.21 \pm 0.07) + \cos^2 \theta'.$$

The branching ratio $\sigma(\text{unbound})/\sigma(\text{total}) = (47 \pm 8)\%$. The shape of the unbound spectrum is not in agreement with that predicted by the phenomenological theory but this spectrum and also the high experimental branching ratio can be explained by the inclusion of a term $\sigma_{10}''(\text{Pp}) \simeq 1.2\eta_{\text{max}}^8$ in the theory.

§ 1. INTRODUCTION

A phenomenological theory proposed by Brueckner and Watson and later extended (Brueckner and Watson 1951, 1953, Brueckner 1952, Watson 1952) has been used with great success to explain meson production processes in nucleon-nucleon collisions. The subject has recently been extensively reviewed by Rosenfeld (1954 a) and Gell-Mann and Watson (1954). They show that by using semi-empirical expressions for the cross sections the behaviour of the reactions can be predicted in most cases, but one obvious discrepancy remains. This occurs in the relation between the cross sections of the deuteron forming reaction $p + p \rightarrow \pi^+ + d$ (1), the 'bound' reaction, and the corresponding reaction producing an unbound neutron and proton $p + p \rightarrow \pi^+ + n + p$ (2). The value of the ratio $\sigma(\text{unbound})/\sigma(\text{total})$ is found by experiment (Cartwright *et al.* 1953, Peterson *et al.* 1951, Rosenfeld 1954b, de Carvalho *et al.* 1954) to be much larger than that predicted by the theory.

The total meson spectrum of reactions (1) and (2) consists of a line spectrum, due to the bound reaction (1), which lies just above the high energy cut-off of a continuum due to the unbound reaction (2). The separation of these spectra in the centre-of-mass system is about 2 MeV; the binding energy of the deuteron corrected for relativistic effects. The energy resolution in most experiments is poor, making the division of the spectra unreliable and a detailed study of the unbound reaction impossible. Further errors are often introduced by neglecting low energy mesons and also, since measurements are usually only made at a few fixed angles in the laboratory system, the conversion of the spectrum to the centre-of-mass system is inaccurate.

† Now at the Institute for Nuclear Studies, University of Chicago.

‡ Now at C.E.R.N., Geneva with the Synchrocyclotron Group.

Figure 4. Beam profile (actual size) obtained when x-ray film was exposed at the beam entry window of the chamber. The lead blocks in front of the chamber were moved slightly after this picture was taken so that the lead did not obstruct the beam on the left-hand side.

Figure 5. A typical cloud chamber picture taken during the experiment. A well collimated beam of 383 mev protons of intensity $\sim 2 \times 10^4$ enters the chamber at the top of the picture. A π -meson of radius of curvature 11 cm is produced to the left of the beam at an angle of 135° in the laboratory system. This π -meson can be seen decaying in the chamber gas into a μ -meson.

The present experiment is a study of the reactions

- (1) $p + p \rightarrow \pi^+ + d$ Bound reaction
 (2) $p + p \rightarrow \pi^+ + n + p$ Unbound reaction.

The high intensity external proton beam from the synchrocyclotron is well collimated and observations are made on the production angle and momentum of the pions using a hydrogen-filled diffusion cloud chamber in conjunction with a pulsed magnetic field. This method has the advantage that all production angles and meson energies can be observed accurately in one experiment and the accuracy of the momentum measurement is closer than 2%. The 'bound' and 'unbound' spectra can be separated, and a detailed study of the unbound spectrum and angular distribution can be made. The results show that there is a definite discrepancy between the experimental and predicted values of both the ratio $\sigma(\text{unbound}) / \sigma(\text{total})$ and the unbound spectrum. However, this discrepancy can be explained by an extension of the theory.

§ 2. APPARATUS AND TECHNIQUE

2.1. The Diffusion Cloud Chamber

Figure 1(a) is a schematic diagram of the 18 in. diameter diffusion cloud chamber. The bottom section is of non-magnetic stainless steel with total height 7 in. The lower part of the walls are 5/16 in. thick and the base 1 in. thick. The two illumination windows are of 1 in. thick Perspex and are placed on the ends of short extension ports which are rectangular in shape, 10 in. wide and 4 in. high. The incident particles enter the chamber through a rectangular beam entry port placed midway between the illumination ports and with its centre 1½ in. above the base.

The top section of the chamber embodies the vapour tray which contains about 200 cm³ of liquid. It is made of cast phosphor bronze and is electrically insulated from the rest of the chamber for the application of a clearing field. Above the tray is a 15 in. diameter armour plate glass 1½ in. thick. It is clamped in position by a cast phosphor bronze ring, which leaves an aperture of 13 in. diameter. With pressure in the chamber the glass is pushed against the top ring and the seal is of the Bridgman type. All the seals are made with rubber gaskets. The chamber can withstand 600 lb in.⁻² and is used with hydrogen gas fillings of between 300 and 450 lb in.⁻².

A good photographic background is obtained by having 'nigrosine', a black dye, dissolved in the pool of alcohol at the bottom of the chamber and by covering the walls with black velvet to prevent reflection. A 70 mm stereoscopic camera is placed 20 in. above the top glass window on a light-tight mounting. Two Mullard LSD 17 quartz flash tubes are mounted in light-tight boxes at the ends of the illumination ports, and illumination of the tracks is provided by discharging 400 μF at 2000 volts through each tube.

The base of the chamber is cooled to -60°C by passing cold acetone through copper pipes soft-soldered to the base (Alston, Crewe and Evans 1954). Heat is applied to the top part of the chamber by a heating tape wrapped round the top ring and heating wires passing through a tube soldered to the side walls just above the ports. The wire is in four sections because less heat is required above the side ports than between them since the thermal paths are different and a uniform temperature around the wall must be maintained at any height above the

Figure 1 (a) Schematic drawing of the 18 in. diffusion cloud chamber: A, armour-plate glass window; B, insulated alcohol tray; C, rectangular Perspex window; D, beam entry port; E, heaters.

(b) Operational temperature distributions: 1, hydrogen at 20–28 atmospheres; the gradient in the sensitive region is 5 deg cm^{-1} ; 2, air at 1 atmosphere; the gradient in the sensitive region is 7.5 deg cm^{-1} .

base. The top glass is kept just above room temperature by a stream of hot air. The best operational temperature distributions, as measured on the outside of the chamber wall, for operation with 1 atmosphere of air or 20–28 atmospheres of hydrogen, exposed to cosmic-ray background, are shown in figure 1(b). With these temperatures a sensitive depth of $2\frac{1}{2}$ in.–3 in. is maintained. It can be seen that the temperature gradient for hydrogen is only 5 deg cm^{-1} , a much lower value than that quoted by other authors (Fowler *et al.* 1953, Sargent *et al.* 1955). For the experiment the chamber was filled with 28 atmospheres of hydrogen and the temperature gradient was increased to 5.5 deg cm^{-1} to cope with the larger ionization level.

2.2 Magnetic Field and Timing Sequence

A uniform magnetic field was produced in the sensitive region of the chamber by passing a large pulsed current through a pair of air-cored water-cooled coils mounted as a Helmholtz pair with their axes vertical. The exciting current of the generator was controlled by a metadyne and the output was extremely stable. For calibration a low steady field was compared with a known field to obtain the

coil constant of the field coils. The field profile on the median plane (figure 2(a)) and the field variations in the chamber were also measured. The field variations in the sensitive region were less than 3%. The absolute value of the pulsed magnetic field at any time during the pulse was then found by a current measurement. The measurement of the pulsed field was accurate to 1½% and the pulse shape is shown in figure 2(b). The value of the field from one pulse to another was found to be constant on the latter part of the curve, but to be slightly variable at the beginning.

Figure 2. (a) Magnetic field plot on the median plane of the field coils (b) Magnetic field pulse shape and timing sequence. 1, Clearing field off 5 seconds before the beginning of the main sequence; 2, start of sequence; 3, magnetic field on; 4, pulse to synchrocyclotron indicating that particles are required; 5, magnetic field measured; 6, magnetic field off; 7, lights flash; 8, clearing field on; 9, film wound on.

Since several consecutive pulses of particles were accepted from the synchrocyclotron for one cloud chamber picture, the particles were admitted to the chamber about 1½ seconds after the magnetic field pulse began, so that the field was as constant as possible for about 100 msec and was also the same from one pulse to another. The timing of the control sequence was not required to great accuracy and so a mechanical control system was used because of its simplicity and reliability. The timing sequence is shown in figure 2(b). The value of the magnetic field when the particles entered the chamber was $11\,200 \pm 200$ gauss.

2.3. Experimental Arrangement

A very high intensity proton beam of flux 4×10^{10} protons $\text{cm}^2 \text{sec}^{-1}$ is produced by the Liverpool 156 in. synchrocyclotron (Crewe and Gregory 1955). The absolute value of the energy of this beam has been measured as 383 ± 3 mev by a range method and the beam energy spread is negligible. The synchrocyclotron produces beam pulses as 10 msec intervals and a selected number of consecutive pulses can be obtained from the machine when the cloud chamber magnetic field has reached a steady value. For the experiment very good collimation of the proton beam was required to prevent background from obscuring the tracks

coming from the main beam. Collimation was made more difficult by the large fringing field of the cloud chamber magnet (figure 2 (a)) which bent the proton beam considerably.

The beam entry window of the chamber was made of 0.006 in. thick Dural and was $\frac{3}{4}$ in. in diameter. It was placed on the end of an extension tube 10 in. long, so that any unwanted low energy particles produced in the window were bent away from the main beam by the magnetic field and did not enter the sensitive region of the chamber.

A diagram of the experimental arrangement is shown in figure 3. A preliminary collimator with an aperture 6 in. long by $\frac{1}{4}$ in. diameter was placed just outside the cyclotron tank at the object point of the proton bending magnet, giving a beam profile $\frac{1}{4}$ in. high by $1\frac{1}{2}$ in. wide at the focus of the magnet. The main collimator was placed at this focal point, about 5 feet in front of the chamber. It would have been desirable to place the collimator closer to the beam entry window to reduce multiple scattering in the air, but this was not possible because the collimator must be placed outside the fringing field of the cloud chamber coils. The collimator consisted of a brass tube with an accurately machined centre hole and copper plugs with various sized centre holes which fitted into the tube. Each plug was $2\frac{1}{2}$ in. long, the half range of the protons in copper. The beam direction was determined by exposing x-ray film at two points in its path and the collimator was then set up optically with its axis in line with the centres of the beam profiles.

Figure 3. Experimental arrangement.

The chamber was then placed behind the collimator so that the beam passed symmetrically through it when no magnetic field was applied. The best combination of collimator plugs and the final position of the collimator was found by making visual observations of the proton beam as it passed through the chamber. The final arrangement was: 5 in. $\times$ $\frac{1}{8}$ in. dia. + $2\frac{1}{2}$ in. $\times$ $\frac{1}{2}$ in. dia. + $2\frac{1}{2}$ in. $\times$ $\frac{1}{8}$ in. dia. + $2\frac{1}{2}$ in. $\times$ $\frac{1}{2}$ in. dia. + $2\frac{1}{2}$ in. $\times$ $\frac{3}{16}$ in. dia. (figure 3.) The actual collimation was produced by the first 5 in. $\times$ $\frac{1}{8}$ in. dia. hole and the other apertures removed slit scattered protons as much as possible. In order to find the trajectory of the beam when the pulsed magnetic field was applied to the chamber an x-ray film was exposed at the approximate position of the beam entry window. To obtain a sufficiently dense image about 100 beam pulses were required. The cloud

161 mesons between 40° and 160° is similar to that shown in figure 9(a). The energy of the peak indicates that either the choice of incident proton energy is not correct or the magnetic field measurement is inaccurate. Since an error of 3 Mev in the proton energy makes more error in the meson energy than an error of $1\frac{1}{2}\%$ in the magnetic field measurement, the momentum measured in the experiment is considered to be correct and all subsequent calculations are based on this value. The inaccurate choice of proton energy makes no appreciable error in the curves already drawn in figure 7.

Figure 7. A plot of the acceptable mesons on a graph of R (the corrected radius of curvature) and θ (the laboratory angle). Lines of equal angle θ' in the centre-of-mass system are drawn at 20° intervals. Lines of equal kinetic energy T in the centre-of-mass system are drawn at 4 Mev intervals from 8 to 36 Mev and 2 Mev intervals from 36 to 44 Mev.

The accurate separation of the 'bound' and 'unbound' spectra is difficult because they overlap. Since the peak energy of the line spectrum is 41–42 Mev the upper limit of the unbound spectrum, ignoring the experimental spread, is 39–40 Mev and its maximum should be at $37\text{--}38$ Mev. The spectrum (40° to 160°) is divided at 38 Mev to ensure that the number of mesons from the unbound spectrum is not over-estimated. Our experimental angular distributions will not be affected by a possible error of 2 Mev in the point of division, since they are found to be similar.

The angular distributions in the centre-of-mass system are plotted in 20° intervals (figure 8). The distribution for the bound reaction shows that there is a decrease in scanning efficiency below 80° ($<45^\circ$ in the laboratory system) since this distribution should be $A + \cos^2 \theta'$, i.e. symmetrical about 90° . The decrease in efficiency is not surprising as some mesons at low angles are certain to be lost in the 'fan' round the proton beam.

A least squares fit of $A + \cos^2 \theta'$ to the 'bound' distribution between 80° and 160° gives:

$$\frac{d\sigma}{d\omega}(\text{bound}) = \frac{d\sigma'}{d\omega} \propto (0.19 \pm 0.06) + \cos^2 \theta'. \quad \dots\dots (1)$$

The semi-empirical formulae of Rosenfeld (1954 a) give $A = 0.1 + 0.6\eta_D^{-2}$, where η_D is the momentum of the pion in the centre-of-mass system in units of μc .

From our spectrum (see later), $T_D = 41.8$ MeV, and $\eta_D = 0.83$; this gives $A = 0.19$, in agreement with the experimental value.

Figure 8. The angular distributions. (a) The bound reaction. A least squares fit gives $0.19 \pm 0.06 + \cos^2 \theta'$. (b) The unbound reaction. A least squares fit gives $0.21 \pm 0.07 + \cos^2 \theta'$.

The angular distribution of the unbound reaction should be $B + \cos^2 \theta'$ since all contributions are either isotropic or of the form $C + \cos^2 \theta'$, where C is a constant, and there is no asymmetric interference between the contributions. A least squares fit to the experimental distribution between 80° and 160° gives:

$$\frac{d\sigma}{d\omega}(\text{unbound}) = \frac{d\sigma''}{d\omega} \propto (0.21 \pm 0.07) + \cos^2 \theta'. \quad \dots\dots(2)$$

3.3. The Branching Ratio, $\sigma(\text{unbound})/\sigma(\text{total})$

The total spectrum of the 109 mesons lying between 80° and 160° in the centre-of-mass system is plotted in figure 9. A gaussian is fitted to the mesons above 38 MeV giving a maximum at 41.8 MeV, $\eta_D = 0.83$, and an experimental standard deviation of 2 MeV. With this choice of energy the upper limit of the unbound spectrum is $T_0 = 39.8$ MeV and $\eta_{\max} = 0.807$, where $\eta_{\max}$ is the maximum possible momentum of a pion from the unbound reaction in the centre-of-mass system in units of μc . A calculated standard deviation of 2 MeV is obtained by considering the uncertainties in the curvature measurements, angle measurements, magnetic field, and the spread in energy of the incident protons.

If it is assumed that the experimental error of 2 MeV remains constant in the energy range 32–48 MeV the unbound distribution can be folded into this error (figure 9) and shows that the initial division of the spectrum at 38 MeV underestimates the number of mesons from the unbound reaction by one meson. 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.

$$\text{Then } \frac{\sigma(\text{unbound})}{\sigma(\text{total})}(80^\circ-160^\circ) = \frac{51 \pm 7}{109 \pm 11} = (47 \pm 8)\%. \quad \dots\dots(3)$$

Since the angular distributions of the mesons from the two reactions are so similar the branching ratio from 0° to 180° is the same as (3).

Possible cross sections involved in the unbound reaction are (Rosenfeld 1954a, Gell-Mann and Watson 1954) $\sigma_{10}''(\text{Ss})$, $\sigma_{10}''(\text{Sp})$, $\sigma_{10}''(\text{Pp})$, $\sigma_{11}(\text{Ss})$, $\sigma_{11}(\text{Pp})$, $\sigma_{11}(\text{Ps})$. [We use the notation of Gell-Mann and Watson. The subscripts denote the initial and final isotopic spin values of the two-nucleon state; the primes denote the reaction: ', bound; ', unbound; the capital letter gives the angular momentum of the final state of the two nucleons, and the small letter the angular momentum of the pion with respect to the nucleons.] The cross sections $\sigma_{11}(\text{Sp})$ and $\sigma_{10}''(\text{Ps})$ are missing since considerations of parity and spin conservation show that all the transitions contributing to these cross sections are forbidden.

Figure 9. (a) Total spectrum of mesons between 80° and 160° in centre-of-mass system. Note. Change of energy interval at 36 Mev (The gaussian has a maximum at 41.8 Mev and a standard deviation of 2 Mev.)

(b) Unbound spectrum of mesons between 80° and 160° in centre-of-mass system, showing the contributions from $\sigma_{10}''(\text{Ss}+\text{Sp})$ and $\sigma''(\text{Pp})$.

The experimental ratio can be compared with a 'predicted' branching ratio R_1 obtained by Rosenfeld (1954a) and Gell-Mann and Watson (1954) by assuming that $\sigma_{10}''(\text{Pp})$ and σ_{11} are negligible:

$$R_1 = \frac{\sigma(\text{unbound})}{\sigma(\text{total})} = \frac{\sigma_{10}''(\text{Ss}+\text{Sp})}{\sigma_{10}''(\text{Ss}+\text{Sp}) + \sigma_{10}''} = 30\% \text{ at our energy. } \dots\dots (+)$$

This strongly suggests a discrepancy between the predicted ratio and the experimental ratio and indicates that a contribution of appreciable size has been neglected in expression (4).

3.4. The Unbound Spectrum

The unbound spectrum is redrawn in intervals of 8 MeV, figure 9, because the statistics are too poor in 4 MeV intervals.

The contribution $\sigma_{10}''(\text{Ss} + \text{Sp})$ is expected to be predominant but gives a spectrum which is sharply peaked at the high energy end. It is difficult to explain the shape of our experimental spectrum by this contribution alone. Division of the total spectrum at a higher energy would reduce this discrepancy but would, however, increase the difference between the branching ratios (3) and (4). Division at a lower energy would have the opposite effect. The shape of the experimental unbound spectrum and the discrepancy in the branching ratios can be explained by assuming that in addition to $\sigma_{10}''(\text{Ss} + \text{Sp})$ and the small contribution σ_{11} there is an appreciable contribution from $\sigma_{10}''(\text{Pp})$,

$$\text{i.e. } \frac{d\sigma}{dT}(\text{unbound}) = \frac{d\sigma_{10}''}{dT}(\text{Ss} + \text{Sp}) + \frac{d\sigma_{10}''}{dT}(\text{Pp}) + \frac{d\sigma_{11}}{dT}. \quad \dots\dots(5)$$

From Gell-Mann and Watson (1954)

$$\frac{d\sigma_{10}''}{dT}(\text{Ss} + \text{Sp}) = \frac{1}{2\pi} (0.14\eta + 1.0\eta^3) \frac{(T_0 - T)^{1/2}}{B} \frac{1}{T_0 - T + B} \text{ millibarns} \quad \dots\dots(6)$$

where B = deuteron binding energy = 2.23 MeV, T_0 = maximum energy of pion in centre-of-mass system = 39.8 MeV. The shape of the spectrum of σ_{11} is uncertain because the predominant transition could be (Pp) (Rosenfeld 1954 a) or (Ps) (Rosenfeld, private communication). However, since this cross section is small and the shape of the spectrum will have little effect upon the value of $\sigma_{10}''(\text{Pp})$ required to fit our experimental spectrum, we assume that σ_{11} is composed entirely of (Pp) transitions.

Then

$$\frac{d\sigma''}{dT}(\text{Pp}) = \frac{d\sigma_{10}''}{dT}(\text{Pp}) + \frac{d\sigma_{11}}{dT}(\text{Pp}) = K\eta^3(T_0 - T)^{3/2} \quad \dots\dots(7)$$

where K is an unknown constant. No correction is applied to the experimental spectrum 80° – 160° to obtain the spectrum 0° – 180° since comparison of the 'bound' and 'unbound' angular distributions indicates that the angular distributions of the possible $\sigma_{10}''(\text{Pp})$ contribution is similar to that of $\sigma_{10}''(\text{Ss} + \text{Sp})$. Any errors introduced by this procedure would be comparatively small.

A least squares fit of the spectra (6) and (7) to the experimental spectrum, figure 9 (b), gives a ratio

$$\frac{\sigma''(\text{Pp})}{\sigma(\text{unbound})} = \frac{\sigma''(\text{Pp})}{\sigma''(\text{Pp}) + \sigma_{10}''(\text{Ss} + \text{Sp})} = 0.38 \pm 0.30 \quad \dots\dots(8)$$

where 0.30 is the mean error.

The contribution $\sigma''(\text{Pp})$ has an η^8 dependence. By normalizing to the calculated value of $\sigma_{10}''(\text{Ss} + \text{Sp})$ a value of $\sigma''(\text{Pp})$ is obtained from the shape of the unbound spectrum:

$$\sigma''(\text{Pp}) = (1.0 \pm 0.9)\eta_{\text{max}}^8. \quad \dots\dots(9)$$

An independent value of $\sigma''(\text{Pp})$ is obtained from the measured branching ratio alone since

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

Then

$$\sigma''(\text{Pp}) = (1.8 \pm 0.8)\eta_{\text{max}}^8. \quad \dots\dots(11)$$

These two values of $\sigma''(\text{Pp})$ agree within the large statistical errors and the weighted mean is

$$\sigma''(\text{Pp}) = (1.4 \pm 0.6)\eta_{\text{max}}^8 \quad \dots\dots(12)$$

Experiments on the reaction $p + p \rightarrow \pi^0 + p + p$ give a value for σ_{11} but the results are rather inconsistent. A value $\sigma_{11} \simeq 0.2\eta_{\text{max}}^8$ is in fair agreement with the experimental cross sections for incident energies between 340 and 450 MeV (Rosenfeld 1954a and private communications from Rosenfeld and Squire). If this value is assumed then $\sigma_{10}''(\text{Pp}) \simeq 1.2\eta_{\text{max}}^8$.

§ 4. COMPARISON WITH OTHER EXPERIMENTAL RESULTS AND CONCLUSIONS

The results of our experiment show that the discrepancy between the observed and 'predicted' branching ratio can be explained by taking into account the (Pp) transitions in σ_{10}'' , which have been neglected in all previous papers. The absolute value of the cross section is rather unreliable.

Comparison of Experimental and Calculated Branching Ratios

$$R_1 = \text{Old predicted ratio} \quad \frac{\sigma(\text{unbound})}{\sigma(\text{total})} = \frac{\sigma_{10}''(\text{Ss} + \text{Sp})}{\sigma_{10}' + \sigma_{10}''(\text{Ss} + \text{Sp})}$$

$$R_2 = \text{New predicted ratio} \quad \frac{\sigma(\text{unbound})}{\sigma(\text{total})} = \frac{\sigma_{10}''(\text{Ss} + \text{Sp}) + \sigma''(\text{Pp})}{\sigma_{10}' + \sigma_{10}''(\text{Ss} + \text{Sp}) + \sigma''(\text{Pp})}$$

Values Used

$$\sigma_{10}''(\text{Ss} + \text{Sp}) = \int_0^{T_0} (0.14\eta + 1.0\eta^3) \left(\frac{T_0 - T}{B} \right)^{1/2} \frac{1}{T_0 - T + B} \text{mbn}$$

$$\left. \begin{aligned} \sigma_{10}''(\text{Pp}) &= 1.2\eta_{\text{max}}^8 \text{mbn} \\ \sigma_{11}(\text{Pp}) &= 0.2\eta_{\text{max}}^8 \text{mbn} \end{aligned} \right\} \sigma''(\text{Pp}) = 1.4\eta_{\text{max}}^8 \text{mbn}$$

$$\sigma_{10}' = (0.14\eta_D + 1.0\eta_D^3) \text{mbn}$$

Author	Incident Energy (MeV)	η_D	Exptl Ratio (%)	R_2 (%)	R_1 (%)
Cartwright	340	0.59	35 ± 10	25.5	20
Peterson	340	0.59	45 ± 10	25.5	20
Our result	384	0.83	47 ± 8	44	30
Hildebrand	400	0.95	60 ± 15	55	33
Rosenfeld	440	1.07	53 ± 16	67	36

Experimental results for the total reaction $p + p \rightarrow \pi^+ + \text{nucleons}$ have been found by other authors (Cartwright *et al.* 1953, Peterson *et al.* 1951, Rosenfeld 1954b, Passman *et al.* 1952) using nuclear emulsions. Counter techniques have been used by de Carvalho *et al.* (1954) and Dzhelepov *et al.* (1955). Total cross

sections for the reaction $n + p \rightarrow \pi^0 + \text{nucleons}$ have been measured by Rosenfeld (private communication) and Pontecorvo and Selivanov (1955) and a branching ratio has been obtained by Hildebrand (1955, p.245).

The experimental results for incident energies from 340 to 460 MeV are compared with the values given by the theory including a term $\sigma''(\text{Pp}) = 1.4 \eta_{\text{max}}^8$. For this comparison the cross sections obtained from the reaction

$$n + p \rightarrow \pi^0 + \text{nucleons}$$

should be corrected for the different cross sections involved (σ_{01} instead of σ_{11}) and multiplied by the statistical factor 2. The first correction is small and very uncertain and a direct comparison of

with

$$2\sigma(n + p \rightarrow \pi^0 + \text{nucleons})$$

$$\sigma(p + p \rightarrow \pi^+ + \text{nucleons})$$

is made. The table shows the experimental branching ratios and the values predicted by the theory when a term $\sigma''(\text{Pp})$ is included (R_2) and also when this term is neglected (R_1). A comparison of the total cross sections is made in figure 10. No accurate results on the unbound spectrum have been obtained and comparison is not possible. A preliminary result by Stork (1955) showed disagreement between the spectrum and the old theory which neglected $\sigma''(\text{Pp})$.

Figure 10. A comparison of the experimental total cross sections of the reactions $p + p \rightarrow \pi^+ + \text{nucleons}$ and $n + p \rightarrow \pi^0 + \text{nucleons}$ with cross sections calculated assuming the values given in the table.

The results of these comparisons show that better agreement can be obtained between the phenomenological theory and the experimental results if the (Pp) transitions in σ_{10} are included in addition to σ_{11} and a value $\sigma_{10}''(\text{Pp}) = 1.2\eta_{\text{max}}^8$ is used. The large value of the cross section is surprising and seems to indicate

that the interaction between two nucleons in a P-state may be larger than anticipated although the presence of a meson may very possibly influence this interaction.

ACKNOWLEDGMENTS

The authors would like to thank Professor H. W. B. Skinner for his encouragement and advice, Mr. P. R. Williams and the cyclotron crew under Mr. B. Halliday for their cooperation during the cyclotron run, Messrs. A. Cave, H. Price and R. Thompson for building some of the apparatus and Mr. J. W. G. Gregory for designing and installing the radio frequency pulser.

Dr. G. von Gierke wishes to thank Professor Skinner for the hospitality received during his stay in Liverpool.

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