from the reaction in deuterium: $p+p\rightarrow\pi^++d$. However, the calculated ratios of the 90° π^+ deuterium to the 90° π^+ hydrogen cross sections are far too low (matrix elements CI, CII, BI, and BII predict a ratio of 2.2, 1.7, 1.6 and 1.2, respectively, whereas the experimental ratio is 5.6±2.3). This effect is difficult to understand, since it implies that a more energy-dependent excitation function than the $T_m^{\frac{1}{2}}$ or T_m matrix element dependence is required. This is not required, however, to explain the spectral shapes of the heavy elements. An alternative explanation, namely, that the two nucleons in deuterium do not act as independent particles in the process of meson formation, is also difficult to explain, since one might expect that, if the deuterium nucleus as a whole were to interact, a "tritium" peak (reaction $p+d\rightarrow t+\pi^+$) might be appreciable. Furthermore, the spectral shapes of the heavy elements were correctly predicted with the assumptions of independent nucleons. Certainly, in a deuterium nucleus where the binding is weak the assumption of independence should be better. Thus, one might suspect that negative mesons are produced by a different process from positive mesons.

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Excitation Function for Charged π-Meson Production in Hydrogen and Carbon by 345- to 380-Mev Protons*

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The 90° differential cross section for charged meson production in hydrogen and carbon is measured for incident proton energies 345 to 380 Mev. For hydrogen, the 90° π^+ meson production energy spectra occur as peaks in the energy region predicted from the kinematics of the reaction $p+p\rightarrow\pi^++d$. Ratios of these 90° π^+ differential cross sections are $(d\sigma)/(d\omega)$ at 380 Mev: $(d\sigma)/(d\omega)$ at 365 Mev: $(d\sigma)/(d\omega)$ at 345 Mev=2.6:1.6:1 with a statistical uncertainty of 15 percent. For carbon the π^+ meson production spectra show an increase in the energy of the maximum of the broad distributions, with increasing incident proton energy. The $(\pi^+)/(\pi^-)$ ratio in carbon is found to be in the range (10±3):1 for all three proton energies studies. Qualitative agreement with these carbon π^+ meson spectra is obtained from a phenomenological analysis based upon the assumptions of nucleon-nucleon collisions in which the target has a Gaussian momentum distribution.

INTRODUCTION

THE reaction $(p-p, \pi^+)$ has been studied in great detail at Berkeley[1] with both liquid hydrogen targets and polyethylene-carbon subtraction techniques in conjunction with the external 340-Mev proton beam. The resulting π^+ meson energy spectrum was observed as a clustering of the mesons about the maximum energy permitted by conservation laws, which indicates a strong nucleon-nucleon interaction in the final state of the reaction. Therefore, in the case of a triplet final spin state there is a strong possibility of deuteron formation. From the angular distribution of π^+ mesons produced in $p-p$ collisions, Whitehead and Richman[2] conclude that the π^+ production in the center-of-mass system has a $(0.07\pm0.07+\cos^2\theta)$ angular dependence.

Because of the difficulties associated with the quantum theoretical perturbation calculations of nucleon-nucleon meson production, one finds it more reliable if not as fundamental to apply the phenomenological theory of Watson and Brueckner.[3] In their method, the previously discussed qualitative features of the experimental results follow from the principles of conservation of parity and angular momentum together with an application of the exclusion principle, all contingent upon the pseudoscalar nature of the π^+ meson. An important test for this theory is the dependence of the nucleon-nucleon meson production cross section upon the incident proton energy, since the energy dependence of the transition operator for this process is directly related to the type of meson-nucleon interaction assumed.

Experiments concerning the production spectra of charged mesons in carbon and the heavy elements[4]

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[1] Peterson, Illoff, and Sherman, Phys. Rev. **81**, 647 (1951); Cartwright, Richman, Whitehead, and Wilcox, Phys. Rev. **78**, 823 (1950); **81**, 652 (1951).

[2] Marian Whitehead and Chaim Richman, Phys. Rev. **83**, 97 (1951).

[3] K. Watson and K. Brueckner, Phys. Rev. **83**, 1 (1951).

[4] Richman, Weissbluth, and Wilcox, Phys. Rev. **85**, 161 (1952); Block, Passman, and Havens, Phys. Rev. **83**, 167 (1951).

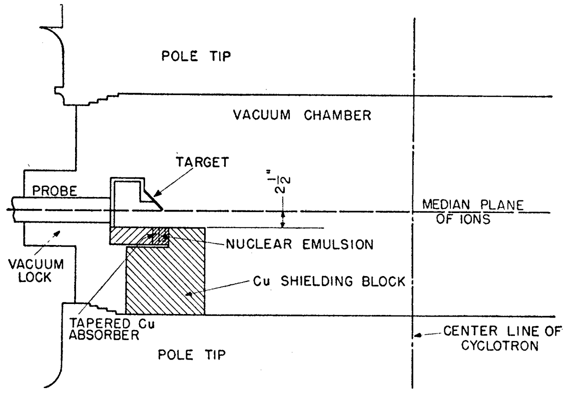

FIG. 1. Cross section view of cyclotron vacuum chamber.

indicate broad single maxima distributions, believed due to the effect of the momentum distribution of the bound target nucleons. Used in this way, the meson probes nuclear structure characterized by internal momenta distributions, just as in the nucleon-nucleon case the meson probes nuclear forces at very close distances.

Theoretical analyses of these heavy element meson production spectra,[5] based upon the impulse approximation, while giving a qualitative explanation of the shape of the observed distributions, have been handicapped because of lack of information concerning the nucleon-nucleon meson production excitation function as well as the paucity of information on the high momentum nucleon states present in the target nucleus. The variation in the cross section of meson production in carbon with increased incident proton energy should give additional information regarding these questions.

EXPERIMENTAL METHOD

The experimental technique, employing nuclear emulsions as detectors for measuring absolute meson production cross sections from targets bombarded by the internal circulating proton beam of the Nevis cyclotron, is basically the same as was reported in the previous paper on the variation of meson production with the atomic number Z and atomic weight A of the target material for 381-Mev protons.[6]

In order to increase the energy resolution for the measurement of the hydrogen meson spectra, the target holder was redesigned so that the thin target is inclined at 45° to the vertical as shown in Fig. 1, rather than the vertical position used in the earlier work. This allows mesons traveling in the downward direction toward the detector to traverse only the thin ~40-mil dimension of the polyethylene target with a consequent small energy loss in the target. To localize the active meson-producing region of the target, a 5 in.×5 in.×1 in. copper beam "clipper" was placed at the same radial distance as the target, slightly ($\frac{1}{4}$ in.) above the median plane of the circulating protons but displaced 90° in azimuth, in order to exclude neutrons, produced in the clipper, from the emulsion region. By this method, proton irradiation was successfully limited to the leading $\frac{1}{4}$ in. of the targets, directly in the median plane, as measured by a monitoring of the C^{11} activity induced in the carbon and polyethylene targets. The copper clipper also serves to prevent a significant degradation of the proton beam energy through multiple traversals of the target, since scattering of the proton beam in the target may send the protons into the clipper region where they are absorbed, stopped, or outscattered.

For the excitation function measurements the energy of the incident proton beam was varied by radially displacing the probe, on which the target and detector are mounted in a permanent relative geometry, to new $H\rho$ values in the vacuum chamber.

Exposures were made at proton energies of 345, 365, and 380 Mev. The upper limit of these proton energies was due to the characteristics of the Nevis cyclotron which had an $n=0.2$ point, where the well-known beam blow-up takes place, at a radial distance corresponding to 381-Mev proton energy. Proton energies below 345 Mev lead to π^+ production from hydrogen at extremely low 90° emission energies, where background difficulties make it impossible to detect mesons using the present photographic technique.

The requirement of bombarding targets by the internal proton beam of the cyclotron involves the problem of incident beam energy degradation due to radial oscillations of the circulating protons as well as multiple traversals of the target. By using the copper clipper, it was hoped to reduce this beam degradation by the removal of some of these protons scattered from the target. Estimates of the remaining beam energy spread can best be made with the help of the meson spectra obtained from hydrogen.

The hydrogen spectrum is expected to occur as a peak at the energy predicted from kinematics of the reaction $p+p\rightarrow\pi^++d$, with a much smaller low energy tail due to the reaction leading to an unbound $N-P$ final state. The observed spread of this peak is a measure of the energy and angular resolution of the detector as well as the spread in incident proton beam energy. From the experimental hydrogen π^+ spectra (shown in Fig. 2) together with estimates of the detector energy and angular resolution, and meson energy loss in traversing the target, in conjunction with the variation in meson energy with emission angle and proton energy, it is

TABLE I. Summary of 90° differential cross sections for meson production, integrated over meson energy, $(d\sigma)/(d\omega)_{90°}$, in cm^2 sterad^{-1}.

Element	At 380-Mev incident proton energy	At 365-Mev proton energy	At 345-Mev
Hydrogen	$(7.5\pm1.8)\times10^{-29}$	$(4.6\pm1.2)\times10^{-29}$	$(2.9\pm0.7)\times10^{-29}$
Carbon	$(6.7\pm1.5)\times10^{-28}$	$(6.4\pm1.4)\times10^{-28}$	$(4.7\pm1.3)\times10^{-28}$

[5] Ernest M. Henley, Phys. Rev. **85**, 204 (1952); Passman, Block, and Havens, Phys. Rev. **83**, 167 (1951).
[6] Block, Passman, and Havens, preceding article [Phys. Rev. **88**, 1239 (1952)].

estimated that the spread in incident proton energy is approximately 10 Mev. As discussed later, these sharply peaked meson spectra produced in hydrogen are observed to occur in the meson energy region predicted from kinematics of the reaction $p+p\rightarrow\pi^{+}+d$, corresponding to an incident proton energy approximately the same as calculated from the $(H\rho)$ value at the target position. Since any uniform spread in incident proton energy extending considerably below this $H\rho$ value would result in a displacement of the meson spectrum peak to lower meson energies, contrary to observation, it is inferred that proton energies corresponding to the proper $H\rho$ value at the target position strongly predominate in the beam energy distribution.

The method of calculation of the absolute differential cross section for meson production, from a knowledge of the areal density of π^{+} meson endings observed along the inclined Ilford C-2 nuclear emulsion, is described in detail in the previous paper.

An accurate monitoring of the incident proton flux is accomplished by an absolute measurement of the target's C^{11} positron activity after bombardment. The excitation function for this reaction, $C^{12}(p,pn)C^{11}$, has been measured by Aamodt *et al.*[7]

The meson production cross sections are corrected for a geometrical nuclear interaction cross section to account for absorption and scattering in the tapered copper absorber.

MESON PRODUCTION IN HYDROGEN

A. Results

The 90° differential cross sections for π^{+} meson production in hydrogen at incident proton energies of 345, 365, and 380 Mev were obtained by a subtraction technique involving thin polyethylene $(CH_2)_n$ and carbon targets. The feasibility of this subtraction method rests upon the experimental fact that the 90° π^{+} spectrum from hydrogen occurs as a sharp peak in the low energy region where the carbon differential cross section is relatively quite small.

The polyethylene targets were 0.23 g/cm² wide in the proton beam direction and only 0.09 g/cm² thick. Mesons of 20-Mev kinetic energy traveling downward through the target toward the detector region (see Fig. 1) will lose less than 1 Mev, on the average, by ionization loss in the target, while the high energy incident protons have a negligible energy loss in traversing the thin targets.

Results for the hydrogen 90° differential cross sections $d^2\sigma/d\omega dE$ at the above proton energies are plotted in Fig. 2 as a function of meson energy. These meson spectra are observed to have peaks at meson energies consistent with energy and the momentum conservation laws for the reaction $p+p\rightarrow\pi^{+}+d$, as indicated by arrows drawn in the figures.

[7] Aamodt, Peterson, and Phillips, University of California Radiation Laboratory Report 526, 1949 (unpublished).

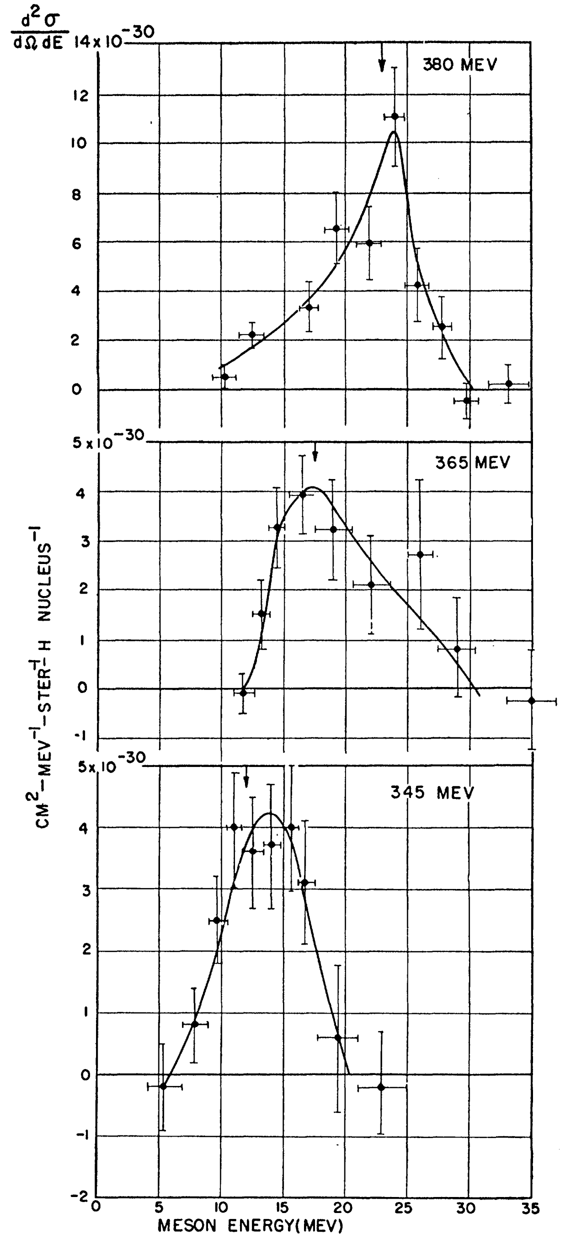

FIG. 2. π^{+} differential cross section in hydrogen at (90°±1.5°) to the proton beam for 345-Mev, 365-Mev, and 380-Mev proton energy.

The statistical uncertainties indicated in the data are the standard deviations of the counting including the errors due to subtraction. The hydrogen spectra are based on the following numbers of observed $\pi-\mu$ decays: 150 events for the H spectrum at 345 Mev, 250 for 365 Mev, and 180 for 380 Mev.

Values for the 90° π^{+} differential cross sections in hydrogen, integrated over meson energy $d\sigma/d\omega$, are given in Table I. These values are obtained by a histogram of the meson energy spectra, and the statistical uncertainties given are for the absolute values of

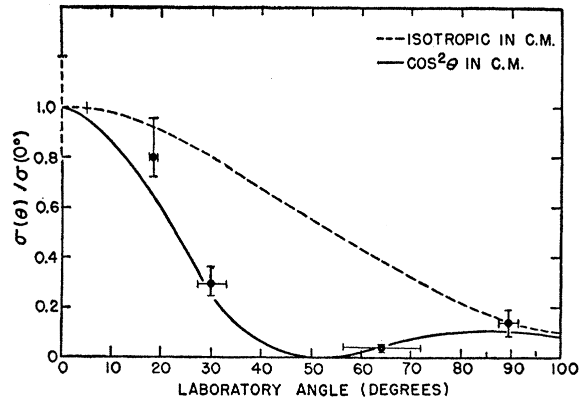

FIG. 3. Angular dependence of π^+ production in $p-p$ collisions, from V. Peterson *et al.*, University of California Radiation Laboratory Report UCRL-1405 (unpublished).

the cross sections. These include the uncertainty in absolute proton flux monitoring using the induced C^{11} activity and the measurements of emulsion thickness, as well as statistics of the counting of mesons.

The uncertainty in the relative increase of the 90° differential cross section for π^+ production in hydrogen with increasing proton energy should involve principally the uncertainty of the histogram computation of the cross section, based on the number of mesons detected. Any systematic error in the absolute calibration will be minimized in these ratios which are $(d\sigma/d\omega)_{90°}$ at 380 Mev: $(d\sigma/d\omega)_{90°}$ at 365 Mev: $(d\sigma/d\omega)_{90°}$ at 345 Mev $=2.6:1.6:1$, with an estimated uncertainty of approximately 15 percent.

B. Analysis

The available evidence concerning meson production in $p-p$ collisions at 340 Mev points to production occurring principally via the reaction $p+p\rightarrow\pi+d$,[8] with an angular dependence proportional to $(0.07\pm0.07+\cos^2\theta)^2$ in the c.m. system. From the work of Durbin, Loar, and Steinberger, who measured the cross section for the inverse process of π^+ absorption in deuterium,[9] there is reason to believe that this angular distribution remains constant in the proton energy interval from 340 to 380 Mev. However, their estimate of the isotropic contribution to the cross section is closer to 0.16 ± 0.08 rather than the 0.07 ± 0.07 given by Whitehead and Richman.

A comparison of our value of the 90° π^+ differential cross section for 345-Mev protons with work done at Berkeley at 340 Mev at other angles is given in Fig. 3. This figure, from an article by Peterson, Illoff, and Sherman,[10] shows the 340-Mev differential cross section $d\sigma/d\omega$, for π^+ mesons produced in hydrogen at 18°, 30°, and 60°, to the proton beam, normalized to Cartwright's measurement at 0°. We have appended our value for $d\sigma/d\omega$ at 90° and 345 Mev. If one assumes the reaction $p+p\rightarrow\pi^++d$, with the resulting line spectrum of mesons in the c.m. system, then from a transformation of the solid angle factor between c.m. and laboratory systems, one can easily derive the dependence of $d\sigma/d\omega$ upon laboratory angle of emission for various assumptions about the c.m. angular dependence. Curves indicating isotropic and $\cos^2\theta$ c.m. angular dependence are shown in Fig. 3. The agreement with experiment is seen to be quite good for the $\cos^2\theta$ assumption.

If one analyzes the 90° π^+ differential cross sections at the incident proton energies of 345, 365, and 380 Mev by assuming the reaction $p+p$ yields π^++d, together with a $\cos^2\theta$ angular distribution in the c.m. system, as indicated from the above discussion, then one can calculate the total π^+ cross sections in hydrogen by means of the solid angle transformation factor between laboratory and c.m. systems at these proton energies. The values of the resulting absolute total cross sections σ_{tot} are 10.6×10^{-28} cm^2 at an incident proton energy of 380 Mev, 6.1×10^{-28} cm^2 at 365 Mev, and 3.5×10^{-28} cm^2 at 345 Mev. The statistical uncertainty in these absolute cross sections is $\sim$25 percent.

In comparing the excitation function for meson production in hydrogen with theoretical predictions, the significant quantity is the *relative* increase in the meson production total cross section with increasing proton energy. Consequently, the excitation function for the total cross section for π^+ meson production in hydrogen, σ_{tot}, relative to the value of σ_{tot} at 345 Mev is plotted in Fig. 4. This curve is arbitrarily normalized to an absolute value of 3.5×10^{-28} cm^2 at 345 Mev. By way of comparison, the point at 340 Mev represents the combined Berkeley results for σ_{tot} as quoted by Peterson *et al.*[1] In Fig. 4, the statistical uncertainties in σ_{tot} relative to the 345-Mev cross section measurement are indicated together with the data. These cross section ratios, σ_{tot} (380 Mev): σ_{tot} (365 Mev): σ_{tot} (345 Mev) $=2.95:1.7:1$, with a statistical uncertainty of approximately 20 percent, are very little affected by small isotropic contributions to the angular dependence of the cross section.

An attempt to fit the experimental excitation function for meson production in hydrogen with a simple power law, such as $(T_{max})^n$, where T_{max} is the maximum c.m. meson energy available in the collision, indicates that the assumption of $n=2$, as shown by the solid curve (B) in Fig. 4, is in fairly good agreement with the data.

The inverse process concerning π^+ absorption in deuterium yielding two fast protons, $\pi^++d\rightarrow p+p$, has been studied by Durbin, Loar, and Steinberger[11] for meson energies between 25 and 53 Mev in the center-of-mass system. This is equivalent to the kinematical situation for the process $p+p\rightarrow\pi^++d$ for incident

[8] F. Cartwright, thesis, University of California, 1951 (unpublished).

[9] Durbin, Loar, and Steinberger, Phys. Rev. **83**, 646 (1951); and H. Loar (private communication).

[10] Peterson, Illoff, and Sherman, University of California Radiation Laboratory Report 1405 (unpublished).

[11] Durbin, Loar, and Steinberger, Phys. Rev. **84**, 581 (1951).

proton energies 350–410 Mev. From detailed balancing considerations, Cheston[12] has shown that these two inverse processes are connected through the relation

$$\sigma_{\text{total}\,(\pi^++d)}=\sigma_{\text{total}\,(p+p)}\times\frac{2}{3(2S+1)}\times\frac{p^2}{q^2},$$

(S = meson spin), where p and q are the proton and meson momenta, respectively, in the c.m. system of the reacting particles. From our work on the excitation function of the $p+p\rightarrow\pi^++d$ process, we can therefore predict an increase in the total cross section for $\pi^+ +d\rightarrow p+p$ of 1.95±20 percent in the meson energy interval 24–39 Mev (corresponding to proton energies 345–380 Mev for the inverse process), in good agreement with the value obtained directly for this process by Durbin *et al.*, namely, 1.9±15 percent.

Brueckner[13] has calculated the cross section for meson production in a nucleon-nucleon collision on the basis of third-order perturbation theory using the methods of Feynman and Dyson applied to meson theory. Only for pseudoscalar theory with pseudovector coupling does the calculation give a nonisotropic angular dependence. The formation of a deuteron is included in this calculation by the incorporation of the deuteron wave function, evaluated at the origin, as an additional factor in the matrix element for the process. The predicted dependence of the $p+p\rightarrow\pi^++d$ meson production process on incident proton energy varies near threshold as the $\frac{3}{2}$ power of the meson's kinetic energy in the center-of-mass system, $(T_{\max})^{\frac{3}{2}}$, for the case of PS theory with PV coupling. Including the contribution of the unbound final $n-p$ state in the proportion estimated by Brueckner, amounting to $\frac{1}{4}$ of the cross section for the bound state at 350 Mev, yields the over-all energy dependence of the $(p-p,\,\pi^+)$ production process shown by the dotted curve (A) in Fig. 4. This theoretical excitation function, which is arbitrarily normalized to a value of 3×10^{-28} cm^2 at 340 Mev, is seen to be significantly below the observed experimental energy dependence in the region of high proton energies.

Because of the inherent difficulties involved in the application of quantum theoretical-perturbation methods to a process involving such strong interaction constants as meson production, the phenomenological theory of Watson and Bruechner[14] has been used. This phenomenological theory, which has been successful in interpreting the 0°, 340 Mev $(p-p,\,\pi^+)$ spectrum of Cartwright,[8] predicts a variation of this $(p-p,\,\pi^+)$ total cross section with increasing proton energy, for the case of a transition operator proportional to the first power of the meson momentum, that is essentially the same as the results previously given from Brueckner's work. For the assumption of a triplet final $n-p$ spin state, including the large contribution due to deuteron formation, the predicted π^+ meson production excitation function of Watson and Brueckner is given by curve A, Fig. 4, arbitrarily normalized to a cross section of 3×10^{-28} cm^2 at 340 Mev, the value quoted by the above authors. This energy dependence, which clearly rises less sharply than the experimental excitation function, can be brought into agreement by requiring that the factor $\Gamma^2(p)$, defined by Watson and Brueckner as the nucleon momentum (p) dependent factor in the matrix elements (but assumed constant in their results), should have a dependence of the order of p^4.

Chew *et al.*[15] have recently pointed out that Watson and Brueckner's treatment does not separate the meson-nucleon interaction from the interaction between the two nucleons. These authors proceed to separate out the effects of nuclear binding in initial and final states of the $p+p\rightarrow\pi^++d$ reaction, in the spirit of explicitly evaluating the transition operator factor $\Gamma^2(p)$ of Watson and Brueckner. These calculations lead to additional factors in the production cross section, proportional to the Fourier amplitude of the deuteron or diproton wave function which are then multiplied by the meson-nucleon matrix elements and kinematical factors to yield the over-all energy dependence of the reaction. These Fourier amplitudes probably decrease fairly rapidly with increasing incident proton momentum, $\sim(1/p^5)$, so that the required *meson-nucleon* interaction must rise even more sharply with energy than was previously estimated, in order to explain the steep experimental excitation function for the over-all production process. Durbin, Loar, and Steinberger[11] speculate that this steep energy dependence is probably

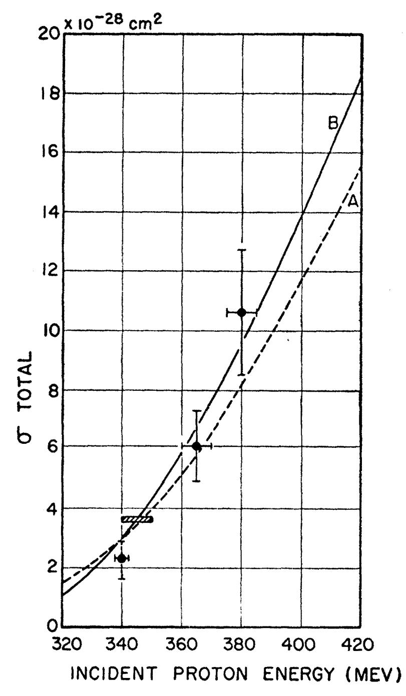

FIG. 4. Variation of the total cross section for meson production in $p-p$ collisions with increasing incident proton energy.

[12] W. Cheston, Phys. Rev. **83**, 1118 (1951).
[13] Keith A. Brueckner, Phys. Rev. **82**, 598 (1951).
[14] K. Watson and K. Brueckner, see reference 2.
[15] Chew, Goldberger, Steinberger, and Yang, Phys. Rev. **84**, 581 (1951).

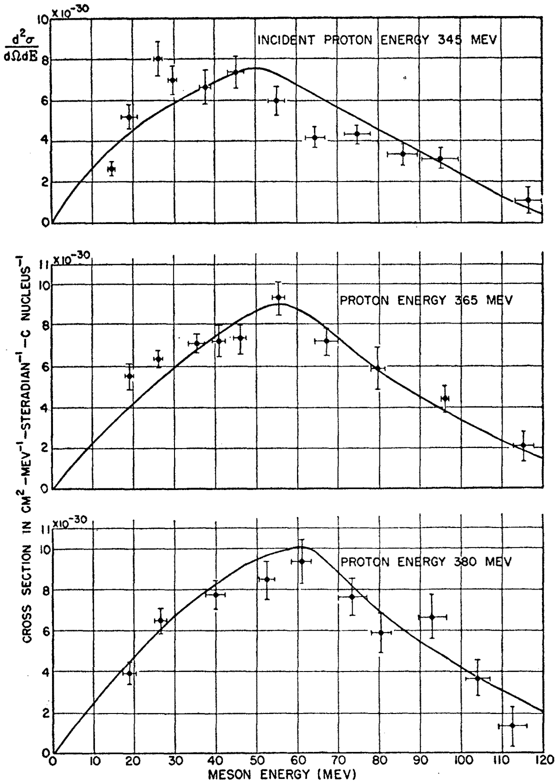

FIG. 5. π^+ meson differential production cross sections in carbon at ($90°\pm5°$) to the proton beam for 345-Mev, 365-Mev, and 380-Mev proton energy. The curves represent theoretical 90° meson spectra from carbon using a Gaussian target nucleon momentum distribution together with a $(\bar{T}_{max})^2$ empirical nucleon-nucleon meson production excitation function.

of the same origin as the sharp excitation function in neutral photomeson production. To explain this latter process, Brueckner and Case[16] have suggested the influence of a resonance interaction with a nucleon isobar, which is one of the characteristics of strong coupling meson theory. Such a meson-nucleon resonance interaction has also been proposed by Brueckner,[17] to explain the recent experimental evidence[18] for a large, strongly energy dependent π^+ scattering process in hydrogen.

RESULTS FOR MESON PRODUCTION IN CARBON

Carbon targets, 50 mils thick and 75 mils or 0.3 g/cm² in the beam direction, were exposed to the proton beam at $H\rho$ values corresponding to incident proton energies of 345, 365, and 380 Mev. The duration of the exposures averaged about 15 sec, and the incident beam currents striking the target were approximately 0.6×10^{-8} amperes.

Figure 5 shows the 90° differential cross sections $(d^2\sigma)/(d\omega dE)$, for π^+ mesons produced in carbon at the above-mentioned three proton energies. These π^+ spectra are based upon 350 $\pi-\mu$ events for the 345-Mev cross section, 550 $\pi-\mu$ events for the 365-Mev cross section, and 300 $\pi-\mu$ events for the 380-Mev cross section. The absolute value of the 380-Mev cross section is somewhat higher than that reported in the previous paper, although it is within the statistical uncertainties stated, which correspond only to the probable error in counting mesons. The absolute cross section involves the calibration using the C^{11} activity which will introduce an additional error. However, the uncertainty in the relative increase should not involve this absolute calibration.

The meson spectra from carbon are seen to occur as broad single maxima distributions. The shift of the energy of the maximum of the curve from ~45 Mev for a proton energy of 345 Mev, to ~55 Mev at 365 Mev, and to ~62 Mev at 380 Mev, is noteworthy.

To obtain the 90° π^+ differential cross sections integrated over meson energy $(d\sigma^+)/(d\omega)$ the above data are histogrammed, yielding the values given on line 2 of Table I. The uncertainties given include the estimate of the precision of the absolute calibration as well as the statistics of counting. From this table it is seen that the relative increase in the 90° π^+ carbon cross section is less than the increase in the hydrogen cross section in this same incident proton energy interval.

With regard to the production of π^- mesons in carbon the significant experimental fact is that the negatives are produced in much less quantity than the positives, for all three proton energies studied. In the identical regions scanned for π^+ mesons included in the previous distributions, only 23 π^- mesons were found for the 345-Mev spectrum, 21 π^- for 365 Mev, and 29 π^- for 380 Mev.

Because of these limited statistics, only qualitative statements may be made concerning the production of negatives in carbon. The spectrum of π^- mesons appears to shift to lower energies than the corresponding π^+ spectrum at the same proton energy. That is, the energy of the maximum of the curve of the π^- distribution occurs at a lower meson energy than that of the π^+ distribution, and the meson spectrum cut-off energy is also lower for the case of π^- mesons (~90 Mev). The ratios of the π^+ to π^- 90° cross sections for carbon, integrated over meson energy, were within the range $(10\pm3):1$ for all three proton energies studied.

This observed π^+/π^- ratio in carbon is considerably greater than the *a priori* expected ratio of $(A+Z)/(A-Z)=3$, which would be found if the protons and neutrons in the carbon nucleus had equal cross sections for meson production and if the $(p-n, \pi^+)$ reaction had the same probability as $(p-n, \pi^-)$.

Analysis of the still larger π^+/π^- ratio observed for meson production in deuterium by protons[19] indicates that the strong interaction in the final state of the $(p-p, \pi^+)$ reaction may account for this charge assymmetry in meson production.

[16] K. A. Brueckner and K. M. Case, Phys. Rev. **83**, 1141 (1951).
[17] Keith A. Brueckner, Phys. Rev. **86**, 106 (1952).
[18] Anderson, Fermi, Long, and Nagle, Phys. Rev. **85**, 936 (1952).
[19] Passman, Block, and Havens, Phys. Rev. **85**, 370 (1952).

A large π^+/π^- production ratio of the order of 15 was recently observed by Dudziak[20] for mesons produced in carbon at 0° to the Berkeley 340-Mev proton beam. However, Richman and Wilcox in an early experiment on meson production[21] found a π^+/π^- ratio of 5.1 ± 1.0 in carbon at 90° to this same proton beam. The discrepancy between this value and that of the present work occurs principally in the π^+ production, where we find a differential cross section at 345 Mev that is approximately twice as large as that reported by Richman and Wilcox, namely, $(2.3\pm0.5)\times10^{-28}$ cm^2 sterad^{-1}, although the statistical uncertainty in the ratio of these absolute cross sections is $\sim$35 percent. Good agreement with regard to the spectral shape of the energy distributions is found; both experiments indicate a sharp rise in the cross section at low energies, the maximum occurring at an energy of approximately 45 Mev and tailing off at higher energies, although the cross section is still not zero at the maximum energy observed, 120 Mev.

PHENOMOLOGICAL CALCULATION OF π^+ MESON PRODUCTION IN CARBON

Calculation of the production of π^+ mesons in carbon is done in the same manner as in the previous paper using the following assumption:

(a) Meson production in carbon occurs through nucleon-nucleon interactions.

(b) The momentum distribution of target nucleons before collision is Gaussian, falling to $1/e$ of its maximum value at a nucleon energy of $\sim$14 Mev, as suggested by the work of Cladis[22] on the energy spectrum of protons scattered from carbon.

(c) The nucleon-nucleon meson production process has the following properties:

(1) a $\cos^2\theta$ angular dependence in the c.m. system;

(2) a strong final state nucleon interaction which requires the emitted meson to receive all the available kinetic energy $T_{\max}$ in the c.m. system;

(3) the excitation function is proportional to $(T_{\max})^2$ (see Fig. 4).

Results of the calculations at 345, 365, and 380 Mev are plotted together with the experimental data in Fig. 5 and show fairly good agreement with regard to (a) the general shape of the meson spectra, (b) the shift of the meson spectrum peak energy to higher meson energies with increasing proton bombardment energy, and (c) the presence of the high meson energy tail in the distribution, probably due to the high momentum states in the carbon nucleus.

Although the theoretical curves are independently normalized in this figure, the calculations do predict an increase in this 90° differential cross section of $\sim$1.5 in the energy interval 345 to 380 Mev, in good agreement with the experimental increase (see Table I).

A further application of this calculation is to the ratio of 90° π^+ production cross sections in carbon and hydrogen. Based on the above calculation, using a normalized target momentum distribution and the experimental meson production excitation function, it is found that the expected efficiency of a nucleon in carbon for meson production is approximately twice that of a free nucleon at rest. This effect is due to the strong excitation function for π^+ production which weights the collisions in which the target nucleon approaches the incident nucleon, with a consequent increase in the available c.m. meson energy, more than those collisions in which the target nucleon's motion is in the other direction. For the *experimental* ratio of the carbon and hydrogen 90° π^+ cross sections we find ratios of (10–12):1 in the proton energy interval studied. Correcting for meson reabsorption in the target nucleus, from the work of Brueckner, Serber, and Watson,[23] we would expect these production cross sections to stand in the ratio of 18:1. In view of the efficiency factor of 2 for component nucleons of the carbon nucleus, owing to their relative motion, this observed ratio of π^+ production in carbon to hydrogen can be understood if the $(p-n, \pi^+)$ production process has $\frac{1}{2}$ the probability of the $(p-p, \pi^+)$ process, in agreement with *a priori* considerations of the production process, since either proton in the latter case may give rise to the positive meson. While this conclusion is in agreement with analysis of meson production in deuterium,[24] where the large π^+ production cross section requires an appreciable contribution from the $p-n$ reaction, it makes it difficult to understand the observed large positive to negative ratio in carbon and deuterium, since this hypothesis would require an assymmetry in the $(p-n, \pi^+)$ and $(p-n, \pi^-)$ production processes. This asymmetry appears to be contrary to notions of charge independence of nuclear forces at low energy.

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