Pion Production Ratios. II

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(Received June 7, 1954)

The ratio of positive to negative pion production is considered for protons of ~0.35-Bev energy incident on nuclei. The model of a single excited nucleon is used. It is argued that (i) at these energies the meson-producing nucleon state is about equally likely to be $T=\frac{1}{2}$ or $T=\frac{3}{2}$; (ii) structural effects in the final nucleus inhibit π^- production in light nuclei, where isotopic spin is conserved. Effect (ii) may be partly responsible for the observed difference in shape of π^+ and π^- production curves as a function of A.

I. $T=3/2$ PRODUCTION

PREVIOUS considerations[1] of pion production ratios around 1.5 Bev are here extended to lower energies. We begin by correcting[2] a numerical error in I: in the paragraph leading to Eq. (1) of I the fractional weights $\frac{3}{4}$ and $\frac{1}{4}$ should be reversed. The over-all fractional weights for pion production are then $(\frac{5}{6}, \frac{1}{6}, 0)$, and Eq. (1) reads

$$\begin{aligned} (\pi^+)&: \quad (1/15)[26\sigma_2^s+25\sigma_1^s], \\ (\pi^0)&: \quad (1/15)[28\sigma_2^s+5\sigma_1^s], \qquad \text{(C1)} \\ (\pi^-)&: \quad (1/15)[6\sigma_2^s]. \end{aligned}$$

Equation (2) is unchanged, but the corrected Eq. (3) reads

$$\begin{aligned} (\pi^+)&: \quad [1.28\sigma_2^s+0.83\sigma_1^s+0.37\sigma_2^a], \\ (\pi^0)&: \quad [0.90\sigma_2^s+0.52\sigma_1^s+0.37\sigma_2^a], \qquad \text{(C3)} \\ (\pi^-)&: \quad [0.70\sigma_2^s+0.09\sigma_1^s+0.37\sigma_2^a]. \end{aligned}$$

These changes do not alter the essential conclusions of I: ρ is unchanged for $\sigma_2 \gg \sigma_1$ and is increased from 6 to 9 when $\sigma_1 \gg \sigma_2$. The remarks about π^0 production should be deleted.

II. $T=1/2$ PRODUCTION

A number of measurements have been made[3-7] of the ratio $\rho=\pi^+/\pi^-$ at a specific angle of production, using incident protons of 340–380 Mev. For light target nuclei (Be excepted) the values of ρ are large, of order 10 for C and Al, and even larger for D. Among heavy nuclei (Pb, Ag, Cu), ρ drops to around 5, even for $E_\pi=40$ Mev[5] where the pion emission should not be appreciably affected by nuclear Coulomb barriers. Among the light targets Be is exceptional in having $\rho \sim 5$ like the heavy nuclei.

The part of the pion production that occurs through the resonant $T=\frac{3}{2}$ state is predominantly due to single-nucleon excitation at $E^p \sim 1$ Bev,[1] and should be even more so at $E^p \sim 0.35$ Bev. This type of production has $\rho(3/2)\approx 10$, which is appreciably larger than the value observed for heavy nuclei. The simplest modification of the model is to assume that some production occurs through a $T=\frac{1}{2}$ excited nucleon state; such production has $\rho(1/2)\approx 3$. Let $\bar{\rho}\approx 5$ be the measured ratio for a heavy nucleus, and $\pi(3/2)$, $\pi(1/2)$ the total pion production (all charges) proceeding through single excitation of a nucleon to a $T=\frac{3}{2}$ or $T=\frac{1}{2}$ state. For proton bombardment of a nucleus with Z protons and N neutrons, the procedure of reference 1 yields

$$\frac{\pi(3/2)}{\pi(1/2)}=\left\{\frac{2Z+N}{\lambda Z+N}\right\}\left\{\frac{\bar{\rho}-\rho(1/2)}{\rho(3/2)-\bar{\rho}}\right\}, \qquad (1)$$

$$\lambda=2\sigma_1^{s\prime}/(\sigma_1^{s\prime}+\sigma_1^{a\prime}).$$

Here the σ_1' are cross sections for single excitation of a nucleon to a $T=\frac{1}{2}$ state in an $n-p$ collision; the superscripts s, a denote respective compound states of $T=1, 0$.

In lieu of any information on the subject, we assume $\lambda\approx 1$. Then for a heavy nucleus with $Z=0.8N$, $\rho(1/2)=2.6$, and by Eq. (C3) $\rho(3/2)=9.2$. Substitution of these values with $\bar{\rho}=5$ into (1) yields

$$\pi(3/2)/\pi(1/2)\approx 0.8. \qquad (2)$$

Result (2) is compatible with the high-energy results indicating $\pi(3/2)\gg\pi(1/2)$, if the $\pi(3/2)$ excitation is assumed to be resonant at some energy above that generally reached by $E_p\approx 0.35$-Mev protons, while the $\pi(1/2)$ excitation is not. This is in accord with the observations on π-nucleon scattering.

III. LIGHT NUCLEI

The enhancement of ρ for light nuclei at the same E_p must now be attributed to structural effects in these nuclei: in particular, to the validity of isotopic spin as a quantum number for initial and final states, and the strong dependence of nuclear binding energy on this quantum number. Pion production increases rapidly with proton energy around $E_p=0.35$ Bev.[8] This implies that the initial production process (regardless of subsequent meson scattering or absorption in the nucleus)

[1] D. C. Peaslee, Phys. Rev. **94**, 1085 (1954); hereafter referred to as I.
[2] H. A. Bethe (private communication).
[3] Block, Passman, and Havens, Phys. Rev. **88**, 1239 (1952).
[4] J. Carothers and C. G. Andre, Phys. Rev. **88**, 1426 (1952).
[5] R. Sagane, Phys. Rev. **90**, 1003 (1953).
[6] S. L. Leonard, Phys. Rev. **93**, 1380 (1954).
[7] W. F. Dudziak, Phys. Rev. **94**, 756 (1954).
[8] Passman, Block, and Havens, Phys. Rev. **88**, 1247 (1952).

tends to concentrate most of the available energy in the meson and leave the residual nucleus in a state of low excitation. Consider the final state of the nucleus (bound or unbound) after emitting the π but no nucleons. If the initial light nucleus had $T=0$ in its ground state ($N=Z$), the final nuclear state will have $T=\frac{1}{2}$, $\frac{3}{2}$ for π^+ emission, but $T=\frac{3}{2}$ only for π^- emission. For light, odd-A nuclei, however, the lowest $T=\frac{3}{2}$ state lies above the lowest $T=\frac{1}{2}$ state by $\Delta(\frac{3}{2},\frac{1}{2})\approx 10$ Mev.[9] Thus the low-lying residual states have a preponderance of $T=\frac{1}{2}$ levels, which will tend to inhibit π^- production and increase the value of ρ.

This mechanism of π^- inhibition should be most effective for production from deuterium: here $\Delta(\frac{3}{2},\frac{1}{2})$ presumably has a maximum value, and the center-of-gravity energy is the lowest for a given E_p. The observations agree with this expectation: ρ achieves its largest values for D; and, even more satisfactory, it increases rapidly with E_π for fixed E_p.[4]

The above argument for light nuclei is special to targets with $T=0$. For light, odd-A targets with $N=Z+1$, both π^+ and π^- emission lead to nuclear states with $T=1$, 2 that differ only by Coulomb energy. For a light nucleus the Coulomb difference should be small, so that ρ would approach the uninhibited value. This is in agreement with the observations on Be.

An Al target, on the other hand, shows a relatively high value of ρ. In this case the Coulomb energy difference between the final nuclear states is $\gtrsim 10$ Mev, even though isotopic spin appears not to have broken down seriously. This Coulomb energy difference is again in the direction to inhibit π^- production.

These arguments for light nuclei indicate that with protons on $N=Z+1$ target nuclei π^0 production should be considerably enhanced for $A=4n-1$ target but not for $A=4n+1$, because[9] the $\Delta(1,0)$ of the final nuclei are of order 15 and 0 Mev, respectively.

For heavy nuclei isotopic spin is no longer a good quantum number, and a tendency to balance exists between the energies of nuclear symmetry and of Coulomb repulsion. The residual nuclei from π^+ and π^- emission have relatively small energy differences in their ground states—of order 4, 3, and 2 Mev for Cu, Ag, and Pb targets. Structural effects of heavy nuclei therefore provide relatively little π^- inhibition.

The inhibition of π^- production by protons on light nuclei may partly account for the observation that π^- production increases more steeply with target number A than π^+ production. Among light nuclei, π^- production should show strong isotope dependence (e.g., B^{10}, B^{11}); no such dependence is expected for π^+ production, and none has been found.[10]

[9] For notation see D. C. Peaslee, Phys. Rev. **95**, 717 (1954).

[10] J. Merritt, University of California Radiation Laboratory Report UCRL-2424, 1953 (unpublished).

PHYSICAL REVIEW VOLUME 95, NUMBER 6 SEPTEMBER 15, 1954

Phase Shift Analysis of the Scattering of Negative Pions by Hydrogen*

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(Received May 6, 1954)

A phase shift analysis of the scattering of negative pions by hydrogen in the range 115 to 215 Mev is presented. In the present paper two solutions are given that represent the data within the experimental error by two rather different sets of phase shifts. One of these solutions is excluded on the basis of some information on the scattering of positive pions. The other solution is compatible with all the experimental data known at present. It is pointed out, however, that this is not the only solution that has such properties. In addition, calculations carried out on scattering of positive and negative pions at 61.5 Mev are presented.

I. INTRODUCTION

THIS paper describes some systematic attempts to analyze in terms of phase shifts the experimental data on pion-hydrogen scattering.[1,2] Two essentially independent calculations are described. Part 1 is concerned with the analysis of the experimental results of B[1] on the scattering of negative pions in the energy range 115 to 215 Mev. These calculations that are now being published have been completed during the spring and summer of 1953 and have been circulated privately. In the intervening period there have been a number of other attempts at interpreting essentially the same data.[3]

* Research supported by a joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

[1] Anderson, Fermi, Martin, and Nagle, Phys. Rev. **91**, 155 (1953), quoted as A; Fermi, Glicksman, Martin, and Nagle, Phys. Rev. **92**, 161 (1953), quoted as B.

[2] Bodansky, Sachs, and Steinberger, Phys. Rev. **90**, 997 (1953); **93**, 918, 1367 (1954).

[3] M. Glicksman, Phys. Rev. **94**, 1335 (1954); R. Martin, this issue [Phys. Rev. **95**, 1583 (1954)]; and in particular de Hoffmann, Metropolis, Alei, and Bethe, following paper [Phys. Rev. **95**, 1563 (1954)], where the calculations presented in this paper are extended and attempts are made to choose one out of several possible solutions.