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Seminar in Meson Physics

THE RATIO OF THE PRODUCTION CROSS SECTIONS OF CHARGED PIONS PRODUCED BY NUCLEON BOMBARDMENT

L. Neher
Radiation Laboratory, University of California
Berkeley, California

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Introduction

A general review of pion production in nucleon-nucleus collisions may be found in Chapter III of R. E. Marshak's book, "Meson Physics," published in December, 1952, by McGraw-Hill Book Co. Experiments recently completed at the Berkeley Radiation Laboratory provide some additional unpublished ratio data. It is with the kind permission of the various experimenters who were involved in experiments 3, 4, 5, 6, 8, 9, 10, 11, that the ratio data in Table I have been made available for discussion.

Comparison of Data and Detection Methods

It is evident from an inspection of Table I that pion production has been studied with nucleon beam energies ranging from 240 to 381 Mev. Two types of pion detectors were employed: the nucleon emulsion and the scintillation counter. A magnetic field was usually placed between the target and the detectors to reduce the charged-particle background and to separate the negative and positive pions. In nuclear emulsions, the positive pions are recognized by their decay to positive muons. About three quarters of the negative pions form stars.

With scintillation counters, pion identification was made by measuring velocity and/or range of the particles, and their curvature in the magnetic field. Counter arrangements yield pion data at a greater rate than the emulsion detectors. The principal disadvantage

of counters is in detecting low-energy pions (because of the thickness of the scintillation material) and in separating electrons and high-energy pions of the same momentum. If the production of pions is very small compared to the charged particle background, the nuclear emulsion scanner tends to count too few pions, whereas the scintillating counter methods tend to count too many pions. This type of systematic effect tends to yield pion ratios that are either too small or too large.

More data exist as direct-ratio data, fewer as pion energy spectra. For this reason it was decided to compare the pion differential cross sections as a function of pion energy in a given energy range, rather than the integrals of the cross section over the pion energy. In forming the ratios from the energy spectra we have avoided the extreme low and high energy regions, since the ratios approach 1 and ∞ respectively, and the number of charged pions of one sign approaches zero. The energy range for the directly determined ratios was about 15 percent to 25 percent, depending upon conditions chosen by the experimenter. The same energy range has been roughly considered in forming ratios from the energy spectra data. The data can be compared from the following plots. Lab angles and pion kinetic energy in lab system are used.

Discussion of Data

The main features of the charged pion ratios produced in nuclear-nucleus collisions, based upon the preceding data, are as follows:

(a) Independent of target and beam energy

1. The ratio R is high.
   i.e., protons incident, $\pi^+/\pi^- >> 1$
   neutrons incident, $\pi^-/\pi^+ >> 1$
2. R increases as a larger pion kinetic energy T is observed.
3. For a fixed T, R decreases as pion angle of emission θ is increased.

(b) As atomic number of target is increased, R decreases.

(c) For a fixed target, R probably decreases as beam energy is raised.

Some of the data may not be consistent with these general statements. The aluminum ratio at $\theta = 90^\circ$ seems to decrease as T is increased; however, the statistical errors are large. No other data on Al exist. The ratio for carbon at $\theta = 180^\circ$ (Fig. 7) is of the same order as or higher than its ratio at $\theta = 90^\circ$ (Fig. 5). For neutrons incident on carbon the ratio continues to drop for angles greater than 90° (Fig. 1). Finally the ratios for carbon 90° increase from about 5 to 10 when incident proton energy is raised from 340 to 381 Mev (Fig. 5).

We believe now that charge independence, and conservation of isotopic spin, are the principal reasons why the process $n + p \rightarrow \pi\pm$ is restricted compared to $p + p \rightarrow \pi^+$ or $n + n \rightarrow \pi^-$. The exclusion and coulomb arguments are still operative, but are not the main causes for the large ratios.

(1) Exclusion Argument

The general features of the ratios, however, such as the variation with pion energy, beam energy, and angle of emission, have been predicted by Chew and Steinberger[1]. Their argument is as follows. Pion production is assumed to take place in collision between a high-energy incident nucleon and one of the nucleons in the nucleus. In their theory, the pion production probability is modified by the interaction of the two final nucleons, after collision, with those nucleons in the nucleus that did not take part in the collision. If the two collision nucleons do not have enough energy to escape from the nucleus, than they must be accommodated into the nuclear structure. The Pauli Principle excludes one or both nucleons from entering cells in phase space which are already filled. According to the statistical gas model of the nucleus, the cells in phase space are filled up to a maximum momentum corresponding to a Fermi kinetic energy E_F of about 25 Mev. Owing to the uncertainty principle, the energy value is not precise.

1 G. Chew and J. Steinberger, Phys. Rev. 78, 497 (1950)

Chew and Steinberger made a rough estimate of the relative efficiency for π^+/π^- production in proton-nucleus collisions with the result that

$$\frac{\pi^+}{\pi^-} = \frac{1 - (E_F/T_m - T)}{1 - (2\,T_F/T_m - T)}$$

where T_m is the maximum possible laboratory kinetic energy of the pion, T is the observed laboratory kinetic energy, and E_F is the kinetic energy of a nucleon in a degenerate Fermi neutron - proton gas.

The expected charged-pion ratio from a nucleus containing equal numbers of protons and neutrons is:

$$\frac{\pi^+}{\pi^-} = 3 \text{ for proton incident}$$

$$\frac{\pi^-}{\pi^+} = 3 \text{ for neutron incident}$$

This assumed that the following processes are each equally probably:

For protons incident,

$$p + p \rightarrow \pi^+ + p + n$$

$$p + p \rightarrow \pi^+ + n + p$$

$$p + n \rightarrow \pi^+ + n + n$$

$$p + n \rightarrow \pi^+ + p + p$$

The net result for the final nucleus is that one extra neutron is formed when a π^+ is made. Two extra protons must be accommodated when a π^- is made. The modified Chew and Steinberger result for protons incident is

$$\frac{\pi^+}{\pi^-} = 3\left(1 - \frac{E_F}{T_m - T}\right) \Big/ \left(1 - \frac{2E_F}{T_m - T}\right)$$

For neutrons incident, the equation is the same for π^-/π^+ ratio.

(2) Agreement with Experiment

In attempting to fit this formula to the experimental ratio data, for example, helium, Fig. 3, as a function of T, one finds that to obtain a high ratio -- greater than about 4 -- over a wide range of T, the quantity $T_m - T$ (the nuclear energy) must remain fairly constant. Therefore, any constant value for T_m is ruled out. The maximum pion energy depends upon the target nucleon momentum and angle of collision with the incident nucleon, so that various values of T_m are expected, and are compatible with over-all energy conservation. However, it seems difficult to predict the correct value of T_m before the experimental ratios have been determined. With constant $T_m = 164$ Mev, $E_F = 20$ Mev, the ratio formula is fitted to the highest π^+/π^- experimental ratio for helium (Fig. 3). The disagreement is largely due to the non-linear nature of the formula. Most of the ratio data can be expressed as linear function of the pion energy, or -- for constant pion energy -- as a linear function of the angle of emission. If T is held constant, then π^+/π^- decreases as θ is increased, if T_m is increased. T_m is expected to increase because larger target nucleon momenta are required to produce pions of the same energy at larger lab angles.

(3) Other Ratio Factors

(a) Coulomb Effect for Low-Energy Mesons

The analogy to β decay predicts that the nuclear charge will tend to accelerate a π^+ leaving the nucleus, and decelerate a π^-. The effect is the greatest for low-energy pions and high-Z elements. Thus the π^+/π^- ratio is expected to decrease as Z is increased, for either a proton or a neutron beam. The experimental π^+/π^- ratios for lead are smaller than for helium.

(b) Coulomb Effect for Final Nucleons in Nucleus

As an extra proton in a nucleus is expected to be more forbidden than an extra neutron because of the Coulomb repulsion between protons, Machida and Tamura[2] have used this effect to explain the variation in the π^-/π^+ ratio from ligh nuclei bombarded by high-energy gamma rays. This Coulomb effect in addition to the exclusion effects tends to increase the π^+/π^- ratio for proton bombardment. For neutron bombardment, the effect would not be as great because in π^+ production, two extra neutrons are found.

(c) Ratio of Neutrons to Protons Increases with Atomic Number

This tends to decrease the π^+/π^- ratio for high Z.

2 S. Machida, T. Tamura, Progress of Theo. Physics 6, 1080 L(1951).