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Introduction

Single-pion production and meson-nucleon interaction studies have been an active area of physics research ever since artificial production of mesons was achieved in the laboratory more than 40 years ago. This activity is indicative not only of the amount of knowledge already gained, but also of that yet to be learned. The work described herein is, in all generality, an attempt primarily to improve our understanding of the nuclear strong force via the study of pion-nucleon interactions in light nuclei.

Meson-nucleon studies and the research leading up to this work originated with Yukawa's extension [Yk35] of the exchange force concept to describe the nucleon-nucleon (N-N) interaction. Although firm evidence did not yet exist[1] to support the exchange character of the interaction, Yukawa postulated that the force experienced by two nucleons in close proximity is the result of emission of a massive boson from one nucleon with subsequent absorption by the other. Mathematically, a scalar potential for this force satisfies the Klein-Gordon equation for a boson of mass m,

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial}{\partial t^2}\right)\phi = \frac{m^2c^2}{\hbar^2}\phi.$$

A static solution is

$$\phi(r) = \frac{g}{4\pi r}e^{-r/r_0},$$

[1] The charge exchange process $\mathrm{p} \rightarrow \mathrm{n} + \pi^+$ was discovered in n-p scattering more than 15 years later.

where $r_0 \equiv \hbar/mc$ and g is a constant. In the limit $m \to 0$, this solution is analogous to a Coulomb potential for a point charge of strength g.

The key characteristic of Yukawa's potential is the range of the interaction as specified by the parameter r_0: a boson mass of $m \approx 200$ MeV corresponds to a typical nuclear dimension of 1 fm. The particles in this mass range are today known as *pions*, and form an isospin $T = 1$ triplet: π^+, π^0, and π^-. Pions, as strongly-interacting particles with integral spin ($S_\pi = 0$), are part of the meson family (see Table 1.1). Since the total number of mesons is not necessarily conserved in an interaction, these particles are composed of quark-antiquark pairs, the lightest examples of which are u$\bar{\text{d}}$ (π^+) and $\bar{\text{u}}$d (π^-).

Particle	Quarks	Mass (MeV)	τ or Γ	T(J$^\text{P}$)	Decay
$\pi^\pm$	u$\bar{\text{d}}$, $\bar{\text{u}}$d	$139.5675 \pm .0004$	2.6×10^{-8} sec	$1(0^-)$	$\pi \to \mu\nu$
π^0	u$\bar{\text{u}}$, d$\bar{\text{d}}$	$134.9739 \pm .0006$	8×10^{-17} sec	$1(0^-)$	$\pi^0 \to 2\gamma$
η	u$\bar{\text{u}}$, d$\bar{\text{d}}$, s$\bar{\text{s}}$	$548.8 \pm .6$	1.2 keV	$0(0^-)$	$\eta \to 2\gamma, 3\pi$
σ (?)	(?)	~ 560	broad	$0(0^+)$	(?)
$\rho^\pm$	u$\bar{\text{d}}$, $\bar{\text{u}}$d	$768.3 \pm .5$	~ 150 MeV	$1(1^-)$	$\rho^\pm \to 2\pi$
ρ^0	u$\bar{\text{u}}$, d$\bar{\text{d}}$, s$\bar{\text{s}}$	~ 768	~ 150 MeV	$1(1^-)$	$\rho^0 \to 2\pi$
ω	u$\bar{\text{u}}$, d$\bar{\text{d}}$, s$\bar{\text{s}}$	$781.95 \pm .14$	8 MeV	$0(1^-)$	$\omega \to 3\pi$

Table 1.1 A summary [Pd90] of the mesons most important to the nucleon-nucleon interaction at low and medium energies. The existence of the σ meson as a true resonance has not yet been verified. Only the primary modes of decay are listed in the rightmost column.

Although the exchange of pions is only part of a complete N-N interaction scenario, this mechanism is responsible for the "long-range" ($r \gtrsim 1.5$ fm) component of the nuclear binding force. In a modern picture, this force is a consequence of gluon exchange between the quarks of which mesons (see Table 1.1) and nucleons are comprised, and in principle can be described via low-energy QCD theory. Some success has been achieved, for example, by treating the meson-nucleon interaction as an overlapping collision of quark "bags" (e.g., see [Ln87]). These and other calculations can at least qualitatively reproduce the important features of the short- and medium-range N-N interaction. However, no QCD-motivated model to date can even qualitatively describe the long-range (pion-exchange dominated) part of the interaction. In the absence of a complete QCD calculation, a full description of the long-range nuclear force via the study of the π-N interaction is clearly an important step toward understanding the strong force.

Proton-induced pion production from light nuclei is a particularly important means of exploring the π-N mechanism in the nuclear medium. With the existence of a pion in the final state, the (p, π) production channel is indicative of the possibility of directly sampling the π-N interactions as they occur inside a bound nuclear system. By comparison with data obtained from the study of elementary pion production channels such as $\mathrm{pp} \rightarrow \mathrm{pn}\pi^+$, the analysis of (p, π) reactions in nuclei may reveal information about differences between the free and bound nucleon-nucleon interactions.

High-resolution studies of the (p, π) reaction began [Da71] in Uppsala, Sweden, more than 20 years ago, and many of the original motivations for this spectroscopic research remain today. One primary interest in reactions of this type stems from the large momentum transfers that are available. For example, in $^{12}\mathrm{C}(\mathrm{p}, \pi^+)^{13}\mathrm{C}$, the minimum momentum transfer[2] is $\Delta p \approx 500$ MeV/c (or $\Delta k \approx 2.5\ \mathrm{fm}^{-1}$) for $E_p = 200$ MeV. Since the wavelengths of incident protons in this energy range are less than 2 fm, only a few target nucleons are available to participate in the reaction. In this way, the (p, π) reaction should be sensitive to the high-momentum components of single-particle nuclear wave functions.

Although the nuclear structure emphasis on these motivational considerations has changed somewhat since Uppsala, (p, π^+) studies continue to be an important focus of intermediate-energy nuclear physics. The proton-induced production of *two* pions from light nuclei is of more recent interest: the study of these reactions may yield valuable information on the medium-range ($0.8\ \mathrm{fm} < r < 1.5\ \mathrm{fm}$), higher-order π-N interactions. Relatively little is known about $(\mathrm{p}, \pi\pi)$ from light nuclei, however, due not only to the theoretical complexity in describing such reactions (to which many elementary production channels can contribute), but also to the experimental difficulties in obtaining cross-section data. Even so, a comparison of the relative population of different ion species via $(\mathrm{p}, \pi\pi)$ reactions may reveal key information about the importance of specific, high-order π-N diagrams to the nuclear strong force.

This work reports on a study of proton-induced single- and double-pion production in $^{12}\mathrm{C}$, at proton energies ranging from 166 MeV to 350 MeV. The study is comprised of the IUCF Cooler ring experiment designated [Se87] CE-06. Chapter 2 details the theoretical and experimental interests in pion production from light nuclei. The Cooler ring, detection apparatus, and other scientific equipment associated with the CE-06 experiment are dis-

[2] Other reactions such as $^{12}\mathrm{C}(\mathrm{p},\mathrm{p}')^{12}\mathrm{C}$ can achieve similar momentum transfers but only for large-angle scattering of the light exit particle.

cussed in Chapter 3. Techniques used in the analysis of the data are presented in Chapter 4 along with subsequent results, and this work concludes with a summary in Chapter 5.