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Conclusion

Meson-nucleon interaction studies are a key component of modern intermediate-energy nuclear physics, in that the current quantitative understanding of the nuclear strong force depends heavily on models incorporating the exchange of mesons between nucleons. The work described here, embodied by the CE-06 experiment, has attempted to improve this understanding through the study of exclusive proton-induced pion production from ^{12}C. Data were taken using proton beams ranging in energy from the near threshold region ($E_p \approx 150$ MeV) up to $\sqrt{s} \approx M_{^{12}\mathrm{C}} + M_\Delta$. In this work, a full analysis was completed for three of these energies (166 MeV, 294 MeV, and 330 MeV) to extract differential ($d\sigma/d\Omega$) and total (σ) cross-sections for single- and double-pion production processes.

At $E_p = 166$ MeV, differential cross-sections[1] for $^{12}\mathrm{C}(\mathrm{p},\pi^+)^{13}\mathrm{C}$ and $^{12}\mathrm{C}(\mathrm{p},\pi^0)^{13}\mathrm{N}$ leading to bound final nuclear states were measured. With an extensive database for $^{12}\mathrm{C}(\mathrm{p},\pi^+)^{13}\mathrm{C}$ in the near-threshold energy region already well-established, the concern here was primarily to investigate an apparent anomaly in the π^0 total cross-section compared to $\sigma(\pi^+)$. Using the (p,π^+) data and previously measured cross-sections as a normalization for the differential (p,π^0) cross-section, the value $\sigma(\pi^0) = 374 \pm 46$ nb was obtained. The shape and magnitude of this cross-section is in good agreement with the only previous measurement [Ho92] of the process, leading to a ratio here of $R \equiv \sigma(\pi^+)/\sigma(\pi^0) = 1.5 \pm 0.2$. Although the ratio is in apparent discord with that predicted by isospin invariance ($R = 2$),

[1] More properly, $d^2\sigma/d\Omega\, dE_p$ (angular distributions) and $d\sigma/dE_p$ (excitation functions) were measured.

other results yielding ratios from $R = 1.27 \pm 0.05$ [Ho92] to $R = 1.73 \pm 0.27$ [Pi93] while using the same $\sigma(\pi^0)$ result suggest that the disagreement may rest primarily in a proper Coulomb analysis of the $\sigma(\pi^+)$ data. Combining the result of a recent such calculation [Pi93], and the $\sigma(\pi^0)$ data from this work, the value $R = 2.0 \pm 0.3$ is obtained.

Pion-production data at 294 MeV and 330 MeV were also analyzed in this work. The first extremely forward-angle (p, π^+) measurements ($\theta_\pi < 20°$) made at intermediate energies were reported, showing a fairly flat small-angle cross-section with little or no large-angle peak, as seen at $E_p \lesssim 200$ MeV. As in the analysis at $E_p = 166$ MeV, the π^+ data at 294 MeV were used to normalize the measurement of $\sigma(\pi^0)$. The lack of previously measured (p, π^+) cross-sections in this energy range, however, made the luminosity calculation difficult and error-prone; the absolute scaling of the π^0 cross-section is therefore preliminary. Nonetheless, the ratio $\sigma(\pi^+)/\sigma(\pi^0)$, the calculation of which here depends only on the knowledge of the relative $^{13}\mathrm{C}_{\mathrm{g.s.}}$ contribution to the total bound-state (p, π^+) cross-section, was found to be in reasonable agreement with that expected from isospin invariance.

As a means of testing underlying symmetries in the diagrams describing pion-nucleon dynamics, a first-ever measurement of $(\mathrm{p}, \pi\pi)$ processes in nuclei was attempted. At $E_p = 330$ MeV, a search for $(\mathrm{p}, \pi\pi)$ events was carried out, using the data at $E_p = 294$ MeV (just below the $(\mathrm{p}, \pi\pi)$ threshold) as a basis of background comparison. The number of valid $(\mathrm{p}, \pi\pi)$ candidates at 330 MeV was determined to be consistent with zero. Using the concurrently measured single-pion production data as a normalization, this result leads to an upper limit (2σ confidence level) of $\sigma_{\pi\pi} < 17$ nb, which corresponds to less than 1% of the (p, π^+) strength at $E_p = 330$ MeV.

This work, as a recoil detection experiment based on an electron-cooled storing ring using very thin internal targets, demonstrates much promise for future studies. Many of the limitations in the data encountered here stem from low integrated luminosities rather than high background levels or other more intrinsically intractable problems. With L_{int} in the 5×10^{35} cm^{-2} range (along with a reliable independent means of measuring this quantity), the CE-06 experimental method is ideally suited to exclusive measurements of other processes which are difficult to measure by standard means.

For example, the study of (p, π^-) reactions such as $^{12}\mathrm{C}(\mathrm{p}, \pi^-)^{13}\mathrm{O}$ (much more weakly populated than (p, π^+), and not seen in CE-06 due to the small value of L_{int}) is well-suited to the recoil method; a PC optimized for heavily-ionizing recoils (it is position sensitive in two dimensions) has been designed [Sg92] for use in a CE-06 follow-up experiment. Exclusive photo-production, such as the astrophysically important process $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}$, is a good candidate for study via the recoil method, since the complications of detecting high-energy γ rays are avoided (the same reasoning applies to the study of (p,π^0) in this work). Future measurements of $(\vec{\mathrm{p}},\gamma)$ are planned using the CE-06 apparatus and the recently developed high-intensity polarized ion source at IUCF. Further and more conclusive studies of the $(\mathrm{p},\pi\pi)$ reaction near threshold in nuclei are also clearly warranted: the relative populations of different $(\mathrm{p},\pi\pi)$ processes close to threshold are important to know, as is verification of possible resonant $\pi\pi$ states near $E_p = 350$ MeV. Such projects may indeed be very difficult or impossible to accomplish via more standard (non-recoil) methods.