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Momentum Spectra in High-Energy Hadron-Deuteron Interactions

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We have measured momentum spectra for the scattering of protons by deuterons at 2.784 GeV/c incident proton momentum and the scattering of negative pions by deuterons at 5.53 GeV/c incident pion momentum. These measurements of $d^2\sigma/d\Omega dp$ test multiple scattering theories and have been compared with the Glauber high energy approximation and Regge-pole models.^{1,2,3} In particular the roles of double scattering processes, interference phenomena, nucleon-nucleon correlations, and production processes have been examined. The previously published data for the proton-deuteron spectrum at 18.29 GeV/c contain a large pion-production background, which makes comparison with theoretical predictions difficult.^{4,5,6}

The pion scattering experiment was performed at Argonne National Laboratory. The beam transport system focused 2×10^5 pions/pulse at the rate of 1000 pulses/h on a 2.31-inch liquid deuterium target with a momentum spread of $\pm 1\%$. Angular divergence of the beam was ± 3 mrad vertically and ± 5 mrad horizontally. Four scintillation counters detected the incoming pions with the beam size limited to 0.75 in by 0.75 in. Beam pions that did not interact with the target were vetoed by a scintillation counter placed downstream from the target. Scattered pions

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were detected in a single-arm spectrometer which consisted of a bending magnet, two scintillation counter arrays, and a single scintillation counter behind the first array to define azimuthal acceptance. The polar acceptance was determined by the 1.0-in. width of an element in the first array. A good event satisfied the following criteria:

- 1) a count in the beam counters, 2) a count in an element of the first array with a count in the corresponding element of the second array,
- 3) a count in the azimuthal counter, and 4) no count in the veto counter.

The events satisfying these criteria were stored in a multi-channel analyzer and displayed on scalars. The background was determined by measuring the process with an empty target. Corrections were applied to the data for electron and muon contamination of the pion beam, electronic deadtime effects due to the veto counter, nuclear absorption of the scattered pion, impurities in the liquid-deuterium target, attenuation of the pion beam, decay of the scattered pion, multiple Coulomb scattering, and background events.

The proton scattering experiment was performed at Brookhaven National Laboratory. The beam momentum was determined to ± 0.06 GeV/c, and 8×10^7 to 1×10^9 protons/pulse at the rate of 1800 pulses/h were focused on a 3.03 in. liquid deuterium target. The beam had a maximum diameter of 1.5 in. with an angular divergence of less than 1.5 mrad in both vertical and horizontal planes. Two sets of scintillation counters were used for monitoring the beam, and polyethylene foils were irradiated for normalization purposes. The scattered protons were detected by a single-arm spectrometer which consisted of a bending magnet and two overlapping telescopes formed by three scintillation counters in each. The

bending magnet was supported by a motorized carriage which was constrained to move on tracks along the arc of a circle. Two overlapping counters were placed in front of the magnet and two sets of two overlapping counters were placed behind the magnet to form the two telescopes. A good event consisted of 1) a count in the beam counters, and 2) a count in each of the three counters forming a telescope. The fraction of accidental coincidences were determined through empty target measurements. Corrections to the data have been made for beam attenuation in the target, nuclear interaction of the scattered proton, counter dead time, counter efficiency, background events and multiple Coulomb scattering. The experimental apparatus are described in greater detail elsewhere.⁷

The results for pion-deuteron and proton-deuteron total scattering are displayed in Figs. 1 and 2. The errors shown are statistical errors and do not include the 8% normalization uncertainty for proton scattering and the 7% normalization uncertainty for pion scattering. The curves in the graphs have been derived via the Glauber high energy approximation.⁸ Following the notation of Bertocchi⁵ and of Straumann and Wilkin⁶, the doubly differential cross section can be written as the sum of a single scattering term, a double scattering term, a double scattering term, and an interference term. If spin dependence and final state interactions between proton and neutron are neglected, the scattering amplitude for the scattering of particle X by a deuteron is the coherent sum of single- and double-scattering contributions given by

$$A = f_{xp}(t) \psi(\vec{k}_n) + f_{xn}(t) \psi(\vec{k}_p) + \frac{i}{2\pi p_i} \int d^2\vec{q} \psi(\vec{q}-\vec{k}) f_{xp} \left[-(\vec{q}-\frac{\vec{A}}{2})^2 \right] f_{xn} \left[-(\vec{q}+\frac{\vec{A}}{2})^2 \right]$$

where f are the particle-nucleon amplitudes, ψ is the deuteron wave function in momentum representation, P_1 is the incident momentum, P_2 is the final momentum of particle x , $K_{p(n)}$ is the recoiling proton (neutron) momentum, and

$$t = (P_2 - P_1)^2, \quad \vec{\Delta} = \vec{P}_2 - \vec{P}_1 = -(\vec{k}_p + \vec{k}_n), \quad \vec{k} = \frac{1}{2}(\vec{k}_p - \vec{k}_n),$$

$S = (K_p + K_n)^2$. Using the Gaussian deuteron wave function of Verde⁹ $\psi(p) = N e^{-b_f p^2}$, $b_f = 66 (\text{GeV}/c)^{-2}$

and purely imaginary and charge independent particle-nucleon amplitudes given by

$$f_{xp} = f_{xn} = (i p_1 \sigma / 4\pi) e^{-b_s t/2}$$

the differential cross section away

from the forward direction is approximated by:

$$\frac{d^2\sigma}{d\Omega dp_2} = \left(\frac{d^2\sigma}{d\Omega dp_2} \right)_{\text{single}} + \left(\frac{d^2\sigma}{d\Omega dp_2} \right)_{\text{double}} + \left(\frac{d^2\sigma}{d\Omega dp_2} \right)_{\text{int.}}$$

where

$$\left(\frac{d^2\sigma}{d\Omega dp_2} \right)_{\text{single}} \approx G(p_2) \left(\frac{P_1 \sigma N}{2\pi} \right)^2 \frac{\pi}{16 \Delta b_f} \exp \left\{ b_s t - \frac{b_f}{2} \left[\Delta - ([S - 4m^2][1 + \frac{\Delta^2}{S}])^{\frac{1}{2}} \right]^2 \right\}$$

$$\left(\frac{d^2\sigma}{d\Omega dp_2} \right)_{\text{double}} \approx G(p_2) \left(\frac{P_1 \sigma N}{2\pi} \right)^2 D^2 \left(\frac{\pi}{4} \right)^{\frac{3}{2}} \left[\frac{2(b_s + b_f)}{b_f^2} \right]^{\frac{1}{2}} \exp \left[\frac{b_s t}{2} - \frac{b_s b_f (s - 4m^2)}{2(b_s + b_f)} \right] \\ \cdot \text{erf} \left[\left(\frac{(s - 4m^2) b_f^2}{2(b_s + b_f)} \right)^{\frac{1}{2}} \right]$$

$$\left(\frac{d^2\sigma}{d\Omega dp_2} \right)_{\text{int.}} \approx G(p_2) \left(\frac{P_1 \sigma N}{2\pi} \right)^2 D \left(\frac{\pi}{4} \right) (s - 4m^2)^{\frac{1}{2}} \exp \left[\frac{3b_s t}{4} - \frac{b_f \Delta^2}{4} - \frac{b_f}{4} \left(1 + \frac{b_s}{b_f} \right) (s - 4m^2) \right] \\ \cdot \int_0^1 d\lambda \cosh \left[\frac{1}{2} b_f \Delta \lambda (s - 4m^2)^{\frac{1}{2}} \right] I_0 \left(\frac{1}{2} b_f \Delta \left[(s - 4m^2)(1 - \lambda^2) \right]^{\frac{1}{2}} \right) \\ \cdot \exp \left[-\frac{1}{4} \left(\frac{b_f^2}{b_s + b_f} \right) (s - 4m^2) \lambda \right]$$

$$G(p_2) = 2 p_2 (2m + E_1 - E_2) / E_2, \quad E_1 = (m_x^2 + p_1^2)^{\frac{1}{2}},$$

$$E_2 = (m_x^2 + p_2^2)^{\frac{1}{2}}, \quad D = \sigma / 16 \pi (b_s + b_f)$$

where m is the nucleon mass, m_x is the particle mass, I_0 is the modified Bessel function of zeroth order, and Δ_t is the component of $\vec{\Delta}$ perpendicular to $\vec{p}_1$. For 2.784 GeV/c proton scattering, we have used the values $b_s = 7.62 \text{ (GeV/c)}^{-2}$ and $\sigma = 44 \text{ mb}$; and for 5.53 GeV/c pion scattering, we have used the values $b_s = 7.15 \text{ (GeV/c)}^{-2}$ and $\sigma = 28 \text{ mb}$. The experimental and theoretical differential cross sections are functions of both the magnitude and the angle of the final momenta. For the pion data the final laboratory angle varies from 6.1° to 10.4° ; whereas for the proton data the final laboratory angle varies from 14.0° to 27.9° . This simple approximation shows reasonable agreement with the pion scattering data until $p_2 < 5.35 \text{ GeV/c}$ as seen in Fig. 1. For proton scattering, production processes have already become significant for most of the data obtained. In both figures the dashed curves display the portion of the cross section due to double scattering of the incident particle. The double scattering contribution is less than 1% of the total scattering in both of the experimental momentum ranges. The dot-dash curves display the negative of the interference term. Away from the forward direction, the interference term in $d^2\sigma/d\Omega dp_2$ is small as can be seen in the figures.

The significant parameters for the pion-nucleon scattering amplitudes are available for π^-p and can be obtained for π^-n by charge symmetry with π^+p . A more accurate expression for the scattering amplitudes can be used to determine the differential cross section in the region for $p_2 < 5.35 \text{ GeV/c}$. In this manner, the deuteron wave function can be examined and compared

with existing representations of the wave function. Further work on this application is in progress. The proton scattering data shows that significant production processes must be considered for scattered protons of momenta less than 2.65 GeV/c. In the absence of particle production, a good determination of the proton-neutron differential cross section in the forward direction could have been made. However, once particle production must be included in the theoretical model, the determination of the proton-neutron cross section decreases considerable in accuracy due to unknown parameters in the final state interactions and particle production due to double scattering mechanisms.

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Figure Captions

Figure 1. The differential cross section for the total scattering of pions by deuterons in the laboratory system.

Figure 2. The differential cross section for proton-deuteron total scattering in the laboratory system.