PROTON-DEUTERON ELASTIC SCATTERING AT HIGH MOMENTUM TRANSFERS*

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In this Letter we report measurements of 1.0- to 2.0-GeV proton elastic scattering on deuterons at high four-momentum transfers. For incident proton kinetic energies of 1.0, 1.3, and 1.5 GeV, we have measured the elastic differential cross sections for values of four-momentum transfer squared ($-t$) from 2.6 to 5.0 $(\text{GeV}/c)^2$, corresponding to cosine of center-of-mass scattering angles ($\cos\theta^*$) from -0.5 to -0.9. At 2.0-GeV incident proton energy, the measurements covered values of $-t$ from 0.44 to 1.54 $(\text{GeV}/c)^2$, corresponding to $\cos\theta^*$ from -0.875 to -0.565. Bayukov et al. have measured a single point of the differential cross section at high four-momentum transfer for three energies, 0.715, 1.0, and 3.66 GeV.[1] Others have studied the interaction either for the forward diffraction peak or at cyclotron energies.[2-4] Proton-deuteron scattering provides an observation of the collective interaction of nucleons at high energies, and an examination of current dynamical theories of particle interactions.[5-7] We have previously studied[8] the reaction $p+p\rightarrow d+\pi^+$ in the energy region 1-3 GeV and have interpreted[9] these data in terms of a one-neutron exchange mechanism. The motivation for the present experiment was to provide a test of the one-neutron exchange model in backward proton-deuteron elastic scattering.

The external proton beam was supplied by the Cosmotron at Brookhaven National Laboratory. Three bending magnets and three quadrupoles focused the beam on a 3-in. long liquid deuterium target. At the target, the beam had a maximum radius of $1\frac{1}{2}$ in. and a maximum angular divergence of $3\frac{1}{2}$ mrad. The beam intensity was approximately 5×10^8 external protons per pulse, with energy known to better than $\pm2\%$.

Both of the scattered particles were detected by scintillation-counter telescopes. The first counter of the two-counter proton telescope determined the solid angle subtended from the target. This solid angle of acceptance ranged from 0.7 to 2.9 msr depending upon the radial position of the counter. The proton telescope was readily movable in both r and θ. The deuteron telescope consisted of the three sets of overlapping counters and a bending magnet with a 40-ft flight path between the first and last set of counters. The momentum selection and time-of-flight criteria separated the deuterons from the scattered protons and pions in the deuteron channel. The detection apparatus was movable on a circular arc to desired proton and deuteron angles. For the 2.0-GeV forward differential cross sections, the roles of

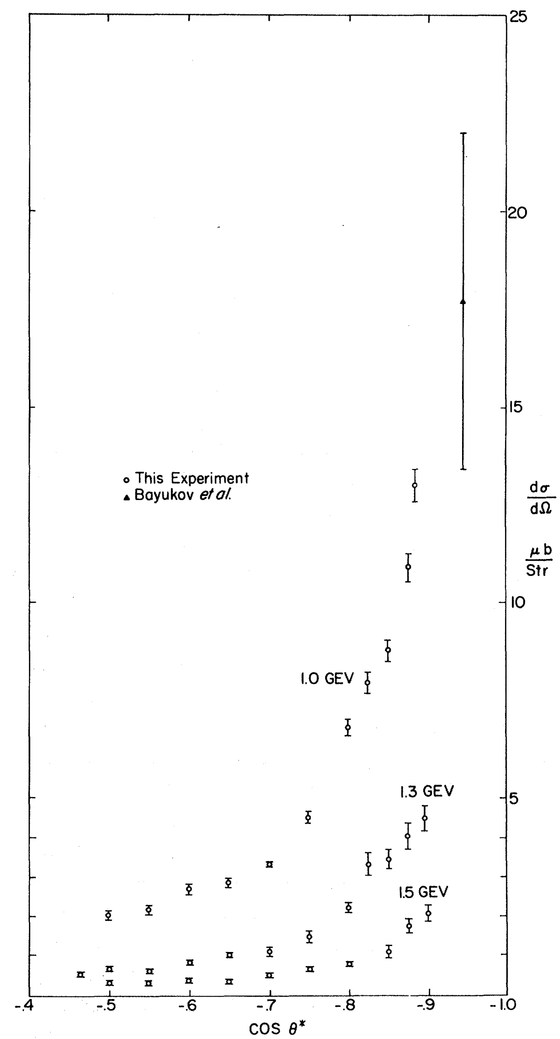

FIG. 1. Differential cross sections versus $\cos\theta$ in the c.m. system at 1.0-, 1.3-, and 1.5-GeV incident proton kinetic energies.

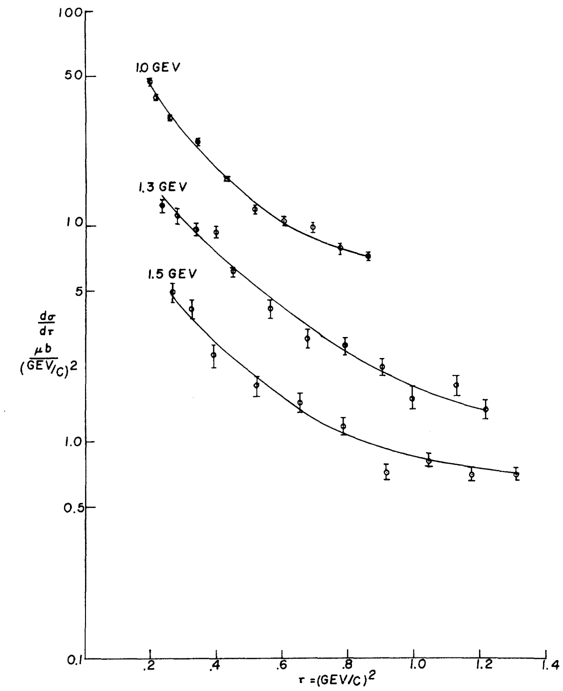

FIG. 2. The function $\exp(a+b\tau+c\tau^2)$ fitted to the differential cross sections, where $\tau=t-t_m$.

the proton and deuteron telescopes were exchanged to provide greater separation of the scattered protons.

The cross sections were normalized by foil activation using the reaction $C^{12}(p,pn)C^{11}$. The beam rate was adjusted to insure accidental coincidences to be less than 10% of the good coincidences. Standard commercial modules were used for the electronic logic. Time-of-flight delay curves, angular correlations, magnet current curves, and changes in counter sizes provided checks for assurance that proton-deuteron elastic scatterings were being measured. The data have been corrected for beam attenuation in the target, nuclear interaction of the scattered protons and deuterons, multiple Coulomb scattering, counter dead time, counter efficiency, and background events.

The values of $d\sigma/d\Omega$, the differential elastic cross sections, versus $\cos\theta^*$ are shown in Fig. 1 for 1.0-, 1.3-, and 1.5-GeV incident protons. The value at $\cos\theta^*=-0.94$ was observed by Bayukov et al.[1] The error bars given indicate the standard deviations from counting statistics. The absolute normalization is uncertain to 10%. The curves of Fig. 1 appear approximately exponential in character. In other related experiments, it has been found useful to express differential cross sections as exponentials in four-momentum transfer.[10] In Fig. 2 we have fit the backward cross sections with the function

$$d\sigma/d\Omega=\exp(a+b\tau+c\tau^2)\ \mu\text{b/sr},$$

where τ equals $t-t_m$ with t_m evaluated at 180°. The values of a, b, and c are given in Table I.

Table I. Coefficients in exponential.

T_p (GeV)	a	b $[(\text{GeV}/c)^{-2}]$	c $[(\text{GeV}/c)^{-4}]$
1.0	−4.97	6.48	−3.54
1.3	−3.58	4.47	−1.49
1.5	−2.66	4.68	−1.82

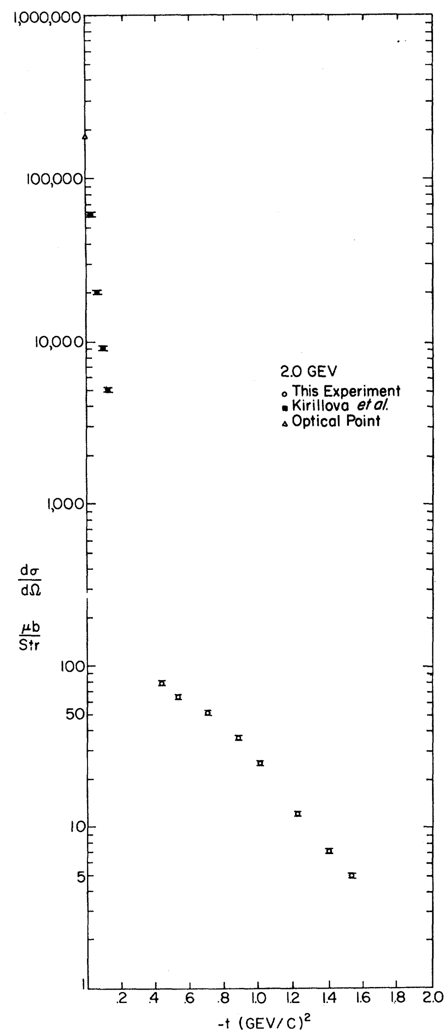

FIG. 3. Differential cross sections versus $-t$ for 2.0-GeV incident proton kinetic energy.

This behavior is typical of single-particle exchange processes, but the magnitude and width of the backward peak must receive special attention.

At 2.0-GeV incident proton energy the values of $d\sigma/d\Omega$ are shown versus $-t$ in Fig. 3. The points below $-t = 0.13$ $(\text{GeV}/c)^2$ were measured by Kirillova et al.[2] The shoulderlike departure of the data at $-t = 0.5$ to $-t = 1.2$ $(\text{GeV}/c)^2$ from the exponential trend of the diffraction peak indicates that the secondary peak observed in $\pi^{\pm}p$ and $K^{-}p$ elastic scattering may also be evident in pd scattering.[11]

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RELATIVISTIC WAVE EQUATIONS AND LAGRANGIAN FIELD THEORY FOR ARBITRARY SPIN*

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Attempts to formulate relativistic field theories for higher spin particles have in the past always met with grave difficulties.[1] The equations proposed by Dirac, Pauli, and Fierz,[2] Rarita and Schwinger,[3] and Bargmann and Wigner,[4] for example, are suitable only for the description of free particles. The existence of subsidiary conditions which are consistent only with the free-field equations precludes the introduction of interactions.[5] There appeared, therefore, to be a fundamental difference within the framework of field theory between particles of spin 0, $\frac{1}{2}$, and 1 on the one hand and those of all higher spin on the other.

We demonstrate in this note that this difference can be considerably narrowed. Using a precedure first proposed by Joos[6] (see also the work of Weinberg[7] and Pursey[8]) to construct covariant wave functions from the single-particle-state (or canonical) basis vectors, we show that there is a whole class of possible covariant wave equations, without subsidiary conditions, that can describe a particle of definite spin and mass.[9] These equations can be derived from a Lagrangian. Interactions can be introduced into the equations in the standard manner and no inconsistency will arise. All of the equations are equivalent in the absence of interactions, but become inequivalent when interactions are introduced. In particular, there are always two sets of first-order equations which are very much similar to those of the well-known cases of spin 0, $\frac{1}{2}$, and 1. These linear equations, in their simplest form, reduce to the Kemmer equations for spin 0 and 1 and to the Dirac equation for spin $\frac{1}{2}$.

We have not avoided all the previously known difficulties[1] for field theories of higher spin. The deeper questions of field theory are hardly touched at all. In fact, the new possibilities