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LARGE-ANGLE p-d SCATTERING AT 580 MeV

J. S. Vincent, W. K. Roberts, and E. T. Boschitz*
Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio

and

L. S. Kisslinger
Carnegie-Mellon University, Pittsburgh, Pennsylvania†

and

K. Gotow
Virginia Polytechnic Institute, Blacksburg, Virginia‡

and

P. C. Gugelot
University of Virginia, Charlottesville, Virginia

and

C. F. Perdrisat and L. W. Swenson§
College of William and Mary, Williamsburg, Virginia

and

J. R. Priest
Miami University, Oxford, Ohio
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The elastic scattering of protons from deuterons has been measured at 580 MeV. The results for large-angle scattering are presented and discussed here. The backward peak observed in the experiment is consistent with a baryon-exchange mechanism including the transfer of baryon resonances.

A pronounced increase in the cross section at large angles has been observed for proton-deuteron scattering in the energy range 1-1.5 GeV.[1,2] This back peak is also seen in the present experiment.[3] The magnitude of the peak is found to decrease rapidly with increasing proton energy.

The explanation of this effect most likely involves the transfer of a baryon, that is a pickup mechanism, because the momentum transfer required at the deuteron vertex is much smaller than that for a single or double impulse collision. This is also seen in a number of calculations. At 1 GeV the impulse series for back-scattering gives results more than an order of magnitude smaller than experiment,[4] while a dispersion relation calculation which includes the transfer process obtains a peak of the correct order of magnitude.[5] Using the $pp\rightarrow\pi d$ experimental results as the input, Craigie and Wilkin[6] have recently treated the back-scattering with a model that includes a baryon-transfer mechanism and also obtained the correct order of magnitude for the back peak at 1-1.5 GeV.

Kerman and Kisslinger[7] have studied the large-angle p-d cross section for 1-GeV protons as a baryon-transfer reaction. They find that the S-state component of the deuteron wave function, which by itself is satisfactory for the calculation of nucleon-transfer reactions at low energies, gives a negligibly small contribution at 1 GeV. Using a variety of wave functions with 6-7% D state, only about 50% of the cross section can be accounted for. They also point out from general principles that the deuteron contains components with baryon resonances of about 1%. With about a 2% component in the deuteron wave function consisting of a nucleon and the first excited nucleon state with appropriate quantum numbers (the 1688-MeV, $\frac{5}{2}^+$, $I=\frac{1}{2}$ resonance), called a D^* component, one obtains agreement with the 1-GeV experimental results. If the assumptions of this theory are correct, a study of the back-scattering cross section for different bombarding energies could provide a sensitive map of the baryonic structure of the system. Above 1 GeV the inelasticity in the nucleon-nucleon scattering introduces considerable complications. An energy around 600 MeV is quite favorable in that these new effects are still important while the complications of inelasticity are not. Thus, a comparison of the 600-MeV and 1-GeV results can be an excellent test for the theory.

The experiment was performed using an arrangement similar to that presented in Ref. 8. Protons from the 600-MeV cyclotron of the NASA Space Radiation Effects Laboratory were focused on a CD_2 target.[9] The target thickness was small compared to the range of the back-scattered protons. Coincidences between a proton and a deuteron telescope set at the elastic p-d kinematic angles identified the scattering events. The second counter of the deuteron telescope defined the angular resolution and the solid angle which amounted to $\Delta\theta_d = 0.75°$ (full width at half-maximum) and $\Delta\Omega_d = 5\times 10^{-4}$, respectively. Since reactions on the carbon nuclei present in the target also could produce coincidences, we measured and subtracted these background events with the help of carbon targets containing the same number of carbon nuclei as the CD_2 targets. Monitoring of the incident beam was performed by two additional range telescopes which viewed an aluminum target placed downstream from the CD_2 target and the calibration of this monitor was carried out by an activation of ^{12}C with the (p, pn) reaction.[10]

A fraction of the observed coincidences were due to protons from deuteron break up. Therefore the following methods were used to determine and to correct for these events:

(1) Those scattered protons which stopped within the range interval corresponding to the full width of the Bragg peak in the differential range curve were assumed to come from the elastic scattering. Considering the shape of the range curve we estimated that less than 10% of the events resulted from deuteron breakup at the backwards angles.

(2) By moving one of the telescopes away from the kinematically correct angle one could observe the nonelastic background. The result obtained was in agreement with the estimate obtained in (1).

(3) Finally, a magnetic spectrometer and time-of-flight system enabling unambiguous identification of the recoiling deuteron in coincidence with the back-scattered proton provided the cross section at a deuteron angle of 12°. Within counting statistics these three methods gave consistent results for the elastic cross sections.

Figure 1 shows the experimental cross section over the whole angular range investigated in the present work. The dotted curve represents the experimental result obtained by Bennett et al.[2] at 1 GeV. The energy dependence of the backwards cross section is clearly demonstrated.

The differential cross section for a one-nucleon transfer mechanism using the Born approximation can be written in terms of the Fourier component of the deuteron wave function, $\psi_d(\Delta)$, in the variable $\Delta = |p(\text{initial}) - d(\text{final})/2|$, the momentum transfer of the protons in the center of mass. The contributions from resonance transfer involve new components of the deuteron wave function in the same variable Δ. For energies between 0.5 and 1 GeV it is expected that the $N(1688)$, spin-$\frac{5}{2}^+$ resonance is the most significant. This also agrees with a Regge interpretation using a nuclear Regge trajectory exchange.[7] Thus, in this analysis, only the $N(1688)$ reso-

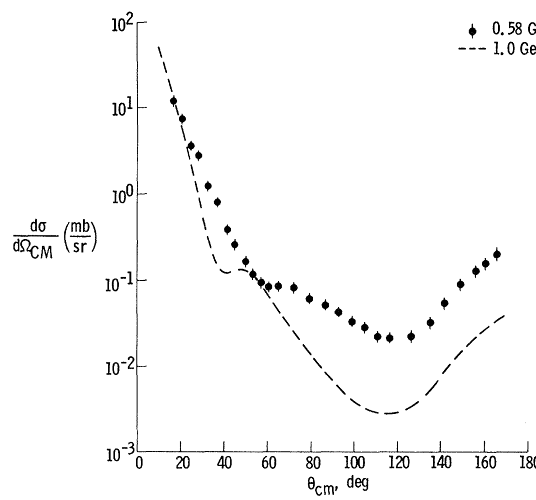

FIG. 1. The p-d differential cross section obtained in the present experiment. The dashed curve represents the Brookhaven data at 1 GeV (Ref. 5).

nance is included with the usual nucleon components. We shall refer to the component of the deuteron which consists of a nucleon and an $N(1688)$ as the D^* component. From Ref. 7 the differential cross section including baryon-resonance transfer is

$$\frac{d\sigma}{d\Omega}=\frac{3}{16(2\pi)^4}\left[\frac{E_pE_d}{(E_p+E_d)M_n}\right]^2\{(K^2+\Delta^2)^2[I_S^2(\Delta)+I_D^2(\Delta)]^2\}+f(\Delta)I_{D^*}^4(\Delta)+g(\Delta,I_S(\Delta),I_D(\Delta))I_{D^*}^2(\Delta),$$

where E_p and E_d are the proton and deuteron total energies, and K^2 divided by the nucleon mass M_n is the deuteron binding energy. $I_S(\Delta)$, $I_D(\Delta)$, and $I_{D^*}(\Delta)$ are related to the Fourier transforms of the S, and D, and D^* states, respectively. The functions f and g are defined in Ref. 7.

In Fig. 2, where the back-scattering data at 0.58 and 1 GeV are both plotted against the proton momentum transfer variable Δ, it is seen that there is a region of smooth overlap. This should be compared with Fig. 1, where the same data are plotted against scattering angle. In Fig. 1, one sees that at the two energies the forward cross sections as a function of momentum transfer $t=(p-p')^2$ are closely related, as is expected in an impulse mechanism. However, the back-scattering shows no obvious relation at the two energies when plotted as a function of scattering angle θ. On the other hand, to the extent that a baryon exchange mechanism is dominant for the back-scattering, the backward cross sections for the same Δ at different energies should be quite similar. These results strongly suggest the dominance of the baryon-transfer mechanism. Several corrections to this model will have to be made, as neither impulse scattering nor higher order corrections to the baryon transfer have been included.

The theoretical results following from Eq. (1) are plotted in Fig. 2, displaying the contributions from the various components of the deuteron wave function. These differ from Ref. 7 at 1 GeV in that the amount of the D^* component in the deuteron has been increased to a 2.5% probability for fitting the data.[11,12] We have used a variety of wave functions corresponding to various potentials derived from the two-body data with results similar to those shown in Fig. 2. Since the S-state component of the wave function has a zero at about 2.0 F^{-1}, its contribution is very small at both energies. This can be best understood from Fig. 3, in which the Fourier transforms of the various components of the deuteron radial wave function are given. The interval of Δ involved in the back-scattering peak at various energies is shown by the hatched areas. At low energies the S state dominates. At energies be-

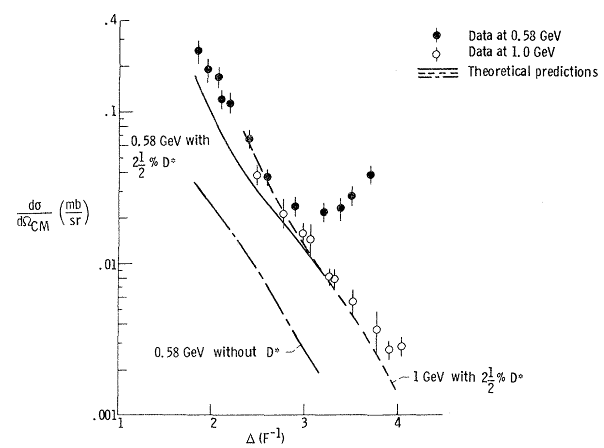

FIG. 2. The 0.58- and 1.0-GeV differential cross sections at back angles plotted against $\Delta=|p-d'/2|$. At 0.58 GeV, $\Delta=1.8\ F^{-1}$ at 180° and increases for smaller angles. The 180° point at 1.0 GeV is 2.36 F^{-1}. The pickup cross section with conventional wave functions is shown at 0.58 GeV; at 1 GeV the theoretical cross section so obtained is even smaller and is not shown. The theoretical predictions with a D^* component follow from the equation in the text using a Bressel wave function.

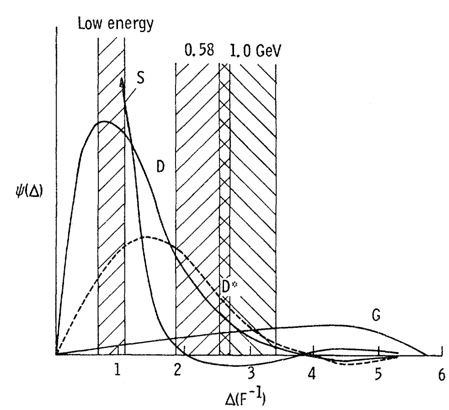

FIG. 3. Fourier transform of the S, D, D^*, and G components of the deuteron wave function. The hatched areas show the Δ interval covered over the back peak at various energies. The G component (which has been sketched for qualitative considerations only) presumably could be significant at 1.5-2.0 GeV. No ordinate scale is given since some quantitative details, such as the relative importance of the D^* and D components, depend upon further assumptions within the model (Ref. 7).

tween 0.5 and 1 GeV the D- and D^*-state contributions dominate. Even considering the theoretical corrections yet to be made, it seems unlikely that conventional wave functions can fit the data. Moreover, with the amount of the D^* expected from general considerations[7] it is found that approximately half the scattering arises from this component at the energies considered here. In Fig. 3 there is also a sketch of the $L=4$ (G) component due to the occurrence of even higher spin resonances in the deuteron. Because of the property that high angular momentum states peak at higher and higher momentum components, this G-state component might dominate the (p,d) back-scattering at still higher energies.

These results show that it is very likely that the pickup process can account for the high-energy p-d large angle scattering. The analysis suggests that the high-spin baryon resonances which are small components of the wave function play a major role in this process. If the inelasticity is satisfactorily included, experiments at higher energies would be most interesting in that the presence of even higher spin resonances (e.g., the $\frac{9}{2}^+$ on the nucleon Regge trajectory) might be detectable.

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*Present address: Institut für Experimentelle Kernphysik, Universität Karlsruhe, Karlsruhe, Germany.

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§Present address: Physics Department, Oregon State University, Corvallis, Ore. 97331.

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[12]After the completion of this paper we were informed by C. Wilkin that the model of Ref. 6 gives an excellent agreement with the 580-MeV data. However, that model considerably underestimates the 1-GeV back peak (Ref. 6).