# PROTON-DEUTERON SCATTERING AT 1 BeV†

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This paper is a report of elastic and inelastic scattering of protons on deuterons for center-of-mass angles between 10 and 170 deg. The measurements were carried out with a monochromatic beam of $T = 1$ BeV protons at the Brookhaven Cosmotron. A high-resolution magnetic spectrometer, utilizing digital wire spark chambers, was used to measure the momentum of the scattered particles. Figure 1 is a schematic diagram of the equipment. The details of the apparatus have been described elsewhere.[1] For this report it suffices to state that an on-line computer was used to partially analyze and display the data as they were being taken to guarantee that the system was performing properly. All data were recorded on magnetic tape for later analysis. The pertinent experimental parameters are the angular resolution of $\pm 0.1°$ and the energy resolution of 3-MeV full width at half-maximum.

In order to cover the full range of scattering angles, the measurements were carried out by detecting the protons in the high-resolution spectrometer for the forward-scattering angles and the deuterons in the spectrometer for the background angles. For center-of-mass angles between 9.8 and 74 deg (proton angles between 5.4 and 44 deg in the laboratory), proton momentum spectra were measured. The general features of the momenta spectra in this angular range are a main "elastic" peak followed by a break-up spectrum which increases, relative to the elastic part, with increasing angle.

For center-of-mass angles between 87 and 170 deg the recoil deuterons were detected in the high-resolution spectrometer with corresponding laboratory angles between 44 and 5 deg. The spectra contain a single peak separated by ~150 MeV from a large continuum associated with events from the reaction $p + d \rightarrow p + d + \pi$. At the momentum of the elastic deuterons no protons are kinematically possible;

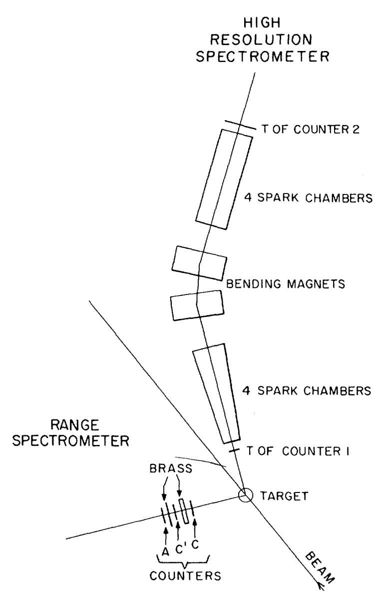


FIG. 1. Experimental layout showing the magnetic spectrometer, described in detail in Ref. 1, and the range spectrometer which was used to measure the relative production of the virtual deuteron.

however, a large number of protons are scattered from the magnet into the trigger scintillation counters. These were separated from the deuterons by a time-of-flight measurement.

All the data have been corrected for absorption in the liquid-deuterium target, accidentals, and target-empty counting rate.

The results for elastic scattering are shown in Fig. 2. The error bars include the statistical uncertainty and the systematic uncertainty in the background correction. In the worst case this background, which arises from the deuteron break-up, amounts to about 10 % of the elastic intensity. A correction has not been made for the presence of $d^*$ production which, as discussed below, was found to be small. The value shown at 0° equals $(k\sigma_T/4\pi)^2$, where the total cross section, $\sigma_T$, is taken from the work of Bugg et al.[2] The integrated elastic cross section is 13.8 ± 1.8 mb which, when subtracted from the total cross section[2] of 83.04 ± 0.06 mb (error quoted is only statistical),[2] gives a reaction cross section of 69.2 ± 1.8 mb.

The elastic forward-scattering results may be used to test the multiple-scattering theory of Glauber,[3] where the incident nucleon interacts successively with one or more of the nucleons in the target, and the nucleon-nucleon interaction inside the nucleus is assumed to be the same as the free nucleon-nucleon interaction. Franco and Coleman[4] have applied this theory to $p$-$d$ elastic scattering at 2 GeV, but the crucial region of the experimental data ($t \sim -0.35$ BeV/$c^2$) where the single- and double-scattering interference effects are maximum had not been measured. This region is particularly sensitive to the ratio of real to imaginary parts of the nucleon-nucleon forward-scattering amplitudes. Using a computer code written by Bassel and Wilkin[5] for the multiple-scattering theory, in which the ratio of real to imaginary scattering amplitudes is not a function of momentum transfer, we have computed the differential cross section for sever-

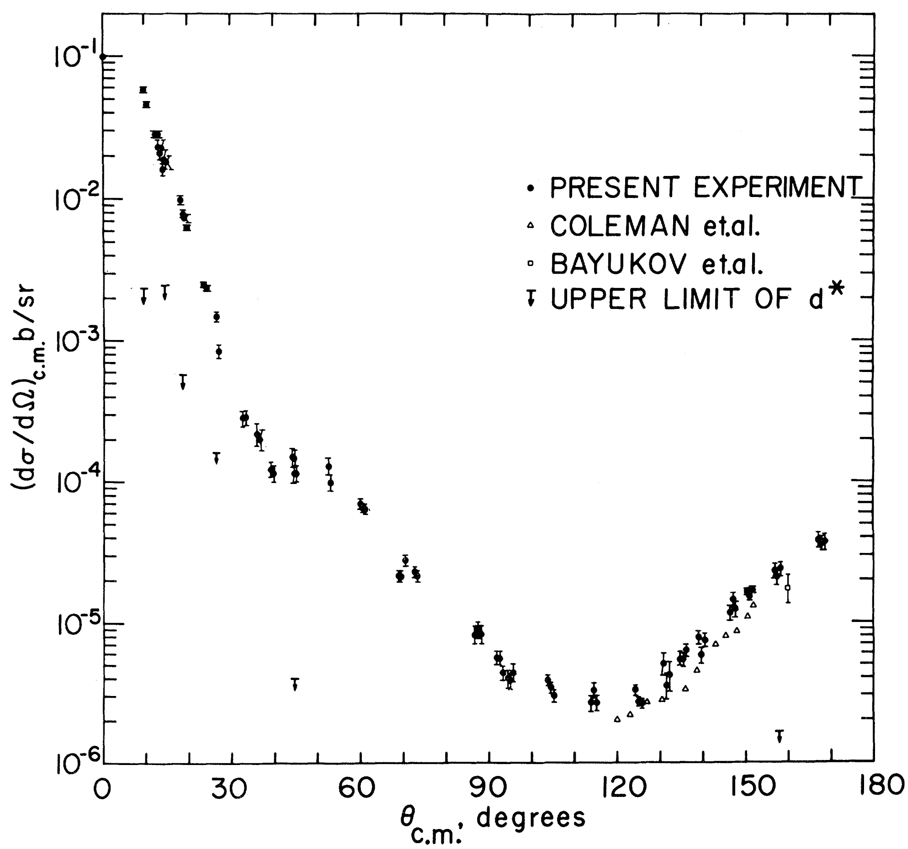


FIG. 2. Elastic 1-BeV proton-deuteron scattering. $\theta_{\text{c.m.}}$ is the scattering angle of the proton in the center-of-mass system. $d^*$ refers to the singlet state of the deuteron. Triangular points are from E. Coleman, R. M. Heinz, O. E. Overseth, and D. E. Pellett, Phys. Rev. Letters 16, 761 (1966), and the square point is from Yu. D. Bazukov, D. Vorofev, G. Lekain, V. Federov, and V. Khovansky, to be published.

al values of the ratio of real to imaginary parts of the $n$-$p$ and $p$-$p$ forward-scattering amplitudes ($\rho_n$ and $\rho_p$), using spin-averaged scattering amplitudes. Bassel and Wilkin[5] have obtained good agreement with our 1-BeV $p$-$^4$He elastic-scattering data (diffraction minimum at $-t \sim 0.24$) using $\rho_n = \rho_p = -0.33$. Other reasonable values which keep the average $\rho \sim -0.33$ will also give good agreement. For deuterium these values give a very poor fit as they produce a much deeper diffraction minimum than is experimentally observed (see Fig. 3). Reasonable agreement can be obtained using $\rho_p = -0.6$ and $\rho_n = -1.2$. The dispersion relation values for $\rho_p$[6] and $\rho_n$[7] at $t=0$ are $-0.05 \pm 0.05$ and $-0.4 \pm 0.2$, respectively. Neutron-proton charge exchange data[8] imply $\rho_n(t=0) \sim -0.65$, and small angle $p$-$p$ scattering data[9] agree with the dispersion value for $\rho_p$. The above-mentioned data are all suggestive of a $t$ dependence of $\rho$. Indeed, there is no a priori reason for the ratio of real to imaginary parts of the nucleon-nucleon scattering amplitudes to be independent of momentum transfer. Admittedly, spin dependence has not been included in the multiple-scattering theory calculations. Avison,[10] using a phase shift analysis of 30-GeV proton-proton scattering data, calculates real and imaginary parts of the scattering amplitude which vary markedly with $t$. Since a functional dependence of $\rho_p$ and $\rho_n$ on $t$ may be required, it is interesting to speculate on its form. Using the measured and calculated values for $\rho$ at $t=0$ and those that fit the minimum in $p$-$^4$He scattering ($t = -0.24$ GeV$^2/c^2$) and that fit the present $p$-deuteron data in the sensitive $t$ region ($t \sim -0.35$ GeV$^2/c^2$), a possible relation is

$$\rho_n^p = -\begin{Bmatrix} 0.05 \\ 0.6 \end{Bmatrix} + 0.6|t| - 6.3t^2$$

for $|t| < 0.4$ GeV$^2/c^2$.

The backward peak in $p$-$d$ elastic scattering at $T = 1$ BeV was observed previously by Coleman et al.[11] A comparison of their data with ours indicates that both sets of measurements have approximately the same shape, but their results are consistently lower by about 30% in absolute value. Coleman[12] has attempted to fit the backward peak using a one-neutron-exchange mechanism. The shape of the peak obtained is consistent with the data, but the calculated absolute value is a factor of about 5 larger than the Michigan data.

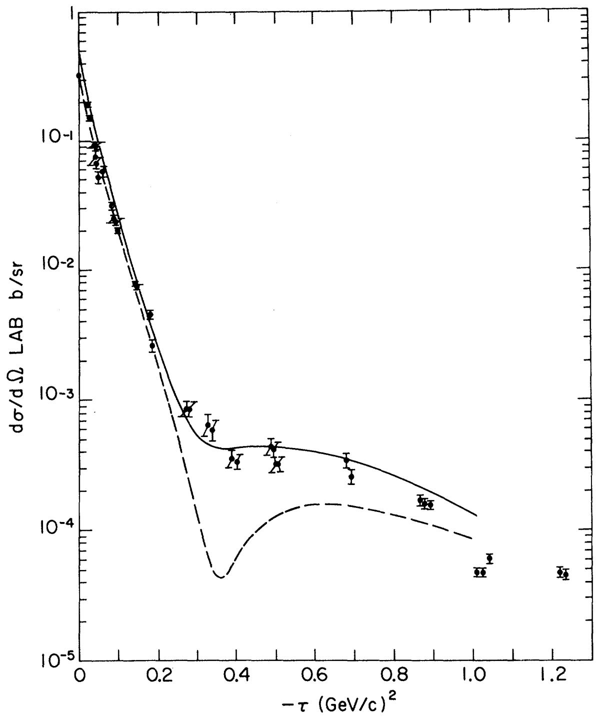


FIG. 3. Elastic 1-BeV proton-deuteron scattering versus the square of the four-momentum transfer, $-t$. The broken curve uses all the same nucleon scattering parameters that Bassel and Wilkin (Ref. 5) used to fit the $p$-$^4$He 1-BeV elastic-scattering data ($\rho_p = \rho_n = -0.33$). The solid curve is a good fit using $\rho_p = -0.6$ and $\rho_n = -1.2$. The fit is relatively insensitive to small increases in $\rho_p$ and decreases in $\rho_n$ provided the average $\rho$ is not changed. The deuteron wave function used in these calculations was the MORAVCSIK III, which Franco and Coleman (Ref. 4) used in their 2-BeV proton-deuteron scattering analysis.

Two classes of inelastic events were investigated in detail. One is the collision process in which a target deuteron is excited to the virtual, spin-singlet, or $d^*$ state; the data on the second type of collision in which sufficient energy is transferred to dissociate the deuteron completely, will be reported elsewhere. The major difficulty in analyzing the $d^*$ events is that the difference in proton energy between elastic and $d^*$ events is only 2.2 MeV—less than the system resolution. The analysis is simplified by the fact that the resolution function for the system is well fitted (within 2%) by a Gaussian shape. This basic function was determined from spectra for scattering angles between 0° and 4°. The appropriate resolution function at each angle was then obtained by including the effects of kinematic broadening and energy spread in the target. The main peak in the proton energy spectrum was considered to be the result of the superposition of elastic and $d^*$ Gaussian peaks. The $d^*$ contribution was always found to be in the order of a few per cent. An upper limit for $d^*$ at each angle was determined by considering what relative component must be added 2.2 MeV from the elastic peak in order to generate a peak which is wider by two standard deviations than the experimentally measured curve. These upper limits are shown in Fig. 2; the largest value is 13% of the elastic cross section. At angles larger than 30° (c.m.) the $d^*$ cross section becomes very small requiring a different experimental method of determination; coincidence measurements were made using the range spectrometer shown in Fig. 1. The following two measurements were made:

(1) Coincident events were required between protons scattered at 25 deg (lab.) into the magnetic spectrometer and recoil deuterons, or $d^*$, scattered into the range spectrometer. A trigger from the range spectrometer required a particle to transverse counters $C$ and $C'$ and the brass absorber of variable thickness $t$ between them, but not the last counter, $A$, separated from $C'$ by 5 mils of brass. Thus, each event denotes a particle with a range in brass between $t$ and $t+5$ mils. The virtual deuteron, being unbound, appears in the range spectrometer as a proton with half the range of an elastic deuteron. When the cross section for coincident events, corrected for absorption of the $d$ and $d^*$ in brass, is plotted versus absorber thickness, the areas under the elastic and virtual deuteron peaks are a measure of the relative frequency of these events. The ratio of $d^*$ to $d$ at a center-of-mass angle of 44° is found to be $0.015 \pm 0.015$.

(2) To measure $d^*$ production at a laboratory deuteron angle of 9° (center-of-mass angle of 160°), coincidences were required between deuterons in the magnetic spectrometer and elastic protons in the range spectrometer set at the kinematic angle. One measurement was made with the magnetic spectrometer adjusted to detect elastic deuterons, and another with the spectrometer adjusted to detect the $d^*$ protons which have half the momentum. The result is

$$\sigma(d^*)/\sigma(d) = 0.05^{+0.02}_{-0.05}.$$

The cross section for the production of a virtual deuteron from the collision of a proton and real deuteron is an important parameter in the understanding of the large number of quasifree $n$-$p$ pairs observed in the scattering of 1-BeV protons from He, C, and O.[13]

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