Extreme back angle $n\,^2$H elastic scattering at 794 MeV*

B. E. Bonner and J. E. Simmons
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545

M. L. Evans,† G. Glass, J. C. Hiebert, Mahavir Jain,† and L. C. Northcliffe
Texas A&M University, College Station, Texas 77843

C. W. Bjork‡ and P. J. Riley
University of Texas, Austin, Texas 78712

C. G. Cassapakis§
University of New Mexico, Albuquerque, New Mexico 87131

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The cross section for elastic scattering of 794-MeV neutrons by deuterium has been measured for neutron center of mass angles from 139° to 179°. The angular distribution is fitted very well both by an empirical function $\alpha e^{\beta(\mu-\mu_{180°})}$ and by a calculation that uses the one parameter Craigie-Wilkin triangle diagram technique.

[NUCLEAR REACTION $n^2\mathrm{H}\to{}^2\mathrm{H}n$, $E=794$ MeV; measured $\sigma(\theta)$. Calculated $\sigma(\theta)$ with triangle diagram techniques.]

I. BACKGROUND

The failure of the one-nucleon-exchange (ONE) mechanism to fit the backward peak observed in the pD elastic scattering cross section at medium energy led to the postulation[1] of excited nucleon states (N^*N) and double Δ ($\Delta\Delta$) components in the deuteron. Various experiments[2] searching for such components have yielded conflicting results with probabilities deduced ranging from 1 to 16%. To date the most convincing evidence for the still tenuous postulate remains the original failure of ONE to account for the observed peak in elastic pD scattering.[3] Several calculations have embellished the original idea by the inclusion[4] of many possible N^*'s, but it appears that N^* probabilities are small.

Another approach[5] has utilized the Yao technique to relate the backward peak in pD scattering to the cross section for the process $pp\to d\pi^+$ by the use of triangle diagrams. The striking variation of the 180° c.m. cross section with bombarding energy is thus explained in terms of the 1232-MeV resonance in π^+p elastic scattering rather than by a variation of the probability for finding excited nucleon states in the deuteron.

A recent calculation by Gurvitz and Rinat[6] using a noneikonal multiple scattering approximation plus ONE appears to fit the backward peaking in pD scattering over a wide range of incident proton momenta by postulating a deuteron form factor at large q^2 that is radically different from that obtained by extrapolation of conventional deuteron wave functions to the high momentum transfers encountered in backward p^2H scattering. Recently published measurements from SLAC[7] appear to support this postulated behavior of the deuteron form factor at large q^2, thus resurrecting the original hope that information on the high momentum components of the deuteron wave function can be obtained by elastic scattering of hadrons of modest energy.

All previous measurements[8] of nucleon-deuteron elastic scattering above 150 MeV have utilized proton or deuteron beams. Most of the angular distributions below 1-GeV proton energy do not extend beyond the proton center of mass angles of 160° to 165°. There are several plots in the literature, however, of the extrapolated 180° c.m. cross section as a function of energy. The extrapolation procedures that were used vary and can lead to quite different results. In addition, large discrepancies are apparent between existing data sets at the same energy.

An important advantage of using a neutron beam for measurement of nucleon-deuteron scattering is that the spectrometer used to detect the recoil deuterons can be positioned at 0° with respect to the neutron beam, which allows measurements to be made at 180° c.m. In this paper, we report the first such measurement for n^2H elastic scattering at medium energy. We have measured the differential cross section for c.m. angles between 139° and 179° at an incident neutron energy of 794 MeV.

II. EXPERIMENTAL TECHNIQUES

The nearly monoenergetic [~10 MeV full width at half maximum (FWHM)] neutron beam and spectrometer system used in the present experiment have been described in previous publications.[9] Briefly, the 800-MeV, 1-μA proton beam from the Clinton P. Anderson Meson Physics Facility (LAMPF) passed through a 10.6-cm-thick liquid deuterium target and was then bent through 60° and buried in a remote beam stop. Neutrons emerging from the target at 0° were collimated to a half angle of 0.1°, and after being cleared of charged particles, the beam encountered a 12.6-cm-thick liquid deuterium target placed upstream of a multiwire proportional chamber spectrometer. The momenta and flight times of charged particles emerging from this target into the acceptance of the spectrometer were measured. The momentum resolution was about 1% FWHM. Particle identification was unambiguous and since the deuterons resulting from elastic collisions were the highest momentum particles observed in this experiment, they were easily identified despite the presence of other peaks of much higher intensity. The angular acceptance of the spectrometer was ±2 degrees

III. RESULTS AND DISCUSSION

Using the apparatus described in the preceding section, we have measured the cross section for elastic scattering of neutrons by deuterium at nominal spectrometer angles of 0°, 4°, 8°, and 16°. This covers neutron center of mass angles from 139° to 180°. A typical 0° deuteron momentum spectrum is shown in Fig. 1. The peak at the highest momentum is due to the process of interest here, elastic n^2H scattering. The much stronger and broader peak at lower momentum arises from quasifree deuteron production in the reactions $n``p" \to {}^2\mathrm{H}\pi^0$ and $n``n" \to {}^2\mathrm{H}\pi^-$, where the quotation marks indicate a bound nucleon in the target deuteron. The cross section for quasifree deuteron production from these reactions is about 90% of the sum of the two free cross sections, and the shape of the angular distribution follows that observed in $pp \to {}^2\mathrm{H}\pi^+$. A similar observation in p^2H interactions has been reported previously.[10] The width of the quasifree peak is a manifestation of the Fermi momentum distribution of the struck nucleon inside the deuteron. The continuum at lower momenta is caused by neutrons in the low-momentum tail of the incident neutron beam spectrum.

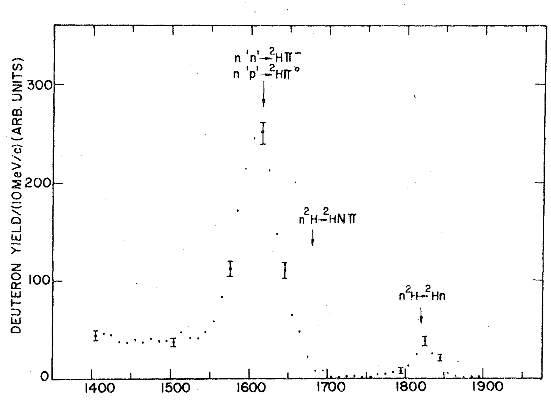

FIG. 1. Spectrum of deuterons from a single run at 0° laboratory resulting from 794-MeV neutrons incident on deuterium. The expected positions of the elastic and quasifree peaks are indicated as well as the maximum momentum allowed for coherent pion production.

The deuterons arising from elastic scattering were sorted into 10-mrad angular bins and summed over the peak, which was defined as those deuterons with momenta greater than that given by elastic scattering of an incident neutron with a kinetic energy of 750 MeV. Absolute normalization was obtained by comparison with the results of a separate experiment[11] performed with the same apparatus in which deuterons from the reaction $np \to {}^2\mathrm{H}\pi^0$ were detected. Using isospin invariance, the cross section for that reaction was taken to be one-half the well-known cross section for the reaction $pp \to {}^2\mathrm{H}\pi^+$. From the deuteron yield in that experiment we calibrated a monitor counter in terms of the product (number of incident neutrons) × (number of H target atoms). When allowance is made for the difference in the density of the two liquid targets, this calibrated monitor provided absolute normalization for the present measurement. The estimated error in this procedure results in a ±8% scale error in the cross sections reported here.

Corrections to the data consisted of the following:

(1) Deuteron loss from nuclear interactions in the material traversed in the spectrometer. This was calculated according to two prescriptions[12]; both yielded a value of 3.6%.

(2) Deuterons in the peak arising from neutron interactions in target walls and other material in the beam. This correction was determined from measurements made with the scattering target empty; it was found to vary with angle, being 5.8% at 0° and 2.3% at 16°.

(3) Deadtime effects in the data acquisition system. The data reported here were taken at rates that gave rise to deadtimes of 5% to 40%. The deadtime for each run was measured, and data taken for widely different values were compared and found to be consistent.

TABLE I. Cross section for n^2H elastic scattering at 794 MeV. The quoted errors are due to counting statistics only.

$\theta^n_{c.m.}$ (deg)	$\lvert\tau\rvert = \lvert u - u_{180°}\rvert$ (GeV/c)^2	$\frac{d\sigma}{d\Omega_{c.m.}}$ (μb/sr)
178.57	0.00043	57.8 ±5.9
177.70	0.00111	62.1 ±4.2
175.64	0.00396	56.0 ±3.9
173.49	0.00883	56.9 ±4.0
171.80	0.01399	54.1 ±5.0
170.51	0.01875	57.9 ±3.0
168.33	0.02831	52.6 ±2.9
166.15	0.03983	51.5 ±2.9
163.96	0.05327	46.8 ±2.7
161.94	0.06744	45.6 ±2.5
159.76	0.08452	46.9 ±2.6
157.59	0.10344	38.8 ±2.3
155.41	0.12417	35.5 ±2.2
144.95	0.24827	22.4 ±2.2
142.80	0.27865	17.8 ±1.9
140.64	0.31052	17.8 ±1.9
138.82	0.33871	14.8 ±2.0

The cross sections measured for 794-MeV n^2H elastic scattering are tabulated in Table I and plotted versus c.m. angle in Fig. 2. Also plotted there are data on p^2H backward scattering from other experiments[13-17] at nearby energies. It is apparent that the three measurements near 1 GeV (Refs. 15–17) differ greatly in normalization as well as shape. The flattening of the shape beyond about 160° which we observe is also apparent in the 1-GeV data of Dubal *et al.*[17] but not in the other measurements.

When the cross section values are plotted versus the momentum transfer variable $\tau = (u - u_{180°})$, where u is the square of the exchange four-momentum transfer, then a very simple shape is manifest: A simple exponential suffices to fit the present results. This backward peaking is characteristic of reactions proceeding via particle exchange in the u channel. Such a plot is shown in Fig. 3. The χ^2 per degree of freedom for the fit to our data of the function $d\sigma/d\Omega_{c.m.} = \alpha e^{\beta\tau}$ is 0.5, with $\alpha = 60.0 \pm 1.3$ and $\beta = 4.04 \pm 0.21$. Also shown in the figure are the data from the other experiments mentioned above for $\tau > -0.6$ (GeV/c)^2. Table II gives the values of α, β, and χ^2 that we determined for these measurements. An alternative representation of the data can be obtained in terms of the variable Q, defined by Noble and Weber[18] to be the Fermi momentum of a nucleon in the rest frame of the deuteron.

For the one-nucleon exchange diagram, one would associate the slope parameter β with the mass of the particle being exchanged ($\beta \simeq 1/m^2$). However, it is apparent that the value of the slope not only is changing over the energy range from 600 to 1000 MeV, but it is far from the value of about unity expected from ONE.

We have performed a calculation using the Craigie-Wilkin Model in which the cross section for n^2H scattering is related to the $NN \to {}^2$Hπ cross

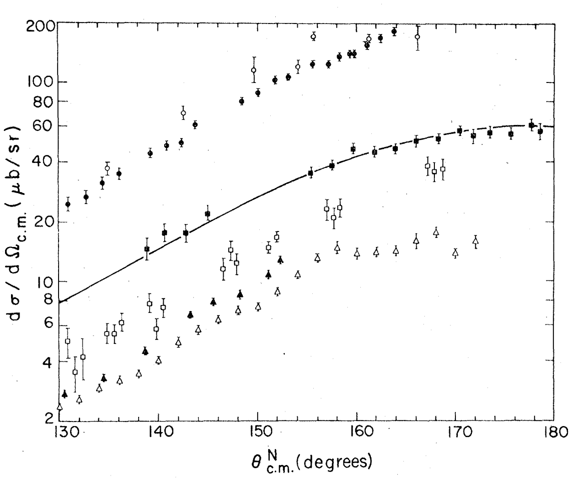

FIG. 2. Center-of-mass angular distributions of the elastic scattering cross section for n^2H at 794 MeV and p^2H at nearby energies. The energies, plotting symbols used, and corresponding references are 582 MeV (○) (Ref. 13), 590 MeV (●) (Ref. 14), 1000 MeV (□) (Ref. 15), 1000 MeV (▲) (Ref. 16), 1017 MeV (△) (Ref. 17), and (■) present experiment. The curve gives the result of the fit to the present data using Eq. (1).

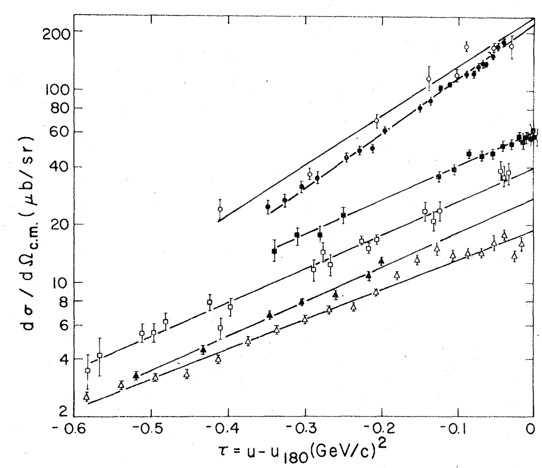

FIG. 3. Plot of the data from Fig. 2 versus $\tau = (u - u_{180°})$, where u is the square of the exchange four-momentum transfer. Only data for $\tau > -0.6$ (GeV/c)^2 are included. The solid lines represent least-squares fits to the function $d\sigma/d\Omega_{c.m.} = \alpha e^{\beta\tau}$ for each experimental data set. Symbols and references same as in Fig. 2.

TABLE II. Parameters determined for exponential fit $\alpha e^{\beta\tau}$.

Energy (GeV)	α (μb/sr)	β (GeV/c)$^{-2}$	χ^2/ν	Reference
0.582	242.5 ± 9.6	6.00 ± 0.26	3.7	Boschitz (Ref. 13)
0.590	222.4 ± 4.0	6.59 ± 0.13	1.0	Alder (Ref. 14)
0.794	60.0 ± 1.3	4.07 ± 0.21	0.5	Present expt.
1.000	27.3 ± 1.1	4.09 ± 0.12	2.4	Coleman (Ref. 16)
1.000	39.1 ± 1.9	4.01 ± 0.16	1.0	Bennett (Ref. 15)
1.017	18.9 ± 0.4	3.57 ± 0.06	3.7	Dubal (Ref. 17)

section via a triangle diagram. The formula used is the one given by Barry[5]:

$$\frac{d\sigma^{n^2\mathrm{H}\to{}^2\mathrm{H}n}}{d\Omega_\theta}=\frac{\zeta^2}{2}\,\frac{3\epsilon\alpha}{1-\alpha r_t}\,\frac{G^2}{4\pi}\,\frac{F^2(k_1^{\,2})k_1^{\,2}}{(k_1^{\,2}+\mu^2)^2}\times\frac{s_{pp}}{s_{nd}}\,\frac{|p|}{|D|}\,\frac{3}{2}\,\frac{d\sigma^{pp\to{}^2\mathrm{H}\pi^+}}{d\Omega_\phi}\,, \qquad (1)$$

where ϵ is the deuteron binding energy (2.23 MeV), $\alpha=\sqrt{m\epsilon}$ is the Fermi momentum in the deuteron, r_t is the triplet np effective range (1.75 fm), $G^2/4\pi$ is the on mass shell π-N coupling constant (14.7), $F(k_1^{\,2})=[1+(k_1^{\,2}+\mu^2)/60\mu^2]^{-1}$ is the Ferrari-Selleri form factor that is used in order to account for the internal pion being off shell, s_{pp} and s_{nd} are the squares of the total c.m. energies in the two reactions, $|p|$ and $|D|$ are the c.m. momenta of the proton and deuteron in the reactions $pp\to{}^2\mathrm{H}\pi^+$ and $n^2\mathrm{H}\to{}^2\mathrm{H}n$, respectively, and k_1 is the c.m. momentum of the internal pion. The cross sections are evaluated at the same laboratory kinetic energy and two prescriptions are given[5] for relating the c.m. angles, θ and ϕ, in the two reactions. We have used the fixed $\cos\theta$ prescription that has the virtue of avoiding unphysical values of the angles.

The cross section for $pp\to{}^2\mathrm{H}\pi^+$ was taken from the compilation by Richard-Serre *et al.*[19] This cross section is usually written as

$$\frac{d\sigma^{pp\to{}^2\mathrm{H}\pi^+}}{d\Omega}=\frac{\sigma_t}{(A+\frac{1}{3}-\frac{1}{5}B)}\,(A+\cos^2\theta-B\cos^4\theta)\,.$$

The values $\sigma_t=1.290$ mb, $A=0.31$, and $B=0.478$ were used in a least-squares fit of Eq. (1) to the present data, varying the single parameter ζ. The significance of this parameter is discussed by Barry and is related to the one-pion-exchange coupling strength at the $p^2\mathrm{H}n$ vertex and is expected to be energy independent. For $\zeta=3.97\pm0.03$, we obtain a fit with χ^2 per degree of freedom equal to 0.7. This value of ζ is in agreement with the trend indicated in Ref. 17. The fit is compared with the data in Fig. 2.

IV. CONCLUSIONS

We have reported a measurement of the extreme back angle n^2H elastic-scattering cross section. The shape of the angular distribution is fitted very well by a simple function $\alpha e^{\beta\tau}$, indicative of particle exchange. A calculation using the Craigie-Wilkin model[5] also fits the data. The value of the c.m. cross section at 180° determined from the present data is 60.0 ± 1.3 μb/sr.

If the Craigie-Wilkin model[5] is accepted as being a reasonable description of the n^2H elastic process at back angles, then the fact that the value of the parameter ζ which we obtain is consistent with the values extracted from the data at 590 (Ref. 14) and 1017 MeV (Ref. 17) would tend to support the normalization of Ref. 17 at 1 GeV compared to the other two data sets[15,16] at that energy. It is interesting to observe that the original motivation for introducing isobars in the deuteron wave function[1] was that the ONE calculation fell a factor of 2 below the backward peak observed[15] in p^2H elastic scattering at 1 GeV. The data of the present experiment tend to support the results of Ref. 17, which are about a factor of 2 lower than those of Ref. 15 at back angles.

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†Present address: Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545.

‡Present address: University of Wyoming, c/o LAMPF Visitors Center, Los Alamos, New Mexico 87545.

§Present address: Science Applications, Inc., LaJolla, California 92037.

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