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p-d Elastic Cross Section and Polarization at 198 MeV*

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p-d elastic cross-section and polarization measurements are presented at an incident energy of 198 MeV, over the center-of-mass angular range 80° to 170°. The peak in the backward or pickup region is examined in terms of a simple nucleon-exchange parametrization.

I. INTRODUCTION

We have measured the cross section and polarization in proton-deuteron elastic scattering at 198 MeV.[1] The angular range covered was 80° to 170° in the center-of-mass system and includes the so-called pickup region near 180° where the deuteron in the final state emerges forward in the lab system with nearly the full beam energy.

The pickup region should be characterized by baryon exchange at medium and high energies as the form factor for the direct process, where the proton recoils against the deuteron as a whole, should be negligibly small. Coleman[2] has studied the 180° elastic cross section at 1.0-, 1.3-, and 1.5-GeV incident proton energy, and also derived the cross section for the pickup process assuming a one-nucleon-exchange peripheral model. The form of the cross section for this process is

$$\frac{d\sigma}{d\Omega}=\frac{64\pi^2N^4}{3}K(q)\frac{[F(q)]^4}{(\alpha^2+q^2)^2}\,. \tag{1}$$

N is the deuteron wave-function normalization constant, α is the binding energy of the deuteron, q is the difference between the three-momenta of the incoming proton and the outgoing deuteron as measured in the center-of-mass system, and $K(q)$ is a strictly kinematic factor[3] which goes to unity at low energy. $F(q)$ is the deuteron vertex form factor and has the property $F(q)\to 1$ as $q^2\to-\alpha^2$.

For the Hulthén wave function

$$F(q)=\frac{\beta^2-\alpha^2}{\beta^2+q^2},\quad \beta=5.2\alpha\,. \tag{2}$$

We will use this theory to compare our data with large-angle *p-d* elastic data at other energies.

II. EXPERIMENTAL METHOD

The experiment was performed in the external proton beam of the Rochester 130-in. synchrocyclotron. The beam was extracted by scattering from an internal carbon target, thus achieving a vertical polarization of $(94\pm1.5)\%$. The energy of the beam was determined using a copper absorber; the energy at the center of the target was found to be 198 ± 6 MeV. The relative intensity of the beam was monitored using a set of multicounter telescopes looking at a carbon target placed downstream of the deuterium target.

The signature used for separating large-angle *p-d* elastic events from the more copious inelastic events was the presence of a high-energy deuteron in the forward direction. The deuteron was identified by measuring its time of flight and energy. The time-of-flight counters 1 and 2 and the total-energy plastic scintillator E are indicated in Fig. 1, a diagram of the apparatus. The time-of-flight and energy information for each scattered particle were read into a two-parameter matrix

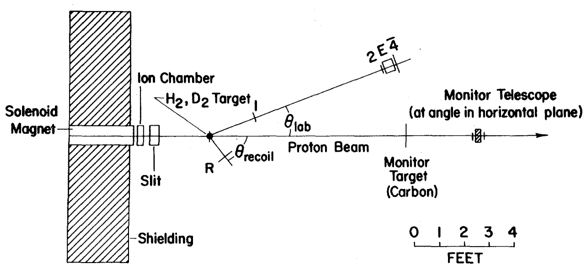

FIG. 1. Layout of the apparatus in the 198-MeV, 94% polarized proton beam of the University of Rochester synchrocyclotron (side view).

using a PDP-8 computer on-line. The number of deuterons detected followed from an analysis of this time-energy spectrum. The deuteron separation was very clean and typically contributed only a 1–2% normalization uncertainty at a data point.

A solenoid magnet was used to precess the spin of the protons into the horizontal plane. By reversing the sense of the precession and measuring the flux of deuterons at a given angle both above and below the beam, both the cross section and polarization could be measured free of first-order misalignment corrections. The measured rate was normalized by filling the 2-in. target cup with liquid hydrogen and calibrating the detection system using the 200-MeV proton-proton cross section as measured by Marshall *et al.*[4]

A correction was required for the difference in

TABLE I. Polarization and center-of-mass cross section for elastic proton-deuteron scattering at 198 MeV as a function of center-of-mass angle. The errors in the cross section include the error in the normalization.

$\theta_{c.m.}$	P	ΔP	$\frac{d\sigma}{d\Omega}$ in mb/sr	$\Delta\sigma$
170°	0.048	0.025	0.609	0.033
165°	0.153	0.015	0.346	0.015
160°	0.164	0.010	0.301	0.010
155°	0.178	0.009	0.242	0.008
150°	0.201	0.008	0.214	0.007
145°	0.197	0.009	0.186	0.006
138.5°	0.112	0.009	0.163	0.004
135°	0.091	0.009	0.148	0.005
129°	−0.010	0.008	0.128	0.004
125°	−0.078	0.009	0.111	0.004
120°	−0.139	0.013	0.104	0.003
115°	−0.254	0.011	0.097	0.003
110°	−0.300	0.009	0.106	0.003
105°	−0.417	0.007	0.102	0.002
100°	−0.433	0.005	0.108	0.004
95°	−0.478	0.005	0.121	0.004
92.5°	−0.541	0.010	0.131	0.004
90°	−0.504	0.005	0.138	0.004
85°	−0.493	0.006	0.165	0.007
80°	−0.480	0.010	0.197	0.010

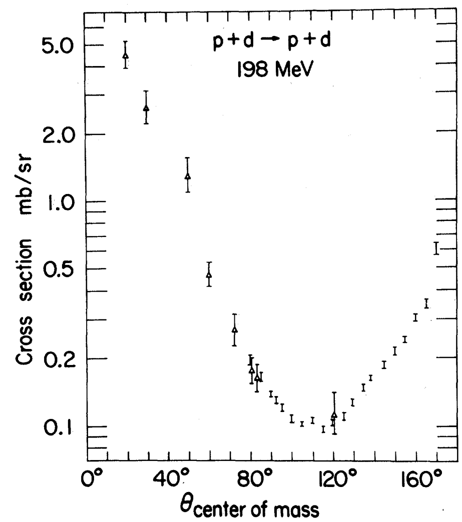

FIG. 2. Center-of-mass cross sections for elastic *p-d* scattering at 198 MeV (vertical bars). Small-angle data (Ref. 6) at 240 MeV were renormalized by a factor of 0.625 (triangles).

the total inelastic cross section for protons and deuterons in the total-energy scintillator. Calculations were made using measured *p*-CH and *d*-CH inelastic scattering data[5]; these calculations were checked by inserting absorbers in front of the counter. The calculations agreed with measurements to within 3%. The size of the correction to the cross section varied from 32% at 170° to 5% at 80° in the center-of-mass system. The correction did not affect the polarization.

III. RESULTS

The cross-section results were calculated by taking the measured deuteron rates, multiplying by the appropriate Jacobian to transform to the center-of-mass system, multiplying also by an absolute normalization constant which was determined from the runs with a hydrogen target. A tabulation of the results of these measurements of *p-d* elastic scattering at 198 MeV is given in Table I. The errors quoted include the published errors in the hydrogen scattering data used in the normalization. Figure 2 shows a plot of these values as a function of center-of-mass scattering angle. Also included in Fig. 2 are the 240-MeV data of Schamberger[6] normalized by a factor of 0.625 to join smoothly onto the 198-MeV data.

The polarization results are also included in Table I. The sign convention is based on the scattered proton. The errors quoted include the uncertainty in the incident-beam polarization. Figure 3 shows a plot of the polarization parameter as a function of center-of-mass angle.

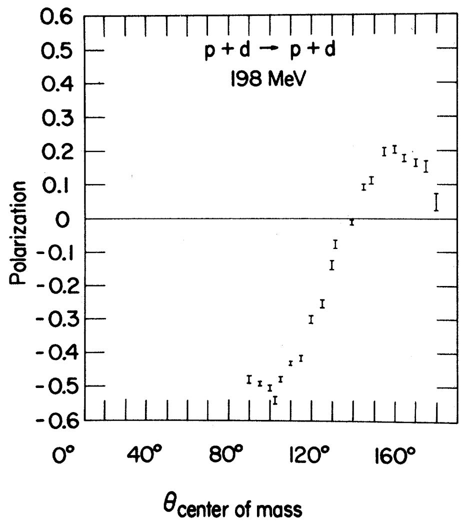

FIG. 3. Polarization parameter in 198-MeV p-d elastic scattering.

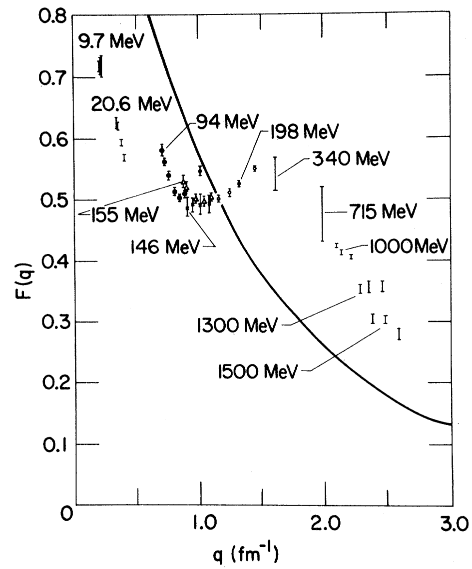

FIG. 4. Reduced form factor $F(q)$ used to parametrize p-d elastic scattering for center-of-mass angles greater than 150°. Data at various incident proton energies (Ref. 7) are compared with $F(q)$ as derived from the Hulthén wave function (solid line).

In order to compare our data with measurements at other energies, we have used Eq. (1) to parametrize the data in the pickup or backward direction. In the spirit of using Eq. (1) as a parametrization, we will call $F(q)$ the reduced form factor. Using data on p-d elastic scattering at different incident proton energies and at center-of-mass angles larger than 150°, we have extracted the value of the reduced form factor. Figure 4 shows the resulting values of $F(q)$ plotted as a function of q for incident energies ranging from 9.7 MeV to 1.5 BeV. There is a discernable trend in the data points which indicates that this method of parametrization has some validity. The references for the various data points at other energies can all be found in a comprehensive survey of p-d elastic scattering by Seagrave.[7] Also indicated on the graph is the form of $F(q)$ derived from the Hulthén wave function [Eq. (2)]. It is not surprising that the backward cross section does not follow such a simple form as the Hulthén form factor. Clearly such effects as interference with the direct amplitudes and exchange of higher resonances[8] can affect this u-channel behavior. Note that the existence of a fairly large polarization at these backward angles as seen in Fig. 3 implies that there must be more than a single-exchange amplitude contributing to the cross section. The interference with the direct forward amplitudes possibly generates this polarization.

IV. CONCLUSION

The cross section for p-d elastic scattering at 198 MeV was measured and showed a peak at 180° in the center-of-mass system, the pickup region. This backwards peak is characteristic of u-channel exchange processes. A nonzero polarization was also measured in the region of this peak. This polarization cannot be generated by a simple one-nucleon-exchange mechanism. We have parametrized p-d elastic cross-section data to define a reduced form factor $F(q)$. This parametrization shows some interesting features when used to correlate data from 9.7 MeV to 1.5 GeV. Effects of the exchange of higher resonances may be indicated. Most certainly more data on the value of the 180° p-d elastic cross section as a function of energy would be invaluable in shedding more light on this conceptually simple u-channel process.

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[3]Note, $K(q)$ was calculated incorrectly in Coleman's article:

$$K(q)=\frac{3}{2}\left(\frac{M_d}{U}\right)^2\left(\frac{mM_d-p_1\cdot d_2}{2mM_d}\right)^2\frac{mM_d-n\cdot d_2}{2mM_d}\;\frac{mM-n\cdot d_1}{2mM_d},$$

where p_1, d_1, and d_2 are the proton, initial- and final-deuteron center-of-mass 4-momenta, respectively; U= total energy in the c.m. system; m = proton mass; M_d = deuteron mass; $n=d_2-p_1$.

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Relative Capture Rates for Slow π^-, K^-, Σ^- in a Neon-Hydrogen Mixture

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We find the relative hydrogen capture rates for π^-, K^-, and Σ^- in a 24 mole percent mixture of neon in hydrogen to be $(17\pm5)\%$, $(26\pm5)\%$, and $(48\pm6)\%$, respectively. A possible mechanism for these differences is presented.

INTRODUCTION

The details of the atomic processes which precede the nuclear capture of slow, heavy, negative particles have long been of interest. If the fundamental physical properties of nuclei and/or elementary particles are to be investigated using these absorptions, it is necessary to know the atomic state from which nuclear absorption occurs. When the stopping material is an elemental mixture, the first priority is clearly the delineation of the fraction of absorptions occurring on each element. The earliest estimate of this fraction was given by Fermi and Teller[1] in their so-called Z law which states that the relative capture probability of negative mesons by the atoms of chemical compounds is proportional to NZ, where Z is the atomic number and N is the number of atoms in the compound. While the general tenor of the experimental data[2] has been confirmatory of this prediction, many deviations are known. In particular, the class of hydrogenous mixtures and compounds, for which the concept of a degenerate electron gas is a poor approximation, requires a different approach since a mesonic hydrogen atom forms a small system relative to atomic dimensions, and is capable of readily diffusing throughout the stopping medium. Because of the lower energy states available for heavy mesonic atoms, the meson can undergo transfer from the proton to a heavier atom. Early experiments[3] with negative muons indicated that all muons interact with neon when the neon concentration in liquid hydrogen is as small as 30 ppm. The problem is more interesting for strongly interacting particles where the interaction rate between the negative particle and proton may be sufficiently rapid so that the mesonic atom disintegrates prior to the transfer of the meson from the proton to a more massive system.

Relative capture data for heavy, negative, strongly interacting particles stopping in liquid