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# 240-Mev Proton-Deuteron Scattering*†

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A scattering apparatus within the tank of the 130-inch cyclotron has been used to investigate proton-deuteron scattering by measuring coincidences between the proton and deuteron in elastic scattering and the two protons in inelastic scattering. The incident beam has been measured by measuring the $C^{11}$ beta-activity produced in the heavy paraffin targets. The differential elastic scattering cross section has been obtained from 20.5° to 100° for the proton scattering angle in the center-of-mass system. That portion of the inelastic scattering which results in a low energy neutron has been investigated. The differential cross section for this quasi-proton-proton scattering has been obtained at three angles in the center-of-mass system of the two protons. The cross section, equal to about one half of the free proton-proton cross section at 90°, decreases as the proton scattering angle decreases. Maximum energies for the low energy neutron distribution have been obtained at laboratory neutron angles of 0°, 90°, and 180° with respect to the incident proton direction for proton scattering angles of 40°, 67°, and 90° in the *p-p* center-of-mass system.

## INTRODUCTION

WHEN the preliminary results of high energy nucleon-nucleon scattering became available, it was felt that the measurement of the elastic proton-deuteron cross section might be valuable in the interpretation of the nucleon-nucleon data since the proton-deuteron scattering might include appreciable interference effects between the neutron-proton and proton-proton scattering.

The apparatus which has been used to investigate the scattering of 240-Mev protons by deuterons is described in the preceding paper.[1] The only changes made were the substitution of a heavy paraffin[2] target for the polyethylene target used in the investigation of proton-proton scattering and the reduction from 2 cm to 0.7 cm of the lower crystal dimension parallel to the path of the particle when low energy particles were being detected. The paraffin targets consisted of a strip of paraffin, $\frac{5}{8}$ in.$\times\frac{1}{8}$ in.$\times$0.003 in., mounted on a 0.00023-inch aluminum support. The target thickness was the same for all runs to facilitate the evaluation of the $C^{11}$ activity measurement. The measured efficiency of the beta-counter was modified slightly to account for the change in target thickness and the backscattering from the aluminum support.

### Elastic Scattering

The general procedure described in connection with the proton-proton scattering measurement[1] has been followed in this experiment. The chance background and the background from carbon have been evaluated in the same manner. No coincidence background has been observed from the aluminum target support. An additional background has been observed which produced a somewhat broader coincidence *vs* target position plateau than that resulting from an elastic collision. This has been attributed to an inelastic proton-deuteron process. The information which has been obtained on this process will be presented in the following section. For the measurement of the elastic cross section, it must be considered an undesirable background since, at most scattering angles which were investigated, the elastic and inelastic plateaus overlapped.

For proton scattering angles of 20.5° and 31° in the proton-deuteron center-of-mass system, the pulses produced by the deuterons were smaller than the pulses produced by the protons reaching the lower crystal, so that the inelastic background could be measured directly. At scattering angles of 42° and 54° the pulse heights, while not the same, were not sufficiently different to make the separation completely unambiguous. However, at these angles the flat tops of the plateaus were just resolved, and, with the aid of the information from the pulse heights, the sloping sides of the inelastic plateau could be determined. At scattering angles above about 70° the plateaus were well enough resolved to permit the extrapolation of the tail of the inelastic plateau under the elastic plateau when necessary without introducing a large error in the measurement of the elastic cross section. A background of proton-proton scattering from the $H^1$ impurity in the target was expected. However, it could not be separated experimentally from the inelastic scattering.

The measurement at 75° was further complicated by the fact that two elastic plateaus were superimposed. When a proton scattered at 75° in the center-of-mass system reached the upper crystal and the recoil deuteron reached the lower crystal, a proton scattered at 79° could be recorded in the lower crystal and the recoil deuteron in the upper crystal. In both crystals the energy lost by the deuteron was greater than the energy lost by the proton, so that by raising the discriminator setting in one channel the pulses from the protons corresponding to one of the angles of scattering

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† This work was assisted by the ONR and AEC.
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[1] C. L. Oxley and R. D. Schamberger, Phys. Rev. 85, 416 (1952).
[2] The heavy paraffin, prepared by the Texas Company, was obtained from the AEC.

could be eliminated. Unfortunately, this also eliminated some of the deuterons. As a result, about 12 percent of the coincidences which were known to be the result of elastic scattering could not be assigned to the proper scattering angle of an experimental basis. These coincidences have been assigned so that the cross section at 75° in the center-of-mass system is slightly larger than the cross section at 79°.

Preliminary results of the measurement of the elastic scattering cross section have been reported.[3] A few small corrections have been made to the cross sections which were published. The cross sections in the center-of-mass system are given in Table I. The errors indicated include the statistical errors in the coincidences and estimated errors in those factors which influence the relative cross section. The errors on the values at 75° and 79° have been increased to cover any division of the arbitrarily assigned coincidences mentioned above. The reader is referred to the preceding paper[1] for the discussion of the errors in the absolute scale. The angular resolution in the center-of-mass system was about $\pm 1°$ at a scattering angle of 20.5° and $\pm 3°$ at a scattering angle at 75°.

A theoretical analysis of the data presented in Table I and of other available *p-d* data is being made by J. B. French and P. B. Daitch of this laboratory. The results of their calculations will be published when completed.

## Inelastic Scattering

An interesting by-product of the measurement of the elastic scattering cross section was the observation of the inelastic process mentioned as a background in the elastic measurement. When the target was moved either radially or parallel to the incident beam, the coincidence *vs* target position plateaus were broader than those obtained when observing an elastic collision. The center of the inelastic plateau was located at the same position as the center of the plateau from proton-proton scattering. The pulse heights were also the same as in proton-proton scattering with a slight smearing of the pulse-height distribution at laboratory angles around 45°. The number of coincidences was too large to be explained by the $H^1$ impurity in the target.[4] These

TABLE I. The 240-Mev elastic proton-deuteron scattering cross section in the center-of-mass system.

| Center-of-mass proton scattering angle | *P-d* cross section (millibarns/steradian) |
|---|---|
| 20.5° | $7.2 \pm 0.6$ |
| 31° | $4.31 \pm 0.20$ |
| 42° | $2.01 \pm 0.22$ |
| 54° | $0.76 \pm 0.09$ |
| 64° | $0.45 \pm 0.15$ |
| 75° | $0.29 \pm 0.05$ |
| 79° | $0.27 \pm 0.04$ |
| 100° | $0.11 \pm 0.03$ |

[3] R. D. Schamberger, Phys. Rev. **83**, 1276 (1951).

[4] An analysis of the heavy paraffin has been made by the National Bureau of Standards.

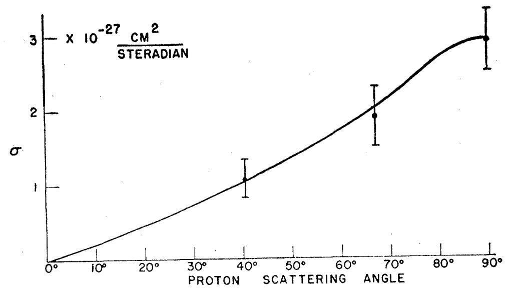


FIG. 1. The 240-Mev quasi-proton-proton scattering cross section in the center-of-mass system of the two protons. The solid curve has been used to estimate the total cross section.

plateaus, therefore, were not produced principally by free proton-proton scattering, but were the result of a process which closely resembles it. A proton-deuteron collision resulting in two protons and a low energy neutron satisfies all of the requirements.

The cross section for this quasi-proton-proton scattering was measured on the assumption that the volume under an elastic or inelastic plateau was proportional to the cross section. The solid angle subtended by the counters at the center of the plateau was used as an average solid angle in the calculation. The cross section which has been computed is the cross section per unit solid angle, in the center-of-mass system of the two protons, for the emission in a proton-deuteron collision of a proton at the angle $\theta$ and a low energy neutron at any angle.

The proton scattering angle varied over the plateaus, so that some average cross section was actually measured. The cross section probably does not vary rapidly enough with angle to introduce a large error in the measurement. The method, however, might not be suitable for a precise measurement of the cross section.

The quasi-proton-proton scattering cross section has been measured at three proton scattering angles, 90°, 67°, and 40°, in the center-of-mass system of the two protons. The measurement at 90° was made relative to the 90° proton-proton cross section. The measurements at 67° and 40° were made relative to the elastic proton-deuteron cross section at 54° and 31°, respectively. The contribution from free proton-proton scattering was calculated on the basis of a $H^1:H^2$ ratio of 1:19[4] and a *p-p* cross section of 4.97 millibarns/steradian.

The experimental cross sections are plotted in Fig. 1. The cross section is a maximum at a scattering angle of 90° and decreases at smaller proton scattering angles where the competing elastic scattering has a larger cross section. The error in each of these measurements is large since the volumes under the plateaus could not be measured accurately in a reasonable length of time. Figure 1 also shows the curve which has been used to calculate the total cross section. A total cross section of $11 \pm 3$ millibarns has been obtained.

Some information about the energy of the neutrons can be obtained from the shape of the inelastic plateaus.

TABLE II. The "upper limit" energies of the low energy neutron spectrum. The neutron angles are in the laboratory system. The proton scattering angles are in the $p$–$p$ center-of-mass system.

| Proton scattering angle | "Upper limit" neutron energies (Mev) | | |
|---|---|---|---|
| | 0° | 90° | 180° |
| 40° | 0.15±0.07 | 0.38±0.2 | 0.07±0.03 |
| 67° | 0.89±0.3 | 0.46±0.15 | 0.37±0.1 |
| 90° | 3.2 ±1.1 | 2.6 ±0.6 | 1.7 ±0.4 |

The minimum and maximum scattering angles for the two protons have been calculated from the geometry and the limits of the inelastic tangential plateaus. The maximum energy of the neutrons in the forward direction has been calculated from the maximum scattering angles, the maximum energy in the backward direction from the minimum scattering angles. The extension of the radial plateau yields a value for the maximum neutron energy at 90° in the laboratory system. A summary of the results of these calculations is given in Table II.

These neutron energies are the "upper limits" of the low energy neutron peak. A precise definition of "upper limit" cannot be given. However, the number of neutrons emitted with the "upper limit" energy was less than the number emitted at the peak of the distribution by a factor of about five or ten.

There are two features of the neutron energies which are significant. The increase in the neutron energy as the proton scattering angle is increased is real. Also, the ratio of about 2:1 between the neutron energies at 0° and 180° is significant. The accuracy of the measurements does not warrant making a positive statement about the high energy of the neutrons at 90° with a proton scattering angle of 40°. The errors on the neutron energies have been estimated on the basis of the precision of the measurements of the plateaus. Comparison of these results with theoretical calculations is not practical at this time since no detailed calculations on the neutron energy spectrum have been published.

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# Energy Levels in $C^{12}$ from $Be^9(\alpha,n)C^{12}$*

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A thin polonium source and thin beryllium target have been used to investigate energy states in $C^{12}$. The neutron spectrum was determined from proton tracks in Eastman NTA emulsions. By investigating the neutrons emitted in the forward and backward directions, neutrons associated with the transition to the ground state of $C^{12}$ were detected, and excited levels in $C^{12}$ were identified at 4.2 and 7.5 Mev above the ground state.

## INTRODUCTION

THE neutron spectrum from a mixed Po+Be source has been studied previously.[1] It seemed wise to study the spectrum under improved geometrical conditions so as to resolve better the neutron groups associated with the various energy states in $C^{12}$. A compromise between good and poor geometry was utilized in the experiment reported in this paper so as to obtain as good resolution as possible compatible with sufficient neutron intensity. Preliminary reports have been given previously.[2]

## EXPERIMENTAL PROCEDURE

The experimental arrangement is shown in Fig. 1. The polonium source on a thick nickel foil had a strength of ~100 millicuries and was supplied by the Canadian Radium and Uranium Corporation. It had an area of 4 cm² and was reported to be very thin. The beryllium foil, 0.25 mg/cm² in thickness, was kindly supplied by H. Bradner of the University of California. It was masked by a brass washer so that a circle of area 4.9 cm² was exposed to the alpha-particles. The perpendicular distance from the polonium to the beryllium was 2.2 cm. The angle of incidence of the alpha-particles striking the beryllium ranged from 0° to 47°. 50 micron and 100 micron Eastman NTA nuclear track plates were used to detect the neutrons through observation of the knock-on protons in a forward cone having a half-angle of 12°. The plates were wrapped in aluminum foil and then in paper. The polonium source and beryllium target were placed inside a brass cylinder which was kept evacuated by a Cenco HiVac pump. The entire apparatus was suspended by a wire near the geometrical center of a

* Supported in part by the AEC.
[1] B. G. Whitmore and W. B. Baker, Phys. Rev. 78, 799 (1950); Perlman, Richards, and Speck, MDDC-39 (1946).
[2] W. H. Guier and J. H. Roberts, Phys. Rev. 79, 719 (1950); and Phys. Rev. 81, 317 (1951).