Scattering of Protons by Tritons*

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The proton-triton differential scattering cross section has been measured for laboratory angles between 45° and 135° and proton energies between 0.7 and 2.5 Mev. In this angular range the scattering is predominantly nuclear and shows a rapid increase in intensity for angles greater than 90° in the center of mass system. Some indications of anomalous behavior near the threshold for $T^3(p,n)He^3$ are reported.

I. INTRODUCTION

THE systematic study of the scattering of the lightest nuclei may, one hopes, lead to a better theoretical knowledge of the nature of nuclear forces. Such studies have been made, with sufficient accuracy for detailed theoretical treatment, of the scattering of neutrons by protons[1] and deuterons;[2] of protons by protons,[3] deuterons[4] and alpha-particles;[5] and of deuterons by deuterons.[6] The recent advent of the nuclei of T^3 and He^3 in the laboratory increases greatly the number of light scattering pairs available for experimental investigation.

The possibility of obtaining, at low energies, experimental information of use in calculations involving specific nuclear force theories may arise from the large size of the nuclei immediately above hydrogen, with the result that waves with angular momentum quantum number $l \geq 1$ become effective (as pointed out by Buckingham and Massey[7] for the scattering of neutrons by deuterons). Extension of their theory has allowed Critchfield[8] to explain the main features of *p-d* scattering for proton energies below the $D^2(p,n)$ threshold. The work described below adds experimental information on the scattering of hydrogen of mass one by mass three hydrogen nuclei.

Measurements of proton-triton scattering were first made during a preliminary investigation of the proton-triton interaction using the Los Alamos 2.5-Mev electrostatic accelerator to project protons into a target of tritium gas. During this early work the comparison of scattering of protons by tritium and hydrogen targets proved to be a practical means of ascertaining the relative abundance of the hydrogen contaminant in a tritium sample.[9] It was soon apparent that the small volume scattering chamber, already described elsewhere,[10] was quite suitable for the observation of charged particle scattering and detailed measurements were made.

II. EXPERIMENTAL

The tritium target pressure was set at approximately 5 cm of mercury and was read with a traveling microscope on a mercury manometer. The target temperature was indicated by a thermometer waxed to the body of the target. These two measurements, together with the concentration of tritium in the target as determined by *p-p* scattering give the volume density of tritons. The scattered particles were detected by an argon-filled proportional counter with a slit system to define a small solid angle at the center of the target. The counter could be set at any angle between 45° and 135° with respect to the direction of the incident protons. The differential scattering cross section at scattering angle θ is

$$\sigma(\theta) = Y \sin\theta/(Nng),$$

where Y is the number of scattered particles counted at angle θ per microcoulomb of beam current integral, $N(=6.25\times10^{12})$ is the number of protons per microcoulomb of beam current integral, n is the number of tritons per unit volume, and g is a geometry factor for the counter slit system.[10]

A few minor changes in the target as described originally have been made. A background count, inde-

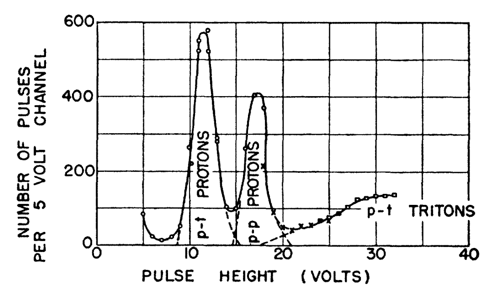

FIG. 1. Pulse height distribution from an argon-filled proportional counter at a laboratory scattering angle of 45° and a proton beam energy of 2.335 Mev.

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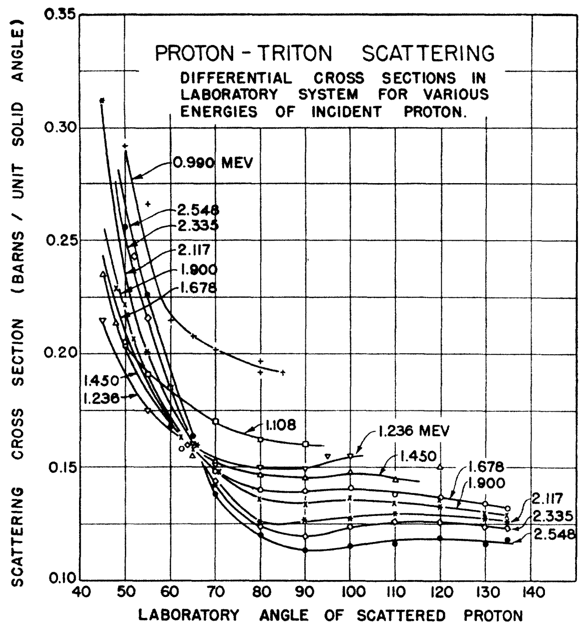

FIG. 2. Proton-triton scattering, differential cross sections in the laboratory system for various energies of protons incident on a gaseous tritium target. Additional points at 750 kev not conveniently plotted are 45°, 0.571; 50°, 0.475; 60°, 0.338.

pendent of gas pressure, due to scattering at the edge of the entrance aperture to the target was eliminated by the use of a second slightly larger aperture inside the target. An insulated ring, placed just ahead of the Faraday cage used for current measurement and held at a potential of -200 volts, served as an effective electron barrier to prevent the escape of secondary electrons formed in the cage. Scattering measurements with and without a transverse magnetic field in this region gave identical results.

The beam current integrator circuit built by H. T. Gittings[11] was checked frequently and was stable and accurate to ± 0.2 percent.

The pulses from the several groups of scattered particles were resolved, as was done by Sherr *et al.*[4] in the *p*-*d* scattering experiment, by means of the Sands 10-channel pulse height selector.[12] In the present experiment there are, in addition to the protons scattered by tritons, the recoil tritons and the protons from contamination proton-proton scattering if the angle is less than 90°. At the lower incident proton energies the recoil tritons were stopped in the 0.1-mil thick aluminum counter window that separated counter and target fillings. As the beam energy was increased, the tritons showed up at small pulse height and the peak in their pulse height distribution moved gradually across the more nearly stationary peaks of scattered protons. In Fig. 1 is shown a pulse height distribution at a high energy where the triton peak is at the extreme right. Systematic observations were necessary to avoid the possibility at some angles of two of the peaks coinciding in pulse height. A small shift in the beam energy or scattering angle, or even the target pressure, shifts the relative position of the scattered particle peaks considerably and this expedient was used to improve resolution or to identify the various peaks when there was any question about them. All of the *p*-*T* scattering measurements were made on the proton peak.

The proton energy scale for the accelerator was established by the measurement by Herb, Snowden, and Sala[13] of the $Li^7(p,n)$ threshold. The threshold for $T^3(p,n)He^3$ was measured recently in this laboratory,[14] so the effective thickness for the entrance window to the target was determined by measuring the beam energy at which neutrons were observed from the target. The energy loss in the window was then determined for other beam energies from the range-energy relation for protons.

In the early phases of this work frequent measurements were made of proton-proton scattering in order to establish the reproducibility of measurements and to check all parameters of the measurement. An error of 5 percent (results were too high), which persisted in *p*-*p* scattering measurements, referring to those of Herb, Kerst, Parkinson, and Plain[3] as standard, is ascribed to an error in the determination of *g*. Since it has not been possible so far to re-measure the distances involved (because the target has been in use), all measurements have been normalized to agree with those of HKPP.

For this type of experiment the 0.1-mil aluminum counter window must be perfectly tight. The decay rate of tritium is so great that the slightest leak in this window, even though the counter pressure was greater than target pressure, let enough tritium diffuse into the counter to produce excessive counter background noise. The selection and trial of a suitable aluminum foil for this window was so tedious that the use of a nylon window was attempted, but it proved to be much too transparent to tritium, even though it was quite tight for argon. When a good aluminum window was finally selected it served for all measurements and the argon counter filling was not disturbed over a period of five months.

There was a small but continuous change in concentration of tritium in the target, possibly due to exchange of tritium in the stopcock grease of the conical seals, which suggests that chemically stable packings should be used instead of ground cones for further work of this kind. The proton-triton scattering at 50° was measured frequently during a run at any energy and these data were used to correct for small changes in the tritium concentration. As a further check, above the

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threshold for the reaction $T^3(p,n)$, the concentration was monitored and corrected by counting neutrons with a long counter.[15]

The measurements reported below were made with a front target window of 0.2-mil aluminum (0.9 cm air equivalent) and an exit window of the same thickness. The lowest beam energy used was 750 kev after passage through the front foil, and this was reduced to 380 kev by the exit window. This residual range appears to be great enough to permit accurate measurements of beam current since the calculated energy straggling[16] in each of the 0.2-mil foils is approximately 15 kev at 10 Mev incident proton energy.

III. RESULTS

The laboratory system differential cross sections measured are shown in Fig. 2. The proton energies shown are calculated for a point at the center of the scattering volume. The cross sections are good to about ±5 percent for $E_p \geq 1.1$ Mev on the basis of estimated systematic and statistical errors, including the error of the tritium concentration measurement. For proton energies below about 1.2 Mev additional factors which become important in the measurement are the large energy loss in entrance and exit foils to the scattering volume and the rapidly increasing small angle Rutherford scattering in the entrance foil. The energy straggling, which is about 15 kev in the entrance foil at 1 Mev, contributes primarily to spreading the proton energies and is therefore most serious where the change in cross section is most rapid, i.e., at low energy. The Rutherford scattering by the foil into small angles is presumably of second order importance because a proton leaving the entrance foil with such an angle as to miss the gas volume which can be seen by the counter would also miss entering the Faraday cage and therefore no false contribution to the measurement can be made for single scattering. The energy *spread*, however, can falsify a cross-section measurement when some of the protons fail to have enough energy to enter the Faraday cage through its entrance foil; this would lead to an apparently high cross section at the very lowest proton energies, and for this reason there may be some doubt about the 700 and 800 kev values shown in Fig. 4, although only 550 kev are necessary for the *average* proton to penetrate the foil into the cage.

The center of mass system differential cross sections are shown in Fig. 3. These are calculated from the observed laboratory cross sections of the scattered protons from

$$\sigma(\phi)=\cos(\phi-\theta)(\sin^2\theta/\sin^2\phi)\sigma(\theta),$$

where $\sigma(\theta)$ and $\sigma(\phi)$ are respectively the laboratory and

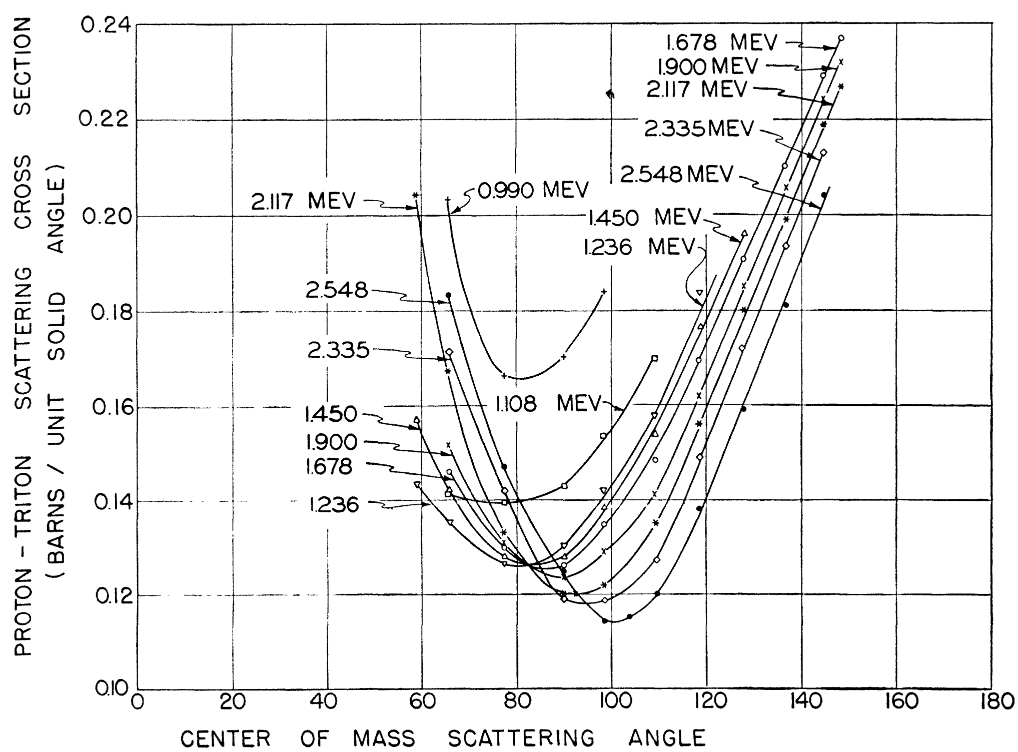

FIG. 3. Proton-triton scattering, differential cross sections in the center of mass system for various energies of incident protons. Additional points at 750 kev are 58.8°, 0.381; 65.7°, 0.330; 77.5°, 0.256.

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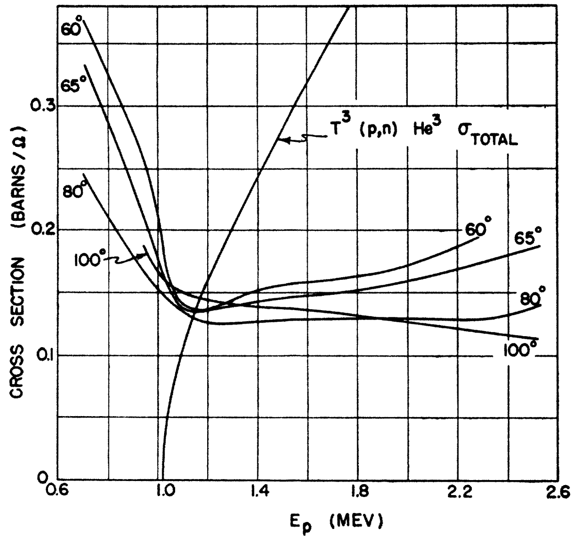

FIG. 4. Proton-triton scattering, data from Fig. 3 plotted as a function of energy to show the minimum near the threshold for $T^3(p,n)$.

center of mass differential cross sections at the corresponding angles θ and ϕ.

Figure 3 shows the rapid increase in intensity at angles beyond about 90° which is indicative of strong nuclear scattering. At the smallest angles and energies a considerable portion of the differential cross section arises from coulomb scattering as calculated from the Rutherford formula, but even here the observed values are at least five times Rutherford.

A rather striking similarity exists between the p-T scattering in the angular range observed here and the same range in p-d scattering.[4] This is especially apparent

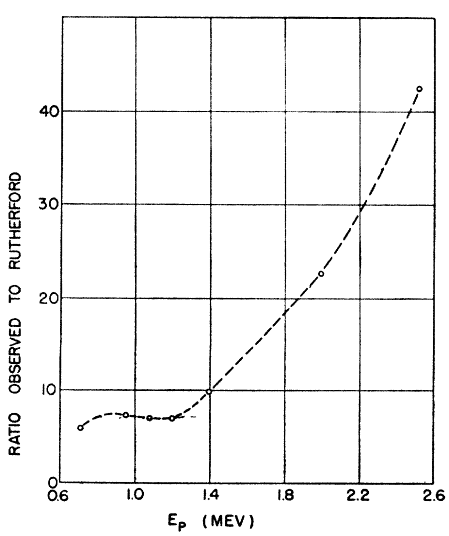

FIG. 5. Ratio of differential scattering cross section to Rutherford scattering cross section for center-of-mass scattering angle of 65°.

if one plots $k^2\sigma(\phi)$ against $\cos\phi$, where $k=2\pi/\lambda$ for the proton, as done by Critchfield,[8] and comparing curves corresponding to the same center of mass energy.

In Fig. 4 are shown some curves for differential cross section at several fixed angles as a function of proton energy, together with a plot of the total cross section[17] for the $T^3(p,n)He^3$ reaction, the threshold of which is at 1019 kev.[14] It will be observed that all the differential cross sections appear to increase suddenly near this threshold as the proton energy is decreased. Although the lowest energy cross-section values and trend with energy are subject to the straggling and scattering difficulties mentioned above it would seem that the phenomenon observed is too large to be accounted for entirely by such processes. As the proton energy is reduced, the contribution to the cross section from coulomb scattering increases rapidly but one finds that between 1.2 Mev and 0.8 Mev the ratio of observed to Rutherford scattering at 65° is approximately constant, while above 1.2 Mev it increases rapidly, as is shown in Fig. 5.

Tentatively, it would appear that the sudden increase in scattering at energies below 1.1 Mev is associated with the threshold for the $T^3(p,n)He^3$ reaction. From the viewpoint of the older theories on pure potential scattering far from a resonance the phenomenon apparently observed should not occur, but a recent theory of Wigner[18] points out that even an elastic scattering cross section may show a cusp of the form $a+b|E-E_n|^{\frac{1}{2}}$ +higher order terms in $|E-E_n|$ near the threshold E_n for a new nuclear process, which in this case is the p,n reaction. The phenomena to be expected are thus somewhat similar to those in resonance scattering. The constants a and b are not determined by the theory and in any case would be complicated by the large Rutherford scattering at these low energies.

The experimental difficulties inherent in the low energy measurements which lead to the above interpretation are understood by the writers, as discussed above, and several check experiments, together with reductions in the entrance foil thicknesses are being pursued to investigate this low energy region in particular. Similar experiments near the threshold of $Li^7(p,n)Be^7$ would perhaps be more satisfactory because of the higher incident energy.

Since resonance scattering could produce somewhat similar effects, we wish to point out that we have found no evidence for a sharp excited state in He^4 at an energy corresponding to 1 Mev for this collision, but there does appear to exist a broad excited state of the alpha-particle at about 2.5 Mev as observed[19] in the yield of gamma-rays from $T^3(p,\gamma)He^4$.

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The writers are indebted to E. S. Robinson and his colleagues in the Radiochemistry Group at Los Alamos for their collaboration in the preparation and handling of the tritium samples, and they gratefully acknowledge the assistance of G. G. Everhart in the operation of the electrostatic accelerator.

APPENDIX

TABLE I. Proton-triton scattering; experimental results for differential cross sections in both laboratory and center-of-mass systems as a function of angle in barns per unit solid angle.

		$E_p=0.708$ Mev		$E_p=0.990$ Mev		$E_p=1.108$ Mev		$E_p=1.236$ Mev		$E_p=1.45$ Mev		$E_p=1.678$ Mev		$E_p=1.90$ Mev		$E_p=2.117$ Mev		$E_p=2.335$ Mev		$E_p=2.548$ Mev	
θ_{lab}	ϕ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}
45	58.8	0.571	0.381					0.215	0.144	0.235	0.157					0.306	0.204				
50	65.7	0.475	0.330	0.292	0.203	0.204	0.142	0.195	0.135	0.204	0.142	0.210	0.146	0.218	0.152	0.240	0.167	0.256	0.171	0.264	0.183
60	77.5	0.338	0.256	0.219	0.166	0.184	0.140	0.167	0.127	0.169	0.128	0.171	0.130	0.173	0.131	0.176	0.133	0.185	0.140	0.193	0.147
70	90.0			0.202	0.170	0.170	0.143	0.155	0.130	0.152	0.128	0.150	0.126	0.147	0.124	0.143	0.120	0.142	0.119	0.148	0.125
80	98.5			0.194	0.184	0.162	0.154	0.150	0.142	0.146	0.138	0.142	0.135	0.136	0.129	0.129	0.122	0.124	0.118	0.120	0.114
90	109.4					0.160	0.170	0.149	0.158	0.145	0.154	0.140	0.148	0.134	0.142	0.127	0.135	0.120	0.127	0.113	0.120
100	118.8							0.153	0.184	0.147	0.176	0.141	0.169	0.135	0.162	0.130	0.156	0.124	0.149	0.115	0.138
110	128.									0.144	0.196	0.140	0.191	0.136	0.185	0.132	0.180	0.126	0.171	0.117	0.159
120	136.8											0.137	0.210	0.134	0.206	0.131	0.199	0.126	0.193	0.118	0.181
130	144.8											0.134	0.229	0.131	0.225	0.128	0.219	0.124	0.213	0.116	0.199
135	148.5											0.132	0.237	0.129	0.232	0.126	0.227	0.121	0.218		
55	71.1			0.251	0.182																
65	83.7			0.208	0.166	0.176	0.140			0.160	0.127										
75																0.135	0.120				
85										0.149	0.149									0.115	0.115
95										0.152	0.171										

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Cross Section as a Function of Angle for the D(d,n)He^3 Reaction for 10-Mev Bombarding Deuterons*

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By counting He^3 particles with a proportional counter, the differential cross sections for the reaction D(d,n)He^3 have been measured at laboratory angles from 16.5 degrees to 38.2 degrees (39.3 degrees to 95.0 degrees in center of mass system), for an incident deuteron energy of 10.3 Mev. In the center of mass system, the differential cross section is 4.5×10^{-27} cm^2 at 90 degrees, decreasing to a minimum of 2.2×10^{-27} cm^2 at about 45 degrees, and rising steeply at lower angles. By determining the neutron yield with Cu^{63}(n,2n)Cu^{62} detectors, the differential cross section at zero degrees is found to be about five times that at 90 degrees (center of mass).

I. INTRODUCTION

SINCE the discovery of the D+D→He^3+n reaction by Oliphant, Harteck, and Rutherford,[1] a number of investigations[2–11] of the yield and the angular distribution of the products have been made for bombarding energies below five Mev. The earlier measurements on the angular distribution were made at zero and 90 degrees to the beam direction and the differential cross section in the center of mass system was fitted to a $(1+A(E)\cos^2\theta)$ law. This law has been found to hold[12–17] at a number of angles for the competing reaction, D+D→H^3+H^1.

For the D(d,n)He^3 branch of the reaction in the bombarding energy region above one Mev, more recent work[18–19] shows that terms up to $\cos^6\theta$ must be included in the Fourier expansion of the differential cross section

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