Production of Tritons in High-Energy Deuteron-Deuteron Collisions*

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The differential cross section for the process $d+d\rightarrow H^3+p$ has been measured at six angles extending from 20° to 85° in the center-of-mass system. Deuterons of 190 Mev from the Berkeley 184-inch synchrocyclotron were used. A coincidence counting system, consisting of scintillation counters for both particles, was employed. Time of flight and range of the particles were made use of, both in identifying the process and in discriminating against background. The resulting cross section is highly peaked in the forward direction. The behavior is explained qualitatively by a theoretical calculation based on an extension of the stripping mechanism first proposed by Serber. The total cross section for the reaction is estimated to be 4.1 millibarns.

INTRODUCTION

WHEN high-energy deuterons in the Berkeley 184-inch synchrocyclotron were first allowed to strike a target, it was found that an intense cone of high-energy neutrons was projected in the same direction of motion as the incident deuterons. Serber[1] proposed a "stripping" mechanism to explain its formation. In this process, one nucleon of the deuteron interacts suddenly with the target nucleus while the other nucleon is largely unaffected in its motion. It was felt that the formation of H^3 and He^3 particles in deuteron-deuteron collisions might be considered as a stripping process in which the neutron or proton, respectively, of one deuteron might interact with and "stick to" the other deuteron—leaving its partner to continue with essentially the same momentum it had at the instant of stripping. A theoretical calculation by Heckrotte and Bludman[2] obtained the general shape of the angular distribution for the pure stripping process. The present experiment was designed to measure the absolute differential cross section for the process $d+d\rightarrow H^3+p$ over as wide a range of angles as possible and compare it with that expected of a stripping process.

EXPERIMENTAL PROCEDURE

Since the external deuteron beam is essentially monoenergetic, the kinematics of the above process can be calculated uniquely for any scattering angle by applying the laws of conservation of energy and momentum. This calculation was carried out relativistically. Since the colliding deuterons are indistinguishable, the cross section must be symmetric about 90° center of mass. It is necessary to measure the scattering only from 0° to 90° to obtain the complete differential cross section.

The high background in the Berkeley "cave" has been one of the major difficulties to be overcome for any low-cross-section experiment. Recently, time-of-flight techniques have been used successfully in the cave to reduce the effect of this background. The range of energies and angles required in this experiment seemed quite suitable for the application of similar methods in the above process. Since the time of flight of the tritons over an eleven-foot path (the usable length of the cave) from target to detector was the order of 30 millimicroseconds, it was necessary to use a coincidence circuit considerably faster than this. The circuit used had a resolving time of about 3 millimicroseconds. As a further aid in discriminating against background and providing identification, absorbers were used in front of the detectors.

The experimental arrangement for a typical scattering angle is shown in Fig. 1. The apparatus, electronics, and experimental procedure are so similar to those described by Frank[3] in measuring the differential cross section for the reaction $p+d\rightarrow H^3+\pi^+$, that they need not be repeated here.

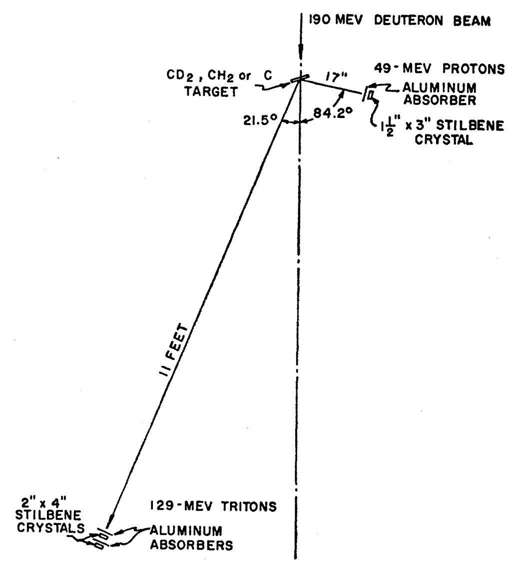

FIG. 1. Experimental arrangement for observing the process $d+d\rightarrow H^3+p$.

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[1] Robert Serber, Phys. Rev. 72, 1008 (1947).
[2] W. Heckrotte and S. Bludman (private communication).
[3] Frank, Bandtel, Madey, and Moyer, Phys. Rev. 94, 1716 (1954).

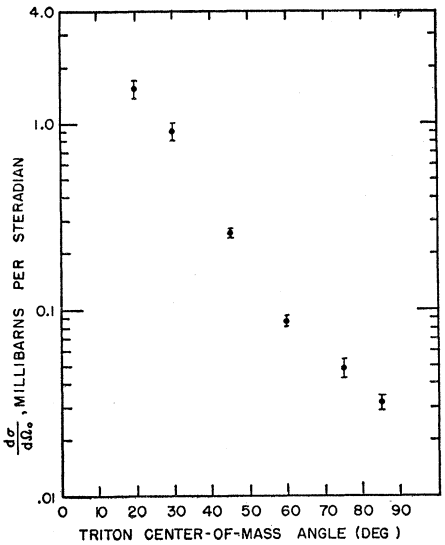

FIG. 2. Experimental angular distribution for the process $d+d \rightarrow H^3+p$ on semilog coordinates.

RESULTS AND CORRECTIONS

Data for an angular distribution were taken at six laboratory angles chosen to cover as nearly as possible the center-of-mass scattering range of 0° to 90°. These uncorrected data are summarized in Table I. This difference rate is the counting rate R that appears in the cross-section formula. The apparent high counting rates for the last two readings are due to use for these data of a monitor having a calibration differing by a factor of ten from that used for the other data.

Three corrections were applied to the original difference counting rate. The first was caused by absorption of protons in passing through the aluminum absorber. This correction was calculated from the absorption cross sections measured by Kirschbaum.[4] The correction was only 7 percent in the worst case.

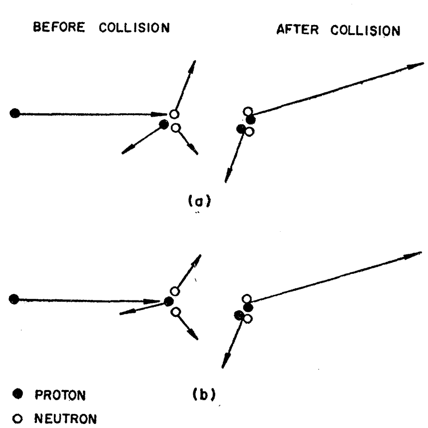

FIG. 3. Diagram showing typical laboratory momenta of particles before and after collision in the $p+H^3 \rightarrow d+d$ process: (a) for pure pickup interaction, (b) for indirect pickup interaction resulting in same external momenta.

[4] Albert J. Kirschbaum, thesis, University of Californai Radiation Laboratory Report No. UCRL-1967 (unpublished).

TABLE I. Counting rate with CD_2 target minus counting rate with C target in counts per volt of integrated beam.

Triton c.m. angle	Difference between CD_2 and C rates	Ratio of CD_2 to C rates
20°	7.69±0.85	2.3:1
30	6.88±0.76	5.3:1
45	10.31±0.65	7.4:1
60	5.23±0.36	5.3:1
75	24.7 ±2.9	7.5:1
85	10.9 ±1.0	12.0:1

The second correction was necessitated by absorption of the tritons in the aluminum absorbers or in the first stilbene crystal. It is not possible to make a rigorous correction for this effect. The following attack was employed to give an estimate of the correction. Crandall[5] has measured the total inelastic cross section of high-energy He^3 particles for various elements. By assuming that the probability of a nuclear event at high energy is the same for a H^3 as for a He^3, it is possible to calculate the attenuation of the tritons in going through the absorber. The majority of the inelastic events, however, constitute stripping processes in approximately two-thirds of which a fast deuteron continues in the forward direction. Since these deuterons, in general, still produce a pulse in the triton detector, only something of the order of one-third of the inelastic events are lost. Since the inelastic attenuation in the worst case was 21 percent, the maximum correction is around 7 percent.

The third correction was that for small-angle scattering losses. These losses were minimized by having the proton detector subtend a considerably larger solid angle than the triton detector. Under these conditions, the worst correction amounted to 8 percent.

The correction factors are summarized in Table II.

The center-of-mass differential cross section is obtained from the relation

$$d\sigma/d\Omega_0 = RC/N_b N_t \Delta\Omega_0.$$

The numerator is the product of the original difference rate R and the total correction factor C. N_b is the deuteron beam flux in deuterons per integrated beam unit; it is calculated from the ion-chamber calibration factor and the capacitance of the integrating condenser. N_t is the target particle density in deuterons per cm^2; it depends on the weight, area, and composition

TABLE II. Correction factors for proton and triton absorption and scattering

Triton c.m. angle	Proton absorption	Triton absorption	Scattering	Total
20°	1.00	1.07	1.07	1.14
30	1.00	1.06	1.03	1.09
45	1.00	1.05	1.08	1.13
60	1.01	1.03	1.07	1.11
75	1.04	1.02	1.08	1.15
85	1.07	1.01	1.08	1.17

[5] Walter E. Crandall (private communication).

of the target and the angle made by the target with respect to the beam. $\Delta\Omega_0$ is the center-of-mass solid angle subtended by the triton detector; it is calculated from the laboratory solid angle by means of the calculated relativistic transformation. The final results are given in Table III and plotted in Fig. 2.

The errors shown are the statistical deviations related to the number of counts constituting the original data. The errors in N_b, N_t, and $\Delta\Omega_0$ have been neglected as far as relative angular distribution data are concerned, since they are the same for each angle and affect only the total absolute cross section. The error in N_b is estimated to be several percent; in N_t about 1 percent or 2 percent; and in $\Delta\Omega_0$ around 5 percent. The corrections to the data are relatively small, but if it is assumed that they could contribute an error of 5 percent, one can estimate that the absolute results have an uncertainty of about 15 percent. When a smooth curve is drawn through the data of Fig. 2, the integrated total cross section is estimated to be 4.1 millibarns.

CONCLUSION

A discussion of the mechanism for the production of tritons in the reaction $d+d\rightarrow H^3+p$ can be facilitated by considering instead the inverse process $p+H^3\rightarrow d+d$. This merely changes one's point of view; i.e., we now consider a pickup mechanism instead of a stripping mechanism. By the law of detail balance, however, the interaction matrix remains the same. One postulates that there is a sudden interaction between the proton and one of the H^3 nuclei, and further that the momenta of the other two nuclei of the H^3 are essentially unaffected by the interaction. Two cases are of interest: (a) where the two interacting nuclei end up in the same deuteron, and (b) where they end up in different deuterons. Momentum diagrams for these two interactions are shown in Fig. 3. Both these processes have been observed in the proton bombardment of nuclei. The first situation is identical to the pickup mechanism proposed by Chew and Goldberger[6] to explain the presence of fast deuterons in the forward direction when matter is bombarded with high-energy protons or neutrons. The second situation might be called an indirect pickup, as it consists of a proton's scattering in a nucleus and then finding a pickup partner of momentum compatible to the formation of a deuteron. This indirect pickup process could contribute to the scattering process at wide angles where the pure pickup cross section would be negligible. Using 360-Mev protons, Wilmot Hess is measuring the indirect pickup cross section for various elements. Preliminary results[7] indicate that a substantial fraction of the deuterons observed at 40° laboratory system for p-d scattering are a result of indirect pickup rather than pure pickup. In the $p+H^3\rightarrow d+d$ process, one would expect a comparatively low cross section, since the momenta must be compatible to the formation of two deuterons instead of just one. In the pure pickup interaction, for example, not only must the two interacting particles form a deuteron, but also the two remaining nuclei of the H^3 must be left in a state corresponding to that of a deuteron.

TABLE III. Corrected experimental differential cross section for the process $d+d\rightarrow H^3+p$.

Triton c.m. angle	$\frac{d\sigma}{d\Omega_0}$ (millibarns/steradian)
20°	1.54 ±0.17
30	0.905 ±0.100
45	0.258 ±0.016
60	0.0871±0.0060
75	0.0486±0.0057
85	0.0317±0.0029

Using the Born approximation, Dr. Bludman and Dr. Heckrotte set up the integrals for the matrix elements of the cross sections for the $d+d\rightarrow H^3+p$ reaction. There were two integrals involved; one corresponding to the pure pickup and the other corresponding to the indirect pickup contribution. The pure pickup cross section was readily solved in terms of the momentum distributions of the deuteron and the triton. On the assumption of the Hulthén wave function for the deuteron, and the wave function proposed by Messiah for the triton, the distribution of the $d+d\rightarrow H^3+p$ cross section was calculated. It was found to behave exponentially in the forward direction in a manner similar to the experimental data. The slope of the theoretical curve, however, was greater than that of the experimental curve. The contribution of the pure pickup calculation at wide scattering angles became negligible, whereas the experimental curve shows an appreciable contribution at these angles.

Hess's experiments suggest that the indirect pickup mechanism contributes substantially to the cross section at wide scattering angles. Unfortunately, the integral for the indirect pickup interaction was too difficult to solve without an undue expenditure of time.

One can conclude that the pure pickup (or stripping) mechanism can explain qualitatively the shape of the cross section for scattering angles up to about 45° c.m., but that substantial contributions must be made by other processes.

ACKNOWLEDGMENTS

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[6] G. F. Chew and M. L. Goldberger, Phys. Rev. 77, 470 (1950).
[7] Wilmot N. Hess (private communication).