that (M/M_0) varies as the Brillouin function for $S=5/2$. It is found that $(H_0)_{\text{crit}}$ rises nearly linearly from 10^5 oersteds at $0.2T_c$ to 1.7×10^5 oersteds at T_c. This is essentially the same dependence as given by Yosida.[4]

Another method of measuring H_A is by means of antiferromagnetic resonance. Here in the absence of a field H_0 the resonance frequency is given by

$$\omega/\gamma\cong(2H_EH_A)^{\frac{1}{2}}=1.0\times10^5(M/M_0), \qquad (21)$$

where use has been made of Eq. (20). This frequency corresponds to a wavelength[20] of 1.1 mm at 0°K and about 2 mm at $0.9T_c$. Above this temperature our theory should break down as there is no justification for a simple two-sublattice picture near the Curie point.

[20] The reader is cautioned that these estimates are subject to the uncertainties in H_E and H_A mentioned above.

By using 1-cm waves Hutchison[21] has found a complete disappearance of the paramagnetic resonance line of MnF_2 as the temperature drops below 67°K.

In the absence of millimeter waves one could take advantage of the minus sign in Eq. (13) and employ large fields H_0 to bring the resonance into centimeter range.[22] This requires fields just short of the critical field, i.e., fields increasing from 10^5 oersteds at 0°K to 1.7×10^5 oersteds near the Curie point. The reason the fields must be just short of the critical field is that the critical field represents the size of H_0 necessary to bring the resonance frequency to zero.

I should like to express my thanks to Professor Kittel for many stimulating discussion of antiferromagnetism. This research was assisted in part by the ONR.

[21] C. A. Hutchison (private communication to Professor Kittel).
[22] This possibility was first pointed out by C. Kittel, Phys. Rev. **82**, 565 (1951).

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Cross Sections of the D(T,n)He^4 Reaction for 80- to 1200-Kev Tritons

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Gas targets of deuterium with an aluminum entrance foil of 1.5 mg/cm^2 were bombarded by tritons. Straggling and scattering of the tritons by the foil have been carefully considered and found to introduce reasonably small corrections. Energy loss in the entrance foil was determined by assuming that the sharp resonance peak in the reaction occurs at 165-kev triton energy as measured by T. W. Bonner, and then making use of the dE/dx curve of S. D. Warshaw. Neutrons from the reaction were observed by means of a BF_3 long counter whose energy response has been investigated. Angular distributions of the neutrons were measured and found to be isotropic in the c.m. system below 600 kev. Near 1 Mev the distributions deviate from isotropy, more neutrons coming off at the back angles. The maximum cross section is 4.93 barns at the resonance. The limit of error on cross sections is ±10 percent. A one-level nuclear dispersion formula has been fitted to the experimental curve and the resonance is ascribed to a level in the He^5 compound nucleus, arising from an S-wave interaction of the T and D, with quantum numbers $J=\frac{3}{2}$, $l=2$.

I. INTRODUCTION

THE reaction

$$T+D\rightarrow He^4+n+17.577\pm0.02 \text{ Mev}$$

has proved to be a very useful laboratory source of high energy monoenergetic neutrons. Although many experimenters have been making use of the reaction for a neutron source, the yield in the low energy region has not been well known. Early experimenters[1] have shown that the yield is very high and indicated the existence of a strong nuclear resonance in the vicinity of 200-kev incident triton energy. In the region between 200- and 1500-kev triton energy the cross section is particularly poorly known. There have been arguments that the rise at 200 kev may not be a resonance.[2] The above uncertainties and the general interest in the reaction inspired the present investigation. The measurements described in this paper were made during the summer of 1950.

The earlier measurements showed an isotropic yield in the c.m. system at the low energies. Since the angular distribution is very helpful in the assignment of states it was decided to check the isotropy near 200 kev and also at the higher energies.

II. EXPERIMENTAL PROCEDURE

The experimental method followed in determining the absolute cross section for the D(T,n)He^4 reaction was to

[1] Baker, Holloway, King, and Schreiber, Atomic Energy Commission Declassified Report No. 2226 (1943); E. Bretscher and A. P. French, Phys. Rev. **75**, 1154 (1949); Taschek, Everhart, Gittings, Hemmendinger, and Jarvis, Atomic Energy Commission Declassified Report No. 2250 (1948); D. L. Allan and M. J. Poole, Nature **164**, 102 (1949); D. L. Allan and M. J. Poole, Proc. Roy. Soc. (London) **204**, 488 (1951); D. L. Allan and M. J. Poole, Proc. Roy. Soc. (London) **204**, 500 (1951).

[2] D. L. Allan and M. J. Poole, Proc. Roy. Soc. (London) **204**, 488 (1951).

measure the number of neutrons emitted per unit solid angle with a long counter, integrating over an angular distribution wherever necessary. The reaction took place in a deuterium gas target, into which a triton beam entered through a thin aluminum foil.

A. Determination of Energy Straggling and Absolute Energies

The aluminum foils used were made by the Cochran Foil Company, Louisville, Kentucky, and are of two thicknesses, one approximately 1.5 mg/cm^2 and the other 1.1 mg/cm^2. The uniformity of thickness of this foil is exceedingly good. The aluminum foil served to slow the tritons down sufficiently so that energies of 80 kev in the gas target were attained. The possible errors inherent in this technique were carefully investigated. Although the multiple scattering and energy straggling imposed upon the tritons in losing five-sixths of their incident energy could be serious, the experiments and calculations show that relatively small corrections can take account of these effects.

A measure of the energy straggling introduced by the foil was obtained by observing neutrons from the T(p,n)He^3 reaction near threshold, with a tritium pressure of 1 cm of mercury in a 3-cm long gas target. The T(p,n)He^3 threshold is at 1019 kev proton energy.[3]

Since this is an endoergic reaction the neutrons come off in a forward cone in the laboratory system when the protons are just above the threshold energy. The spatial distribution of neutrons within the cone is such that most of the neutrons are contained in the region near the edge of the cone.[4] As the incident proton energy is raised above the threshold the angle of the cone will increase until at 128 kev above threshold the cone will be completely open, giving neutrons at all angles in the laboratory system. This geometrical effect near threshold due to the center-of-mass motion of the reacting system results in an extremely high and narrow peak in the neutron yield *vs* proton energy when observed with a distant BF_3 long counter[5] at 0°. In our case the counter subtended a cone of half-angle 4°. For protons 2.5 kev above the neutron threshold the cone has opened to a half-angle of 4° and as the energy of the protons increases the cone opens out past the detector and the observed yield drops sharply to the differential cross section yield for 0°.

Figure 1 shows the effect of the opening of the cone of neutrons when the incident protons have been passed through a 0.2 mil aluminum foil (1.47 mg/cm^2). The theoretical straggling[6] is 11.5 kev (standard deviation) and any straggling introduced by surface irregularities in the foil would increase the observed straggling. The

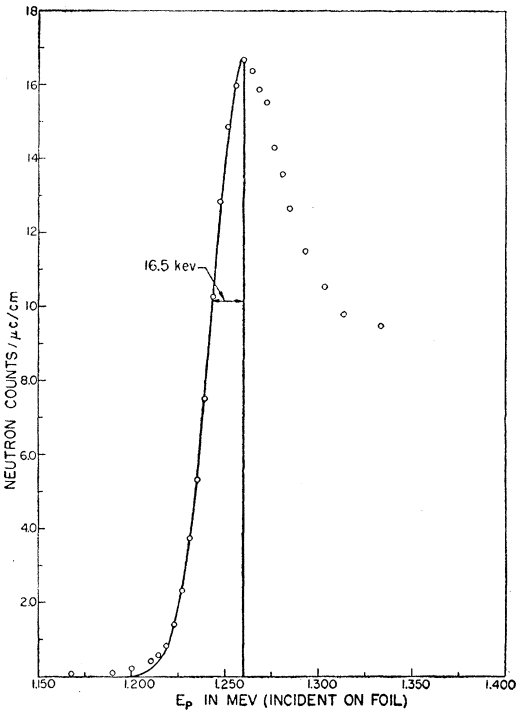

FIG. 1. 0° yield from T(p,n)He^3 near threshold showing energy straggling caused by 0.2-mil aluminum foil. The tritium gas target is 2.4-kev thick. The neutron counter subtends a cone with 4° half-angle. The solid line is a Gaussian fitted to the experimental points with $\sigma = 16.5$ kev.

rise in yield above the "observed" threshold is completely dominated by the energy straggling of the protons, the position of the peak being the true neutron threshold for the proton of average energy emerging from the foil if the target is sufficiently thin. The target thickness for this measurement was about 2.4 kev and the incident beam energy spread had a standard deviation of 0.7 kev. These two effects are negligible when compared with the much larger straggling due to the foil. The solid curve in the figure is a Gaussian of standard deviation 16.5 kev normalized to the observed data at the peak on the assumption that the shape of the low energy side of the peak is determined solely by the energy straggling in the foil. The foil thickness measured by the distance of the peak above the 1019-kev neutron threshold is 241 kev.

The total straggling in the 0.2-mil aluminum foil is measured to be 16.5 kev. This is the sum of the straggling arising from non-uniform foil thickness and the "true" energy straggling due to the statistical nature of the slowing down process. Assuming that these add as the square root of the sum of the squares one finds that the straggling from non-uniformity of foil thickness is 11.8 kev. This type of straggling is expected to be proportional to the total energy loss in the foil.

It is in the region of the resonance peak that the best energy resolution is required and it is here that the foil straggling is expected to be the most troublesome.

[3] Taschek, Argo, Hemmendinger, and Jarvis, Phys. Rev. **76**, 325 (1949).
[4] Jarvis, Hemmendinger, Argo, and Taschek, Phys. Rev. **79**, 929 (1950).
[5] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[6] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 283 (1937).

Tritons emerging from the aluminum foil entrance window with an energy of 183 kev will have lost 568 kev in passing through the foil. On the basis of the above straggling measurement there will be an energy straggling of 27.9 kev arising from the non-uniform foil thickness. In addition there is a "natural" straggling of 12.8 kev,[4] thus the over-all straggling turns out to be about 31 kev. The observed data have been corrected for the effect of this straggling. The resonance is sufficiently broad that the correction in the cross section never becomes serious, being 6 percent at the peak and dropping off rapidly on either side. On the low energy side the yield decreases so sharply that the straggling correction again becomes important, reaching 7 percent at the lowest energy point of 80 kev.

One of the more serious problems that results from the use of an entrance foil to slow the tritons down is the lack of knowledge of the energy after being slowed down. Warshaw[7] has measured the stopping power for protons in aluminum up to 330-kev energy, giving a range-energy curve for tritons of energies up to 1 Mev. The greatest uncertainty in using this curve is in determining the foil thickness. Warshaw also considers the foil thickness as his greatest source of error, the shape of the dE/dx curve being more reliable than the absolute values. This possible error was eliminated from both our measurements and Warshaw's by assuming the position of the T-D peak to be at 165 kev, as measured by Bonner[8] with a thin Zr-T target. Bonner's measurement of the energy is probably good to within ± 2 kev, which is a greater accuracy than could be attained by use of the dE/dx curve and a weight measurement of the foil. In essence, then, the entrance foil thickness was obtained by measuring the energy loss of the tritons in the foil at the T-D peak and comparing this energy loss with Warshaw's data. The T-D peak is sharp enough to determine the energy loss to within ± 5 kev, or about 1 percent. All other energy losses were then read from Warshaw's range-energy curve using this foil thickness. Weight measurements of the foils were in good agreement with the above results, but were taken merely as a check.

The scattering of the tritons in passing through the entrance window proved to be conveniently small even at the lowest energy of 80 kev. Simplified arguments[9] predict an rms scattering angle of approximately 12° for tritons emerging from the 1.5 mg/cm^2 aluminum foil with 175-kev energy. A more careful calculation by Dickinson and Dodder[10] gives an rms scattering angle of 10.9°, and an estimate that the observed cross section of the T-D reaction is approximately 8 percent too low when measured using a gas target that is 3 cm long and 1 cm in diameter. For a 1 cm long target the correction reduces to 1 percent, the observed value being too high. For 80-kev tritons, the lowest energy recorded in these measurements, the calculated rms scattering angle is 13.4° giving a 2.5 percent correction for a 1-cm target. The calculations were checked experimentally by measuring the yield with a 3-cm target and a 1-cm target, the results being as predicted within the experimental error.

As discussed above, the target was held to 1 cm in length to minimize the effects of entrance foil scattering. In other details the target was identical with the gas target described by Jarvis *et al.*[3] A potential barrier of 200 volts was maintained in front of the entrance foil to suppress secondary electrons produced in the foil by the incident tritons. The beam current was measured directly, the target chamber being insulated from ground. A Gittings-type[11] current integrator measured the current integral to within ± 0.2 percent.

B. Triton Beam and Gas Target

The deuterium gas was admitted to the target chamber through a simple manifold. A 6-inch Wallace-Tiernan pressure gauge with scale from 0 to 30 cm was used to determine the gas pressure. This gauge was calibrated to better than 0.5 percent accuracy in the region where it was used. The pressure could be measured at any time since the gauge was connected directly to the target. Pressures of about 8.8 cm of Hg were used, giving a target half-thickness of 17 kev at the resonance peak of 165 kev. A measurement of the target temperature was also made during the experiment.

The concentration of the deuterium in the target was carefully checked. The target gas was replaced several times each day with fresh samples from a container for which a mass-spectroscopic analysis showed a deuterium concentration of 96.97 percent. Earlier experiments showed that any trace of stopcock grease in the target would result in a rapid exchange of the deuterium target gas with the hydrogen in the grease while the beam was passing through the gas. Careful cleaning of the target minimized this, but to insure that no changes in the deuterium concentration were taking place the neutron yield for a fixed energy of triton beam was checked frequently.

Analyzed triton beams have been available from the Los Alamos 2.7-Mev electrostatic accelerator since October, 1949. The tritium gas from the ion source was collected by connecting the output of the main oil diffusion pump into an oil diffusion booster pump that would work into a back pressure of 0.3 mm of Hg. Two Hg Toepler pumps working in parallel but 180° out of phase took the gas at 0.3-mm pressure and pushed it into a collection tank for reuse. The exchange of tritium with hydrogen in the pump oil was found to

[7] S. D. Warshaw, Phys. Rev. **76**, 1759 (1949).
[8] T. W. Bonner, Proc. Harwell Nuclear Physics Conf. (September, 1950).
[9] E. Fermi, *Nuclear Physic Notes* (University of Chicago Press, Chicago, 1950), p. 37.
[10] W. C. Dickinson and D. C. Dodder, Los Alamos Report No. 1182 (1950).
[11] H. T. Gittings, Rev. Sci. Instr. **20**, 325 (1949).

be about 10 percent per passage through the system and as the vacuum system was tight, the dilution of the original charge was not prohibitive. The ion source has been run very successfully on a tritium concentration as low as 8 percent.

One of the interesting aspects of accelerating such tritium-hydrogen mixtures in an electrostatic accelerator is the multiplicity of beams that are available for use. Masses 1, 2, 3, 4, 5, 6, 7, and 9 are observed in good focus on a quartz focusing plate, when the beam is magnetically analyzed, corresponding to H^+, HH^+, HHH^+ and T^+, HT^+, HHT^+, TT^+, TTH^+, and TTT^+ beams, respectively. Deuterium is a completely negligible contamination. Since mass 3 beam contains an unknown mixture of triton and triatomic hydrogen ions, mass 4 beam is the lightest containing a known concentration of tritium. This has the disadvantage that the triton carries only three-fourths of the machine energy and thus limits the upper energy available, but makes low energy tritons more easily obtainable. Mass 2 beam was used to control the machine energy in the usual way, utilizing an electrostatic analyzer. For the highest energies the mass 3 beam was deflected into the target tube and the neutron yield was normalized against the yield from mass 4 beam at an overlapping energy point; in this case the variations in magnetic deflection of the mass 3 beam controlled the energy of the machine.

C. Detector Response

Neutrons from the reaction were detected with a BF_3 long counter[5] whose absolute sensitivity was determined for 14.1-Mev neutrons. The absolute calibration was done by measuring the neutron counts per alpha-particle counted in known geometry from the T(d,n)He^4 reaction produced on the 250-kev Cockcroft-Walton accelerator at Los Alamos. From the counting geometry for alphas, and the effects of scattering and background, the absolute sensitivity of the long counter at 14 Mev is known to about ± 4 percent.

Earlier measurements had shown that this particular long counter had a sensitivity independent of neutron energy to within about ± 4 percent from 200 kev to the mean energy for RaBe neutrons around 5 Mev. A careful comparison of sensitivities for 14-Mev neutrons and for those from a standardized RaBe source known to ± 5 percent showed that at 14 Mev the detection efficiency had dropped to 67 percent of that for RaBe neutrons. In the measurements of angular distributions for bombarding energies of tritons up to 1.2 Mev, the neutrons emerge from the reaction at energies in the laboratory system as high as 17.7 Mev at 0° and as low as 13 Mev for back angles. It was thus desirable to try to determine whether a further change in long counter sensitivity occurred in this energy interval in addition to the change between 5 Mev and 14 Mev.

Two methods were used to determine the change in sensitivity between 13 and 18 Mev. In the first, copper foils were irradiated at several angles between 0° and 120° and counted for the 10-minute activity produced in $Cu^{63}(n,2n)Cu^{62}$. At the triton energy of 1.2 Mev used, the long counter gave a distribution of neutron intensity independent of angle in the laboratory system so the Cu^{62} activities found were directly normalized to the data of Brolley, Fowler, and Schlacks[12] at one neutron energy. The normalized Cu^{62} activities agreed with the Brolley *et al.* energy dependence curve to within ± 5 percent indicating that the long counter gave the correct angular distribution of neutron intensity.

The second check on the counter sensitivity was made by comparing the angular distributions taken with our long counter and one of a different design due to E. Graves. The latter counter, in which the BF_3 tube was embedded behind about 8 cm of paraffin, had the same sensitivity to 14-Mev neutrons as it had to RaBe neutrons, in qualitative agreement with the theoretical sensitivity curves determined Kusherniuk;[13] similarly Kusherniuk's calculations would predict for our long counter a rather rapid drop in sensitivity between 6.5 and 8 Mev and a subsequent flattening off. The experimental angular distributions of the two counters agreed within the statistical errors implying that the sensitivities of both are approximately independent of energy between 13 and 17.5 Mev.

Although these checks of the energy dependence of the long counter sensitivity are not of great accuracy, it is believed that the total cross sections calculated from angular distributions are good to about ± 10 percent. This comes from the fact that the contributions to total cross section from angles close to zero and 180° are small because of the solid angle available. Thus one-fourth of the solid angle lies between 0° and 60° and one-half between 60° and 120°; at $E_T = 1.2$ Mev the neutron energy changes from 17.6 Mev to 15.9 Mev between 0° and 60° and from 15.9 Mev to 13 Mev between 60° and 120°; the 14-Mev energy at which the long counter is calibrated occurs at about 98° for all E_T. Thus, an average yield in the first angular interval twice as large as the yield in the 60° to 120° interval would, if compensated by the counter having half-sensitivity between 0° and 60°, make an error of only 25 percent in total cross section. Such a large change in counter sensitivity appears very unlikely as does also a very rapid change in true angular distribution since the measurements at $E_T = 380$ kev and $E_T = 570$ kev where the energy interval is only slightly smaller show essentially spherical symmetry in the center-of-mass system.

The detector was placed 144 cm from the target and for the angular distributions was swung about the target on a carriage at the end of a rigid arm. A second

[12] Brolley, Fowler, and Schlacks, Bull. Am. Phys. Soc. **27**, No. 3, 30 (1952).

[13] S. A. Kusherniuk (private communication from Chalk River to H. M. Agnew).

TABLE I. Total cross sections for D(T,n)He^4. Angular distributions were taken at the energies indicated by asterisks.

E_T (kev)	σ (barns)	E_T (kev)	σ (barns)
80	1.76	224	3.97
87	2.21	244	3.54
96	2.62	264	3.10
104	3.11	284	2.78
114	3.67	304	2.54
124	4.13	324	2.26
134	4.58	344	2.04
144	4.82	364	1.85
154	4.90	377	1.67*
164	4.93	384	1.67
174	4.90	404	1.50
184	4.80	575	0.77*
194	4.61	980	0.38*
204	4.40	1200	0.30*
214	4.20		

fixed long counter was used as a monitor during angular distribution measurements.

D. Determination of Backgrounds

One of the major sources of trouble in the measurements came from background neutrons; this was particularly true at triton energies above about 600 kev where the intensity of reaction neutrons is small while the background neutron sources are increasing in strength. These background neutrons arise primarily from triton induced reactions occurring in the target tube ahead of the gas target proper, one of the major sources being the limiting aperture directly in front of the target entrance foil. These background neutrons were greatly reduced by making the limiting aperture of gold and trapping with liquid nitrogen nearby to prevent carbon deposition. The brass aperture used initially, rapidly became a source of T(T,2n)He^4 neutrons as has also been observed by the Chalk River group.[14] Above about 1.1 Mev, neutrons from the aluminum entrance foil became one of the principal sources of background and above about 1.5 Mev these made good measurements impossible.

The background was measured as a function of energy by replacing the deuterium in the target chamber with helium and repeating each run. The operating conditions within the ion source varied somewhat over the period of several hours and affected the amount of waste current in the accelerating tube and the relative strengths of the various beams. The focus of the HT^+ beam also shifted for the same reasons. Since the background was due to reactions from those accelerated particles that did not get into the target chamber, it was necessary to compare the helium background run against the deuterium run under the same operating conditions. To do this an electrostatic shutter in the target tube about 1.5 meters before the target chamber was used. A "shutter in" and "shutter out" measurement was taken for each energy point with deuterium in the target and again with the helium in the target. The net counts were then obtained using the formula

$$\text{Net Counts} = D_{\text{shutter out}} - He_{\text{shutter out}}(D_{\text{shutter in}}/He_{\text{shutter in}}),$$

where D and He refer to the observed counts with deuterium or helium in the target. In general, the background varied from 2 to 5 percent. At the two highest energy points, 980 kev and 1200 kev, where angular distributions were taken the background was more troublesome, being as high as 50 percent for the back angles. However, by using the above technique the results were consistent within the statistical scattering.

In order to determine what fraction of the neutrons originating in the target would count in the long counter after a scattering process took place, a steel cone 30 cm long (about seven mean free paths for any collision) was put in line with the long counter at 0° and at 90° to the beam. The angle of the cone was just large enough to shadow the long counter 144 cm from the target. By measuring the counting rates first with cone out, shutter in and out, then with cone in, shutter in and out, it was possible to determine whether an appreciable number of primary neutrons were scattered into the counter. In the worst case at $E_T=1.2$ Mev the direct "shutter in" background was half the total counting rate with the beam in the target; putting the cone in and leaving the shutter in showed that about 12 percent of the background neutrons came from a region very close to the target itself presumably from the apertures and that less than 5 percent of the total background with cone in and shutter out came from scattered T-D neutrons.

R. Calculation of Cross Sections

To summarize, the observed long counter counts per microcoulomb of tritons corrected for background,

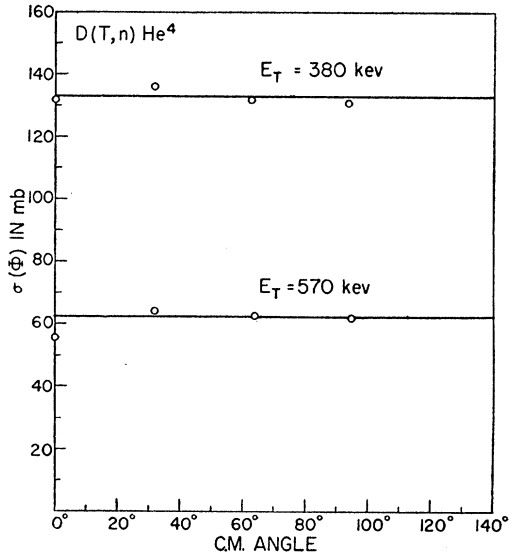

FIG. 2. Angular distributions of neutrons in the c.m. system from D(T,n)He^4 for incident triton energies of 380 and 570 kev.

[14] Allen, Almquist, Dewan, Pepper, and Sanders, Phys. Rev. **82, 262 (1951)**.

scattered primary neutrons, and target gas deterioration were converted to number of incident neutrons by use of the 14 Mev absolute calibration. From the number of deuterons cm^2, as determined from a mass spectroscopic analysis of the sample, the target length, temperature and pressure, a cross section was calculated. The mean energy at which the reaction had this cross section was determined from the primary triton energy and energy loss in the foil. From measurements and calculations on foil straggling the low energy cross sections were corrected for effect of energy spread.

III. DISCUSSION OF RESULTS

The total cross sections for the D(T,n)He^4 reaction for triton energies from 80 kev to 1200 kev are given in Table I. The numbers identified by asterisks are the results of integrations of the angular distributions taken at the indicated energies. The remaining points were taken with the detector at 0° and assuming the reaction to be isotropic in the c.m. system. These data have an estimated over-all accuracy of ±10 percent; this 10 percent arises almost entirely from the straggling and energy correction uncertainties up to energies of about 300 kev. Above 300 kev the accuracy is primarily determined by background and by poor knowledge of the energy sensitivity of the long counter. The yield has a very characteristic resonance shape, which indeed can be fitted by a single level dispersion theory as discussed below.

Figures 2 and 3 show four angular distributions taken at $E_T=380$ kev, 570 kev, 980 kev, and 1200 kev, respectively. The two lower energy measurements show an isotropic yield in the c.m. system, in agreement with the early measurements below 200 kev. However, at 980 kev the angular distribution is beginning to deviate from isotropy, more neutrons being observed at the back angles. At 1200 kev the deviation is even more pronounced, indicating that higher angular momenta are beginning to contribute to the reaction.

The observed isotropic yield of neutrons from the D-T reaction in the resonance region leads one to believe that an S-wave interaction is taking place. The two possible spin combinations give $J=\frac{1}{2}$ or $\frac{3}{2}$, where J is the total angular momentum. In order that the total angular momentum and parity of the system be conserved the neutron and the He^4 nucleus must come off with a relative angular momentum of 0 or 2, assuming l-s coupling. This gives a possibility of $J=\frac{1}{2}$ or $\frac{3}{2}$ for the emerging particles. However, if the Breit-Wigner nuclear dispersion theory is applied to this resonance it is possible to fit the experimental data very well by assuming the total yield is from a single state with $J=\frac{3}{2}$. A single state with $J=\frac{1}{2}$ cannot give the high cross sections that are observed. If $J=\frac{3}{2}$, then the product particles must leave the scene of the reaction with relative angular momentum $l=2$.

The one-level nuclear dispersion formula as given by

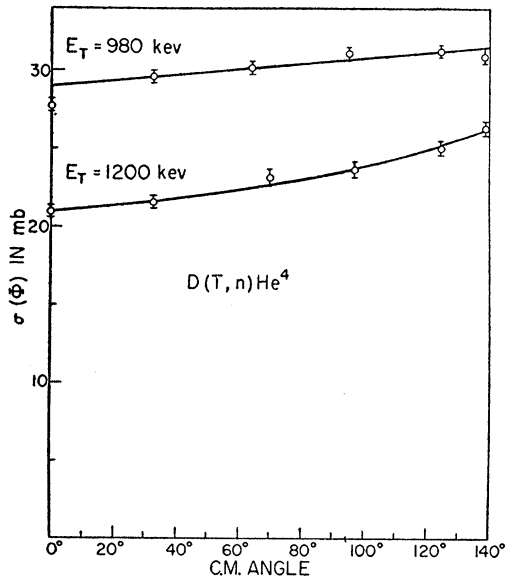

FIG. 3. Angular distribution of neutrons in the c.m. system from D(T,n)He^4 for incident triton energies of 980 and 1200 kev.

Wigner and Eisenbud[15] reduces to

$$\sigma=\frac{(2J+1)}{(2S+1)(2i+1)}\frac{4\pi}{k^2}\frac{\Gamma_n\Gamma_t}{4(E_\lambda+\Delta_\lambda-E)^2+(\Gamma_n+\Gamma_t)^2} \quad (1)$$

for this case. J is the total angular momentum of the system; S is the spin of the incident particle; i is the spin of the initial nucleus; Γ_n and Γ_t are the reaction width and scattering width, respectively, the two competing modes of break-up being He^4+n and T+D. In general the Γ's are energy dependent and it is customary[16] to redefine them in terms of energy dependent and non-energy dependent factors $\Gamma=2\kappa\gamma^2P$, where κ is the wave number of the emitted particles. γ^2 is known as the "reduced width" and is assumed to be a constant. It is proportional to the probability that the T and D wave functions within the radius of interaction will interact. P is a penetration factor arising from the Coulomb barrier of the nucleus and is defined by

$$P_L=[F_L^2(a)+G_L^2(a)]^{-1}, \quad (2)$$

where F_L is the regular Coulomb wave function with orbital angular momentum L, G_L is the irregular function, and a is the radius of interaction. F_L and G_L were evaluated at a, making use of the Coulomb wave function tables provided by Breit and his collaborators.[17] The parameter a is one of the three parameters that have been adjusted to make the resonance formula fit the experimental data.

[15] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947).
[16] See R. F. Christy and R. Latter, Revs. Modern Phys. **20**, 185 (1948); E. P. Wigner, Am. J. Phys. **17**, 99 (1949); Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947).
[17] Bloch, Hull, Broyles, Bouricius, Freeman, and Breit, Revs. Modern Phys. **23**, 147 (1951).

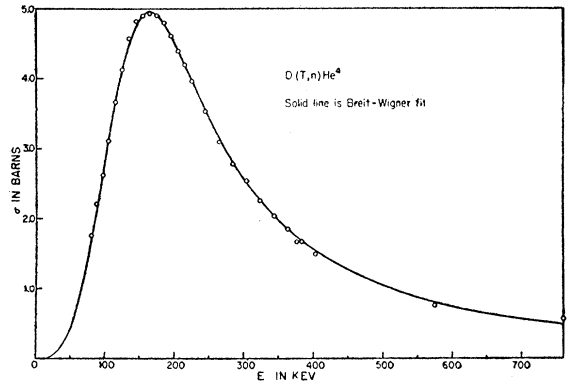

FIG. 4. A fit of the resonance data by a one level nuclear dispersion formula. $J=\frac{3}{2}$, $\Gamma_t=165$ kev (laboratory system), $E_r=194$ kev incident triton energy, and $a=7.0(10)^{-13}$ cm.

As a result of the high Q of the reaction Γ_n is approximately constant over the energy interval covered by the resonance. k_n, the wave number for the He^4 and neutron in the c.m. system, is very insensitive to the incident particle energy. Similarly, the high reaction energy and small barrier for neutron emission leave P_n essentially constant. P_n was evaluated at the resonance making use of the expression for D-wave penetration (assuming $l=2$)

$$P_n=x^4[9+3x^2+x^4]^{-1}, \quad x=k_n a. \tag{3}$$

However, Γ_t is a rapidly varying function of the incident triton energy. k_t is the same as the k in Eq. (1), hence it will vary as the square root of the energy. P_t, the penetration factor for the T and D particles, was calculated from Eq. (2).

Δ_λ, the level shift, was calculated by the procedure outline by Thomas[18] and for the case of the scattered component has a very material effect upon the shape of the calculated resonance curve. Δ_λ for the reaction component turns out to be negligible. $E_\lambda+\Delta_\lambda$ is the apparent resonance energy, and has been called E_R here.

Fitting the experimental data with Eq. (1) involved the adjustment of three parameters: the interaction radius a, the reaction width Γ_n, and the apparent resonance energy E_R. The fit is relatively insensitive to a and very sensitive to Γ_n and E_R. Figure 4 shows a calculated curve drawn through the experimental points. As is usual when fitting a Breit-Wigner curve to an observed resonance, the data give two possible values for the ratio of Γ_n to Γ_t at the resonance. An equally good fit to the data is possible with either value, and without additional knowledge about γ_t^2 it is not possible to choose between them. It is interesting that for this resonance the cross section is so nearly equal to the maximum permissible value $(2J+1)(2S+1)^{-1}\times(2i+1)^{-1}\pi\lambda^2$ that the Γ_n/Γ_t ratio is close to unity. For this reason the two solutions do not give widely differing parameters as best fits. In the absence of additional information as to which solution is the correct one, a simple averaging of the two sets of parameters gives numbers that are still of considerable interest. Table II is a tabulation of the two sets of numbers.

A value of $7.0(10)^{-13}$ cm for a was found to give the best fit regardless of the other parameters.

From the table it may be seen that the ratio of the reduced scattering width to reaction width is large. In units of $\hbar^2/2Ma$ the ratio averages about 50. In these same units the dimensionless widths in the last two columns should not exceed 3, the sum rule limit.[19]

TABLE II. Reaction parameters for the nuclear dispersion theory fit to the resonance data.

Γ_n/Γ_t	E_λ	γ_t^2	γ_n^2	$\frac{\gamma_t^2}{\hbar^2/2M_t a}$	$\frac{\gamma_n^2}{\hbar^2/2M_n a}$
>1	−0.067 Mev	$3.3(10)^{-13}$ Mev cm	$1.1(10)^{-14}$ Mev cm	1.33	0.030
<1	−0.126 Mev	$5.0(10)^{-13}$	$1.2(10)^{-14}$	2.0	0.034

Assuming the Q of the reaction to be 17.577 Mev, the position of the excited level in He^5 is either 17.510 or 17.451 Mev, depending upon which solution to the quadratic equation for Γ_n/Γ_t one takes. The uncertainty in the individual numbers is probably about as great as the difference between them.

As pointed out by Thomas,[20] the analysis of Allan and Poole's[2] data made by Flowers[21] is equivalent to the familiar resonance theory applied above. The concept of the complex reaction lengths introduced by Flowers can be reduced[20] to the well-known[15,16] form of the nuclear dispersion theory by suitable substitution. Since the peak cross section used by Flowers was about 1 barn higher than the data reported here he was unable to fit the curve with the single "transition" involving $J=\frac{3}{2}$ and had to add a contribution from $J=\frac{1}{2}$. In the usual notation this corresponds to having the reaction go with channel spins of both $\frac{3}{2}$ and $\frac{1}{2}$.

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