The proposed scheme of Fig. 8 with the newly postulated ~605-kev transition encounters difficulties when one considers the deexcitation of the 1365-kev level by only the 563-kev gamma ray. The situation would be partially alleviated if the 1367-kev gamma ray led from the 1365 level to the ground state. The measured conversion coefficient is then too small to be consistent with the spin assignments. In addition, the coincidence measurements indicate that more low-energy beta decays are followed by 605-kev gammas than by 796-kev gammas. The 1367-kev transition as shown has the appropriate "shunting" effect. For this reason too it is difficult to justify inverting the order of the 796 and 605 gammas, although such an inversion would improve the consistency of the 1038 and 1168 gamma rays.

A ground-state spin of 4 has been measured for Cs^{134} by Bellamy and Smith.[18] An even parity is predicted by the shell model. The principal beta transitions shown in Fig. 8 are therefore allowed and the high logft values must be assumed to result from l-forbiddenness. Similar conclusions apply to the two weaker transitions.

The newly-proposed decay scheme is consistent with the lack of coincidences between high-energy beta particles and the 563-kev internal conversion electrons only if the 683-kev beta component is assumed to be less than ~10 percent of all beta transitions.

We wish to thank T. J. Morgan and the cyclotron crew for the production of Mn^{52} and Cs^{134m}, and J. R. Penning for assistance with the delayed gamma-ray measurements.

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Deuterium He^3 Reaction*

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By the use of accelerated He^3 ions, the reaction $H^2(He^3,p)He^4$ has been studied in the energy range 100–800 kev (He^3 energy). The angular distribution of the protons was found to be isotropic at bombarding energies of 200, 290, and 350 kev. The reaction cross section has a peak of 695±14 millibarns as determined with reference to the peak value 5.00 barns for the comparison reaction, $H^3(H^2,n)He^4$. The comparison was effected by alternately bombarding the same deuterium target with tritium and He^3 ions, and counting the alpha particles. The peak occurred at 640-kev He^3 ion bombarding energy.

From considerations of the absolute value of the cross section, it is concluded that the resonance at 640 kev is associated with a $J=\frac{3}{2}$ level in the compound nucleus. The experimental shape of the peak is well fitted by resonance parameters in the one-level dispersion formula having the following values: interaction radius R, 5×10^{-13} cm; reduced width for proton emission γ_p, 41.9 kev; reduced scattering width γ_α, 2930 kev; "formal" resonance energy in the center-of-mass system ϵ_s, 391 kev; energy of the level above the ground state of Li^5: 16.2±0.3 Mev. These values agree within experimental error with analogous values associated with the similar resonance which occurs in the $H^2(H^3,n)He^4$ reaction.

INTRODUCTION

THE reaction $H^2(He^3,p)He^4$, which we will speak of simply as "the He^3 reaction" is in a sense the mirror image of the $H^2(H^3,n)He^4$ reaction, which we will herein call "the tritium reaction." The former involves Li^5 (three protons and two neutrons) as the intermediate nucleus, and the latter He^5 (two protons and three neutrons). If nuclear forces are charge symmetric, then the two intermediate nuclei should possess energy levels equivalent in character, differing in fact only in Coulomb energy. It is therefore of interest to compare the cross sections of the two reactions as accurately as possible to see if the known resonances have comparable characteristics. It is also of interest to compare the shapes of the resonance peaks with the shapes predicted by the one-level dispersion formula to see if this kind of theoretical treatment can have validity when applied to nuclei possessing as few as five nucleons.

The tritium reaction has been extensively studied in the energy region below 1 Mev,[1–6] with the result that the peak at 163 kev has been characterized in a satisfactory manner both with respect to reduced width and to absolute cross section. The analogous peak in the He^3 reaction is, however, perhaps less well known, although it also has been the subject of a number of

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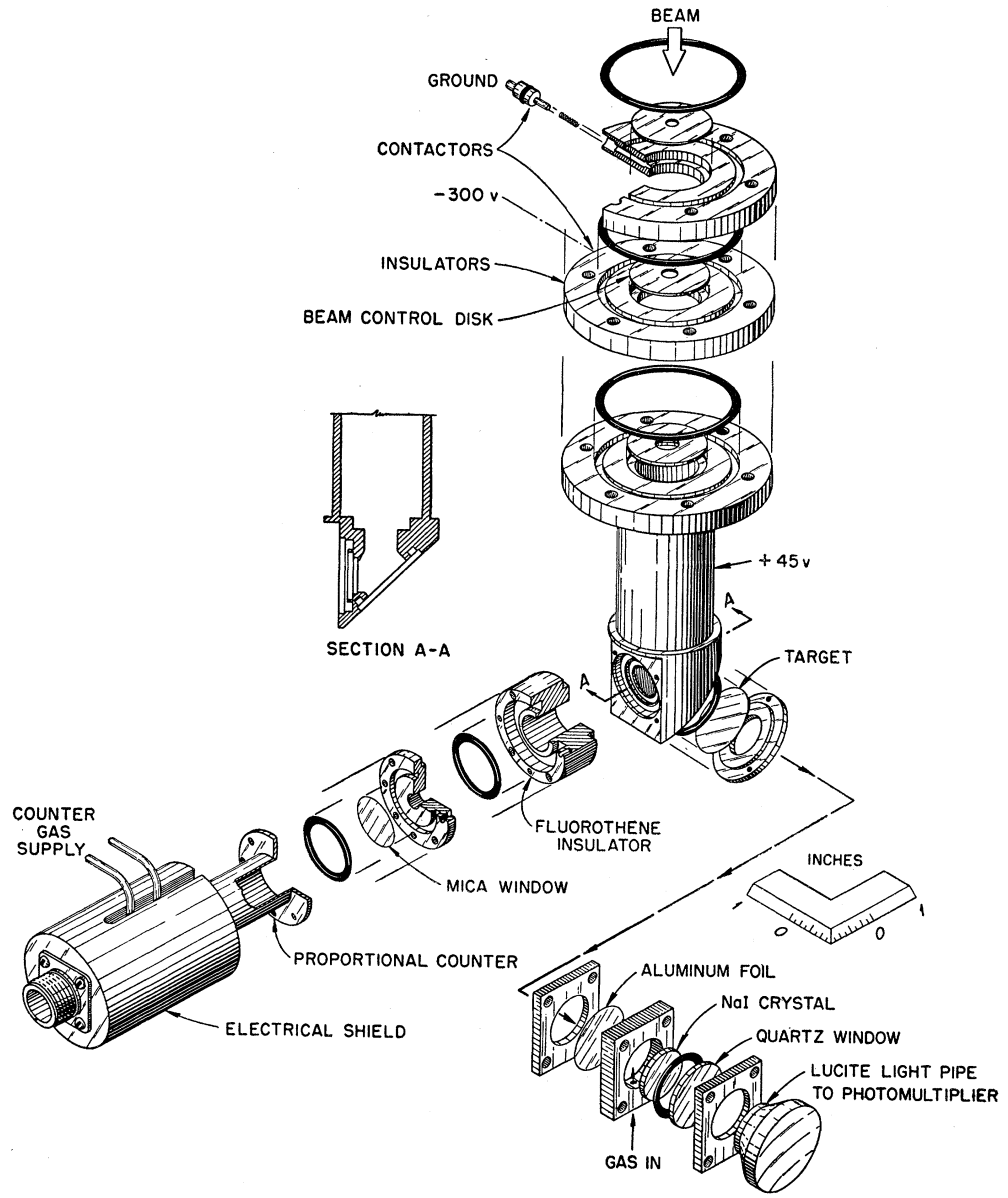

FIG. 1. The target apparatus and counters. Alphas from both the He^3 reaction and the tritium reaction were counted by the proportional counter. The NaI crystal-photomultiplier combination was used to count protons from the He^3 reaction.

investigations.[7–13] In much of the experimental work of this kind, a deuterium beam has been used, with gas targets. In the experiments to be described here, the reversed procedure was used; a common solid deuterium target was bombarded in turn with tritium and with He^3 ions. Accepting the absolute value of the cross section for the tritium reaction as measured by others, it was thus possible to obtain the He^3 reaction cross section by a comparison which kept the target and detecting equipment unchanged while switching from one reaction to the other. With the new information on the He^3 reaction thus obtained, it has been possible to make significant comparisons of the parameters associated with the analogous levels in He^5 and Li^5, and to examine the shapes of the resonance peaks in the light of the dispersion theory.

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EXPERIMENTAL

The He^3 and H^3 ion beams used in these experiments were produced in the Oak Ridge Cockcroft-Walton accelerator. The accelerator yields a potential of 400 kv, but it was possible to take advantage of a weak,[14] doubly-charged component of the He^3 beam to carry the bombarding energies to 800 kev.

The first part of the experiment consisted of the determination, on a nonabsolute basis, of the shape of the yield curve of the He^3 reaction from 100 to 800 kev. Figure 1 shows the arrangement of the target and detecting apparatus. The latter consisted of a proportional counter, set at 90 degrees to the incident beam, which detected the alpha particles but was biased against registering the protons, and in addition a NaI crystal-5819 photomultiplier combination, at 45 degrees, used to count the protons only. The NaI crystal subtended 20 times the solid angle presented by the counter to the source, so that it was useful in regions of low yield. Elsewhere the two detectors could be used simultaneously. The number of bombarding He^3 particles was determined by current integration, a 300-volt bias (Fig. 1) preventing the escape of secondary electrons. Charge exchange in the incident ion beam was reduced by keeping the residual gas occupying the 75-cm distance between the beam-bending magnet of the accelerator and the target at a pressure below 5 or 6×10^{-6} mm of mercury.

A thin target was needed in the yield curve determination because the energy loss rate of He^3 ions of these energies in the target material is not well known. Deuterated polyethylene of thickness about $1\mu g/cm^2$ was used; this would present a stopping equivalence of about 1 kev to 300 kev He^3 ions, so the uncertainties involved would be small and the effective He^3 ion energy would be well determined. The targets had the disadvantage of instability; with ion beam densities of about $1\mu a/cm^2$, about half of the target would disappear in a few minutes of bombardment, but the loss rate thereafter decreased slowly.

Singly-charged He^3 ions were used in the energy region 100 to 400 kev, and doubly-charged ions in the range 320 to 800 kev. In the region of overlap, agreement in yield was observed within an accuracy of 0.5 percent—evidence of lack of He^{3++}-to-He^{3+} conversion through charge neutralization. Likewise there was negligible He^{3+}-to-neutral He^3 conversion, as shown by a test in which the charged beam was deflected from the target by means of an external magnet.

To keep up with the loss of target material, a yield determination was made at 640 kev, followed by one at the energy under investigation, and by a repeated determination at 640 kev. Above 300 kev, the two 640 kev yields agreed within 3 percent, but at 100 kev the target loss between the two 640-kev determinations was as much as 30 percent. The yield at the energy under investigation was always related to the mean of the two 640-kev determinations.

The second part of the experiment consisted of a comparison of the peak yields of the He^3 reaction and the tritium reaction. This was accomplished using the arrangement of Fig. 1, except that only the alpha-particle detector (proportional counter) was used. The target requirement now was one of stability rather than thinness, so a zirconium-deuterium target 40 $\mu g/cm^2$ thick was installed. (At the peaks, the yields vary only slowly with ion energy, so the requirement of thinness could be relaxed.) The target had been made by evaporation of the required thickness of zirconium onto a platinum backing, followed by heating in a deuterium atmosphere. Using doubly-charged ions, the peak in the yield curve was located and carefully examined with the ion beam slightly defocused so as to reduce errors arising from non-uniform coverage of a possibly non-uniform target. The ion source of the Cockcroft-Walton accelerator and its gas supply were then removed and replaced by similar equipment containing tritium. With target and detector unchanged, alpha-particle yields were determined at the peak of the tritium reaction cross section curve. Then the He^3 ion source was replaced, and the peak yield of the He^3 reaction was redetermined; no change in yield was observed, so it was assumed that the target and detector had remained constant, and the result of the intervening tritium bombardment was taken as valid.

The gas used in the tritium bombardment just described contained 25 percent H^1. The possible presence of H_3^+ ions was guarded against by using low pressures in the ion source, and their absence was checked by use of the mass 4 beam (HT^+). The mass 4 beam was found to change with time, possibly because of an admixture of oxygen which cleaned up slowly as the system was

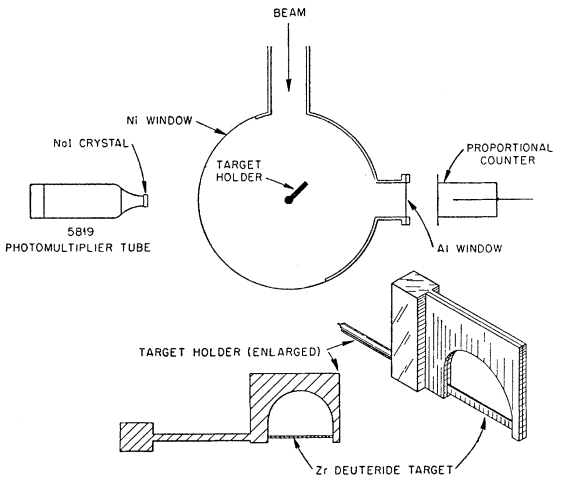

FIG. 2. The apparatus used to determine the angular distribution of the protons from the He^3 reaction. The NaI crystal-photomultiplier combination could be set at various angles to the beam. The fixed proportional counter served as a monitor for the protons produced by the reaction.

[14] 0.5 percent of the total He^3 ion beam.

degassed through operation. (O^+, if accelerated and subsequently stripped to O^{++}, would be magnetically deflected as HT^+.) However, after several hours of operation, the yields from the mass 3 and mass 4 beams agreed within a few tenths of one percent, which implied very little H_3^+ contamination.

A third part of the experiment was required because the He^3-H^3 comparison was carried out at only one angle, *viz.*, 90 degrees relative to the direction of the ion beam. The products of the tritium reaction are known to be isotropic in the center-of-mass system, but similar information was lacking for the He^3 reaction at these energies. Figure 2 shows the target and detector arrangement used to survey the angular distribution. The target chamber was fitted with an extensive nickel window 0.012 cm thick, and a moveable NaI crystal served to count the reaction protons in various directions. The proportional counter at the right counted protons at a fixed angle and served as a monitor. The thick target was a strip 3 mm wide of deuterated zirconium foil, 0.005 cm thick, placed at the axis of rotation of the NaI crystal 20 cm away. In a test of the energy sensitivity of the efficiencies of the two proton counters, the target was rotated 90 degrees without affecting the relative counting rates, whence it was concluded that the target was thin so far as the penetration effects for the protons were concerned.

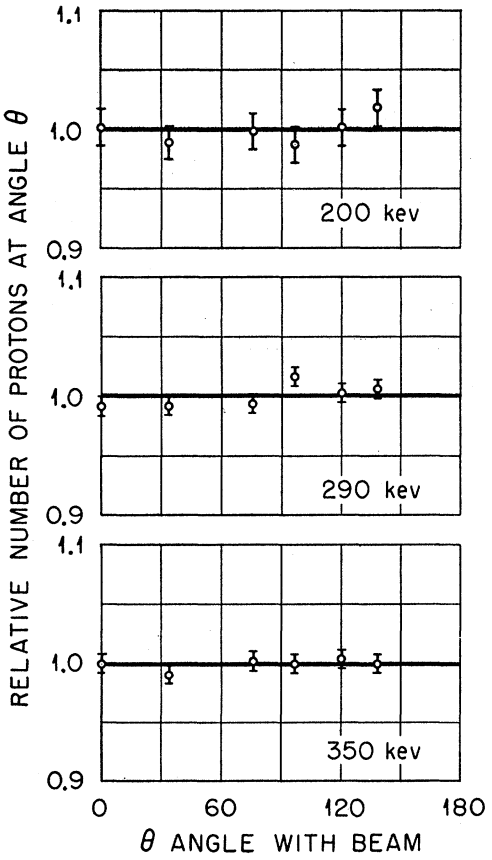

FIG. 3. The center-of-mass angular distribution of the protons from the He^3 reaction. A thick Zr-deuterium target was bombarded at the three energies given. Errors shown are the standard deviations.

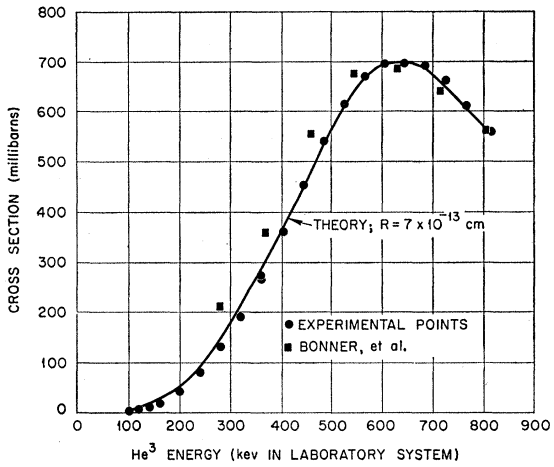

FIG. 4. The cross section of the He^3 reaction as a function of He^3 energy. The solid line is the theoretical cross section obtained by fitting the experimental points by the dispersion formula with the interaction radius, $R=7\times10^{-13}$ cm. The circles are the cross section values determined by this experiment and the squares are the experimental values of Bonner *et al.*

RESULTS

The results of the angular distribution measurements are indicated in Fig. 3. The measurements were taken at 200, 290, and 350 kev and indicate isotropy within limits of about 2 percent; half of the error comes from geometrical uncertainty and half from counting statistics. Earlier results of Bonner *et al.*[10] and Yarnell *et al.*[11] indicate isotropy at somewhat higher energies. It is concluded that at these energies the relative yields of the H^3 and He^3 reactions taken at a single angle can be used directly in deriving the relative reaction cross sections.

Taking the value 5.00 barns (Conner *et al.*[4]) for the cross section at the peak of the tritium reaction, the value 695 millibarns is obtained for the peak cross section of the He^3 reaction. With this normalization, the curves of Figs. 4 and 5 (details of low-energy region) have been derived to show the variation of the cross section of the He^3 reaction with energy. The value 695 millibarns for the cross section at the peak is in agreement with the separate determination by Bonner *et al.*,[10] but it is considerably lower than the 900 millibarns obtained by Yarnell *et al.*[11] and the 940 millibarns obtained by Frier and Holmgren.[13] In Fig. 5, the comparison with the results of Tuck *et al.*[9] indicates lack of agreement amounting to 5 to 10 kev in the energy scale. However, the result of Jarvis and Roaf[12] at 65.6 kev equivalent He^3 energy also indicates a displacement of 6 kev toward higher values than given by Tuck, and is in fact in good agreement with the present results.

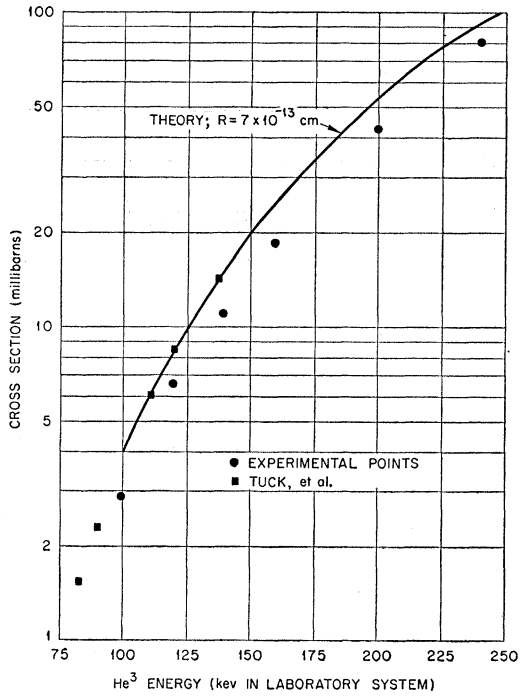

FIG. 5. The expansion of the low energy region of the He^3 reaction cross section. The solid line is the expansion of the theoretical curve of Fig. 4. The circles are the values of the cross section determined by this experiment. The squares are the experimental values of Tuck *et al.*

The experimental error involved in the yield comparison at the peaks of the tritium and He^3 reactions is estimated at less than two percent. Included in this estimate is the spread of about 1 percent in several counting rate comparisons taken with the He^3 and H^3 beams as described above, with slightly varying beam diameters. The current integrator was considered accurate within 0.2 percent, while charge exchange in the H^3 and He^3 beams might amount to a few tenths of one percent as judged from the observations of Kanner[15] and Snitzer.[16] Shifting of the beam on the target might cause geometrical errors which are hard to estimate, but the defocusing of the beam should have reduced this effect far below the maximum value of 6 percent which it would have had in the case of maximum possible shift of a point focus. These considerations taken together led to the cited 2 percent estimated accuracy in the ratios of the peak cross sections.

The cross sections derived for the remainder of the curve have in them the errors involved through the instability of the polyethylene target. As mentioned above, these should be negligible above 400 kev, in view of the manner in which the data were taken. At 100 kev, however, where the target loss was as much as 30 percent in each determination, errors of as much as 5 percent are conceivable, arising from this cause. Changes in the target-detector solid angle caused by beam shift should be negligible because the NaI crystal face was parallel to the target plane. Above 400 kev, where the He^{++} beam was used, defocusing was impossible because the beam was too weak, so about 2 percent error might be involved because of nonuniformity of the thickness of the polyethylene.

In summary, apart from the error in the reference value of 5.00 barns at the peak of the tritium reaction, it is thought that the cross section data of Figs. 4, 5, 6, and 7 are correct in absolute value within ± 10 percent from 100 kev to 400 kev, and ± 5 percent from 400 to 800 kev.

DISCUSSION

The isotropy of the He^3 reaction, herein observed, matches that previously found for the tritium reaction in the same energy region (0 to 200 kev). Because nuclear forces appear to be charge symmetric, the interchange of neutrons and protons in the compound nucleus should affect the Coulomb energy only, and one would expect the nuclear states involved in these two reactions to be identical so far as angular momentum and parity are concerned. States giving isotropy are those with either $J=\frac{1}{2}$ or $l=0$. In both reactions the spin s of the bombarding particle is $\frac{1}{2}$, and the spin i of the target nucleus is one. Therefore the initial states must be either doublets or quartets: ^2S, ^4S, ^2P, ^4P, ^2D, ^4D. . . . The final states of the systems are characteristic of an alpha particle (spin zero) and a neutron or proton (spin $\frac{1}{2}$), so they will be doublets: ^2S, ^2P, ^2D. . . . Assuming spin-orbit coupling, the allowed transitions giving isotropy are then

$$^2S_{\frac{1}{2}} \rightarrow {}^2S_{\frac{1}{2}}, \quad {}^4S_{\frac{3}{2}} \rightarrow {}^2D_{\frac{3}{2}}, \quad {}^2P_{\frac{1}{2}} \rightarrow {}^2P_{\frac{1}{2}}, \quad {}^4P_{\frac{1}{2}} \rightarrow {}^2P_{\frac{3}{2}}, \quad {}^4D_{\frac{3}{2}} \rightarrow {}^2S_{\frac{1}{2}}.$$

We shall now assume that the same transitions are involved in the two reactions. If we assume further that

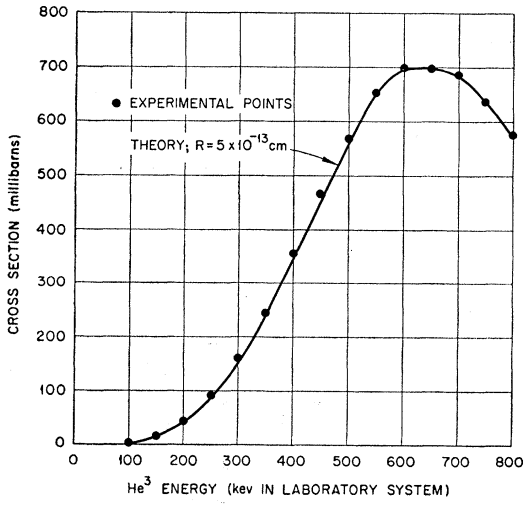

FIG. 6. The cross section of the He^3 reaction. The solid line is the theoretical curve obtained by fitting the experimental points by the dispersion formula with the reaction radius, $R=5\times10^{-13}$ cm.

[15] H. Kanner, Phys. Rev. **84**, 1211 (1951).
[16] E. Snitzer, Phys. Rev. **89**, 1237 (1953).

only one J value is involved, we can deduce whether it is $\frac{1}{2}$ or $\frac{3}{2}$ from considerations of the value of the maximum cross section.[17] The maximum reaction cross section σ_r is given by the expression

$$\sigma_r=\frac{2J+1}{(2s+1)(2i+1)}\pi\lambda^2,$$

so if $J=\frac{1}{2}$, the maximum value that the cross section can have is $\pi\lambda^2/3$. Actually the experimental value for the cross section of the tritium reaction at 200 kev is twice this, so the value $J=\frac{3}{2}$ is required, and the transition must be $^4S_{\frac{3}{2}}\rightarrow{}^2D_{\frac{3}{2}}$. Thus if the same *single* compound state is involved in the two reactions, it must have $J=\frac{3}{2}$ and be of even parity, and we must have $l=0$ for the incident wave. These J and l values will be adopted in the following discussion.

Argo *et al.*[6] were able to fit the experimental shape of the tritium reaction resonance with the level shift form of the one-level dispersion formula. In the notation of Blatt and Weisskopf,[18] the reaction cross section σ_r is given by

$$\sigma_r=\frac{2J+1}{(2s+1)(2i+1)}\pi\lambda^2\frac{\Gamma_\alpha\Gamma_r}{[\epsilon-\epsilon_s+\Delta_l(\epsilon)\gamma_\alpha]^2+\frac{1}{4}(\Gamma_\alpha+\Gamma_r)^2},$$

where $2\pi\lambda$ is the de Broglie wavelength associated with the reduced mass of the particles in their relative motion, ϵ is the center-of-mass energy of the incident particle, ϵ_s is that value of ϵ for which the logarithmic derivative of the wave function is zero and is the "formal" resonance energy, Γ_α and Γ_r are the scattering and reaction widths respectively, γ_α and γ_r are the reduced scattering and reaction widths, and $\Delta_l(\epsilon)$ is given by

$$\Delta_l(\epsilon)=\frac{R}{F_l^2+G_l^2}\left[F_l\frac{dF_l}{dr}-G_l\frac{dG_l}{dr}\right]_{r=R},$$

where in turn R is the radius of interaction and F_l and G_l are respectively the regular and irregular solutions of the radial wave equation as tabulated by Bloch *et al.*[19] The reduced scattering and reaction widths, γ_α and γ_r, are designed to be almost independent of Coulomb effects, and are determined through the expressions

$$\gamma_\alpha=\Gamma_\alpha(F_l^2+G_l^2)/2kR,$$
$$\gamma_r=\Gamma_r/2k_rRP_r,$$

where k is the wave number of the incident particle, k_r is that of the emitted particle, and P_r is the penetrability factor associated with the emitted particle. Using $R=7\times10^{-13}$ cm, Argo *et al.*[6] found two sets of level parameters yielding an energy variation of the cross section which agreed with their experiments. The two sets of parameters were as follows:

ϵ_s(kev)	γ_{H^3}(kev)	γ_n(kev)
−67	471	15.7
−126	715	17.2

Following the same line of reasoning and with $R=7\times10^{-13}$ cm we have analyzed[20] our results for the He^3 reaction using an iterative least squares method on IBM machines,[21] and we likewise find two sets of fitting parameters:

ϵ_s(kev)	γ_{He^3}(kev)	γ_p(kev)
235	62	23
129	780	12

Figures 4 and 5 show the comparison of the theoretical curve, thus calculated, with the experimental points. If we now select the second set of parameters in each case, we find quite reasonable agreement:

$$\gamma_{He^3}/\gamma_{H^3}=1.1, \quad \text{and} \quad \gamma_p/\gamma_n=0.7.$$

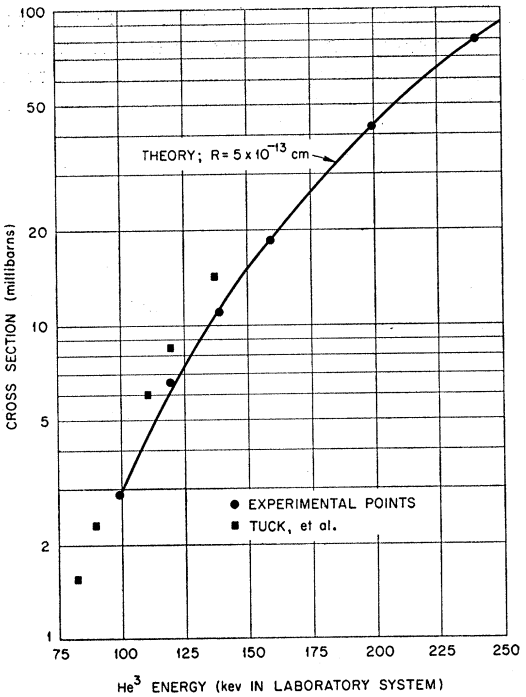

FIG. 7. The expansion of the low energy region of the He^3 reaction cross section. The solid line is the expansion of the theoretical curve of Fig. 6. The circles are the values of the cross section determined by this experiment. The squares are the experimental values of Tuck *et al.*

[17] A. Simon and T. A. Welton, "A Note on the Maximum Cross Section for Resonance Reactions," Oak Ridge National Laboratory Memorandum, (unpublished).

[18] J. M. Blatt and V. E. Weiskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. VIII.

[19] Bloch, Hull, Broyles, Bouricius, Freeman, and Breit, Revs. Modern Phys. **23**, 147 (1951).

[20] Actually the fit for $R=7\times10^{-13}$ cm was to the nonlevel-shift form of the dispersion formula and was converted to the above form by the linear approximation of $\Delta_l(\epsilon)$ as outlined by R. G. Thomas, Phys. Rev. **81**, 148 (1951).

[21] We are indebted to the computer staff of the K-25 laboratory for this assistance.

The errors in these ratios are difficult to estimate because systematic errors in the cross section measurement in the low-energy region would introduce rather large errors in the reduced widths. It is felt that the reduced widths of the He^3 reaction are within ± 25 percent of the values given. If the errors in the tritium reaction measurements are comparable, then the reduced widths associated with the two reactions would agree within experimental error.

The positions of the resonance levels in He^5 and Li^5 are given by $Q+\epsilon_s-$ (the breakup energy into He^4 plus a neutron or a proton, respectively). For He^5, the Q value is 17.577 Mev, and the breakup energy is 1.0 ± 0.1 Mev so that the level is $17.577-0.126-1.0\pm 0.1 = 16.5\pm 0.1$ Mev above the ground state. Similarly the position of the level in Li^5 is $18.341+0.129-1.8\pm 0.3 = 16.7\pm 0.3$ Mev above the ground state. Thus the level positions, as well as the reduced widths, agree within experimental error. The agreement indicates that the difference between the two reactions consists mainly of Coulomb effects.

Let us now examine the effect of varying the parameter R. Following Conner *et al.*[4] and Bonner *et al.*,[10] we choose the value $R=5\times 10^{-13}$ cm. In this case, those investigators found violent disagreement between the resonance parameters of the two reactions, in that the value of the reduced scattering width of the tritium reaction turned out to be fourteen times larger than that of the He^3 reaction. We have taken our new results for the He^3 reaction and have found, as was the case for $R=7\times 10^{-13}$ cm, *two sets* of fitting parameters:

γ_p(kev)	γ_{He^3}(kev)	ϵ_s(kev)
36.3	116	205
41.9	2930	−391

Figures 6 and 7 illustrate the agreement between the experimental points of the theoretical cross section curve computed by the use of either of these sets; the fit is very satisfactory.[22] Now if we choose the second set for comparison with those of Conner *et al.*[4] for the tritium reaction, we obtain

$$\gamma_{He^3}/\gamma_{H^3}=2930/2000=1.5,$$
$$\gamma_p/\gamma_n=41.9/56=0.8.$$

Allowing as before about ± 25 percent experimental uncertainty, it is apparent that on this basis the reduced widths of the resonances in the two reactions are substantially equal. The apparent discrepancy noted in the Rice Institute work resulted from their use of only one set of fitting parameters for the He^3 reaction. The position of the level in He^5 is found to be 16.1 ± 0.1 Mev above the ground level, and in Li^5 the level is at 16.2 ± 0.3 Mev above ground.

Using $R=5\times 10^{-13}$ cm, two points for the He^3 reaction cross section were calculated for higher energies, one at 1190-kev and the other at 1890-kev He^3 energy. The calculated value was 85 percent of the experimental value at 1190 kev and 50 percent of the experimental value at 1890 kev. The experimental values of Bonner *et al.*[10] were used. This comparison, along with the fact that the angular distribution becomes anisotropic at energies above the maximum of the cross section curve, shows that the one-level dispersion formula loses validity rather quickly beyond the maximum of the resonance.

We conclude that both the tritium and the He^3 reactions can be fitted over a large part of the resonance region by the one-level dispersion formula and that the corresponding reduced widths so obtained are equal within the experimental uncertainties. The fact of equality between the reaction widths is rather insensitive to the value chosen for the reaction radius. If ϵ_s is used to obtain the level position in the compound nuclei, He^5 and Li^5, then these levels correspond to the same excitation in the compound nuclei within the rather large experimental uncertainty.

Since nuclear forces are known to be charge-symmetric, the agreement between the two sets of reaction parameters was to be expected if the dispersion formula treatment is valid and if Coulomb effects can be separated from the effects arising from nuclear forces. This indeed is the case in the region near the top of the resonance and at lower energies, but at higher energies the one-level dispersion formula treatment does not agree with experiment.

[22] In this case, the fit was to the level-shift form of the dispersion formula. Thus errors introduced by the linear approximation method used for $R=7\times 10^{-13}$ cm were eliminated. This accounts for the better fit to the experimental points.

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