The conclusions are rather apparent. Though some calculated quantities are not consistent with experiment, the over-all agreement is quite reasonable when second-order corrections are taken into account. Since the onset of these calculations, there has been considerable improvement in the smooth, two-body potentials available. It is hoped that these improved potentials will lead to more accurate Hartree-Fock results, and calculations with the newer potentials are beginning. The results reported here are themselves considered sufficiently enlightening so that the Tabakin force is being utilized in calculations in a greatly enlarged space—from the $1s_{1/2}$ to the $1i_{13/2}$. This will permit investigation of heavier nuclei, in fact, up to Pb^{208} and will test the crucial dependence of the present results on the space truncation for deformed nuclei. A method for extracting more accurate information from the intrinsic state of a deformed nucleus, when the number of particles involved renders present projection techniques inapplicable, is being sought.

Work is also in progress to extract from the Hartree-Fock results reported information about the effective nuclear force and other nuclear properties, such as compressibility.

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Radiative Capture of ^{3}He by ^{3}He†

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The reaction $^3\text{He}+{}^3\text{He}\rightarrow{}^6\text{Be}^*+\gamma$ was observed at 90° for bombarding energies between 0.86 and 11.8 MeV. The total cross section for transitions to the first excited state of ^{6}Be varies smoothly from 0.4 to 9.3 μb (assuming isotropy). No γ-ray transitions to the ground state of ^{6}Be were observed with an upper limit of approximately 10^{-2} μb at 1.4 MeV. Because of these low cross sections, this reaction is of negligible astrophysical importance compared to the ^{3}He(^{3}He,$2p$)^{4}He reaction.

INTRODUCTION

HELIUM-3 capture γ-ray reactions have been observed in several nuclei.[1,2] The capture reaction $^3\text{He}+{}^3\text{He}\rightarrow{}^6\text{Be}+\gamma$ is a possible way of closing the proton chain of stellar energy production since ^{6}Be breaks up into two protons and an α particle.[3] We have observed this reaction and report here measurements of its yield.

LOW-ENERGY MEASUREMENTS

For the measurements from 1.0- to 1.8-MeV incident energy, a $^3\text{He}^+$ beam from the 3-MV Kellogg Radiation Laboratory electrostatic generator was used. The beam entered the 25-cm gas scattering chamber (see Fig. 1) through a differentially pumped canal in which the ^{3}He gas pressure in the chamber could be dropped by more than a factor of 100. The ^{3}He gas in the system was recirculated and passed through a liquid-nitrogen-cooled molecular sieve trap for purification before again entering the target chamber.[4] Stable gas pressures from 13 to 16 Torr were used in the chamber. The beam current, typically 1 to 2 μA, was collected in a thermally insulated low-mass metal cup. Beam power was measured by balancing the collector-cup temperature with a nearby dummy cup of the same geometry but heated electrically. The beam particle flux was then obtained from the integrated electric power dissipated in the dummy cup, after correcting the beam energy for energy loss in the target gas.[4]

A 10-cm-diam by 10-cm-thick NaI(Tl) crystal was introduced into a well in the gas chamber so that its front face was 4.1 cm from the beam line. The beam was completely surrounded by a tantalum shield in order to reduce the background of secondary neutrons produced by the high-energy protons from the ^{3}He(^{3}He,$2p$)^{4}He reaction. The crystal was shielded with lead from both the tantalum entrance canal and the collecting cup. Additional shielding was used to reduce the neutron

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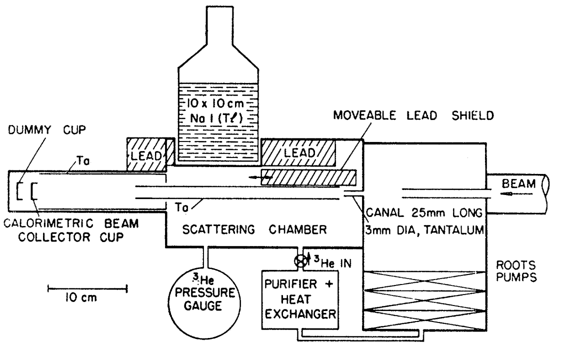

FIG. 1. Experimental arrangement for the low-energy measurements.

background from the accelerator slits and the beam deflecting magnet.

The NaI crystal was calibrated with the 12.17- and 16.60-MeV γ rays from the $^{11}\mathrm{B}(p,\gamma)^{12}\mathrm{C}$ reaction using 0.7-MeV protons, and with the 17.0-MeV γ rays from the $^3\mathrm{He}(d,\gamma)^5\mathrm{Li}$ reaction, using 1-MeV deuterons. The $^3\mathrm{He}+d$ γ rays were produced with the same gas target as that used to investigate the $^3\mathrm{He}+{}^3\mathrm{He}$ γ rays, so that the geometry was the same. Moreover, the $^3\mathrm{He}(d,\gamma)^5\mathrm{Li}$ reaction provided a response curve of the crystal for a nonmonochromatic γ ray, since the ground state of ^{5}Li is about 1.5 MeV wide.[5] The response curves are shown in Fig. 2.

The γ-ray spectra resulting from the bombardment of ^{3}He gas with ^{3}He ions at 1.5-MeV incident energy are shown as triangles in Fig. 3. The squares represent the background observed with no ^{3}He gas in the chamber. Although the beam had slightly greater energy and consequently more potential for background production in the collecting cup with no gas in the chamber, it was hoped that such an effect would be compensated for by the lack of background from the $^3\mathrm{He}(^3\mathrm{He},2p)$ protons. Background above a γ-ray energy of 10 MeV was practically all due to cosmic rays. Subtraction of the background from the ^{3}He run gives the circles plotted in Fig. 3. These points are well fitted by a response curve from the $^3\mathrm{He}(d,\gamma)$ γ rays adjusted to a γ-ray energy of 10.5 MeV corresponding to transitions to the first excited state of ^{6}Be. The observed γ-ray energy is clearly too low for the transition to the ground state of ^{6}Be. Furthermore, a narrower response curve, similar to the spectrum produced by the 12.18-MeV radiation from $^{11}\mathrm{B}(p,\gamma)$ (Fig. 2), would be expected for the transition[6] to the 89-keV-wide ^{6}Be ground state.

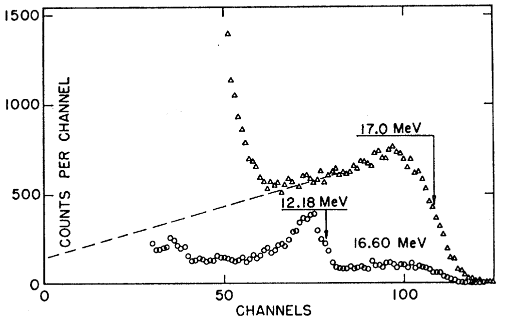

FIG. 2. Response curves for the 10-cm-diam by 10-cm-long NaI(Tl) crystal to the $^{11}\mathrm{B}(p,\gamma)$ (circles) and $^3\mathrm{He}(d,\gamma)$ (triangles) γ rays. γ-ray energies are indicated by arrows halfway up the front edge of the peaks. The dashed line is the assumed extrapolation for the $^3\mathrm{He}+d$ γ rays.

Both the $^3\mathrm{He}+{}^3\mathrm{He}$ and the $^3\mathrm{He}+d$ reaction, at the bombarding energies used, are a copious source of protons with energies above 10 MeV. In order to exclude the possibility that fast neutrons from the (p,n) reaction on the tantalum surrounding the beam contributed more than a few percent to the counts attributed to γ rays from $^3\mathrm{He}+{}^3\mathrm{He}$ and $^3\mathrm{He}+d$, the following experiment was performed: A 1.9-cm-thick lead plate was arranged to slide between the beam and the crystal. The absorption resulting from this arrangement was measured both for the $^3\mathrm{He}+{}^3\mathrm{He}$ and the $^3\mathrm{He}+d$ radiation. The observed ratio "without lead" to "with lead" for the $^3\mathrm{He}(d,\gamma)$ γ rays was 0.28. For these 17-MeV γ rays, this ratio was calculated to be 0.27. With the $^3\mathrm{He}+{}^3\mathrm{He}$ radiation (at $E_{^3\mathrm{He}}=1$ MeV), the ratio was observed to be 0.36, whereas that expected for 10-MeV γ rays was 0.34. The effect of the lead on a possible neutron flux is negligible. The results confirmed that over 92% of the net counts observed in both reactions were in fact from γ rays, and also implied that the angular distribution of the $^3\mathrm{He}+{}^3\mathrm{He}$ γ rays is not markedly different from that of the $^3\mathrm{He}+d$ γ-rays, which have been reported to be

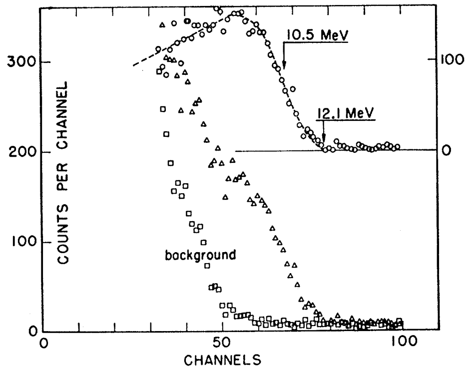

FIG. 3. γ spectra for 1.5-MeV incident ^{3}He energy. The triangles show the crystal response to $^3\mathrm{He}+{}^3\mathrm{He}$ γ rays. The squares are background with no ^{3}He gas in the chamber. The circles show the difference values. The dashed curve is the crystal-response curve for the $^3\mathrm{He}+d$ γ rays (Fig. 2) shifted to 10.5 MeV, which is the γ-ray energy for transitions to the first excited state of ^{6}Be. The location of a possible 12.1-MeV γ-ray response curve for ^{6}Be ground-state transitions (halfway up the front edge of such a peak) is indicated.

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TABLE I. Cross section for the $^3\mathrm{He}+{}^3\mathrm{He}\rightarrow{}^6\mathrm{Be}^*+\gamma$ reaction for various ^{3}He laboratory energies. (The bombarding energy was corrected for energy losses in the gas and the foil.)

$E_{^3\mathrm{He}}$ (MeV) (a) Low energy[a]	$E_{^3\mathrm{He}}$ (MeV) (b) High energy[b]	σ_{total} (μb) (a) Low energy[a]	σ_{total} (μb) (b) High energy[b]
0.86		0.40	
1.41		0.77	
	1.4		0.84
1.72		0.97	
	2.20		1.8
	3.01		2.5
	3.83		3.5
	4.62		4.1
	5.66		4.7
	7.72		6.7
	9.77		7.8
	10.78		9.0
	11.80		9.3

[a] 10 ×10-cm crystal.
[b] With tandem accelerator (12.5- ×10-cm crystal).

isotropic within 10%.[2] An angular distribution which was appreciably different would involve different effective absorption distances in the lead and hence different absorption effects.

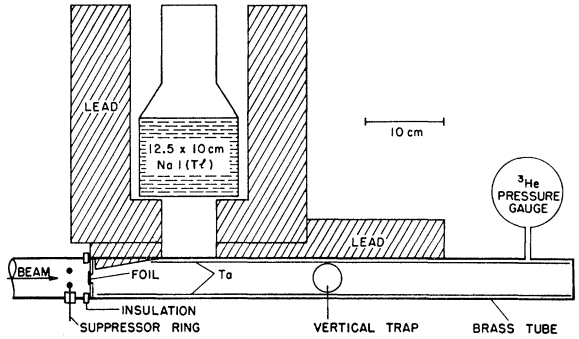

FIG. 4. Experimental arrangement for the higher-energy measurements using the tandem beam.

An absolute efficiency was calculated for the NaI crystal by summing a series of graphical solid-angle determinations taking into account absorption in the tantalum shield and aluminum cup as well as the true absorption in the crystal. The response curve assumed involved an extrapolation to near zero as shown in Fig. 2.

The measured cross sections are tabulated in column (a) of Table I for ^{3}He incident energies of 1.0, 1.5, and 1.8 MeV. These energies have been corrected for the energy loss of the ^{3}He ions in the ^{3}He gas target, before their arrival at the center line of the crystal. Corrections of a few percent have also been made for electronic dead time. The greatest uncertainty comes from the ion-current measurement, especially at the lowest energy. Here, because the beam diameter was appreciably enlarged by small-angle scattering in the ^{3}He gas, the collecting cup barely included it. The power method of measuring beam current is believed to be reliable to 10%, since it has been checked in the same scattering chamber by comparison between observed and known cross sections in the reaction $^3\mathrm{He}(d,p)^4\mathrm{He}$ and the Rutherford elastic scattering of protons on argon. Nevertheless, the current at the lowest-energy point may have an accuracy of only 15%. The absolute crystal efficiency is considered accurate to about 10%. The possibility of a small contribution from neutrons to the counts observed has already been discussed. The remaining factors are all determined to a few percent. Consequently, the values tabulated for 1.41 and 1.72 MeV can be considered accurate to 15%, whereas the 0.86 -MeV value is probably accurate to 20%.

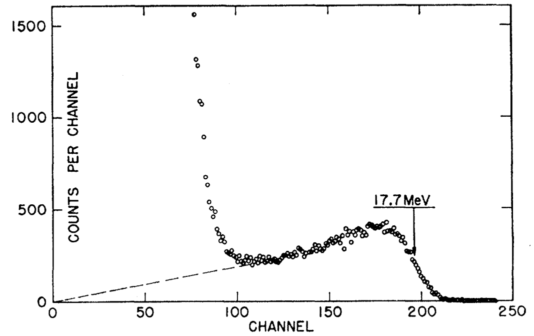

FIG. 5. Response curve for the 12.5-cm-diam by 10-cm-long NaI(Tl) crystal with a 7.3-cm-diam collimator to the $^3\mathrm{He}(d,\gamma)$ γ rays ($E_d=2$ MeV). The dashed line gives the assumed extrapolation to low energies.

HIGH-ENERGY MEASUREMENTS

The higher-energy measurements were made with the ONR-CIT tandem accelerator using neutral ^{3}He injection with either $^3\mathrm{He}^+$ or $^3\mathrm{He}^{++}$ beams. The beam entered a 5-cm-diam by 75-cm-long gas target tube through a nickel foil of 5900 Å thickness (Fig. 4). The ^{3}He gas was introduced into the chamber at a pressure of 80 Torr and kept pure with a liquid-nitrogen-cooled

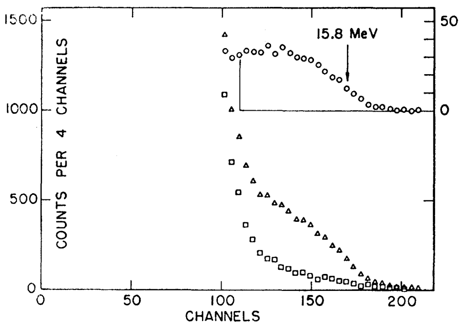

FIG. 6. High-energy portion of the $^3\mathrm{He}+{}^3\mathrm{He}$ γ spectrum at $E_{^3\mathrm{He}}=12$ MeV. The triangles represent the results with 80 Torr of ^{3}He in the chamber, the squares show the "background" with only 10 Torr of ^{3}He. The circles give the difference, which is consistent with a γ ray of 15.8 MeV to the broad first excited state of ^{6}Be.

molecular sieve trap.[7] A 12.5-cm-diam by 10-cm-deep NaI(Tl) crystal was mounted in a thick lead shield with a collimator having a 7.3-cm-diam hole. The front face of the crystal was 10.8 cm from the beam line. The target chamber was lined with tantalum sheet and the crystal was further shielded from the entrance foil as well as the beam stop. Again the NaI crystal was calibrated with the γ rays from the ^{3}He(d,γ) reaction using the same ^{3}He gas. The response curve is shown in Fig. 5 for 2-MeV deuterons. The number of incident ^{3}He ions was measured by integrating the charge delivered to the insulated gas chamber, using an electron suppressor.

The data obtained with ^{3}He^{++} ions of 12 MeV for a target pressure of 80 Torr are shown by triangles in Fig. 6. The squares indicate the background observed with 10 Torr of ^{3}He gas left in the chamber to cool the entrance foil. The difference points are shown as circles and again resemble the calibration curve of Fig. 5. They are interpreted as indicating γ rays associated with transitions to the first excited state of ^{6}Be. The crystal efficiency was again calculated by summing graphic solid-angle determinations taking into account the absorption in the NaI. An extrapolation to low energies as shown in Fig. 5 was used. This extrapolation is different from the one used in the low-energy measurements because of the collimation of the detector. Corrections were made for absorption of the γ rays in the tantalum and brass of the gas tube and in the edges of the lead collimator. Allowance was made for loss of energy of the ^{3}He ions in the entrance foil and in the ^{3}He gas. The results are shown in column (b) of Table I. This set of values is somewhat more accurate than that of the lower energies since the current was more directly measured. The accuracy at the higher energies is limited by the crystal-efficiency calculation, giving values of the cross section which are expected to be accurate to about 10%. The relative accuracy of the points is limited by statistics, etc., to about 5%. The agreement at 1.4 MeV between the two independent and separate sets of measurements supports these estimates of accuracy.

DISCUSSION

The measured cross sections are plotted in Fig. 7. These values are based on the assumptions that the γ-ray emission is isotropic and that the transition to the broad first excited state of ^{6}Be produces a response curve similar to that of the ^{3}He$(d,\gamma)^5$Li reaction. A limit on the transition to the ground state of ^{6}Be can be estimated from the data shown in Fig. 3, giving an upper limit on the ground-state capture cross section of 10^{-2} μb at $E_{^3\mathrm{He}} = 1.4$ MeV.

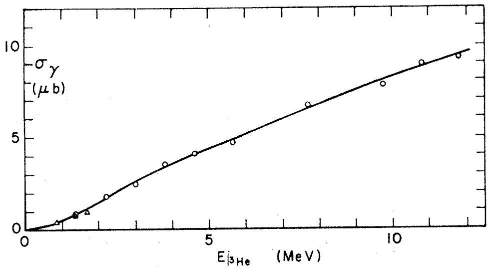

FIG. 7. Total cross section (assuming isotropy) for $^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^6\mathrm{Be}^* + \gamma$ as a function of the ^{3}He laboratory energy. The triangles represent the low-energy measurements and the circles the measurements with the tandem accelerator. The solid line is merely for connecting the points and has no theoretical significance.

When the Coulomb-barrier transmission factor is removed from these cross sections, the resulting S values are relatively small; the minimum value of S is about 0.16-keV b. This is much smaller than the corresponding value[8] of 4 MeV b measured for the ^{3}He(^{3}He,$2p$)^{4}He reaction [at $E_{\mathrm{lab}}(^3\mathrm{He}) = 0.5$ MeV] and indicates that there are no significant astrophysical effects[3] to be anticipated from the capture process.

The predominance of transitions to the first excited state of ^{6}Be can be understood in terms of a direct capture of ^{3}He by ^{3}He in the singlet spin state and with zero orbital angular momentum. This 0^+ configuration would then be forbidden to emit γ rays to the 0^+ ground state of ^{6}Be. Internally produced electron-positron pairs would be allowed but with small probability. However, γ-ray emission for a transition to the 2^+ first excited state (1.66-MeV excitation and 1.2-MeV width)[9] should be allowed with $E2$ multipolarity.

The rise of the cross section above 2 MeV is greater than mere penetration of the Coulomb barrier would suggest. This rise may be associated with the broad $l = 3$ resonance at about 24-MeV excitation in ^{6}Be observed by Bacher and Tombrello[10] in ^{3}He(^{3}He,^{3}He)^{3}He and ^{3}He(^{3}He,$2p$)^{4}He.

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