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The $^{11}B(^3He, n_0)^{13}N$ Reaction

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Abstract

The excitation function from 5·0 to 11·5 MeV and angular distributions at 5·2, 6·5, 8·0, 9·0, 10·0, 11·0 and 12·0 MeV have been obtained for the $^{11}B(^3He, n_0)^{13}N$ reaction. The data were analysed using an incoherent sum of Hauser–Feshbach and DWBA cross sections. Optical model parameters derived from elastic scattering experiments describe the direct reaction component reasonably well.

Introduction

So far little work has been reported on two-particle stripping from ^{11}B although the reactions $^{11}B(^3He, n)^{13}N$ and $^{11}B(^3He, p)^{13}C$ have been used to locate isobaric analogue states. Din and Weil (1966) investigated the $^{11}B(^3He, n_0)^{13}N$ reaction from 2 to 5·6 MeV and analysed the seven angular distributions obtained with the plane wave double-stripping theory of Newns. Honsaker *et al.* (1969) obtained angular distributions at 4·7, 6·1 and 6·49 MeV and carried out their analysis with a mixture of DWBA and Hauser–Feshbach amplitudes. In two other investigations of this reaction (Bryant *et al.* 1964; Brill 1965) cross sections could not be obtained due to the low neutron yield. The 'mirror reaction' $^{11}B(^3He, p)^{13}C$ was investigated by Holmgren *et al.* (1959) from 4·5 to 5·4 MeV and by Marsh and Bilaniuk (1963) from 8 to 11 MeV. Both studies measured excitation functions and angular distributions which were analysed with plane wave direct reaction theories.

The purpose of the present work was to test the applicability of the DWBA procedure for two-nucleon stripping reactions in the 1p shell at low incident energies.

Experimental Procedure

Neutral ^3He beams (0·5 MeV) from a J-type Van de Graaff accelerator were injected into the A.N.U. tandem accelerator to provide $^3He^{2+}$ beams of energies between 5 and 12 MeV. The beam was focused through collimators to produce a small centrally located beam spot on the target which was held in a simple aluminium target chamber at 45° to the beam direction. An electrostatic suppression of -300 V was applied between the target chamber and a nearby isolated section of pipe, so that the target chamber acted as its own Faraday cup.

Both tungsten-backed and foil boron targets were made by bombarding a pellet of compressed 99% isotopically pure ^{11}B powder with electrons from a Varian e-gun. At a temperature of 2500°C and a pressure of 2×10^{-5} torr (2·66 mPa) the

boron was evaporated and collected on a tungsten disc and a clean glass slide, both suspended 7 cm above the pellet. The target thickness was determined by measuring Rutherford scattering of 1·2 MeV protons at 50°, 60° and 70° from the self-supporting target and then comparing the (^{3}He, n) yield from this foil target with the yield from the tungsten-backed target using 8 MeV ^{3}He projectiles. The thickness thus determined was $175 \pm 52\ \mu g\,cm^{-2}$. The large error was caused mainly by the interference between the 1·4 MeV resonance amplitude (Tautfest and Rubin 1956) and the Rutherford scattering amplitude. As a check on this measurement the (^{3}He, n) cross sections from the tungsten-backed target and a tantalum-backed ^{11}B target of known thickness, supplied by Harwell, were compared and found to be consistent to well within the target thickness errors.

Neutrons emitted from the reaction were detected by a 2·5 by 2·5 cm cylindrical stilbene crystal mounted on a Philips 56AVP photomultiplier tube. To reduce the considerable β-ray and low energy γ-ray flux the crystal was surrounded by a 0·95 cm thick lead shield. An Ortec, constant fraction of pulse height, photomultiplier base provided both a linear and a fast negative timing signal to the external electronics. A standard n–γ discrimination circuit (Davis and Din 1972) allowed pulses from only neutrons to enter the ADC. The ADC deadtime did not exceed 2%. The resulting 512-channel spectra were collected and stored in an IBM 1800 computer. The accumulated charge was measured by an Elcor A309B current integrator.

Analysis

The recoil proton spectra consisted of a series of plateaux. To eliminate neutrons from states of higher energy than those being studied here and from the reaction ^{11}B(^{3}He, pn)^{12}C, a bias was set at 1·5 MeV above the energy E_n of the ground-state neutron group.

The spectra were calibrated by fitting a linear least-squares regression line to a plot of the spectra cutoff channel versus E_n for a series of incident energies. The angular distributions were normalized to the excitation function since, as it involved a large energy range, it could be calibrated more accurately.

Little background was apparent in the spectra, partly due to the large Q value (10·182 MeV) of the reaction. On the other hand, this large Q value meant that the neutron energy was high enough to allow an appreciable fraction to escape from the end of the crystal. This effect was corrected for in the analysis using the formula given by Swartz and Owen (1960) for the fraction lost,

$$\Delta N/N_1 = (R_0/L)\{\tfrac{2}{5} - \tfrac{7}{5}(E/E_0)^{5/2}\},$$

where N_1 is the uncorrected number of recoil protons, R_0/L is the ratio of the proton range in stilbene to the crystal length, and E_0 is the maximum recoil proton energy.

The efficiency ε of neutron detection was calculated from the formula

$$\varepsilon(E, H) = (2\pi)^{-1} \int_0^{\theta_2} \{n_H \sigma_H(E)/a(E)\}(1 - e^{-ax}) \sin\theta \, d\theta,$$

where x is the neutron path length through the crystal and

$$a = n_H \sigma_H + n_C \sigma_C.$$

The integration limit θ_2 is the half-angle subtended by the front face of the crystal at the target, and H is the distance from the target to the front face of the crystal. The terms n_H, n_C, σ_H and σ_C are the number of hydrogen and carbon atoms per cm^3 in stilbene and their respective total neutron cross sections (Swartz *et al.* 1957).

The excitation function of the $^{11}B(^3He, n_0)^{13}N$ reaction (Fig. 1) was obtained at 0° to the beam direction at intervals of 100 keV between 5·0 and 11·5 MeV. In the region of overlapping data (5·0–5·6 MeV ^3He energy), there was good agreement with the absolute cross sections obtained by Din and Weil (1966). The cross section decreases with incident energy and in this respect is similar to the cross section for the reaction $^{11}B(^3He, p_0)^{13}C$ (Marsh and Bilaniuk 1963), which is also shown in Fig. 1.

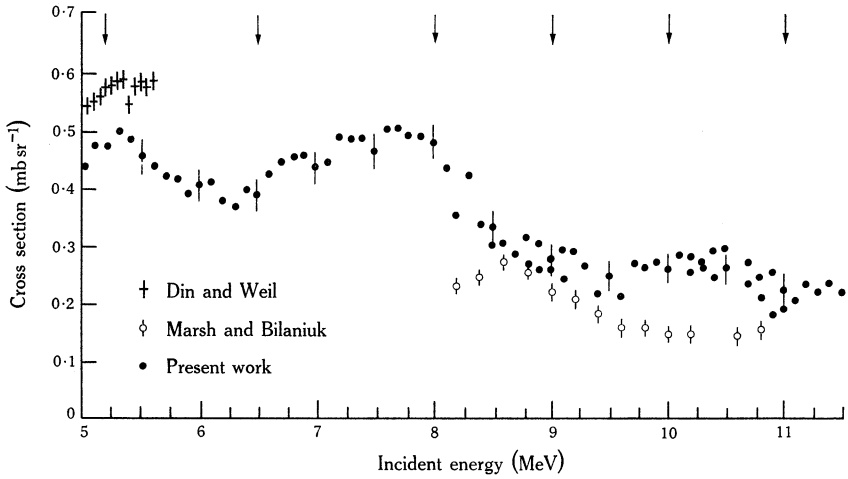

Fig. 1. Excitation function at 0° (lab. system) for the reaction $^{11}B(^3He, n_0)^{13}N$, together with the relative errors at 500 keV intervals. Angular distributions were obtained at the ^3He energies marked by the arrows, and at 12·0 MeV. The energy axis is uncorrected for target thickness (41–78 keV). The excitation functions at 0° for the same reaction from Din and Weil (1966) and at 35° for $^{11}B(^3He, p_0)^{13}C$ from Marsh and Bilaniuk (1963) are included for comparison.

The angular distributions, obtained at the energies marked by arrows in Fig. 1, exhibit more pronounced forward peaking as the incident energy increases, which is consistent with the reaction proceeding principally via a direct process. Both the shape and magnitude of the 5·27 MeV angular distribution measured by Din and Weil (1966) and the shape of the 6·1 MeV angular distribution obtained by Honsaker *et al.* (1969) agree well with the present results. It may be that the difference in the absolute cross section between the results of Honsaker *et al.* and those of Din and Weil and the present work is due to incorrect thickness measurements of either the Harwell and present tungsten-backed targets or that of Honsaker *et al.*

From inspection of the angular distributions (Figs 2 and 3) it appears that both compound nucleus and direct reaction processes contribute to the total cross section. The existence of the former process was supported by values of mean level width to spacing ratios r/D obtained using the formulae of Gilbert and Cameron (1965) and Ericson and Mayer-Kuckuk (1966, their Fig. 7). At energies of 5·0 and 12·0 MeV

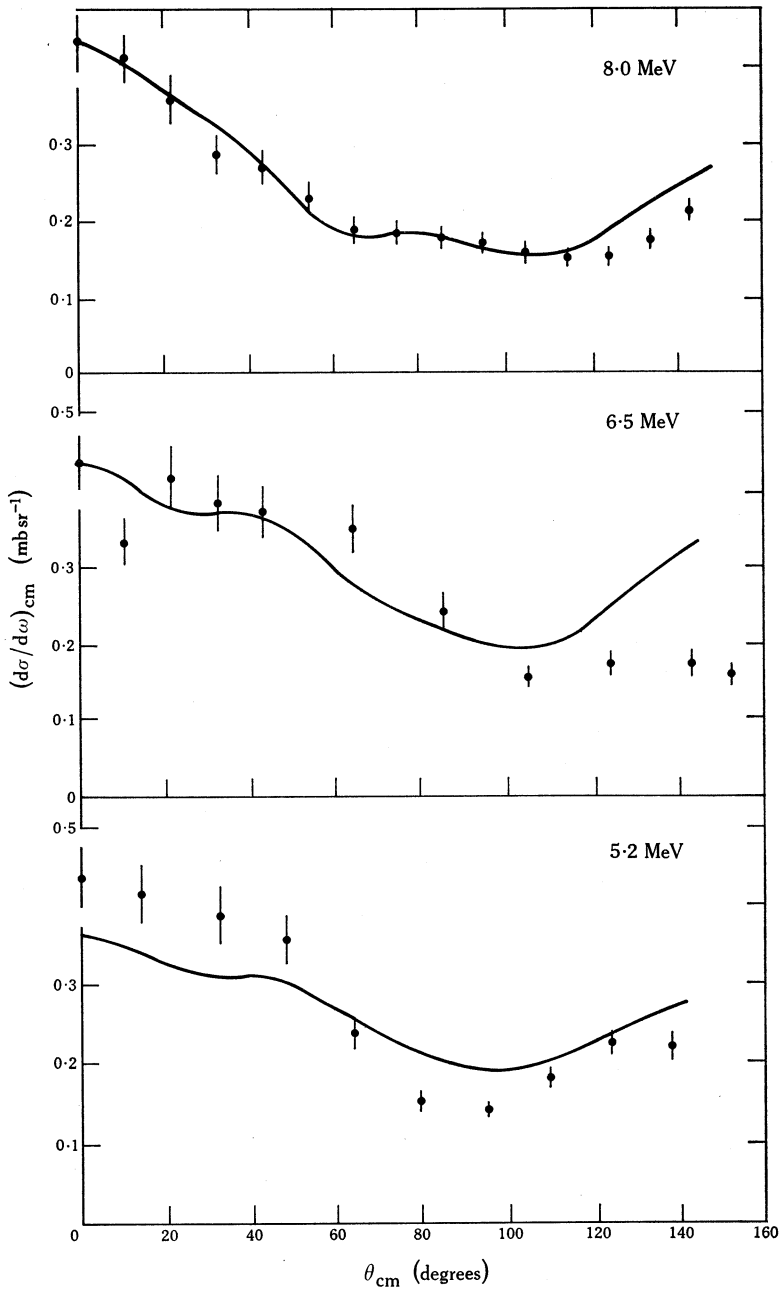

Fig. 2. Angular distributions at 5·2, 6·5 and 8·0 MeV for the $^{11}B(^3He, n_0)^{13}N$ reaction fitted with curves which are mixtures of Hauser–Feshbach and DWBA cross sections. The reduction factor R used at each energy is given in Table 2. At lower energies the angular distributions exhibit a symmetry about 90°, indicating the existence of statistical compound nucleus effects. There is good agreement between the 5·2 MeV data shown here and the 5·27 MeV results of Din and Weil (1966).

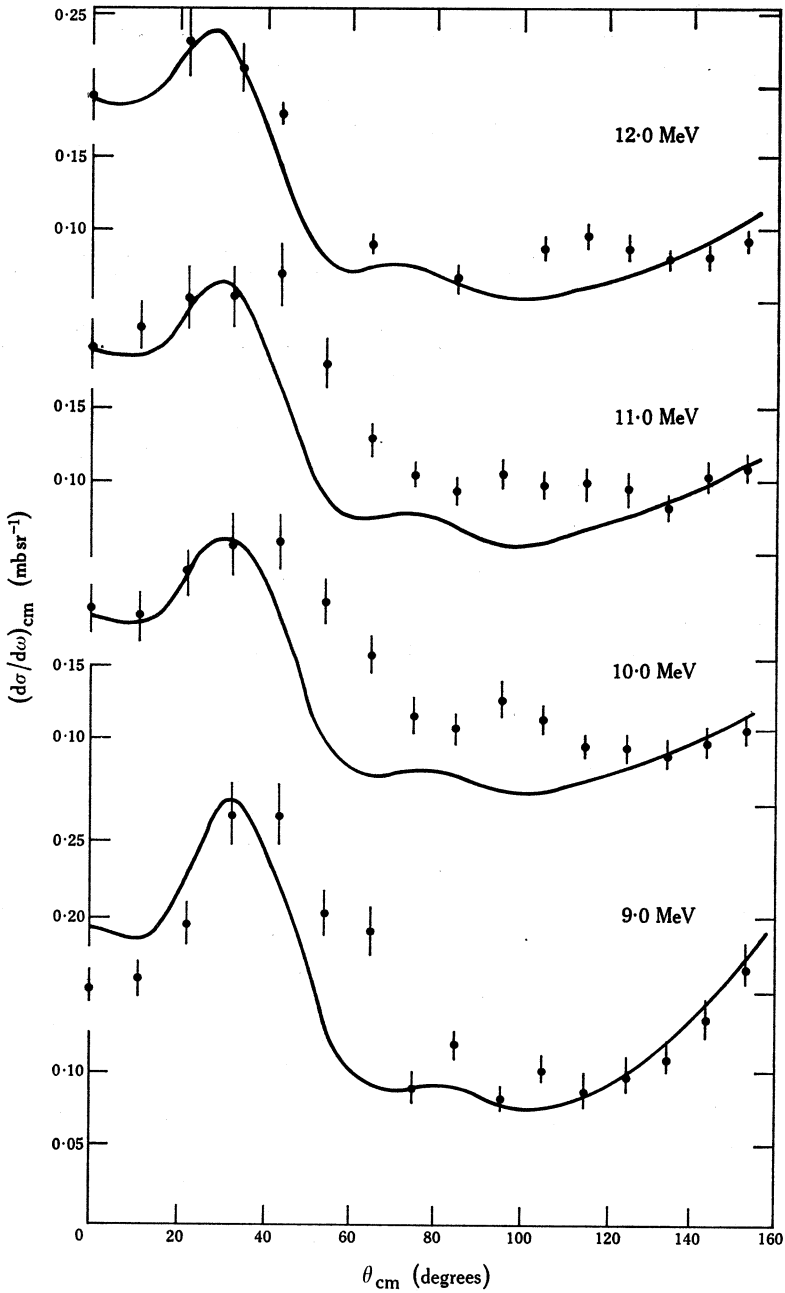

Fig. 3. Angular distributions at 9·0, 10·0, 11·0 and 12·0 MeV for the $^{11}B(^3He, n_0)^{13}N$ reaction fitted with curves which are mixtures of Hauser–Feshbach and DWBA cross sections. The reduction factor R used at each energy is given in Table 2. The allowed transferred c.m. angular momentum of the protons was uniquely $l = 2$ and this assignment was supported by the fits.

this ratio was 10·3 and 23·7 respectively. In the analysis the compound nucleus and direct reaction cross sections were added incoherently.

The statistical compound nucleus effects were estimated from the Hauser–Feshbach theory using the program HAUSER written by Dallimore (1970). Sixty-eight levels of known spin and parity of the final nuclei in the proton, neutron, deuteron and α-particle exit channels and up to 57 levels calculated using the level density formulae of Gilbert and Cameron (1965) were included in the calculations for each angular distribution.

Table 1. Optical model parameters used in Hauser–Feshbach calculation

Exit channel	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_0' (fm)	a' (fm)	V_{so}[A] (MeV)	Reference[B]
$^{13}C+p$	50·5	1·25	0·65	7·5	1·25	0·70	5·5	1
$^{13}N+n$	45·0	1·32	0·66	9·0	1·26	0·47	—	1
$^{12}C+d$	130·0	0·90	0·90	6·88	1·899	0·562	—	2
$^{11}B+^{3}He$	194·6	1·20	0·668	13·0	1·20	0·894	5·2	3
$^{10}B+\alpha$	125·0	1·87	0·50	3·0	1·87	0·30	—	4

[A] The spin–orbit potential had the same geometry as the real central component.
[B] References: 1, Hodgson (1967); 2, Satchler (1966); 3, Park *et al.* (1969); 4, Carter *et al.* (1964).

The optical model parameters for the four exit channels and for the inelastic scattering channel were obtained from the elastic scattering experiments referenced in Table 1. For the neutron, proton and ^{3}He particles, the parameters were calculated from the energy-dependent formulae given in these references for an energy of 10 MeV, whilst for the deuteron and α particles the reported parameter sets varied so much with the incident energy that no reliable energy dependence could be deduced. In these two cases the results obtained at 10 MeV were used.

It was found to be unnecessary to vary the exit-channel optical model parameters with the incident particle energy, as the calculated compound nucleus cross section was insensitive to the parameters used: a change of 10% in all but the ground state neutron well depths caused a variation in the absolute cross section of only 0·4% at 0°. Table 1 shows the potential parameter sets used for each of the channels, the form of the potential being

$$U(r) = V_C - Vg(r, r_0, a) - ia'Wf(r, r_0', a') + lsV_{so}g(r, r_0, a).$$

The functions $g(r, r_0, a)$ and $f(r, r_0', a')$ are the Saxon–Woods and differentiated Saxon–Woods potentials respectively, while V_C is the Coulomb potential for a uniformly charged sphere of radius $R_C = r_C A^{\frac{1}{3}}$, with A the mass number of the nucleus and $r_C = 1{\cdot}25$ fm. The gaussian surface absorption used by Park *et al.* (1969) for the ^{3}He channel was converted to an equivalent differential Saxon–Woods function.

The direct reaction component was estimated using the double-stripping DWBA code DWUCK written by Kunz (1969). Preliminary calculations with this program showed that the absolute value of the predicted DWBA cross sections was very sensitive to the description of the two stripped protons. For the subsequent calculations the bound state potential $r_V = 1{\cdot}25$ fm, $a_V = 0{\cdot}65$ fm was used with the potential depth adjusted to give the correct binding energy for each transferred proton.

A Thomas spin–orbit potential with $\lambda = 25$ was included, and $r_C = 1{\cdot}25$ fm as above. The bound state wavefunction was assumed to be a mixture of $1p_{1/2}$ and $1p_{3/2}$ configurations with the spectroscopic amplitudes represented by the two-particle fractional parentage coefficients (Cohen and Kurath 1967).

For the free-particle channels, ^{3}He optical model parameter sets from a number of sources (Squier *et al.* 1968; Park *et al.* 1969; Gray *et al.* 1970; Adelberger and McDonald 1970; Bohne *et al.* 1970) were tried in conjunction with various neutron parameter sets (Hodgson 1966; Adelberger and McDonald 1970; Bohne *et al.* 1970) to obtain preliminary fits to the 10 MeV angular distributions. Park (1968) and Park *et al.* (1969) have conducted a series of elastic scattering experiments on light nuclei and showed that the parameter sets providing the optimum fits to the data vary considerably, even for adjacent nuclei. Hence it was important to initially establish the parameter sets that gave the best description of the $^{11}B+^3He$ and $^{13}N+n$ channels in the present work.

From the parameter sets investigated, the ^{3}He optical model parameters obtained by Park *et al.* (1969) for the elastic scattering of ^{3}He particles from ^{11}B, and the neutron parameters used by Adelberger and McDonald (1970) for the $^{12}C(^3He, n)^{14}O$ reaction gave the best fit to the data. The ^{3}He parameter set was the same as that used for the compound nucleus calculations.

Since the real central potential depth for the ^{3}He particle is believed to be about three times that for a single-nucleon potential (Rook 1965), this term was adjusted along the Vr^n ($n = 1{\cdot}5$) curve (Cage *et al.* 1972) from that used in the Hauser–Feshbach calculations. All parameters were varied by $\pm 10\%$ to determine their effects on the calculated differential cross section. In general, it was found to be necessary to vary only the central well depths of the ^{3}He particles and the neutrons to achieve fits to the angular distributions from one incident energy to another, although variations of absorptive potentials were sometimes necessary. Table 2 lists the parameter sets used for each angular distribution together with the corresponding values of the volume integral J and the mean square potential radius $\langle r^2\rangle_V$ (Greenlees *et al.* 1968). The potential was taken to have the form

$$U(r) = V_C - Vg(r, r_0, a) - ia'Wf(r, r_0', a'),$$

where the terms are as defined above.

Little is known about the behaviour of the potential volume integrals for light target nuclei. It has been found that, both for single-nucleon and for ^{3}He and t projectiles, J increases with decreasing mass (Abul-Magd and El-Nadi 1966; Nakanishi *et al.* 1970; Urone *et al.* 1971). The values obtained here for neutron potential volume integrals seem to be in general agreement with the values of Holmqvist (1968). For ^{3}He particles, the value of J appears to be higher than that used normally so that the present parameter sets probably belong to a different family than those commonly selected for mass-3 particles.

The neutron parameter sets imply a mean square matter radius for ^{13}N of $6{\cdot}11$ fm^2, which is close to the value of $5{\cdot}38 \pm 0{\cdot}67$ fm^2 found by Wilkinson and Mafethe (1966). Similarly, the optical model mean square radius $\langle r^2\rangle_V$ for the $^{11}B+^3He$ channel satisfies the approximate formula

$$\langle r^2\rangle_V \approx \langle r^2\rangle_m + \langle r^2\rangle_d + \langle r^2\rangle_{^3He},$$

where $\langle r^2\rangle_m = 5{\cdot}38$ fm^2 (Wilkinson and Mafethe 1966), $\langle r^2\rangle_d = 2{\cdot}25$ fm^2 (Greenlees *et al.* 1968) and $\langle r^2\rangle_{^3He} = 3{\cdot}88$ fm^2 (Glendenning 1965).

Table 2 also lists the reduction factors R used in the Hauser–Feshbach calculations and the normalization coefficients N_0, as defined by Broglia *et al.* (1972), which were obtained with the calculated angular distributions normalized to the forward peak of the experimental distribution. The reduction factor measures the fraction of the incident flux penetrating into the nuclear interior and, as expected, this fraction decreases as the incident bombarding energy increases. The normalization constant N_0 is introduced to absorb unknown constants in the double-stripping calculations, and is best estimated when the reaction mechanism is clearly direct. Thus for the lowest three incident energies the calculated values of N_0 vary considerably because of uncertainties in the exact fraction of direct reaction. For the four highest energies, where approximately 90% of the reaction proceeds via the stripping mechanism, the average value of N_0 is 20·0, which is similar to the value obtained by Broglia *et al.* (1972) for the (t, p) reaction and by Georgopulos *et al.* (1972) for the $^{12}C(He^3, n)^{14}O$ reaction (after adjusting for the latter authors' different definition of the normalization coefficient).

Table 2. Parameter sets used for angular distributions

The geometrical parameters were: for ^{3}He particles, $r_0 = 1{\cdot}42$ fm, $a = 0{\cdot}66$ fm, $r_0' = 1{\cdot}30$ fm, $a' = 1{\cdot}90$ fm (gaussian absorption) with the corresponding mean square real radius $\langle r^2\rangle_V = 12{\cdot}0$ fm^2; for neutrons, $r_0 = 1{\cdot}20$ fm, $a = 0{\cdot}51$ fm, $r_0' = 1{\cdot}20$ fm, $a' = 0{\cdot}30$ fm (Woods–Saxon derivative absorption) with $\langle r^2\rangle_V = 8{\cdot}37$ fm^2

^{3}He energy (MeV)	^{3}He particles V (MeV)	W (MeV)	J (MeV fm^3)	Neutrons V (MeV)	W (MeV)	J (MeV fm^3)	Norm. constant N_0	Red. factor R
5·2	170·0	12·0	972	55	12·0	525	45·1	0·22
6·5	174·0	12·0	1003	55	12·0	525	18·6	0·20
8·0	160·0	10·5	922	55	10·0	525	9·7	0·20
9·0	155·0	17·5	894	66	20·0	630	21·0	0·12
10·0	150·0	17·5	865	66	20·0	630	22·8	0·10
11·0	145·0	17·5	836	66	20·0	630	18·4	0·10
12·0	150·0	17·5	865	66	20·0	630	17·9	0·10

Above 8 MeV incident energy the forward peak due to the uniquely allowed $l = 2$ angular momentum transfer of the centre of mass of the two stripped protons becomes apparent. At these energies the fraction of the reaction mechanism proceeding via the compound nucleus state is reduced to one-half, from 0·20 to 0·10. For each of the four high energy angular distributions, the forward peak of the experimental angular distribution is consistently broader than that of the calculated shape. Otherwise the theoretical fits are in reasonable agreement with the experimental data.

Conclusions

This systematic study of the $^{11}B(^3He, n)^{13}N$ reaction has shown that over the incident energy range 5·0–12·0 MeV the contribution to the reaction mechanism from the compound nucleus process decreases from 22% to 10%. Reasonable agreement has been reached between the experimental and theoretical angular distributions by employing an incoherent mixture of differential cross sections from

the Hauser–Feshbach and DWBA theories. The experimental value of the normalization constant N_0 for the $(^3He, n)$ double stripping process is in good agreement with previous results. There is a similarity in the yield curves for the $^{11}B(He^3, n_0)^{13}N$ reaction and its analogue $^{11}B(^3He, p_0)^{13}C$, which is not surprising in view of the mirror final states of these two reactions.

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