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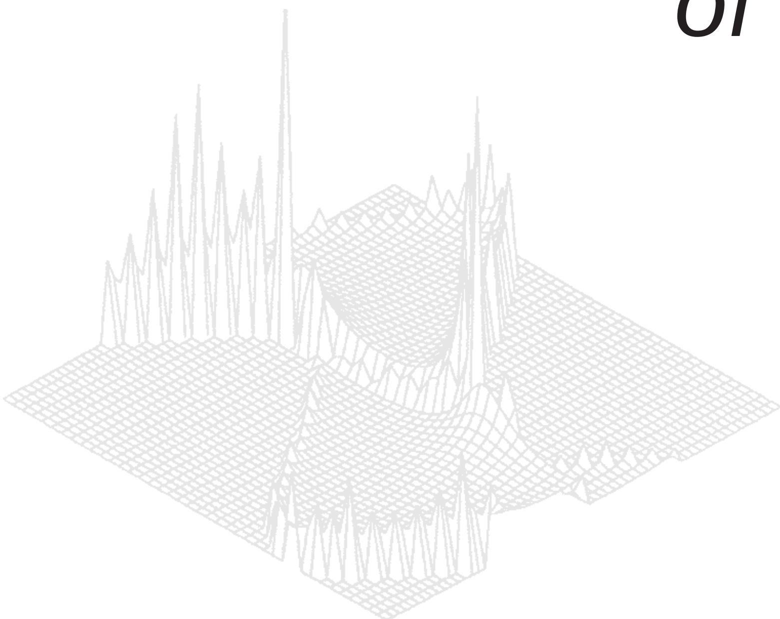

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Deuteron Stripping Cross Section from ^{13}C at Deuteron Energies below 350 keV

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Abstract

Cross sections for deuteron stripping from the ^{13}C nucleus have been measured for 200–350 keV deuterons. The excitation functions of the ^{13}C(d, p)^{14}C reaction were measured at 30°, 66°, 110°, 128°, 146° and 164°, while the angular distributions of the ^{13}C(d, p)^{14}C reaction were measured at deuteron energies of 200, 230, 250, 270, 290, 310, 335 and 350 keV. The excitation functions of the ^{13}C(d, p)^{14}C reaction show a smooth variation of the cross section with energy. The angular distributions of the ^{13}C(d, p)^{14}C reaction are highly asymmetric and are forward-peaked. The asymmetric shape of the angular distribution of the ^{13}C(d, p)^{14}C reaction indicates a dominating contribution from the direct reaction in this channel. The trend in the angular distributions of the ^{13}C(d, p)^{14}C reaction is consistent with published results at higher deuteron energies (Putt 1971).

1. Introduction

Deuteron stripping reactions have been extensively used to study nuclear reactions and structure for a long time. The angular momentum transfer in the transfer reaction is extracted from the angular distribution of the cross section (Putt 1971; Gomes *et al.* 1969). If the stripping reaction is studied with a polarised deuteron beam, the analysing power of the reaction shows a strong dependence on the total angular momentum j transferred in the nuclear reaction. The analysing powers of the nuclear states with $j = l + \frac{1}{2}$ and $j = l - \frac{1}{2}$ have the same magnitude but opposite signs (Yule and Haeberli 1968). Furthermore, the tensor analysing power of the transfer reaction is very sensitive to the tensor component in the nuclear potential of the particle wavefunction. Therefore tensor analysing power of the (d, p) reaction has been used to extract the D-state contribution in the deuteron wavefunction (Brown *et al.* 1971; Knutson *et al.* 1973; Das *et al.* 1992). Generally the nuclear wavefunctions are further used to calculate electromagnetic form factors, structure functions and spectra in electronuclear (*e, enp*) studies (Schiavilla 1990; Schiavilla *et al.* 1990). Mostly these measurements have been carried out just below Coulomb barrier energies because then the nuclear wavefunction of the incident particle is not affected by the nuclear potential of the target nucleus. It is interesting to investigate whether this assumption is still valid at extremely low energies, i.e. in the keV

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energy range. Therefore a research program has been initiated at the 350 keV accelerator laboratory of the Center for Applied Physical Sciences (CAPS), King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, in which nuclear transfer reactions are studied in the keV energy range using polarised and unpolarised beams. Cross section measurements of transfer reactions using keV deuterons have already been started, and excitation functions and angular distributions of the ^{12}C(d, p) reaction (Naqvi *et al.* 1992) and ^{13}C(d, $\alpha_{0,1}$)^{11}B reactions (Naqvi *et al.* 1998, present issue p.903) have been measured at deuteron energies below 350 keV. Now cross sections of the ^{13}C(d, p)^{14}C reaction have been measured for 180–350 keV deuteron energies. The ^{13}C(d, p)^{14}C cross section had already been measured at 410–810 keV deuteron energies by Putt (1971), who also reported DWBA calculations made using the zero-range approximation. However, there is now a need to repeat these cross section calculations using an improved DWBA technique that incorporates the finite-range approximation and includes D-state contributions in the nuclear wavefunctions (Crosson *et al.* 1992, 1993; Kozlowska 1994). We have therefore obtained ^{13}C(d, p)^{14}C cross section data over the 200–350 keV range in deuteron energy for later comparison with such improved DWBA calculations. Results of excitation function and angular distribution measurements of the ^{13}C(d, p)^{14}C reaction at 200–350 keV deuteron energies are presented in this paper.

2. Experimental

The cross section data for the ^{13}C(d, p)^{14}C reaction were acquired along with cross section data for the ^{13}C(d, $\alpha_{0,1}$)^{11}B reactions. The experimental setup and procedure used to measure the cross section of the ^{13}C(d, $\alpha_{0,1}$)^{11}B reactions are given in detail in the accompanying paper (Naqvi *et al.* 1998). The excitation function of the ^{13}C(d, p)^{14}C reaction was measured at 30°, 66°, 110°, 128°, 146° and 164° for 200–350 keV deuterons with an energy interval of 10 keV. The angular distribution of the ^{13}C(d, p)^{14}C reaction was measured at 8 deuteron energies, namely 200, 230, 250, 270, 290, 310, 335 and 350 keV, for 14 angles between 30° and 164°. A typical pulse height spectrum exhibiting proton, triton and α-particle peaks from ^{13}C(d, p), ^{13}C(d, t) and ^{13}C(d, $\alpha_{0,1}$)^{11}B reactions is shown in Fig. 1 in the accompanying paper (see p. 905). At all angles the proton peak from the ^{13}C(d, p)^{14}C reaction is totally resolved.

The statistical uncertainty in the excitation functions at 110°, 128°, 146° and 164° was 4–6% while in angular distributions it was 2–24%. The systematic uncertainties in cross section data due to charge integration, target thickness and the finite angular resolution were estimated to be 4–5%.

3. Results and Discussion

(3a) Excitation Function and Angular Distributions of the ^{13}C(d, p)^{14}C Reaction

The excitation function of the ^{13}C(d, p)^{14}C reaction was measured at 30°, 66°, 110°, 128°, 146° and 164°. Fig. 1 shows the excitation functions at 30°, 66°, 110°, 146° and 164°. For 200–350 keV deuteron energies, the cross section at 110° is almost equal to that at 128°, and the excitation function curves at these angles practically overlap. Therefore only the excitation curve at 110° is

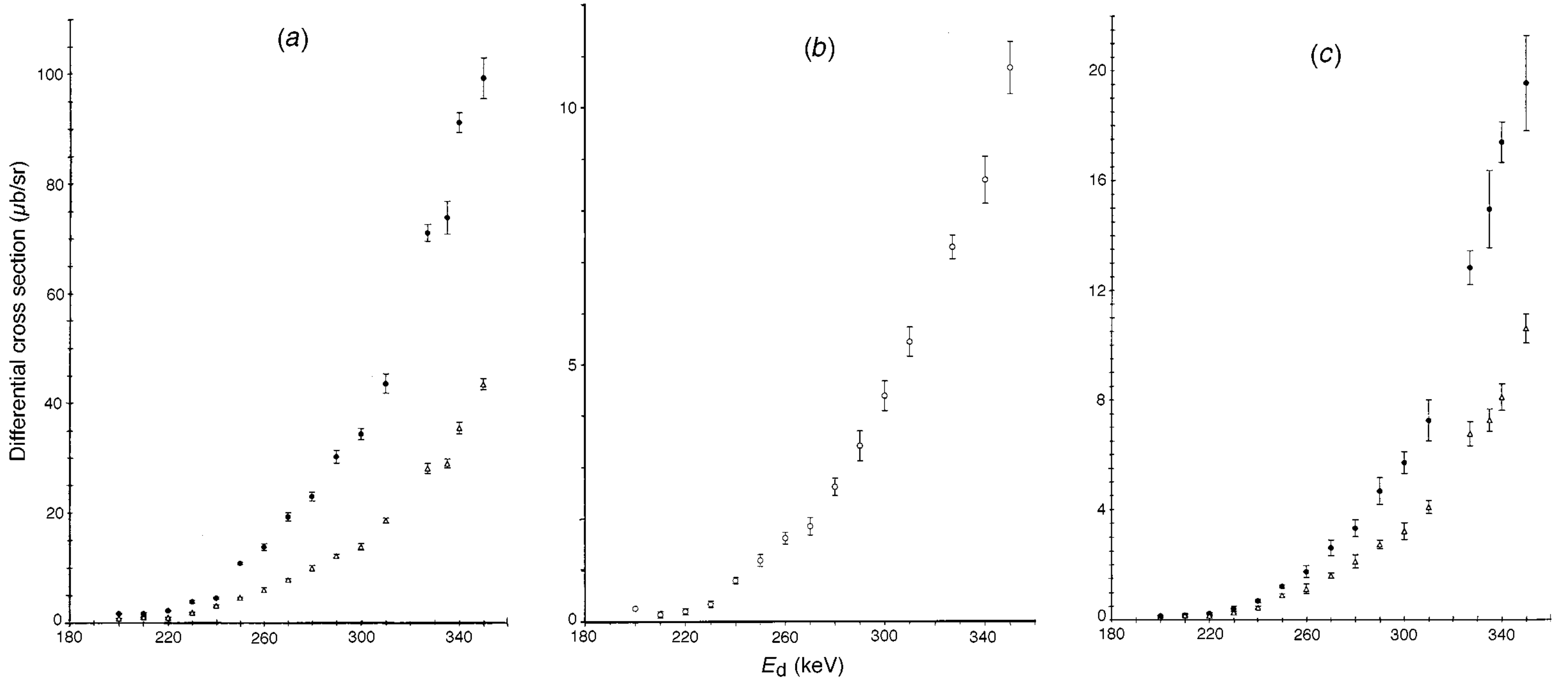

Fig. 1. Excitation function of the $^{13}C(d, p)^{14}C$ reaction at: (*a*) 30° (circles) and 66° (triangles); (*b*) 110°; and (*c*) 146° (triangles) and 164° (circles).

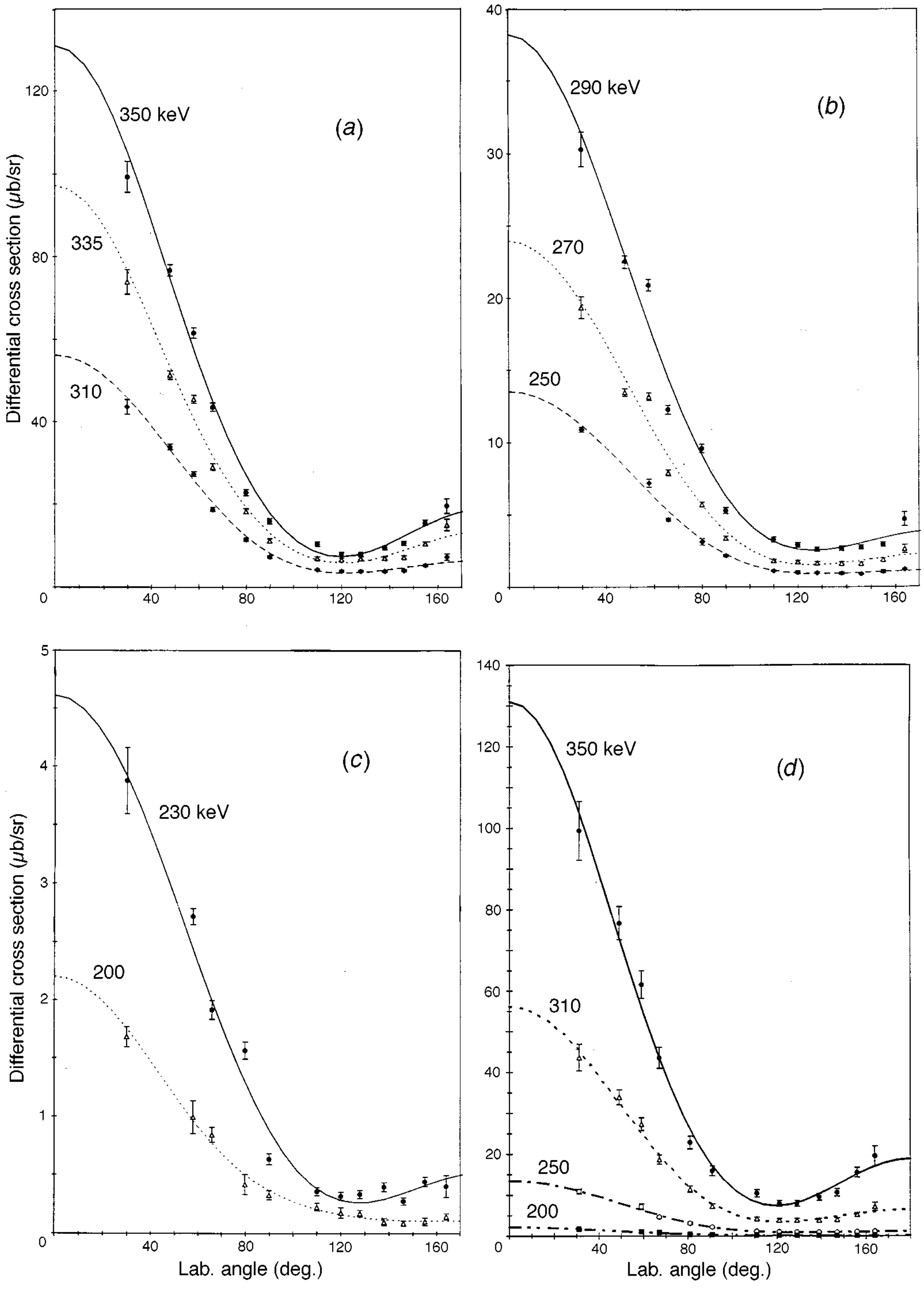

Fig. 2. Angular distribution of the ^{13}C(d, p)^{14}C reaction for: (*a*) 310, 335 and 350 keV deuterons; (*b*) 250, 270 and 290 keV deuterons; (*c*) 200 and 230 keV deuterons; and (*d*) 200, 250, 310 and 350 keV deuterons. The curves are Legendre polynomial fits.

shown in Fig. 1*b*. The excitation functions are structureless and the cross section increases smoothly with deuteron energy, indicating non-resonant behaviour of the reaction mechanism. The cross section at 30° is larger than that at 66°. This indicates a forward-peaking trend of the angular distribution. The cross section at 164° is larger than that at 146°, indicating that the cross section increases over the 146–164° range. The forward-peaking trend in the angular distributions of the ^{13}C(d, p)^{14}C reaction over the 200–350 keV deuteron energy range is shown in Fig. 2. The curves are Legendre polynomial fits. The angular distributions are asymmetric and forward-peaked, with the minimum cross section occurring at around 120°. Above 120° the cross section increases again.

The cross section decreases with deuteron energy, and the angular distribution retains its forward-peaked shape. The cross section at 30° is always about 10 times larger than that at 120°. At backward angles the cross section in the 155–165° range decreases faster with energy than that around 120°. The forward-peaked shape of the angular distributions, as shown in Fig. 2, clearly indicates a dominant contribution from the direct reaction channel over this energy range. For comparison, angular distributions of the ^{13}C(d, p)^{14}C reaction at deuteron energies of 200, 250, 310 and 350 keV are plotted together in Fig. 2*d*. Compared to the forward-peaked angular distribution at 350 keV, which has a maximum cross section of 130 μb at 0°, the angular distribution at 200 keV is practically flat, with a maximum cross section of 3 μb at 0°. In between these energies the cross section at 0° decreases accordingly.

Comparison of the angular distribution data for the ^{13}C(d, p)^{14}C reaction at 200–350 keV with those at 410–810 keV (Putt 1971) reveals almost identical features in the shapes of the angular distributions. Putt observed an increasing trend in the cross section above 120° over the 510–810 keV deuteron energy range, but at 410 keV the cross section beyond 120° levelled off. However, in our data we observe an increasing trend in the cross section beyond 120° for 290–350 keV deuteron energies.

Table 1. Total cross section of the ^{13}C(d, p)^{14}C reaction

Deuteron lab. energy (keV)	Cross section (μb)
200	8±4
230	18±5
250	50±9
270	87±10
290	140±14
310	200±16
335	328±21
350	453±25

(3b) Total Cross Section of the ^{13}C(d, p)^{14}C Reaction

Experimental total cross sections for the ^{13}C(d, p)^{14}C reaction were calculated from Legendre polynomial fits to the angular distribution data and are listed in Table 1. Also given are uncertainties in the total cross section, which were calculated from the uncertainty in a_0, i.e. in the $l = 0$ term of the Legendre polynomial fit. Fig. 3 shows the total cross section of the $^{13}C(d, p)^{14}C$ reaction as a function of deuteron energy. For the sake of comparison, total cross section data for the $^{13}C(d, p)^{14}C$ reaction at 410–810 keV, taken from Putt (1971), are also plotted. The cross section data obtained in the present study follow the smooth trend in Putt's data.

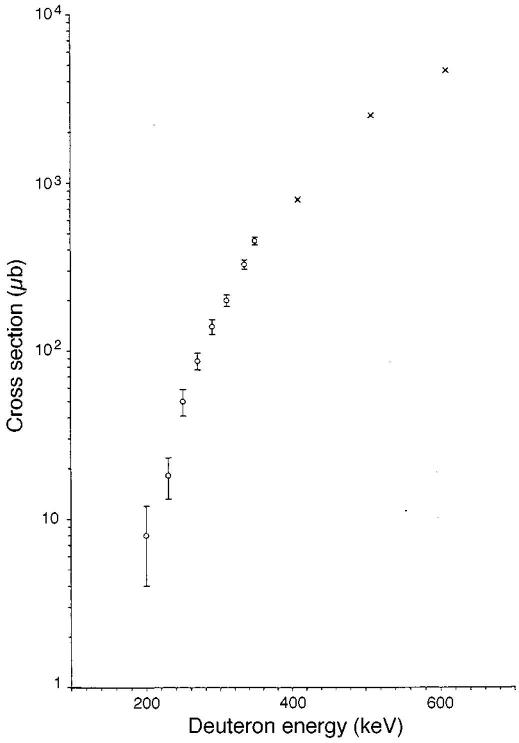

Fig. 3. Total cross section for the $^{13}C(d, p)^{14}C$ reaction for 200–350 keV deuteron energies (circles), together with the data from Putt (1971) (crosses).

(3c) Comparison of Deuteron Stripping Cross Sections from Carbon Isotopes at Deuteron Energies below 350 keV

It may be worthwhile to compare cross sections for the $^{13}C(d, p)^{14}C$ and $^{12}C(d, p)^{13}C$ reactions to obtain a better understanding of deuteron stripping from carbon isotopes. Fig. 4 shows the angular distribution of the $^{12}C(d, p)^{13}C$ reaction at deuteron energies of 200, 220, 250, 280 and 300 keV (data are taken from Naqvi *et al.* 1992). Clear differences are observable between the $^{13}C(d, p)^{14}C$ and $^{12}C(d, p)^{13}C$ differential cross sections, both in their magnitudes as well as in the shapes of the angular distributions. The $^{13}C(d, p)^{14}C$ angular distribution is forward-peaked while that for the $^{12}C(d, p)^{13}C$ reaction is backward peaked. At extremely low energies the $^{12}C(d, p)^{13}C$ differential cross section has a characteristic backward-peak but, with increasing deuteron energies, the cross section has an additional increasing contribution coming in at lower angles.

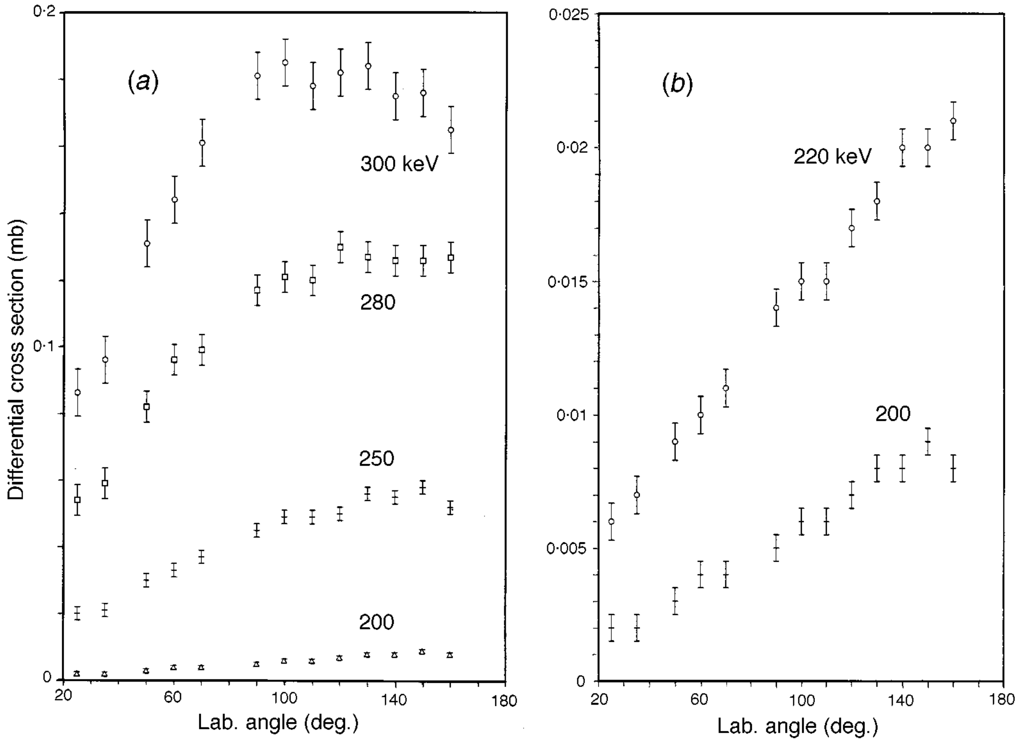

Fig. 4. Angular distribution of the $^{13}C(d, p)^{14}C$ reaction for (*a*) 200, 250, 280 and 300 keV deuteron energies and (*b*) 200 and 220 keV deuteron energies (from Naqvi *et al.* 1992).

This may be due to some resonance contribution in the $^{12}C(d, p)^{13}C$ reaction at those energies. The forward and backward peaking of the (d, p) reaction strongly depends upon the kinetic energy of the outgoing proton and on the Coulomb barrier energy. In the case of the $^{12}C(d, p)^{13}C$ reaction, the kinetic energy of the proton (1·8 MeV) is less than the Coulomb barrier (2 MeV), and the outgoing proton is emitted preferentially in a backward direction. In the case of the $^{12}C(d, p)^{13}C$ reaction, the kinetic energy of the proton (6·0 MeV) is much larger than the Coulomb barrier (2 MeV), and the outgoing proton is emitted in a forward direction after overcoming the Coulomb force.

Deuteron stripping from ^{12}C has a larger cross section than that from the ^{13}C isotope. The maximum value of the cross section for angular distributions of the $^{12}C(d, p)^{13}C$ reaction at 200–300 keV deuteron energies is about four times larger than those of the $^{13}C(d, p)^{14}C$ reaction at the same energy. This larger cross section of $^{12}C(d, p)^{13}C$ is expected because the ^{12}C+d system proceeds through only one (d, p) reaction channel, whereas the ^{13}C+d system proceeds through four different reaction channels, namely the (d, p), (d, $\alpha_{0,1}$) and (d, t) reactions, thereby reducing the effective flux available for the (d, p) channel in the ^{13}C+d system. Furthermore, the unpaired nucleon in the ^{13}C nucleus increases the probability of formation of a few-nucleon system in the ^{13}C+d system. The cross section of the (d, α_0) reaction is even comparable with the (d, p) reaction cross section in the ^{13}C+d system (Naqvi *et al.*). These types of reactions in the ^{12}C+d system are favoured only at very high deuteron energies, where the cross section is large for these reactions.

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