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1953

Physica XIX
1133–1139

ANGULAR DISTRIBUTIONS AND YIELD OF THE $^{13}C(d, p)^{14}C$ REACTION

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Synopsis

Angular distributions have been measured of long-range protons from the $^{13}C(d, p)^{14}C$ reaction at six deuteron energies between 0.30 MeV and 0.65 MeV. Protons were detected using nuclear emulsions. The target consisted of a thin layer of almost pure ^{13}C on a thin aluminium backing.

The experimental angular distributions agree surprisingly well with Butler's theory (for $l_n = 1$), which seems to indicate that even at these low deuteron energies the $^{13}C(d, p)^{14}C$ reaction proceeds predominantly by stripping.

The yield in the forward direction ($\theta = 0°$) also was measured for deuteron energies between 0.25 MeV and 0.675 MeV at 25 keV intervals and for $\theta = 120°$ between 0.50 MeV and 0.70 MeV at 10 keV intervals. Use was made of a thin crystal (NaI) scintillation spectrometer. Indications were found of a resonance at about 0.63 MeV.

§ 1. *Introduction.* In a preceding paper [1]) measurements have been described of the angular distribution of long-range protons from the $^{13}C(d, p)^{14}C$ reaction at a deuteron energy of 0.37 MeV using a relatively thick and inhomogeneous barium carbonate target enriched in ^{13}C content. For measurements of absolute differential cross sections this target was unsuitable.

Thin almost pure ^{13}C targets prepared by magnetic separation have now been obtained from A.E.R.E., Harwell, England *). By the aid of this new target it has now become possible to measure angular distributions and yield of the $^{13}C(d, p)^{14}C$ reaction over a wide range of deuteron energies (0.25 MeV–0.70 MeV).

In § 2 a description is given of the angular distribution measurements where the nuclear emulsion technique was used. The yield

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*) We wish to thank Dr R. H. V. M. Dawton for the preparation of these targets.

measurements with a thin crystal (NaI) scintillation spectrometer are given in § 3, and § 4 contains a discussion of the results obtained.

§ 2. *Angular distribution measurements.* Details of the experimental arrangement for the measurement of angular distributions by means of the nuclear emulsion technique have been given in previous papers [2] [3] [4].

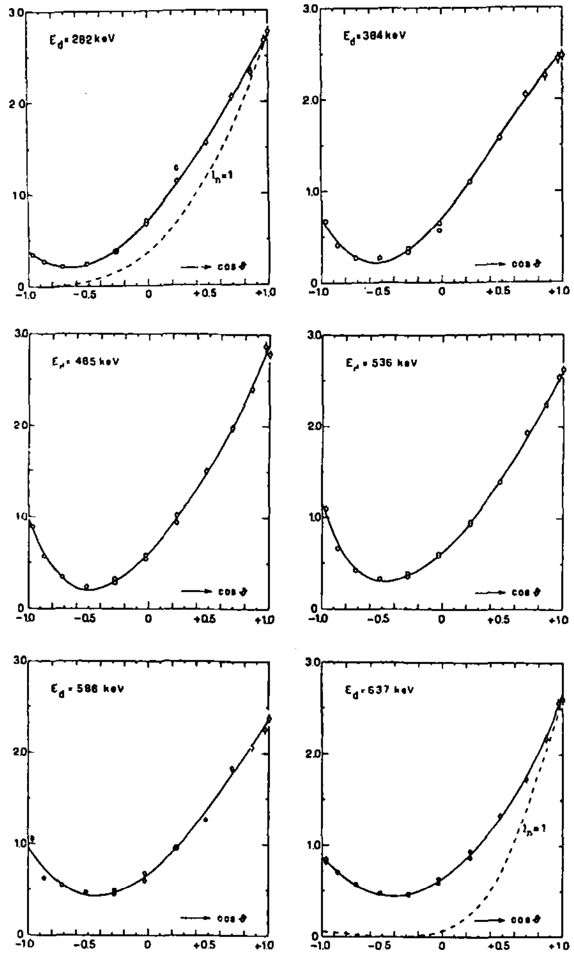

Fig. 1. Angular distributions of long-range protons from the $^{13}C(d, p)^{14}C$ reaction in the center-of-mass system. Dashed curves at E_d = 0.282 MeV and 0.637 MeV have been computed from stripping theory for $l_n = 1$ in the form given by Bhatia e.a. using $R = 7.4 \times 10^{-13}$ cm.

The target consisted of a ^{13}C layer of 40 μg/cm^2 on a 7 μ aluminium backing. The purity of this target was not stated but the ^{12}C content was certainly low enough not to introduce serious systematic errors in the absolute yield measurements. Some proton tracks were found with ranges (well different from that of ^{13}C(d, p)^{14}C protons) corresponding to proton groups of the ^{10}B(d, p)^{11}B reaction indicating that the target contained about 2.5% of ^{10}B.

Rather thick aluminium foils (100 μ) have been placed in the present investigation between target and nuclear emulsions. These foils stopped almost completely all protons from contaminant reactions thus simplifying considerably the scanning of the emulsions for the energetic protons from the ^{13}C(d, p)^{14}C reaction. Bombardments were performed at deuteron energies of 0.3, 0.4, 0.5, 0.55, 0.6 and 0.65 MeV. Effective deuteron energies are obtained from these figures by subtracting half the energy loss of deuterons in the target giving respectively 0.282, 0.384, 0.485, 0.536, 0.586 and 0.637 MeV.

In Fig. 1 the measured angular distributions are given in center-of-mass coordinates. They have been normalized such as to make the average differential cross section equal to unity. About 15,000 tracks were counted for each angular distribution. It is seen that all distributions have a maximum at $\vartheta = 0°$ and a minimum at some angle between 90° and 180° shifting slowly to smaller angles with increasing deuteron energy. The curves drawn in Fig. 1 have been plotted according to expressions of the form: $I(\vartheta) = 1 + \Sigma_{n=1}\, a_n P_n\, (\cos\vartheta)$, where P_n (cos ϑ) are spherical harmonics.

The values of the coefficients a_n are given in Table I. The statistical errors in the coefficients ^{5}) are equal to 0.02 for a_1, a_2 and a_3 and equal to 0.03 for a_4 and a_5. The coefficients have been plotted in Fig. 2 as a function of deuteron energy. It is seen that a_1 goes through a

TABLE I

Total cross section and coefficients of the spherical harmonics series development at six different deuteron energies

E_d (MeV)	σ_{tot} (millibarn)	a_1	a_2	a_3	a_4	a_5
0.282	0.015	+1.28	+0.56	—0.10		
0.384	0.11	+1.17	+0.60	—0.26		
0.485	0.30	+1.14	+0.84	—0.17	+0.09	
0.536	0.54	+0.98	+0.80	—0.20	+0.06	—0.06
0.586	0.73	+0.84	+0.66	—0.13	0	0
0.637	0.84	+0.88	+0.74	0	+0.03	+0.02

minimum at $E_d = 0.6$ MeV. The coefficient a_2 goes through a maximum at $E_d = 0.5$ MeV and through a minimum at $E_d = 0.6$ MeV.

Table I also contains total cross sections computed by integrating the differential cross sections over solid angle. They will be compared in § 3 with the scintillation spectrometer yield measurements.

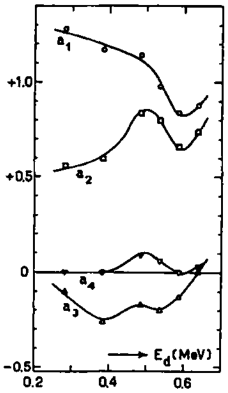

Fig. 2. Coefficients of the spherical harmonics series developments of angular distributions as a function of deuteron energy.

§ 3. *Scintillation spectrometer yield measurements.* The angular distribution measurements described in § 2 are relatively unsuitable for the measurement of the proton yield as a function of deuteron energy. The time interval between bombardments at different deuteron energies was large (of the order of days or weeks) and for every bombardment a different part of the target was used. Thus easily errors are introduced in the absolute measurement of cross sections e.g. by changing deuteron content of the mass two beam, by changing calibration of the current integrator or by inhomogeneity of the target.

These errors are not important when the proton yield in one fixed direction is measured as a function of deuteron energy by means of a thin crystal scintillation spectrometer. The whole measurement then does not take more than one hour and all data are obtained from the same target spot.

A description of the scintillation spectrometer has been given in a previous paper [6]). The proton yield was measured at two angles $\theta = 0°$ and $\theta = 120°$. Low energy protons were stopped completely by using a 160 μ aluminium absorber between target and crystal.

The pulse distribution of ^{13}C(d, p)^{14}C protons thus obtained was Gaussian and had a half-width of 6%.

The yield at 0.5 MeV was taken as reference and was measured before and after the yield measurement at any other energy setting. No evidence was found for evaporation of ^{13}C from the target during a complete run.

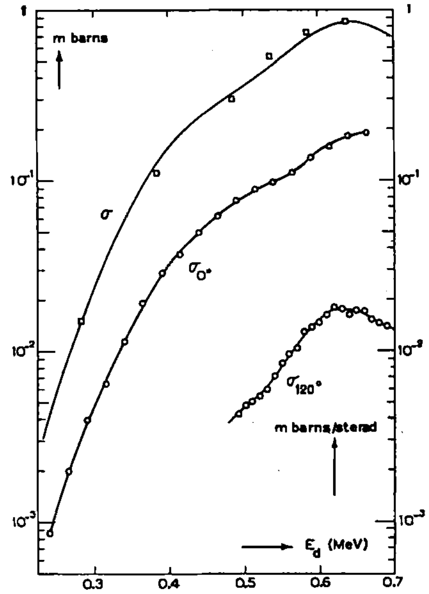

Fig. 3. Differential cross sections of the ^{13}C(d, p)^{14}C reaction at $\theta = 0°$ and $\theta = 120°$ in the laboratory system as a function of deuteron energy (lower curves: right-hand scale). Total cross section derived herefrom (upper curve) and from the angular distribution measurements (squares) (scale on left-hand side).

In Fig. 3 the differential cross sections at $\theta = 0°$ and $\theta = 120°$ are given in the laboratory system as a function of effective deuteron energy (corrected for energy loss in the target). Also total cross sections have been plotted in Fig. 3. They were computed from the data at $\theta = 0°$ correcting for angular distribution. Above $E_d = 0.63$ MeV total cross sections were derived from the data at $\theta = 120°$ using extrapolated angular distribution coefficients. In the same figure the total cross sections obtained from the nuclear emulsion measurements (see § 2) have been indicated. They agree well with the scintillation spectrometer results (within 15%).

§ 4. *Conclusions.* If the $^{13}C(d, p)^{14}C$ reaction were to proceed entirely through stripping one would expect $l_n = 1$, where l_n is the orbital angular momentum transferred to the initial nucleus by the captured neutron. This is to be expected by shell-model considerations and has been substantiated by angular distribution measurements at $E_d = 4$ MeV [7]. At the low deuteron energies of the present investigation it can a priori not be expected that stripping is the predominant process nor must one expect the theory given for the stripping process to be valid at energies appreciably below the Coulomb barrier. Indeed it has been found that current stripping theory cannot describe the angular dependence of the $^{9}Be(d, p)^{10}Be$ reaction at deuteron energies below 0.62 MeV [4].

Thus application of stripping theory to the present measurements seems not encouraging. Yet the strong forward peak in $^{13}C(d, p)^{14}C$ angular distributions suggests that stripping must be important. In Fig. 1 at $E_d = 0.282$ MeV and $E_d = 0.637$ MeV also the theoretical stripping curves have been drawn according to $l_n = 1$ using the theory in the form given by Bhatia e.a. [8]. The stripping angular distribution has been fitted to experiment at $\vartheta = 0°$. For ^{13}C a nuclear radius was used $R = 7.4 \times 10^{-13}$ cm, which is slightly larger than the expression $R = (3.7 + 1.22\,A^{1/3}) \times 10^{-13}$ cm used generally in fitting stripping angular distributions. This larger radius also checks best the measurements of Bromley and Goldman [7] at $E_d = 4$ MeV. It is not in contradiction with the analysis of nuclear radii found from stripping reactions given by Holt [9].

It is seen that the agreement of experimental angular distributions with stripping theory is surprising. The minimum in the distribution is found at the expected position and it shifts to smaller angles with increasing deuteron energy as predicted. That the intensity in the minimum is not equal to zero is also found at deuteron energies of several MeV and is generally attributed to a contribution from compound nucleus formation.

If this last statement is taken seriously and thus the minimum intensity in the angular distribution is taken as a measure of the compound nucleus contribution, then it follows from a scrutiny of Fig. 1 that the relative contribution of compound nucleus formation to the total cross section rises with increasing deuteron energy, contrary to what generally can be expected. This might be regarded as an indication of a resonance at the high energy end of our deuteron energy interval. Another argument for this resonance might be found in the behaviour of the coefficients a_n with energy (see Fig. 2) which vary strongly above $E_d = 0.5$ MeV. Such a resonance in the total cross section has been found by Curling and Newton [10]. They found a maximum in the total cross section at $E_d =$ $= 0.62$ MeV and a minimum at $E_d = 0.70$ MeV, the intensity of the latter being about 25% lower than that of the maximum. This is in good agreement with our scintillation spectrometer yield measurements (see Fig. 3). The maximum in the yield at 120° is much more pronounced than in the yield at 0°, but this is explained by the dependence of angular distribution coefficients on deuteron energy.

In conclusion we may say that the angular distributions offer strong proof that the ground-state transition of the $^{13}C(d, p)^{14}C$ reaction proceeds predominantly through the stripping process at deuteron energies in the 0.30 MeV to 0.65 MeV region. Indications are found for a weak resonance at $E_d = 0.63$ MeV in agreement with the work of Curling and Newton.

Acknowledgements. This work is part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie", which was made possible by a subvention from the "Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek".

The authors are indebted to Prof. J. M. W. Milatz for his interest in this investigation. The assistance of Miss A. M. Hoogerduijn in counting plates was much appreciated.

Received 27-8-53.

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