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ANGULAR DISTRIBUTIONS OF PROTONS FROM THE $C^{13}(d, p)C^{14}$ AND $C^{12}(d, p)C^{13}$ REACTIONS

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Synopsis

Angular distributions have been measured of protons from the ground-state transitions of the reactions $C^{13}(d, p)C^{14}$ and $C^{12}(d, p)C^{13}$ at a deuteron bombarding energy of 470 keV. The target consisted of barium carbonate enriched to 56% in C^{13} content.

The angular distribution of $C^{13}(d, p)C^{14}$ protons shows a pronounced maximum in forward direction and a minimum at 126°. The $C^{12}(d, p)C^{13}$ proton distribution shows minima in forward and backward directions and a maximum at 97°. The ratio of $C^{12}(d, p)C^{13}$ over $C^{13}(d, p)C^{14}$ total cross-sections is equal to 8.7.

§ 1. *Introduction.* The angular distribution of protons from the $C^{12}(d, p)C^{13}$ ground-state transition has been measured by several experimenters ^{1}) ^{2}) ^{3}) but only at relatively high deuteron energies (above 0.75 MeV). No angular distributions have been published for protons from the $C^{13}(d, p)C^{14}$ reaction.

In the present paper measurements are described of angular distributions of both the $C^{12}(d, p)C^{13}$ and the $C^{13}(d, p)C^{14}$ reactions at a deuteron bombarding energy of 470 keV. The experimental procedure is discussed in § 2 and the experimental results are presented in § 3.

§ 2. *Experimental procedure.* General features of the experimental arrangement can be found in a paper by Endt e.a. ^{4}) and some more details are given in a paper by De Jong and Endt ^{5}).

Targets consisted of barium carbonate supplied by the Kodak Co. enriched in C^{13} content to 56%. It was not possible to prepare targets of this material in the usual way by evaporation in vacuum because barium carbonate easily decomposes. Instead the "suspension method" was adopted. First the enriched material was finely ground in a porcelain crucible. A suspension of the resulting powder in tetra was then prepared. After a quarter of an hour when the coarser crystals had sunk to the bottom of the crucible an aluminium backing of 7 μ thickness was placed in the suspension some millimeters below the surface. After several hours the tetra was evaporated and a layer of barium carbonate had settled onto the target backing. It is not possible to prepare very thin targets in this way nor very uniform ones. We used a target of 2.1 mg/cm^2 which corresponds to a thickness larger than the range of 470 keV deuterons in the target material. This was not considered a serious disadvantage because the yield of the $C^{12}(d, p)C^{13}$ and $C^{13}(d, p)C^{14}$ reactions is a steep function of bombarding energy [6]). As a consequence the average energy loss of reacting deuterons is not very large, in this case about 100 keV. For determinations of absolute cross-sections however these suspension targets are unsuitable.

Protons produced in the two reactions investigated were detected in 100 μ Ilford C2 emulsions and distinguished by their range. In Fig. 1 a range analysis is presented of 833 tracks of particles leaving the target in the forward direction. It was obtained from a bombardment in which the barium carbonate target described above was exposed to 2480 microCoulomb of 470 keV deuterons. As explained above the effective bombarding energy (average energy of reacting deuterons) amounted to 370 keV. Tracklength was measured with a total microscope magnification of 420. The four groups in Fig. 1 numbered I through IV can be attributed to the following reactions:

I. $C^{13}(d, p)C^{14}$ $Q = 5.948 \pm 0.008$ MeV,
II. $D(d, p)T$ $Q = 4.030 \pm 0.006$ MeV,
III. $C^{12}(d, p)C^{13}$ $Q = 2.716 \pm 0.005$ MeV,
IV. $O^{16}(d, p)O^{17}$ $Q = 1.917 \pm 0.005$ MeV.

The Q-values quoted have been measured by Strait e.a. [7]). The arrows in Fig. 1 indicate ranges calculated [4]) for the groups mentioned above from the known Q-values and the range-energy relation valid for the emulsion and corrected for energy loss in target, target backing and aluminium screen and for dip in the emulsion. It is seen that the agreement between measured and calculated ranges is good.

The half-width of the groups in Fig. 1 obtained from our thick target is of course somewhat larger than from a thin target. From a comparison with proton groups from thin lithium and boron targets it is estimated that group I in Fig. 1 is about 40% broader than it would be from a thin target. Thus in this case range straggling in the emulsion and target thickness contribute about equally to the total half-width.

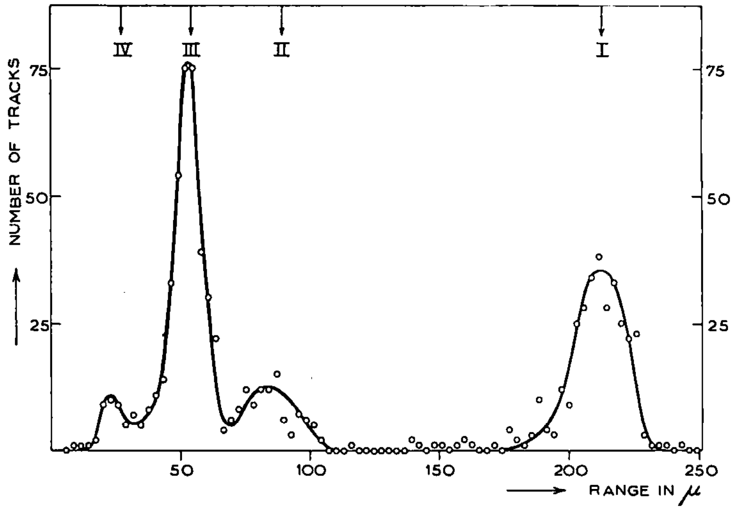

Fig. 1. Range analysis of reaction products from a barium carbonate target (enriched to 56% in C^{13} content) bombarded by 470 keV deuterons. The protons in the groups numbered I through IV result from the reactions: I $C^{13}(d, p)C^{14}$, II $D(d, p)T$, III $C^{12}(d, p)C^{13}$ and IV $O^{16}(d, p)O^{17}$. Arrows indicate ranges calculated from Q-values for the groups indicated above.

The range analysis presented in Fig. 1 was made for protons ejected from the target in the forward direction. For other angles between the proton and deuteron velocity vectors the range analysis is essentially similar with the only difference that ranges get gradually smaller with increasing angle (apart from the gradual variation of relative intensities). For protons in group II resulting from the reaction $D(d, p)T$ this variation of range with angle is very pronounced. At angles larger than 120° their range is even shorter than that of the protons in group III from the reaction

$C^{12}(d, p)C^{13}$. Groups II and III could not be resolved in the region from $\vartheta = 75°$ to $\vartheta = 165°$. Luckily the yield of the $C^{12}(d, p)C^{13}$ reaction can be corrected for this unwanted contribution of $D(d, p)T$ protons because the angular distribution of protons from the $D(d, p)T$ reaction is well known [8]), making it possible to extrapolate the yield of group II measured in forward directions into the region where groups II and III overlap. This correction amounted to at most 5%.

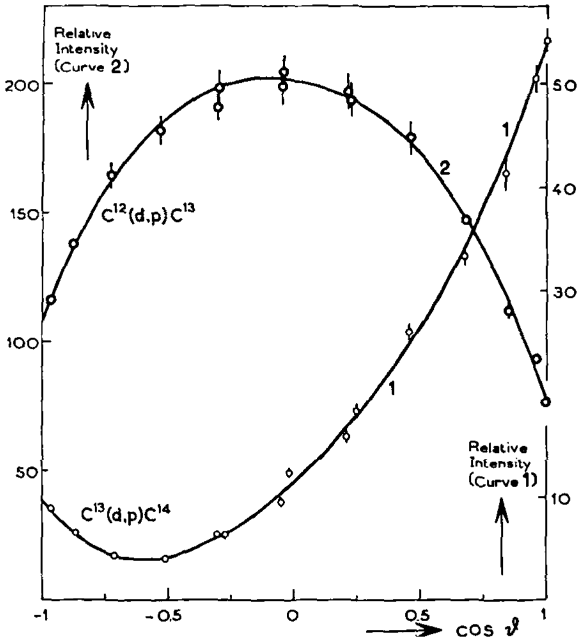

Fig. 2. Angular distributions (in center of mass system) of protons from the reactions $C^{13}(d, p)C^{14}$ (curve 1) and $C^{12}(d, p)C^{13}$ (curve 2) at an effective deuteron bombarding energy of 370 keV. The right hand ordinate scale pertains to curve 1, the left hand one to curve 2. Differential cross-sections are plotted in arbitrary units but the ratio of cross-sections of the two reactions has been represented correctly. The full curves have been drawn according to the expressions:

$$\sigma(\vartheta) = 1 + 1.28\,P_1 + 0.75\,P_2 + 0.08\,P_4 \text{ (curve 1) and}$$
$$\sigma(\vartheta) = 1 - 0.09\,P_1 - 0.41\,P_2 - 0.04\,P_4 \text{ (curve 2).}$$

Angular distributions were obtained by scanning equal areas on fifteen plates placed around the target at intervals of 15°. A total number of 21,379 protons from the $C^{13}(d, p)C^{14}$ reaction (group I) was counted by scanning 58 mm^2 on each plate using a total microscope magnification of 250. For the $C^{12}(d, p)C^{13}$ reaction (group III) 11 mm^2 was scanned on each plate with a magnification of 540 yielding a total number of 14,590 counted protons. On some plates where the counted number of tracks deviated more than the statistical error from a smooth distribution additional points of the distribution were secured by counting areas nearer to or further from the target. The numbers of tracks counted on all plates were finally normalized to a target distance of 60 mm.

The angular distributions of protons from the reactions $C^{13}(d, p)C^{14}$ and $C^{12}(d, p)C^{13}$ are given in Fig. 2 in the center of mass system. They are plotted in arbitrary units but the ratio of the differential cross-sections for these two reactions is presented correctly. This was effected by normalizing the distributions to the same area counted on plates and by taking into account the difference in C^{13} and C^{12} content of the target. Our measurement of this cross-section ratio however is not considered very accurate because usually during bombardment a contamination layer of natural carbon builds up on the target. It was possible to estimate the contribution to group III of this contamination layer by measuring the $C^{12}(d, p)C^{13}$ yield from a blank target backing. This method of correction is admittedly crude because during the two exposures gas pressures and thus the rates of formation of the contamination layer may have been different. The statistical errors of the measured points, resulting from the counting of a limited number of tracks, have been indicated in Fig. 2.

§ 3. *Discussion.* The measured distributions may be expanded into spherical harmonics: $\sigma(\vartheta) = 1 + \sum_{i=1}^{\infty} a_i P_i(\cos\vartheta)$. The coëfficients in this expansion were found by numerical integration [4]. In this way we find for the angular distribution of protons from the $C^{13}(d, p)C^{14}$ reaction:

$$\sigma(\vartheta) = 1 + 1.28\,P_1 + 0.75\,P_2 + 0.08\,P_4,$$

and for protons from the $C^{12}(d, p)C^{13}$ reaction:

$$\sigma(\vartheta) = 1 - 0.09\,P_1 - 0.41\,P_2 - 0.04\,P_4.$$

The full curves in Fig. 2 have been drawn according to these expressions. The good agreement between full curves and measured points shows that it is not necessary to take into account higher spherical harmonics than P_4 and that also the term a_3P_3 can be neglected in both cases. The statistical errors in the coëfficients can be shown [9]) to be about 0.01 for a_1 and a_2 and 0.02 for a_3 and a_4.

The ratio of total cross-sections for the reactions $C^{12}(d, p)C^{13}$ and $C^{13}(d, p)C^{14}$ at the effective deuteron energy of 370 keV is found to amount to 8.7 ± 0.5 (corrected for natural carbon contamination which contributed here 10% ± 5% to the $C^{12}(d, p)C^{13}$ yield).

It is seen in Fig. 2 that the $C^{13}(d, p)C^{14}$ distribution is strongly peaked in forward directions while the $C^{12}(d, p)C^{13}$ distribution is more nearly symmetric around the 90°-plane. Both reactions show resonances at higher deuteron energies [2]) [6]) making it probable that they proceed through compound nucleus formation, a conclusion which probably also holds for the lower deuteron energy used in the present experiment. It is not possible to make more definite statements about the question as to whether stripping or compound nucleus formation predominates before the theory of stripping reactions at low deuteron energies taking into account Coulomb interaction has been developed.

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