# *INVESTIGATION OF THE* $C^{12}(t, p)C^{14}$ *REACTION*

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The differential cross sections of the reaction $C^{12}(t,p)C^{14}$ for the ground state of the residual $C^{14}$ nucleus were measured with tritons accelerated in an electrostatic generator. The measurements were carried out at an l.s. angle of 90° for triton energies between 0.32 and 1.18 MeV. For some of the energies in this range the proton angular distributions were also measured for l.s. angles between 0 and 155°. Total reaction cross sections were obtained for triton energies between 0.37 and 1.16 MeV.

REACTIONS between tritons and carbon have not yet been studied in great detail. Vatset et al [1] measured the neutron yield at 0° from the $C^{12}(t,n)N^{14}$ reaction for triton energies from 0.35 to 2.4 MeV. Seven resonances corresponding to the excited levels of the $N^{15}$ compound nucleus were observed. The neutron angular distributions and total cross sections were measured for five triton energies.

Gutsche et al [2] measured the angular distributions of protons from the $C^{12}(t,p)C^{14}$ reaction and of $\alpha$ particles from the $C^{12}(t,\alpha)B^{11}$ reaction for 1.5-MeV tritons. It was shown that the proton angular distribution has a maximum in the forward direction and a minimum at 75°; the $\alpha$ particles give a broad maximum at 70°.

Jaffe et al [3] studied the angular distributions of groups of protons from the $C^{12}(t,p)C^{14}$ reaction corresponding to the excited states of the $C^{14}$ residual nucleus. The energy of the bombarding tritons was 5.5 MeV. The angular distributions were analyzed in terms of the double-stripping theory [4] and the level scheme of the $C^{14}$ nucleus was given.

Recently, results were published on the study of differential cross sections for reactions between tritons and $C^{12}$ in the 800–2025 keV range.[5] It was found that the angular distributions of the protons and $\alpha$ particles from the $C^{12}(t,p)C^{14}$ and $C^{12}(t,\alpha)B^{11}$ reactions have a complex character and suggestions were made about the mechanism of these reactions.

In the present experiment, we studied the proton angular distributions and the differential and total cross sections for the $C^{12}(t,p)C^{14}$ reaction in order to obtain data for the study of the mechanism of this reaction for incident triton energies below the Coulomb barrier. Moreover, these data are of practical interest for the investigation of other reactions with tritons in order to consider the contribution from the $C^{12} + t$ reaction proceeding in the carbon impurities inevitably present in all targets.

## EXPERIMENTAL METHOD

The tritons accelerated by an electrostatic generator bombarded a thin carbon target obtained by the evaporation of graphite in vacuo on an aluminum base 3 mg/cm$^2$ thick. The target was prepared by the method described by Dearnaley. [6] The target was set at an angle of 45° relative to the incident triton beam. The triton energy loss in carbon was determined from the carbon stopping-power curve obtained from the data in [7-9]. The accuracy of the curve was approximately 5%. The thickness of the carbon layer of the target was obtained by comparison of the proton yield from the reaction on solid and gas targets at the same particle interaction energy (850 keV). It turned out to be 76 $\mu$g/cm$^2$.

To measure the proton angular distributions for the reaction, we used the universal vacuum chamber described earlier. [10] The protons were recorded by means of an FÉU-31 phototube (with a CsI crystal) rotating around the target. A second scintillation counter with an FÉU-S and a CsI crystal placed at 90° relative to the incident triton beam served as a monitor.

The pulses from the rotating counter were applied to a multichannel pulse-height analyzer which permitted the separation of pulses of the proton groups of interest to us from the background pulses and other reactions occurring in the base and in possible impurities of the target.

The angular distributions were measured every 10° in the angular interval 0—155°. The angular resolution of the rotating counter was ± 3.5°. The statistical error of the measurements of each point did not exceed ± 3%.

To measure the relative yield of protons at 90° and the dependence on the triton energy $E_T$, we used a chamber employed previously for the study of the $T^3(t, 2n)He^4$ reaction.[11] The measurements were made on a solid carbon target of the same thickness as in the angular distribution measurements. A scintillation counter with an FÉU-29 phototube and a CsI crystal was used as a proton detector. The pulses from the counter were analyzed in a multi-channel pulse-height analyzer. One of the pulse spectra measured at $E_T$ = 850 keV is shown in Fig. 1.

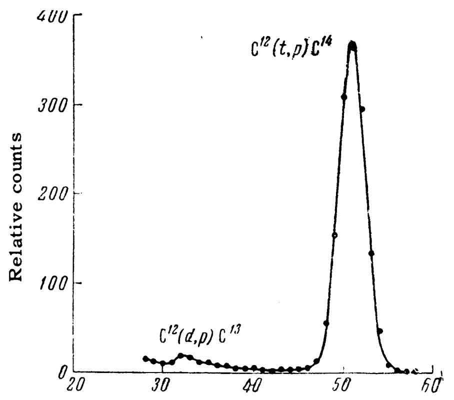


FIG. 1. Proton spectrum from a solid target.

The absolute value of the differential cross section for $E_T$ = 850 keV was obtained with a gas target filled with methane. The design of the target is similar to one described earlier.[11] The gas pressure in the target was about 60 mm Hg. The results of control experiments made with a carbon-dioxide gas target agree, within the limits of experimental error, with the measurements on methane.

## RESULTS OF THE MEASUREMENTS

Figure 2 shows the differential cross section curve for the reaction $C^{12}(t, p)C^{14}$ at 90° obtained from measurements of the relative yield on a solid target and normalized to the differential cross section 233 ± 5 μb/sr measured with a gas target for $E_T$ = 850 keV.

This curve is characterized by the presence of two maxima at 850 and 1117 keV. The first of these maxima does not appear so distinctly on the total cross section curve and the differential cross section curve at other angles, and is apparently

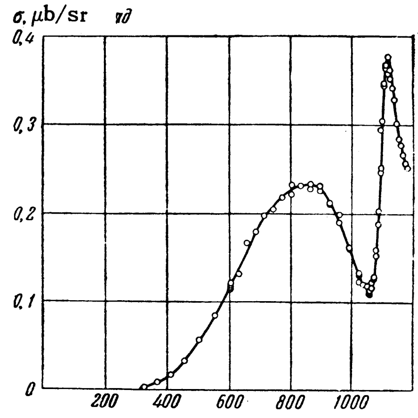


FIG. 2. Differential cross section for the $C^{12}(t, p)C^{14}$ reaction at 90° in the l.s.

due to the character of the angular distributions. The second maximum appears both on the total cross section curve and on the differential cross section curve for the angles 0, 40, 70, and 150° and indicates the presence of a resonance connected with the $N^{15}$ compound nucleus level with excitation energy 15.74 MeV. This level has not been reported in the literature.

Figure 3 shows the proton angular distributions for several energies of the bombarding tritions. It is seen from the figure that the angular distributions are asymmetric relative to 90° in the c.m.s. and very weakly depend on the energy of the bombarding particles. As the resonance at $E_T$ = 1117 keV is approached, the proton yields in the forward and backward directions tend to become equal, although complete symmetry is not observed in this case too. This reaction cannot be completely explained by an isolated compound nucleus level, and it is seen that even for comparatively low bombarding energies some contributions from direct processes are possible.

The proton angular distributions were represented in the form of an expansion in Legendre polynomials and were integrated to obtain the total cross sections. The calculations were carried out on an electronic computer. In the table below, the values of the total cross sections for the reaction and the expansion coefficients for the Legendre polynomial expansion are given.

The table also lists the rms measurement error of the total cross section without allowance for the error connected with the determination of the energy of the bombarding tritons. The error in the determination of the triton energy varied from 2% at $E_T$ = 400 keV to 1.5% at $E_T$ = 1200 keV.

From a comparison of our experimental results with the results of Gutsche et al[5] in the overlapping energy region (0.8—1.2 MeV), we can note a general agreement between the shape of the differential cross section curve at 90° and the shape of

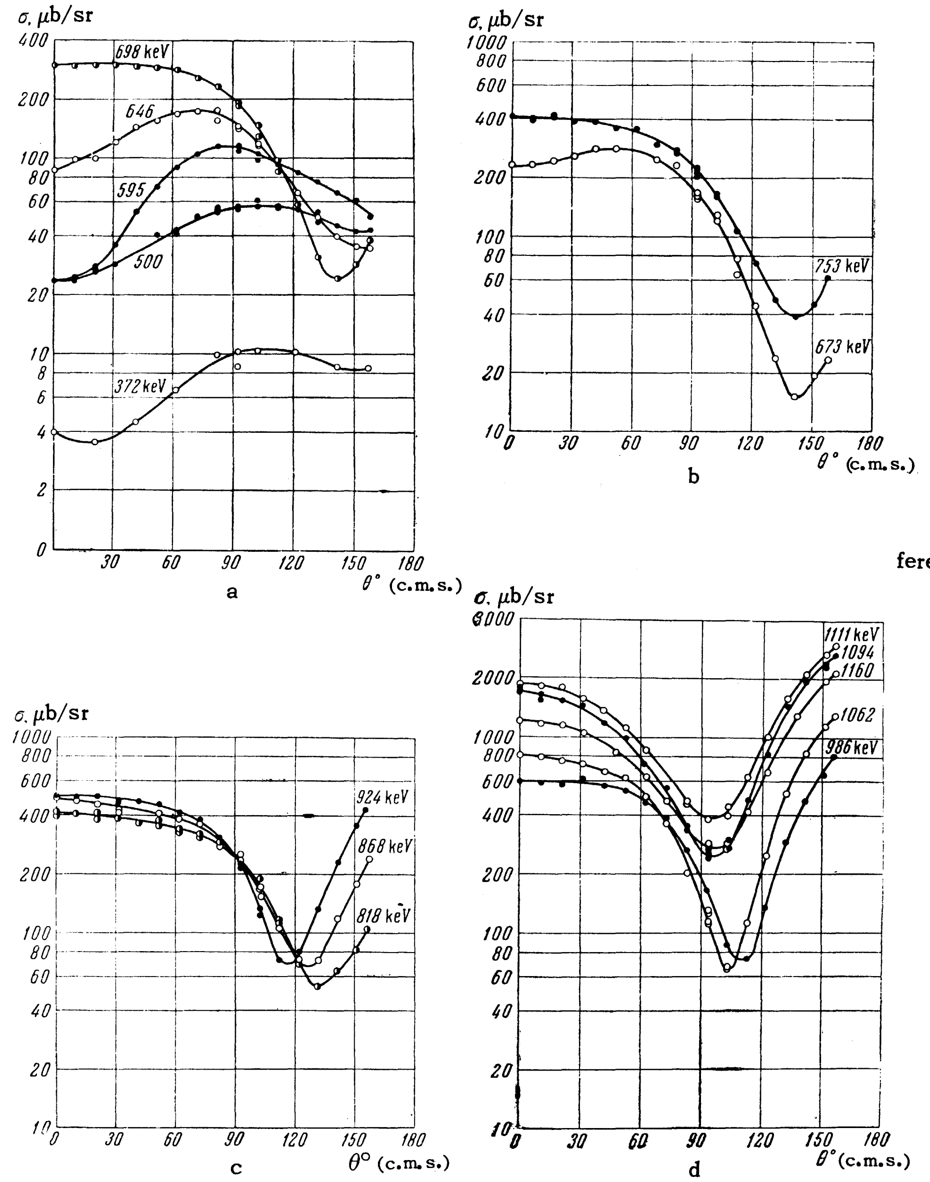


FIG. 3. Proton angular distributions at different values of $E_T$.

Total cross sections for the reaction $C^{12}(t, p)C^{14}$ and expansion coefficients for the Legendre polynomials

| $E_T$, MeV | Total cross section, mb | Expansion coefficients (relative units) | | | | | |
|---|---|---|---|---|---|---|---|
| | | $\alpha_0$ | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\alpha_5$ |
| 0,372 | 0.10±0.01 | 8.03±0.28 | —2.96±0.37 | —3.1±0.6 | 0,78±0,67 | 0,93±0.8 | 0.1±0.7 |
| 0,500 | 0.59±0.02 | 46.9±0.5 | —9.13±0.77 | —17,1±1 | 2,0±1,2 | 1,54±1.5 | —1,3±1,6 |
| 0.595 | 1,02±0,03 | 81.3±0.8 | —8,2±1.0 | —54.8±1,6 | —8,6±1,8 | 5,2±2 | 8.6±2 |
| 0.646 | 1.45±0.04 | 115.7±1.0 | 62,5±1.2 | —62,5±2,2 | —37,7±2,1 | 9,5±2,3 | 1.0±2.5 |
| 0,673 | 2.00±0.05 | 158.9±1.5 | 163±2 | —33,3±2,7 | 64,3±3,3 | 7,4±2.8 | —3,7±3.2 |
| 0,698 | 2.22±0.06 | 177.0±1.7 | 175,4±2.4 | —23,8±3,4 | —53,9±3,7 | 23,9±3.8 | —0.6±4.3 |
| 0.753 | 2,66±0.07 | 211,8±1,6 | 201.4±2.4 | —7,9±3,2 | —54,9±3,4 | 25,9±3.9 | —6.8±4.4 |
| 0.818 | 2,84±0.07 | 226,5±2.1 | 199,5±3.1 | 4,4±4,2 | —70,5±4,3 | 50,3±5 | —2,5±5,6 |
| 0,868 | 3.28±0.09 | 261,0±2 | 199,1±3.3 | 63,1±4,2 | —125,2±4 | 80,6±4,9 | 6.1±5,8 |
| 0,924 | 3.74±0.10 | 297.4±1.7 | 164.4±2.9 | 175,8±4 | —226,0±4,1 | 76,9±5 | 7.9±5.4 |
| 0,987 | 4,73±0.12 | 377,3±3,1 | 57,5±6.5 | 408±8,7 | —356,7±8,2 | 64,6±9,7 | 9.6±10.2 |
| 1,062 | 5.89±0.17 | 469.7±3,2 | —53.2±6,8 | 699,3±8,7 | —404,8±9,1 | 69,8±10,5 | 22,2±10 |
| 1,094 | 12.15±0.36 | 967±5.9 | —336,7±12,9 | 1419,8±15,6 | —451,3±18,4 | 29,2±20 | 63.6±19 |
| 1.111 | 14.14±0.37 | 1126±6,1 | —389.7±12,5 | 1540,8±16 | —486,2±19,7 | 85,8±22 | —13.8±20 |
| 1,160 | 9.88±0.28 | 786.6±5 | —300.8±10.4 | 1068,1±12,1 | —430±14,6 | 85,8±15 | —2,5±16 |

the angular distributions. The absolute values of the differential cross sections obtained by us are approximately one-third of those in [5]. Such a large difference, considerably exceeding the possible errors connected with the comparison of results from the curves in [5], led us to carry out a number of control measurements after our preliminary data had been published as a preprint.[12] These control measurements completely confirmed our earlier results, and we were not able to establish the cause of this large disparity with the data of [5].

In conclusion, the authors consider it their duty to express their gratitude to Tsen Nai-kung for aid in the measurements, to V. I. Furman for the calculation of the angular distributions on the electronic computer, to F. L. Shapiro and V. N. Efimov for discussion of the results, and to the electrostatic generator crew.

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