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$^{12}C(^{3}He,^{3}He\ n)^{11}C$ cross section at 910 MeV

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The $^{12}C(^{3}He,^{3}He\ n)^{11}C$ cross section at 910 MeV was measured by using a Ge(Li) gamma spectrometer to determine the disintegration rate and measuring the incident flux by means of a scintillator telescope. Cross sections for the production of ^{7}Be in C and Al and for the production of ^{24}Na in Al are then determined using the measured cross section as a monitor.

[NUCLEAR REACTIONS $^{12}C(^{3}He,^{3}He\,n)^{11}C$. Measurement of the cross section at 910 MeV.]

The cross section of the reaction $^{12}C(^{3}He,\ ^{3}He\,n)$ ^{11}C was measured in the extracted 910 MeV $^{3}He^{++}$ ion beam at the CERN Syncro-cyclotron. The reason for the measurement was the importance of the reaction for beam monitoring in an experiment of pion production on nuclei.[1] Using the $^{12}C(^{3}He,\ ^{3}He\,n)^{11}C$ reaction as a monitor, the cross sections for the production of ^{7}Be in C and Al and for the production of ^{24}Na in Al have then been determined.

Graphite discs of thicknesses ranging from 1–5 fm were inserted between or placed downstream from two plastic scintillators of dimensions $100 \times 100 \times 2$ mm^{3}. The experimental setup is shown in Fig. 1. Three irradiations with graphite discs were performed.

Irradiation I: Graphite disc of 1 mm in position I.

Irradiation II: Graphite disc of 1 mm in position I + graphite disc of 5 mm in position II.

Irradiation III: Graphite disc of 2 mm in position I + graphite disc of 5 mm in position II.

The irradiations took place at beam intensities of about 8×10^{5} $^{3}He/s$ as determined by the number of coincidences in the two scintillators. The number of coincidences was only slightly lower than the count rate of the individual scintillator. Therefore, in spite of the high count rate, dead time losses were negligible.

^{11}C activity of the graphite disc was then measured using a Ge(Li) gamma spectrometer. Corrections were applied for self-absorption of photons in the disc as a function of thickness. In order to cope with the problem of ^{11}C production due to secondaries the ratio of ^{11}C activity to ^{7}Be activity had to be extrapolated to zero graphite disc thickness assuming that the production of ^{7}Be by secondaries is negligible due to its much higher threshold energy. Unfortunately, the induced ^{11}C activity during these first irradiations was too low for an accurate extrapolation. Therefore, a series of irradiations at the highest $^{3}He^{++}$ beam intensity was performed ($\sim 1.8 \times 10^{12}$ $^{3}He/s$ on a similar set of graphite discs (1, 2, and 5 mm) each time irradiated with a 0.1 mm thick Al foil in front. The relationship for the ratio R of the ^{11}C activity in graphite to ^{7}Be activity in graphite, respectively, Al was determined as a function of graphite thickness d (mm) and found to be

$$R(^{11}C/^{7}Be) = c[1 + (0.02 \pm 0.007)d]\,.$$

This relationship has been used for a least square fit to the data obtained in the first series of irradiations. The fit to the data is presented in Fig. 2. The error bars in the figure correspond

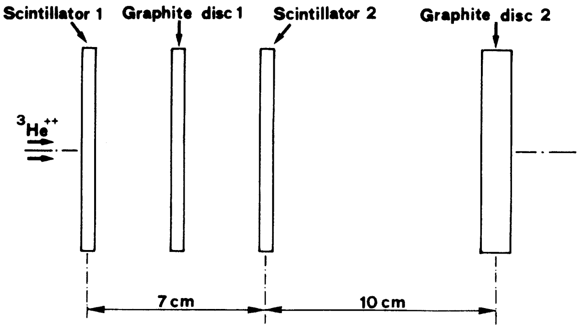

FIG. 1. Experimental setup.

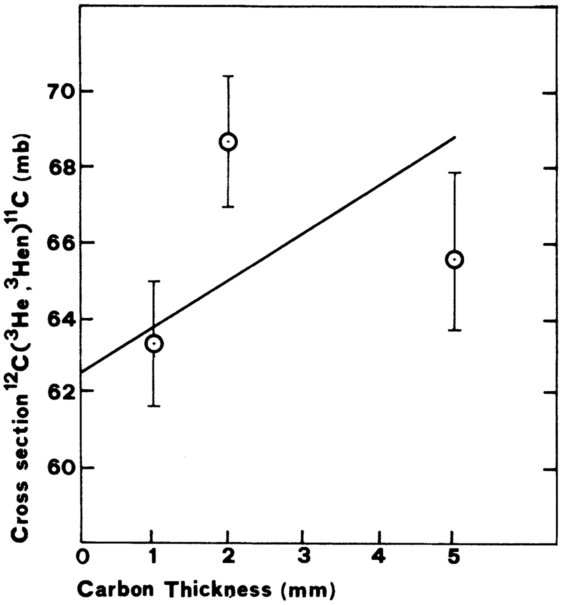

FIG. 2. Least square fit to the data from irradiations at low beam intensity. The slope of the straight line was previously determined from the data at the highest beam intensity.

to the standard deviation in the number of photon counts and do not include possible systematic errors arising from the counting or irradiation procedure. Moreover, the effect of secondaries produced in the scintillators was not taken into account. It was found to be much smaller than the effect of secondaries produced in the graphite discs themselves. The estimated total systematic error, which is included in the error onthe cross section quoted below, is 3%.

The cross section was measured for natural carbon. The possible effect of the presence of 1.1% ^{13}C is not taken into account, and carbon is supposed to be composed of 100% ^{12}C. Assuming the cross section of ^{13}C(^{3}He, ^{3}He 2n)^{11}C to be not greater than the cross section of ^{12}C(^{3}He, ^{3}Hen)^{11}C the absolute cross section for the ^{12}C(^{3}He, ^{3}Hen)^{11}C reaction may be somewhat higher (~1%).

We find an extrapolated cross section of *62.5* ± *5* mb for the reaction ^{12}C(^{3}He, ^{3}Hen)^{11}C at 910 MeV. The result of our measurements corresponds quite well with measurements of Crandall *et al.*[2] Their results together with the cross sections measured for ^{11}C production by other charged particles[3] are presented in Fig. 3. The comparison of the ^{12}C(^{3}He, ^{3}Hen)^{11}C cross section at 910 MeV with the ^{12}C(p,pn)^{11}C cross section at 300 MeV and the ^{12}C(^{4}He, ^{4}Hen)^{11}C cross section at 920 MeV gives

$$R_1=\frac{\sigma[^{12}\mathrm{C}(^3\mathrm{He},\,^3\mathrm{He}n)^{11}\mathrm{C}]_{910\,\mathrm{MeV}}}{\sigma[^{12}\mathrm{C}(p,pn)^{11}\mathrm{C}]_{303\,\mathrm{MeV}}}=1.78\pm0.20$$

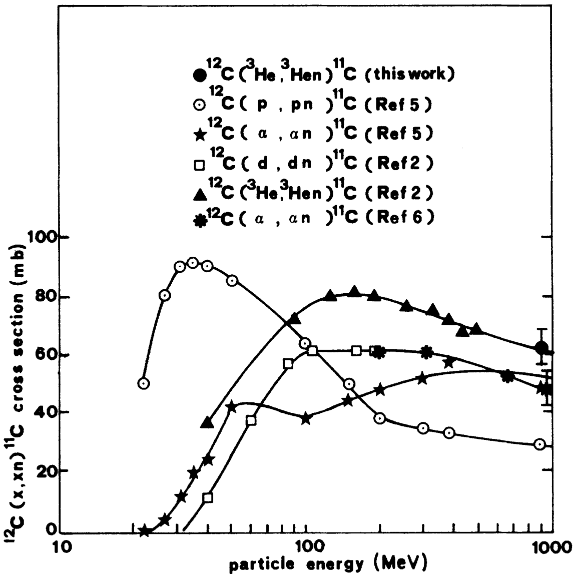

FIG. 3. ^{12}C(X,Xn)^{11}C reaction cross section as a function of the projectile kinetic energy.

and

$$R_2=\frac{\sigma[^{12}\mathrm{C}(^3\mathrm{He},\,^3\mathrm{He}n)^{11}\mathrm{C}]_{910\,\mathrm{MeV}}}{\sigma[^{12}\mathrm{C}(^4\mathrm{He},\,^4\mathrm{He}n)^{11}\mathrm{C}]_{920\,\mathrm{MeV}}}=1.27\pm0.16\,.$$

Within the experimental uncertainties the data seem to indicate that the ^{3}He induced reaction has a cross section which is twice the cross section of the proton induced reaction at the same energy per nucleon. The ratio of the ^{3}He—to the ^{4}He—induced reaction cross section is not very different from unity. This favors the hypothesis that the cross sections are governed by the number of protons at comparable energies. However, there are many reasons for such a naive picture to be modified and for R_1 and R_2 to be different from 2 and 1, respectively. R_1 could be larger than 2 if the neutrons contribution were not negligible; it could also be smaller than 2 due to the attenuation of the incident flux, depending on the mass of the projectile. It was pointed out recently that transparency effects may exist in nuclear reactions beyond 250 MeV nucleon incident energies.[4] Such effects were larger in reactions involving heavier projectiles than in reactions induced by protons in nuclear targets.

The ratio R_2 can be different from 1 due to the mass dependence of the effects mentioned above, but also because of a different "effective" number of constituents participating in the knockout of the neutron. Given the experimental cross section ratios $R_1 \equiv \sigma(\mathrm{He})/\sigma(p)$ for the comparison of the ^{3}He—or ^{4}He—induced reactions with the proton induced ones, the effective number of protons participating in the reaction would be 1.8 in ^{3}He and 1.4 in ^{4}He.

The comparison of the cross sections due to heavier projectiles can be made on the basis of their cross sectional area, i.e., using their rms charge radii squared, which should in a simple way reflect the total reaction probability. Using the known radii[5] for ^{3}He (1.87 ± 0.05 fm) and for ^{4}He (1.63 ± 0.04 fm), the value of $R_2 = (\pi R_{^3\mathrm{He}}{}^2)/(\pi R_{^4\mathrm{He}}{}^2) = 1.32 \pm 0.01$ is obtained in agreement with the experimental value of R_2.

It was beyond the scope of the present communication to study qualitatively high energy nuclear reactions. Systematic energy and mass-dependence measurements are necessary in order to understand their basic properties at intermediate energies. When using the cross section of 62.5 mb for the $^{12}\mathrm{C}(^3\mathrm{He}, {}^3\mathrm{He}\,n)^{11}\mathrm{C}$ reaction as a standard the following reaction cross section can be obtained:

$^{12}\mathrm{C}(^3\mathrm{He}, 2\alpha)^7\mathrm{Be}$: 23.4 ± 2.0 mb

$^{27}\mathrm{Al}(^3\mathrm{He}, {}^3\mathrm{He}\,2pn)^{24}\mathrm{Na}$: 17.5 ± 1.4 mb

$^{27}\mathrm{Al}(^3\mathrm{He}, 11p\,12n)^7\mathrm{Be}$: 34.0 ± 2.0 mb

For comparison the cross sections for similar reactions induced by other charged particles[5] are reported below:

$^{27}\mathrm{Al}(\alpha, X)^{24}\mathrm{Na}$	at $T_\alpha = 380$ MeV	$\sigma = 24 \pm 0.3$ mb
$^{27}\mathrm{Al}(p, X)^{24}\mathrm{Na}$	at $T_p = 380$ MeV	$\sigma = 11 \pm 1$ mb
$^{27}\mathrm{Al}(p, X)^{24}\mathrm{Na}$	at $T_p = 1000$ MeV	$\sigma = 10 \pm 0.6$ mb
$^{27}\mathrm{Al}(p, X)^7\mathrm{Be}$	at $T_p = 1000$ MeV	$\sigma = 7.6 \pm 2.0$ mb
$^{12}\mathrm{C}(\alpha, X)^7\mathrm{Be}$	at $T_\alpha = 920$ MeV	$\sigma = 20$ mb
	(Error not quoted by the authors.)	
$^{12}\mathrm{C}(p, X)^7\mathrm{Be}$	at $T_p = 920$ MeV	$\sigma = 10 \pm 1$ mb

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