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ALPHA-MULTIPLICITY IN ^{12}C INDUCED REACTIONS

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Average α-multiplicities have been determined from α–α coincidence data in the ^{12}C + ^{160}Gd reaction at bombarding energies of 120 MeV and 200 MeV. The results show that the incomplete fusion reactions $\sigma(^{12}\text{C}, \alpha)$ and $\sigma(^{12}\text{C}, 2\alpha)$, and the 3$\alpha$-particle breakup $\sigma(^{12}\text{C}, 3\alpha)$ can account for the large inclusive α-production cross section.

A study of incomplete fusion reactions via γ-charged particle coincidence measurements [1–3] has revealed [3] the main mechanism for the production of fast α-particles in reactions induced by light heavy ions, such as ^{12}C. In contrast to the reactions at low energies in which most of the α-particles appear to be ejected by the target-like nucleus [4], at bombarding energies of about 10 MeV/A, or higher, fast α-particles are mostly the remnants of the projectile: either they are the residues of the incomplete fusion reactions or the products of projectile breakup.

In the present paper we report on the determination of the *average* α-multiplicity in ^{12}C induced reactions. This information is a valuable supplement to the incomplete fusion reaction data from particle–γ coincidence studies. It enables to complete the balance of different processes that lead to the production of fast α-particles.

The experiments were designed to be complementary to our previous study of the ^{12}C + ^{160}Gd reaction [3]. Alpha–alpha coincidence data were taken therefore for the same ^{12}C + ^{160}Gd system at two bombarding energies: 120 MeV and 200 MeV. The ^{12}C(+4) beams from the KVI variable energy cyclo-

tron bombarded a 1.35 mg/cm^2 thick target of metallic ^{160}Gd enriched to 98.6%. Charged particles of $2 \leqslant Z \leqslant 6$ were detected and identified with two ΔE–E solid state counter telescopes consisting of 50 μm (ΔE) and 5 mm (E) detectors. Particle–particle coincidences were written on magnetic tape as five-fold events: ΔE and E signals from both telescope, and the time differences between them.

The data were taken in both singles and coincidence modes for various relative angles over the whole region of forward angles where the yield of fast α-particles is concentrated. For each pair of angles the α-multiplicity, M_α was derived under the assumption that the coincident α-particles are uncorrelated:

$$\frac{\text{d}^2\sigma_{\alpha\alpha}(\theta_1, \theta_2)}{\text{d}\Omega_1\text{d}\Omega_2} = \frac{\sigma_\alpha(\theta_1)\sigma_\alpha(\theta_2)}{\int\sigma_\alpha\,\text{d}\Omega}(M_\alpha - 1), \qquad (1)$$

where $\sigma_\alpha(\theta_1)$ and $\sigma_\alpha(\theta_2)$ are the energy integrated differential cross sections for α-particles observed inclusively at angles θ_1 and θ_2. The energy integration was extended over the whole energy spectra of the α-particles, which at forward angles only contain negligible contributions from evaporation processes. Angular distributions of singles α-particles at the two energies studied are shown in fig. 1.

If the α-particles in coincidence were indeed uncorrelated the α-multiplicities derived from eq. (1) would be independent of the angular configuration of the two telescopes. In fact, weak correlations between the α-particles do exist and the deduced values of M_α
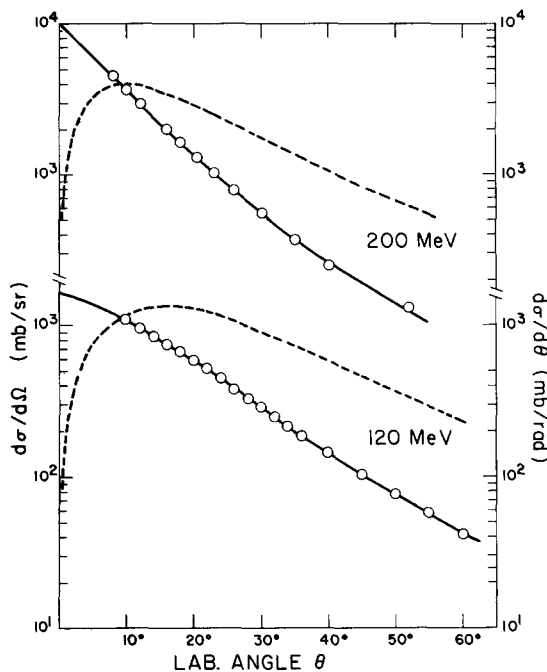
Fig. 1. Angular distributions of singles α-particles from the ^{12}C + ^{160}Gd reaction at E_C = 120 MeV and 200 MeV. The $d\sigma/d\theta$ angular distributions are shown by the dashed lines.
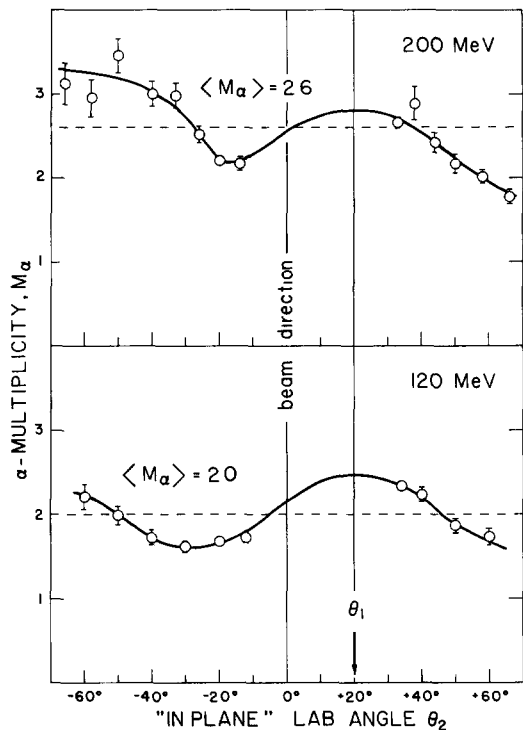

Fig. 2. Alpha-multiplicities determined by making use of eq. (1) for the ^{12}C + ^{160}Gd reaction at two bombarding energies: 120 and 200 MeV. The magnitudes of the average α-multiplicities $\langle M_\alpha \rangle$ are indicated by the dashed lines. For the averaging procedure the "correlation functions" indicated by the solid lines were assumed.

exhibit these effects. Fortunately, as follows from our data, the variations in M_α are relatively small. Therefore, even a very simple averaging procedure will yield the average α-multiplicity with reasonable accuracy.

Fig. 2 shows the α-multiplicities derived from eq. (1) for a number of angular combinations and for two bombarding energies: 120 and 200 MeV. For clarity, only the data for a fixed position of one of the telescopes (θ_1 = +20°) are displayed in the plots. The experimental points show the values of M_α at the angular position ($\theta = \theta_2$) of the second telescope. Both angles, θ_1 and θ_2, are measured in the same reaction plane. Angles at the opposite side of the beam (relative to θ_1) are denoted with a minus sign.

The "correlation functions" for θ_1 = +20° shown in fig. 2 are the most representative for the α-particle production in the studied reactions because the $d\sigma/d\Omega$ angular distributions for singles α-particles are peaked in the region of angles between 15° and 20° (see fig. 1). Several additional angular combinations (e.g. θ_1 = +10°, θ_2 = −10°; θ_1 = +14°, θ_2 = −14°, not presented in fig. 2) have been studied. All these

measurements yielded M_α-values within the same range of magnitudes as for θ_1 = +20°.

In order to estimate possible errors in the M_α-values for the ^{12}C + ^{160}Gd reaction due to light contaminants in the target (mostly from ^{12}C build-up during the experiments), series of measurements similar to those described above were carried out for the ^{12}C + ^{12}C reaction at the same bombarding energies. To minimize ^{12}C contamination, fresh ^{160}Gd targets were used in each series of experiments. Additionally, after each series of measurements the targets were examined by measuring elastic and inelastic scattering at forward angles. With this method an upper limit of about 4 μg/cm^2 of ^{12}C or ^{16}O was deduced. (This may result in an overestimate of the M_α-value by at most 5%.)

The shapes of the "correlation functions" shown in fig. 2 indicate that the emission of two (or more)

α-particles within a relative angle of $\lesssim 25°$ is enhanced over an uncorrelated emission. For $\theta_1 = +20°$ and relatively large negative angles θ_2 another correlation effect is seen that might be related to an enhancement of α-particle emission in the direction of the recoiling target nucleus. (Observation of such a correlation in (^{11}B, HI α) reactions was reported by Bhowmik et al. [5].

The horizontal dashed lines in fig. 2 indicate magnitudes of the average α-multiplicity, $\langle M_\alpha \rangle$, obtained by averaging the M_α ($\theta_1 = +20°, \theta_2$) curves over θ_2 with the weight proportional to the inclusive cross section. "Out-of-plane" correlation effects have not been studied in our experiments. Since the angular width of the "in plane" correlation is rather large (about $40°-50°$) as compared with the width of the forward directed "cone" where the main part of fast α-particles is concentrated, we do not expect within this "cone" for break-up or incomplete fusion type processes any drastic changes in M_α for "out-of-plane" angular combinations.

The average α-multiplicities determined as described above, correspond to a fixed angle $\theta_1 = 20°$. Since the angular distributions of the α-particles are strongly peaked at forward direction we adopt the $\langle M_\alpha \rangle$-values, as determined from the $\theta_1 = 20°$ data, to characterize all the processes of α-particle production at a given bombarding energy. Due to the uncertainties in the averaging procedure it is difficult to judge what the accuracy is of the average α-multiplicities deduced in this work. We, however, believe that this accuracy is better than 20% in the ($\langle M_\alpha \rangle - 1$)-values which are directly related to the $\alpha-\alpha$ coincidence rate [see eq. (1)]. Thus we conclude that $\langle M_\alpha \rangle = 2.0^{+0.2}_{-0.3}$ for $E_C = 120$ MeV and $\langle M_\alpha \rangle = 2.6^{+0.3}_{-0.4}$ for $E_C = 200$ MeV, where the lower limit includes a possible error due to carbon contaminations.

In table 1 we compare the magnitudes of the α-multiplicities with the results of our previous study [3] of the incomplete fusion reactions ^{160}Gd(^{12}C, α) and ^{160}Gd(^{12}C, 2α). In the table given are also the angle integrated cross sections for singles α-particles. [We denote these cross sections by σ_α(incl.).] The inclusive cross section can be written as:

$$\sigma_\alpha(\text{incl.}) = \sigma(^{12}\text{C}, \alpha) + 2\sigma(^{12}\text{C}, 2\alpha)$$

$$+ 3\sigma(^{12}\text{C}, 3\alpha) + ... , \qquad (2)$$

Table 1
Cross sections (from ref. [3]) and α-multiplicities from the ^{12}C + ^{160}Gd reaction at two different bombarding energies.

	$E_C = 120$ MeV	$E_C = 200$ MeV
σ_α(incl.)	850 mb	2100 mb
$\sigma(^{12}\text{C}, \alpha)$	177 ± 17 mb [a]	144 ± 23 mb [a]
$\sigma(^{12}\text{C}, 2\alpha)$	75 ± 9 mb [a]	119 ± 30 mb [a]
$\sigma(^{12}\text{C}, 3\alpha)$ [from eq. (3)]	174 ± 8 mb [a]	573 ± 21 mb [a]
$\langle M_\alpha \rangle$ [experiment]	$2.0^{+0.2}_{-0.3}$	$2.6^{+0.3}_{-0.4}$
$\langle M_\alpha \rangle$ [from eq. (4)]	1.99 ± 0.10	2.51 ± 0.13

[a] The uncertainties in the cross sections do not include a possible error ($\sim$20%) in the absolute values of σ_α(incl.) which were used to normalize the cross sections for the (^{12}C, α) and (^{12}C, 2α) reactions.

where the first two terms correspond to the incomplete fusion reactions, the third term corresponds to the breakup of ^{12}C into three α-particles, and other terms (not written explicitly) would correspond to the breakup of ^{12}C accompanied by the knock-out of one or more α-particles from the target nucleus. Neglecting these "breakup-knock-out" processes one can estimate the magnitude of the (^{12}C, 3α) cross section (see table 1),

$$\sigma(^{12}\text{C}, 3\alpha)$$

$$= \tfrac{1}{3} [\sigma_\alpha(\text{incl.}) - \sigma(^{12}\text{C}, \alpha) - 2\sigma(^{12}\text{C}, 2\alpha)] , \qquad (3)$$

and calculate the expected values of the average α-multiplicity:

$$\langle M_\alpha \rangle = \frac{\sigma_\alpha(\text{incl.})}{\sigma(^{12}\text{C}, \alpha) + \sigma(^{12}\text{C}, 2\alpha) + \sigma(^{12}\text{C}, 3\alpha)}$$

$$= \frac{3\sigma_\alpha(\text{incl.})}{\sigma_\alpha(\text{incl.}) + 2\sigma(^{12}\text{C}, \alpha) + \sigma(^{12}\text{C}, 2\alpha)} . \qquad (4)$$

As is seen from table 1, the average α-multiplicities determined from the $\alpha-\alpha$ coincidence data agree well with those calculated from eq. (4). We conclude therefore that fast α-particles produced in ^{12}C induced reactions originate mostly from incomplete fusion and projectile breakup reactions. The relative importance of these reaction modes strongly depends on the bombarding energy (see table 1, and also ref. [3]). Within the accuracy of our α-multiplicity measurements there is no need to consider the "breakup-knock-out" processes of high α-multiplicity ($M_\alpha \geqslant 4$) to explain the observed $\langle M_\alpha \rangle$-values.

References

[1] T. Inamura, M. Ishihara, T. Fukuda, T. Shimoda and H. Hiruta, Phys. Lett. 68B (1977) 51.

[2] D.R. Zolnowski, H. Yamada, S.E. Cala, A.C. Kahler and T.T. Sugihara, Phys. Rev. Lett. 41 (1978) 92.

[3] K. Siwek-Wilczynska, E.H. du Marchie van Voorthuysen, J. van Popta, R.H. Siemssen and J. Wilczynski, Phys. Rev. Lett. 42 (1979) 1599.

[4] H. Ho et al., Z. Phys. A283 (1977) 235.

[5] R.K. Bhowmik, E.C. Pollacco, N.E. Sanderson, J.B.A. England and G.C. Morrison, Phys. Lett. 80B (1978) 41.