Binary channels of the ^{19}F-on-^{12}C reaction at 92 MeV

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Binary-reaction channels of ^{19}F+ ^{12}C have been studied at $E_{lab}(^{19}F)=92$ MeV using kinematic coincidence techniques. The results are discussed in the light of previous inclusive measurements performed at the same incident energy and for which the occurrence of an important incomplete fusion mechanism after projectile breakup was proposed. Evidence for strong damped binary, especially quasisymmetric, decay processes is found. [S0556-2813(97)04701-8]

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The reaction products of ^{19}F on ^{12}C at 92 MeV have been studied by Kohlmeyer *et al.* [1] in an inclusive experiment in which the cross sections of both direct reaction and fusion channels have been measured after mass identification of the fragments. In particular, a strikingly large yield was observed for the production of ^{15}N fragments. A breakup process, following inelastic excitation of the projectile ^{19}F into ^{15}N+ α, which should be favored due to the unusually small separation energy (4.01 MeV) of the α particle, was then invoked and considered as the strongest direct channel. The importance of this process was confirmed by Smith *et al.* [2] in a study of the ^{19}F α-decaying states through the sequential breakup reaction $^{12}C(^{19}F,^{19}F^* \rightarrow ^{15}N + \alpha)$ at $E_{lab}=82$ and 144 MeV. But the assumption made in Ref. [1], that an important contribution of incomplete fusion resulting from the fusion of ^{15}N with the ^{12}C target following the breakup process should be included to improve the description of the evaporation residue mass distribution, seems to be surprising at an energy as low as 4.8 MeV/nucleon. Therefore, by focusing our interest on the binary products, we intend to learn more about the direct reaction mechanisms and, more generally, to improve our global understanding of the reaction mechanisms at an energy where the limitation of the fusion cross section should be accompanied by the increase of the direct reaction cross section from quasielastic and deep-inelastic processes.

We thus undertook an ''exclusive'' experiment using the kinematic coincidence method where the fragments from the binary channels were detected in coincidence using two silicon position sensitive detectors. The 92 MeV ^{19}F beam was provided by the Strasbourg Tandem accelerator and self-supporting carbon targets of 20 μg/cm^2 thickness were used. The Si detectors were located on both sides of the beam direction at a distance of 9 cm from the target and were covering angular ranges from 15° to 47° and from −61° to −20°. This geometry was chosen to optimize the detection of the most important binary channels expected to be populated in angular ranges above the grazing angles.

First we would like to make some remarks concerning the analysis of the mass distribution of the fusion-evaporation products reported in Ref. [1]. These experimental data were compared to Monte Carlo statistical calculations using the code LILITA [3]. In our calculation special care was taken to include the complete discrete level schemes of the residual nuclei and in particular their yrast levels. This allowed us, as shown in Fig. 1, to improve the agreement between the data and the statistical calculations, although discrepancies are still visible. The authors of Ref. [1], on the other hand, have made the hypothesis that an important contribution from incomplete fusion, ∼30% of the evaporation cross section, should be included so that the resulting calculations were able to reproduce the experimental data nearly perfectly. However, the above assumption is very far away from what can be expected according to the more recent systematics of Morgenstern *et al.* [4], which predict that the contribution of

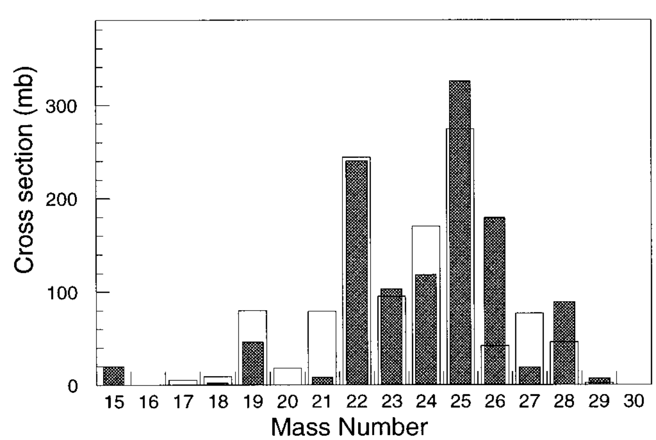

FIG. 1. Calculated (solid histograms) and measured (open histograms) mass distribution of fusion products in the ^{12}C+^{19}F reaction at $E_{lab}=92$ MeV. The data are from Ref. [1].

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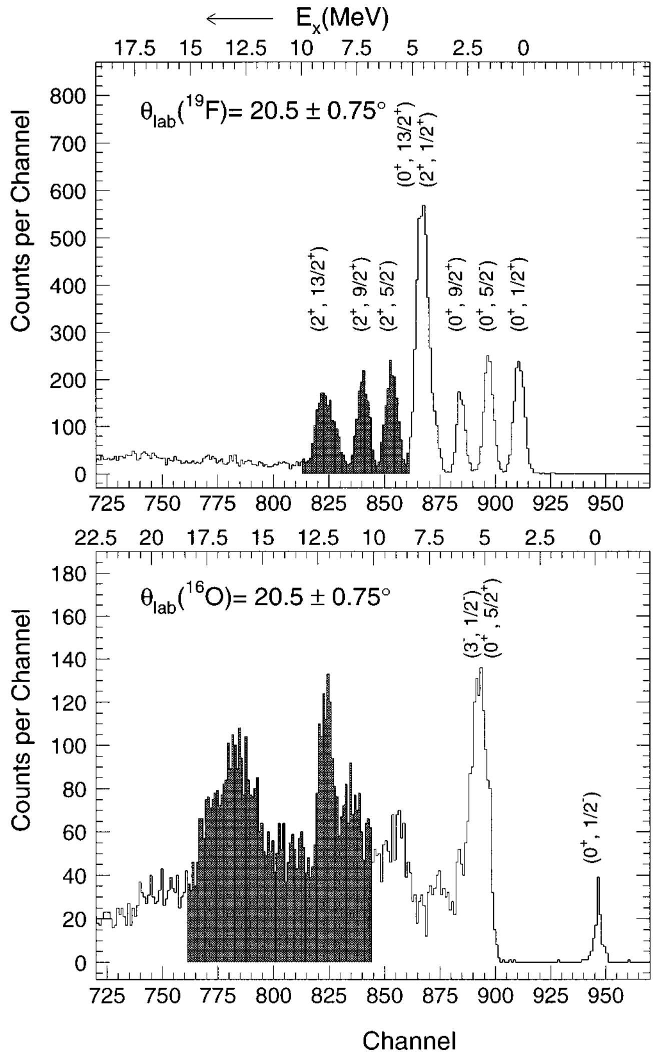

FIG. 2. Total energy spectra of the binary fragments for the most important channels: $^{19}F+^{12}C$ and $^{16}O+^{15}N$. The relevant excitation-energy scale for each channel is drawn on the top of the figure. The full zone of histograms corresponds to mutually excited states.

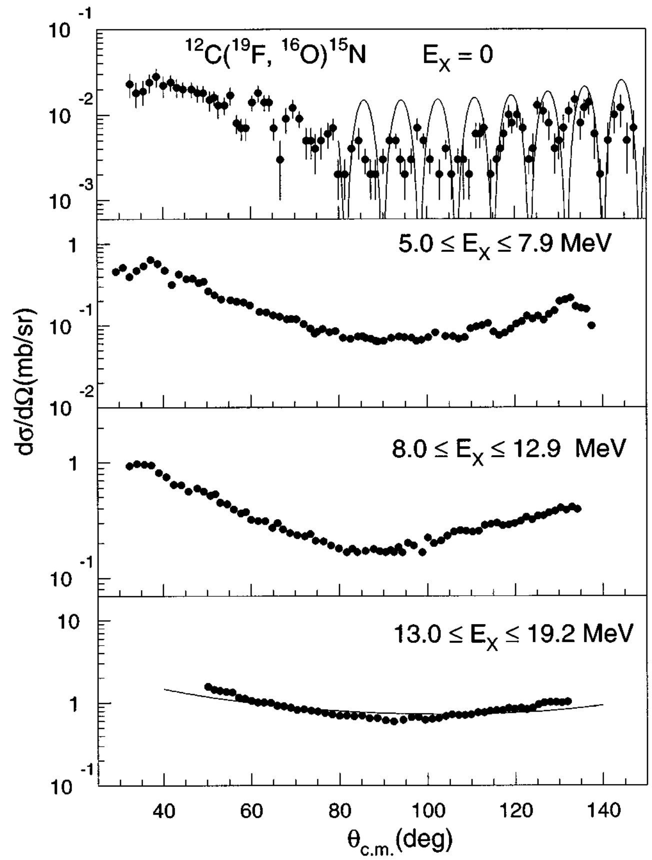

FIG. 3. $^{12}C+^{19}F \rightarrow ^{16}O+^{15}N$ reaction: angular distributions for different groups of states indicated by their excitation energies. The upper part shows a comparison of the backward g.s. angular distribution with a $P_L^2(\cos\theta_{\mathrm{c.m.}})$ form with $L=21$. The curve in the lower part results from a fit with the expression $A\exp(-\mu\theta_{\mathrm{c.m.}})/\sin\theta_{\mathrm{c.m.}}$ (see the text).

the incomplete fusion process in the system under study becomes effective only above 5.6 MeV/nucleon.

Let us now present the results of our exclusive measurements. After mass identification, it has been possible from the Q-value spectra combined to the well-known energy schemes of the produced nuclei to fully identify both exit fragments. The resulting Q-value spectra of the two most important channels are represented in Fig. 2. The $^{12}C+^{19}F$ channel shows a selective feeding of the yrast bound and the mutual excitation states up to a total excitation energy of $E_X \sim 9$ MeV ($E_X=4.65$ MeV in ^{19}F and $E_X=4.43$ MeV in ^{12}C). Above this excitation both nuclei are unbound and follow a particle-decay mode, leading to nonbinary processes which are rejected by our analysis. For the $^{16}O+^{15}N$ channel, which is energetically favored ($Q_0=3.15$ MeV) and resulting from the exchange of nucleons or clusters (α or t), four prominent groups of states are populated up to $E_X \sim 19$ MeV. This is allowed by the nuclear structure of both ^{15}N and ^{16}O where a large number of bound states are available up to $E_X \sim 10$ MeV and $E_X \sim 9$ MeV, respectively. The excitation energy of the more damped group is centered around the mean value $\langle E_X \rangle = 16.5$ MeV which corresponds to a total kinetic energy of the fragments $\langle TKE \rangle \approx 22$ MeV. This value is in good agreement with that expected for a rotating dinuclear system at scission given by [5,6]

$$\mathrm{TKE}=V_{\mathrm{Coul}}(d)+V_{\mathrm{nucl}}(d)+F^2\frac{\hbar^2 L_i(L_i+1)}{2\mu_f d^2}, \tag{1}$$

where $F=\mu_f d^2/(\mu_f d^2+I_1+I_2)$, μ_f is the reduced mass of the exit channel, $I_i = 2/5 m_i R_i^2 (i=1,2)$, and $d=R_1+R_2+\delta$ is the distance between the mass centers of the two nuclei, δ being the neck length. The values of L_i which make the dominant contribution to fully damped collisions lie between the critical angular momentum for fusion, L_{cr}, and the grazing angular momentum L_{gr}. Making the assumption that $L_i=(L_{\mathrm{cr}}+L_{\mathrm{gr}})/2 \approx 20.7$ and $d=(R_{\mathrm{cr}}+R_{\mathrm{B}})/2 \approx 6.62$ fm which corresponds to $\delta=0.7$ fm, we found TKE ≈ 22.5 MeV, which is in good agreement with the observed experimental value.

Other binary channels although weaker such as $^{13}C+^{18}F$, $^{14}N+^{17}O$, and $^{11}B+^{20}Ne$ were also identified, they show the same selectivity in the population of yrast states and mutual excitation states.

Among the measured angular distributions, Fig. 3 shows those for the $^{16}O+^{15}N$ channel for different excitation energies of the emitted fragments. While the ground-state (g.s.) angular distribution displays a well-structured behavior, the distributions become less and less structured with increasing excitation energy . The comparison of the g.s. angular distribution at backward angles to the $P_L^2(\cos\theta_{c.m.})$ forms gives a rather good fit with $L=21$ as displayed in the upper part of Fig. 3. This value corresponds to the higher L value of the partial waves involved in the reaction and is equal to the expected grazing partial wave deduced from semiclassical calculations.

The angular distribution of the most damped group is nicely reproduced with the expression predicted by a simple semiclassical model of a rotating dinuclear system [7]:

$$\sigma(\theta_{c.m.})=A\exp(-\mu\theta_{c.m.})/\sin\theta_{c.m.}, \tag{2}$$

with the parameters $A=1.13$ mb/sr and $\mu=0.26$ indicating the occurrence of an almost fully relaxed process. The observation of such a strong process disagrees with the conclusions of Ref. [1] which exclude a deep-inelastic process by arguing that although the transfer of an α particle from and to ^{19}F should be equally probable, no ^{23}Na is produced with an intensity comparable to that of ^{15}N and that the expected daughters ($A=12$ and $A=14$) from the disintegration of the highly excited reaction partners ^{16}O and ^{15}N, respectively, are not observed with sufficient cross sections compared to the first-step nuclei.

Concerning the angular distributions, the general features mentionned above are also observed for other exit channels: They are structured for the g.s. groups, though less pronounced than for $^{16}O+^{15}N$, and they evolve towards a form close to $1/\sin\theta_{c.m.}$ for the more excited groups. Such a variation reflects an isotropic fragment emission probability which is a signature of long-lived dinuclear configurations. These configurations were also reported in other light nuclear systems [8]. The interpretation of the dynamical nature of the process is still controversial although the general trend is to consider fusion and fission or orbiting depending on the strength of the absorption, i.e., on the number of open channels [9].

We conclude thus that although the production of ^{15}N in the $^{12}C+^{19}F$ reaction at 92 MeV is probably mainly coming from the breakup of the ^{19}F projectile, the contribution of $^{16}O+^{15}N$ binary quasisymmetric decay is important and cannot be neglected. Finally, there is strong indication that the incomplete fusion process, if present, is certainly less important than indicated in Ref. [1] at the energy under study even though breakup of the projectile is favored in the reaction.

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