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Clustering effects in fusion evaporation reactions with light even-even N=Z nuclei

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Abstract. In the recent years, cluster structures have been evidenced in many ground and excited states of light nuclei [1, 2]. In the currently experimental campaign, the NUCL-EX collaboration has measured the ^{12}C+^{12}C and ^{14}N+^{10}B reactions at 95 MeV and 80 MeV respectively. The experimental data corresponding to complete fusion of target and projectile into an excited ^{24}Mg nucleus was compared to the results of a pure statistical model [3, 4]. In addition, data from ^{12}C+^{12}C have been analyzed to investigate the decay of the Hoyle state of ^{12}C* [12] obtained as an intermediate step in the 6α decay channel of the ^{24}Mg* formed in central events.

1. Introduction

The subject of α-chains as possible building blocks of even-even nuclei has been proposed in the late sixties and α-clustering has become a central issue in nuclear physics ever since. At present, the NUCL-EX collaboration has started a campaign of exclusive measurements of fusion-evaporation reactions employing light nuclei as interacting partners. In this campaign, the first studied system has been the ^{24}Mg compound nucleus. The ^{24}Mg has been populated at the same excitation energy through the ^{12}C+^{12}C and ^{14}N+^{10}B reactions in order to study the influence of the entrance channels. In section 3.1, the results obtained from these first measurements are briefly summarized.

For instance, the Hoyle state [5] of ^{12}C (0^+ at 7.65 MeV) is known to manifest α-clustering effects which play a decisive role in the abundance of this element. Most of the recent results indicate a nearly complete agreement with a sequential decay through an intermediate ^{8}Be$_{gs}$ [6, 7], for the Hoyle state . Instead, few other experimental results show also a significant amount of instantaneous 3-α particle decay [8]. In section 3.2, the results from the analysis of central ^{12}C + ^{12}C reactions where the ^{24}Mg* compound nucleus decays in six α-particles, are shown.

2. The experiments

The experiments were performed at the LNL (Laboratori Nazionali di Legnaro), with ^{12}C and ^{14}N beams provided by the XTU TANDEM accelerator. We have studied the two systems ^{12}C + ^{12}C and ^{14}N + ^{10}B, leading to the same compound nucleus ^{24}Mg* at the same excitation energy. The apparatus has been fully described in [9] and hereafter we recall the main characteristics. The experimental apparatus is composed of the GARFIELD detector and the Ring-Counter (RCo) annular detector [10]. The latter apparatus (RCo) covers the forward polar angles ($7^o \div 17^o$) and is divided into three detection stages: an ionization chamber (IC), silicon strips (Si) and CsI(Tl) scintillators. With the current setup, an angular resolution of $\sim \pm\, 0.7^o$ for the polar angle is achieved while $\sim \pm\, 11^o$ for the azimuthal angle is feasible for particles detected in the scintillators. The RCo detector allows reaching energy resolution of percent, charge and mass identification of light particles. The remaning polar angles ($\theta = 30^o \div\, 170^o$) are covered by the GARFIELD detector composed by a drift ionization chamber followed by CsI(Tl) scintillators.

3. Results

3.1. Central ^{12}C + ^{12}C and ^{14}N +^{10}B reaction

Since the experimental apparatus allows a complete reconstruction of the events, a Q_{kin}-value distribution estimating the dissipated energy [11] can be built to further investigate all the channels involving alpha particles in both reactions: $Q_{kin} = \sum_{i=1}^{2} E_{\alpha_i} + E_{Z_{Res}} - E_{beam}$, where E_{α_i} and $E_{Z_{Res}}$ are, respectively, the laboratory energy of α particles and residues, and E_{beam} is the energy of the incident projectile. In figure 1 the obtained Q_{kin} distributions for the channels with the maximum α multiplicity associated to the residue of charge Z are displayed for the two reactions.

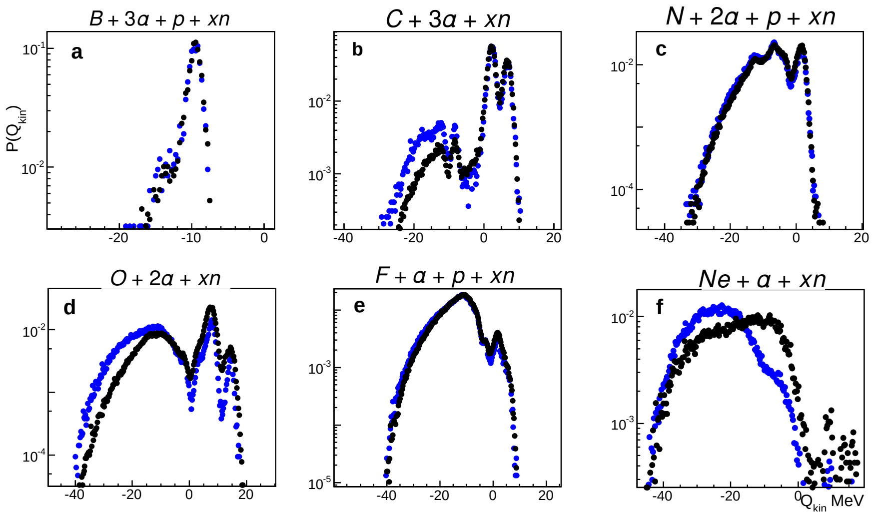

Figure 1. Q$_{kin}$-values distribution for different residues, indicated in each panel, detected in coincidence with the maximum possible number of α-particles. Data from the ^{12}C+^{12}C and ^{14}N+^{10}B reactions are represented by the black dots and by the blu dots, respectively.The Q$_{kin}$ is normalized to the Q-value of ^{14}N+^{10}B data.

In figure 1d), the Q_{kin} distribution for the channel 2α, ^{16}O$^{gs/*}$ is shown. One can clearly notice two distinguished peaks corresponding to different α-decay chains, which populate the ^{16}O residue either in its ground state or in one of its excited bound states. A broader distribution is also observed for lower Q_{kin} values due to events associated with the opening of the 4-body channel ^{15}O+$n + \alpha + \alpha$. The two reactions, ^{12}C+^{12}C (black dots) and ^{14}N+^{10}B (blue dots),

Table 1. For the measured evaporation residues, the table shows the most probable experimental channel and its branching ratio alongside with the value predicted by the HFℓ calculations. Every experimental value has an associated error of 5% which takes into account both statistical error and the particle contamination

Z_{res}	Channel	BR_{exp} NB (%)	$BR_{HF\ell}$ NB (%)	BR_{exp} CC (%)	$BR_{HF\ell}$ CC (%)
5	$^{11-xn}$B+3α+p+xn	99	100	99	100
6	$^{12-xn}$C+3α+xn	96	74	98	78
7	$^{15-xn}$N+2α+p+xn	90	95	91	95
8	$^{16-xn}$O+2α+xn	56	15	63	15
9	$^{19-xn}$F+α+p+xn	91	93	92	88
10	$^{22-xn}$Ne+α+nx	47	3	26	3

show an evident difference in the relative population of more and less dissipative events, as can be evinced from figure 1 [1]. In fact, a much higher percentage of (2α,^{16}O) events populates the less dissipative Q-value region in the ^{12}C sample. This larger deviations are common to all the even-Z residues, while a very good agreement for the Q_{kin} distributions for the odd-Z residues is observed. In Table 1, the branching ratios (BR) for the most populated channel in the experimental sample and HFℓ prediction for both reactions, are shown for each residue. One can notice a good agreement between the experimental and statistical model BR of the dominant decay channels for odd Z residues, while discrepancies can be seen for even-Z ones. For the final Carbon, Oxygen and Neon residues, the evaporation chains show a preferential α decay in both reactions. This α excess could be attributed to the presence of residual α correlations in the excited ^{24}Mg or in its daughter nucleus ^{20}Ne, regardless of the entrance channel of the reaction.

3.2. $^{12}C^*$ Hoyle state in $^{24}Mg^*$ decay: the 6-α channel

As anticipated, the 6-α decay channel for the ^{12}C + ^{12}C reaction was investigated to study the decay of the Hoyle state. We have reconstructed the dissipated energy using the Q_{kin} quantity previously defined ($Q_{kin} = \sum_{i=1}^{6} E_i - E_{beam}$). In figure 2 (left panel) the Q_{kin} distribution is shown, together with the cut used for the analysis.

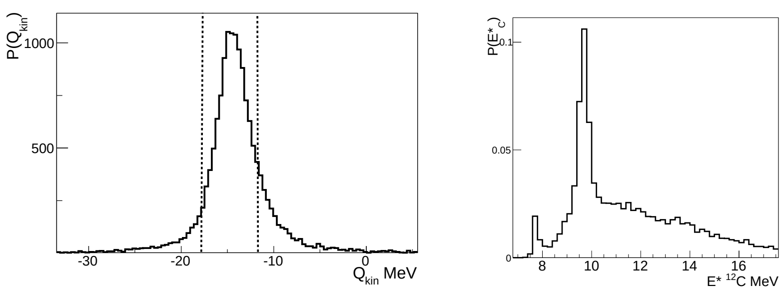

Figure 2. Left panel: Q_{kin} distribution for the six α-particles events. The vertical lines indicate the events retained for the analysis. Right panel: Reconstructed ^{12}C* excitation energy from the three α-particles with the minimum total energy in central collisions.

In order to reconstruct the intermediate ^{12}C* disassembling into 6 alphas of the ^{24}Mg*

[1] with less dissipative we indicate events with Q_{kin} greater than the neutron emission threshold

formed in central collisions we have selected the three (out of six) α-particles corresponding to the minimum ^{12}C* excitation energy. This quantity is shown in right panel of figure 2 where the two peaks correspond to the lowest excited states of ^{12}C* at 7.65 and 9.64 MeV. The former represents the well known Hoyle state. The main debate consists in the interpretation of the decay of this state as sequential, via the $^{8}\mathrm{Be}_{gs}$ formation, or if there is a contribution of instantaneous breakup in alpha-particles. To clarify this point, different observables have been proposed. As an example, we show the energy Dalitz plot where data and HFℓ predictions show the same configuration (see figure 3). The two coordinates of the Dalitz plot are defined as $x_d = \sqrt{3}(e_1 - e_2)$ and $y_d = 2e_3 - e_1 - e_2$, where $\mathrm{e}_{i,j,k} = E_{i,j,k}/(E_i + E_j + E_k)$ are the α-particle energies in the ^{12}C frame, normalized to the total energy.

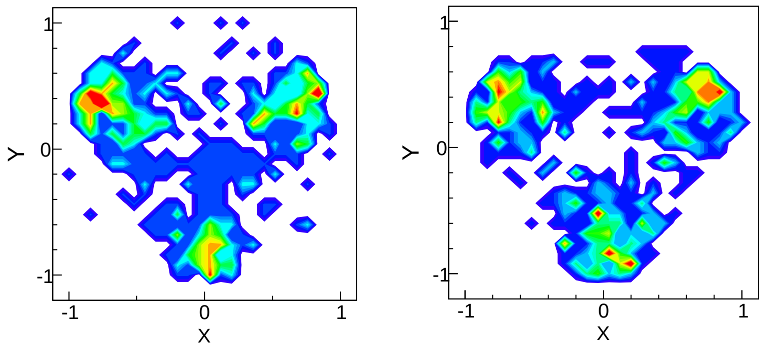

Figure 3. Central collisions. Left panel: experimental energy Dalitz plot. Right panel: HFℓ Dalitz plot.

All the results obtained in inelastic channels in ^{12}C+^{12}C reaction [12] and in various reactions at different energies [6, 7] indicate a very low limit of breakup in alpha-particles of the order of permil.

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