EMISSION OF COMPLEX FRAGMENTS FOR COMPOUND NUCLEI FORMED FAR FROM THE STABILITY LINE FOR A~120

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Experiments and calculations are presented for the emission of complex fragments (Z>2) from compound nuclei around mass 120 and for bombarding energies below 15 MeV/nucleon. It is shown that a strong enhancement in the emission of complex fragments (especially for Z=6) is expected for compound nuclei formed close or at the N=Z line. Several predictions are given that could be tested with the radioactive beams soon to be available. Also results from a recent experiment that utilizes the emission of complex fragments for γ-ray nuclear spectroscopy studies are presented.

1 Introduction

The understanding of the emission of complex fragments (also defined as intermediate mass fragments (IMF) with nuclear charge Z>2) from highly excited compound nuclei is a topic of current interest. For energies above 15 MeV/nucleon, detailed studies of IMF provide important information about the competition between multifragmentation and sequential emission processes. On the other hand, and at lower energies where multifragment emission is not possible, measurements on the emission of IMF have been explained by a complete fusion mechanism and decay described successfully by the Hauser-Feshbach formula, extended to many channels. Particularly, the reaction $^{58}\text{Ni}+^{58}\text{Ni}$ at 8 and 11 MeV/nucleon, shows fairly large cross sections for the emission of B, C, N and O (65 mb for C isotopes mostly $^{12}\text{C}$ in ground and first excited state were measured at 11.8 MeV/nucleon). Also it should be interesting to note that for this reaction the decay channels of C +xn populate the Sn nuclei from 104 to 100.

Until now measurements have been focused on the emission of IMF, their cross sections and reaction mechanisms and no attention has been given to the study of the residual nuclei (or evaporation residues, ER) produced by such a decay. The reason for this lies on the fact that the ER are more difficult to study because they are slow moving heavy fragments traveling along the beam direction. In this contribution we report on a measurement of IMF detected in coincidence with ER detected with the Ge detector array GASP at Legnaro National Laboratory. Also, we describe several measurements of IMF-ER coincidences measured with the HILID detector array at ORNL and Texas A&M University.
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With the use of proton rich radioactive beams, compound nuclei can be formed far from the stability line and close to the proton drip line. For these nuclei, the dominant decay modes should be explored, particularly since the neutron decay becomes strongly inhibited. In this report, we make the case that the emission of IMF may be a very strong decay mode and thus worthy of study.

2. The $^{58}$Ni+$^{58}$Ni System

The $^{58}$Ni+$^{58}$Ni system has been studied in detail at 8 MeV/nucleon and 11.8 MeV/nucleon and the results have been explained by a complete fusion mechanism and decay described successfully by the Hauser-Feshbach formula, extended to many channels (approximately 400 binary decay channels). Figure 1 shows the results for the data at 11.8 MeV/nucleon for the angle integrated cross section ($\sigma$). The hatched histograms are the results of the Hauser-Feshbach calculations performed with the code BUSCO. The absolute normalization of the calculations shown in Fig. 1 is given by the choice of critical angular momentum for fusion, $J_c$, of $68\ h$. This value of angular momentum is consistent with current systematics of the fusion mechanisms for compound nuclei around mass 116. In Ref. 2 and 3, it was pointed out that the center of mass (cm) angular distribution of the fragments emitted below $Z=10$ has the expected equilibrium shape of $1/\sin(\Theta_{cm})$, however, for larger $Z$ there is a substantial amount of forward peaking. Also, the same observations were supported by studying the population of excited states through $\gamma$-ray measurements. As can be seen from Fig. 1, below $Z=10$ the agreement between theory and experiment is very good.

To gain a better understanding of the reaction mechanisms for the emission of IMF the $^{58}$Ni+$^{58}$Ni system was studied in more detail at 8 MeV/nucleon using the HILI detector system. This detector has been described in Ref. 4 and for this work the main comment is that the detector is ideal to study closely-spaced correlations between the IMF and ER. For every event measured with HILI, we have ER, the coincident light particles, and IMF. More details of these experiments are given in Ref. 5. The experimental quantities measured for the IMF were: $Z$, the kinetic energy ($E$), and the direction of emission with respect to the beam axis defined by the polar angle ($\Theta$) and azimuthal angle ($\Phi$). For the ERs only the $E$ and direction of emission were determined and not the $Z$, however, this can be estimated from Monte Carlo calculations.
An interesting quantity that could be helpful in the analysis of the emission of the IMF is the relative kinetic energy $E_{\text{rel}}$ of the coincident pair ER and IMF. It is defined by $E_{\text{rel}} = \frac{1}{2} \mu |V_{\text{IMF}} - V_{\text{ER}}|^2$, where $\mu$ is the reduced mass of the pair, $V_{\text{IMF}}$ is the lab velocity vector for the emitted IMF and $V_{\text{ER}}$ is that of the ER. The experimental results for the relative kinetic energy are shown in Fig. 2 for the case of C in coincidence with the ER. The vertical scale given in the figure corresponds to the differential multiplicity $d\phi/dE$ defined as the number of IMF in a given energy interval $dE$ divided by the total number of ER's registered in the HILI. The crosses plotted in Fig. 2 correspond to the statistical emission process for the IMF and they were done with the code BUSCO using the same set of parameters as the calculations given in Fig. 1. It is interesting to note that the maximum of the spectrum shown in Fig. 2 occurs at about 60 MeV, a value close to the coulomb barrier of C emitted from the compound nucleus $^{116}\text{Ba}$.

Another important consequence of the compound nucleus emission mechanism for the IMF is that they are emitted mostly in the first step of the reaction when the angular momentum of the compound nucleus is the highest. This implies that the IMF and ER lie on the same reaction plane, i.e., the difference of their respective azimuthal angle ($\Phi$) should be $180^\circ$ regardless of the polar angle ($\Theta$). Therefore, a construction of the angular correlation $\Delta\Phi = |\Phi_{\text{ER}} - \Phi_{\text{IMF}}|$ which will reflect the degree of coplanarity of the emission process will be extremely useful. Such angular
correlation was extracted from the presented data and it was confirmed that the emission is highly coplanar.

With the use of the HILI detector other systems have been measured: $^{79}$Br+$^{27}$Al, $^{58}$Ni+$^{24}$Mg and $^{84}$Kr+$^{27}$Al at energies in MeV/nucleon of 11.5, 11, and 15, respectively, and should provide a valuable set of data to help in the understanding of the IMF emission process. These systems are currently under analysis.

3. Enhanced emission of IMF

Measurements using $^3$He and $^4$He projectiles on Ag and Sn isotopes$^{6,7}$ were shown to be consistent with emissions expected from compound nucleus. Of particular interest here are the measurements of Ref. 7 that show a target isotopic dependence on the emission of the IMF in which the cross sections are larger for the lighter compound nucleus. In Fig. 3 we show the measured cross section$^7$ for $Z=6$ fragments for the targets $^{116}$Sn and $^{124}$Sn at a $^4$He bombarding energy of 180 MeV. The horizontal axis plots the N/Z ratio of the compound nucleus and as can be seen the cross section increases significantly with decrease of N/Z. The solid line
Figure 3. Carbon emission in $^4\text{He} + ^{116,124}\text{Sn}$. Data from Ref. 7. Is the result of the Hauser-Feshbach calculation done with the code BUSCO. The main observation to be drawn from the calculations given in Fig. 3 is that they predict a dramatic increase of the cross section with decrease of N/Z. Obviously, it will be interesting to pursue experimentally these isotopic effects, but for the reaction given in Fig. 3, there is little more that can be done because the last possible target is $^{112}\text{Sn}$ (0.9% abundance) that gives the value of N/Z only of 1.23. Also, it should be noticed that the reactions induced by light projectiles like $^4\text{He}$ produce cross sections for emission of IMF which are an order of magnitude lower than for heavy ions like the $^{58}\text{Ni} + ^{58}\text{Ni}$ reaction.

The $^{58}\text{Ni} + ^{58}\text{Ni}$ reaction populates the compound nucleus $^{116}\text{Ba}$ which has a N/Z ratio of 1.07. To study reactions with lower N/Z values in the same mass region the use of a radioactive beam is required. For instance, the study of $^{54}\text{Ni} + ^{58}\text{Ni}$ would form compound nuclei of N/Z=1.0. $^{54}\text{Ni}$ is not one of the heavy beams that will be available at HRIBF, but interesting studies can be done with the $^{63}\text{Ga}$ and $^{64}\text{Ga}$ beams which could be available. In Fig. 4 we show the predictions for the IMF decay of compound nuclei formed by bombarding a $^{50}\text{Cr}$ target with a stable beam $^{69}\text{Ga}$ (hatched histogram), and with radioactive beams of $^{64}\text{Ga}$ (dotted histogram), and $^{63}\text{Ga}$ (dark histogram) which populated compound nuclei of Cs
isotopes with N/Z ratios of 1.16, 1.07, and 1.054, respectively. The bombarding energy of the Ga beams is 5 MeV/nucleon corresponding to about 720 mb of fusion cross section. The vertical axis on Fig. 4 gives the cross section for the emission of IMF from Z=5 to 9 expressed as a percent of fusion, and, as can be seen particularly for C, the cross sections are fairly large for the lighter beam (63Ga) that populates the compound nucleus with the smaller N/Z value. Other systems like 74Kr+40Ca and 54Ni+58Ni have been calculated and show very strongly enhanced emissions of IMF with a maximum in the cross section occurring at about 5 MeV/nucleon.

4. C-γ coincidences

In an attempt to advance the understanding of the IMF emission process and to confirm in an independent way the compound nucleus nature of the mechanism, an experiment was set to observe the γ-rays emitted in coincidence with the emission of IMF, in particular 12C. The 58Ni+58Ni system was chosen because extensive previous measurements exist and the IMF emission produce ER close to A~100. Also, it would be of interest to establish whether or not the IMF emission brings new features into the nuclear structure of the residual nuclei due to the fact that IMF decay occurs from higher angular momentum states than those that decay by α or p.
A bombarding energy of 375 MeV was chosen to maximize the IMF cross section and to produce useful spectroscopic information. The experiment was carried out at the Legnaro National Laboratory using the Tandem-ALPI accelerator facility. The emitted IMF were detected in an array of Si counters placed within the geometry of the GASP high resolution γ-ray spectrometer. Figure 5 shows the resulting γ-ray spectra in coincidence with the emitted C ions. Several comments are important to make from the data given in Fig. 5. The star, open triangle, and solid dot, correspond to characteristic γ-rays of the nuclei, $^{96}$Rh, $^{95}$Ru, and $^{99}$Pd, respectively, indicating that the emission of C produces a heavy fragment of mass close to the compound nucleus ($A=116$) consistent with ER, thus confirming the compound nucleus nature of the emission process. Also, it should be noticed that at the same time γ-ray data were acquired in coincidence with α-particles and very different spectra were obtained in coincidence with 3 α's. In particular, the γ-rays corresponding to the $^{95}$Ru nucleus were seen only in coincidence with carbon. By analyzing the $γ-γ$-IMF correlations, it will be possible to study many of the final

Figure 5. Experimental γ-ray spectra measured in coincidence with C emitted from $^{58}$Ni+$^{58}$Ni at 375 MeV bombarding energy. The symbols correspond to several of the residual nuclei produced.
nuclei populated by the IMF decay and perhaps new features could be encountered. The analysis of this data is in progress.

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