Isospin Dependence in The Emission of Complex Fragments from Compound Nuclei of Mass A ~ 114 and N ~ Z

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1. Motivation

The decay of excited nuclei produced in low-energy nuclear reactions has been the subject of numerous experimental and theoretical investigations. For non fissile nuclei, the cooling down process of nuclei is dominated by multiple light particle emission, well treated in statistical Hauser-Feshbach approaches. However, deexcitation from nuclei at the limit of the nuclear chart is unknown. With the use of proton-rich radioactive beams, provided by the SPIRAL facility, compound nuclei can be formed far from the valley of stability and close to the proton drip line. For these nuclei, the possible decay modes should be explored, particularly since the neutron decay becomes strongly inhibited. In this proposal, we make the case that the emission of complex fragments (also called intermediate mass fragments, IMF, of nuclear charge Z, ($3 \leq Z \leq 12$) may be a very strong decay mode of compound nuclei of mass A ~ 114 and close to the proton drip line.

Previous measurements on the emission of IMF [1,2] for compound nuclei of mass A = 116 have been explained by complete fusion mechanism and their decay described successfully by the Hauser-Feshbach formula, extended to many channels (approximately 400 binary decay channels). Particularly, the reaction ^{58}Ni + ^{58}Ni at 8 and 11 MeV/nucleon shows fairly large cross sections for the emission of B, C, N, and O. For example, a cross section of 65 mb for the emission of C isotopes (mostly ^{12}C in ground and first excited state) was measured in Refs. 1 and 2. A recent measurement [3] for ^{58}Ni + ^{58}Ni at a lower energy (6.5 MeV/nucleon) has also shown large cross sections for the emission of IMF In the same experiment γ-ray spectroscopic studies (for nuclei of mass A ~ 100) were carried out using the carbon emission in coincidence with γ-rays emitted by the residual nuclei. Recent measurements done at GSI by La Commara et al [4] have shown the usefulness of the IMF emission in ^{58}Ni + ^{58}Ni to study nuclei , close to the proton drip line (like ^{101}Sn, and ^{99}Cd) , albeit there were produced with very small cross sections.

Other measurements relevant to the study of IMF emission for compound nuclei around A~116 are those using ^{3}He and ^{4}He projectiles on Sn and Ag isotopes [5,6]. Of particular interest here are the measurements of Ref. 5 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. 1 we show on the vertical axis the experimental cross section deduced from Ref. [5] for C fragments emitted in the reactions 180 MeV ^{4}He on ^{116}Sn and ^{124}Sn . The horizontal axis corresponds to the N/Z ratio of the compound nucleus and, as can be seen, the cross section increases significantly even with a moderate decrease of N/Z. The solid line is the result of the Hauser-Feshbach calculation done with the code BUSCO discussed in Refs. 1 and 2. The main observation to be drawn from the calculations shown in Fig. 1 is that they predict a dramatic increase of the cross section with decreasing N/Z. It will be very interesting to pursue experimentally the isotopic dependence previously mentioned , however for the reaction studied in Ref. 5 there is little more that can be done because the lightest Sn isotope that can be used as a target is ^{112}Sn (0.9% abundance) which gives only a N/Z ratio of 1.23. Furthermore it should be noted that the reactions induced by light projectiles such as ^{4}He produce experimental cross sections for emission of IMF that are two orders of magnitude lower than those for heavy ions like the ^{58}Ni + ^{58}Ni reaction. For example the cross section for C emission is 0.5 mb for the case of ^{4}He on ^{116}Sn [5] compared to 65 mb for the emission of C in ^{58}Ni + ^{58}Ni [1].

The ^{58}Ni + ^{58}Ni reaction populates the compound nucleus ^{116}Ba which has an 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 fusion of ^{74}Kr + ^{40}Ca would form compound nuclei (^{114}Ba) of N/Z of 1.035. Beam of ^{74}Kr is available at SPIRAL with expected intensities of about 10^{4}p/s, in an energy range which is perfectly adapted for complete fusion reactions. Furthermore the decay of the compound nucleus ^{114} Ba by the emission of IMF will populate nuclei at or below the N=Z line for mass 100 to 90 (see ref [3,4]) and thus the importance of determining whether the predicted enhancement on the emission of IMF is present or not.

In Fig. 2 we show calculations with the code BUSCO for the emission of IMF from compound nuclei formed by bombarding a ^{40}Ca target with a stable beam of ^{78}Kr (open circles) and with the radioactive beam of ^{76}Kr (crosses) and ^{74}Kr (solid circles) that populated compound nuclei of Ba isotopes. The calculated cross sections (in mb) are plotted versus the bombarding energy per nucleon and, as can be seen, the maximum of cross section for all target combinations occurs around 5 MeV/nucleon. More important, the maximum cross section increases dramatically with the decrease of N/Z of the compound nucleus. In fig 3, we show the Z distribution of the IMF's for the ^{74}Kr + ^{40}Ca system at a bombarding energy of 400 MeV (close to the optimal energy for Z=6 emission predicted in figure 2) and indeed the production of carbon isotopes clearly dominates the IMF production. It is important to emphasize that the rise of IMF cross section with decreasing N/Z ratio of the compound nucleus is an effect that is evident in the Z distribution and therefore the Z,A distributions, although desirable to be measured, are not necessary. In fact for the calculations given in figure 3 for Z=6 ^{12}C emission represents 80% of the predicted cross section. The cross sections given in figure 2 and 3 are for all particle stable IMF from Z =3 to 14. For example the production of ^{8}Be which is in itself large (80 mb for ^{74}Kr at 400 MeV) is not plotted but certainly is included in the calculation.

2. Experiment

We propose to measure the IMF Z distributions for one radioactive beam (^{74}Kr) on a ^{40}Ca and at a bombarding energy of about 5 MeV/nucleon. To test the equipment and have a reference value of the IMF's cross sections we also request the use of a ^{78}Kr beam at 4, 5, 6 MeV/nucleon on the ^{40}Ca target. We propose to use the

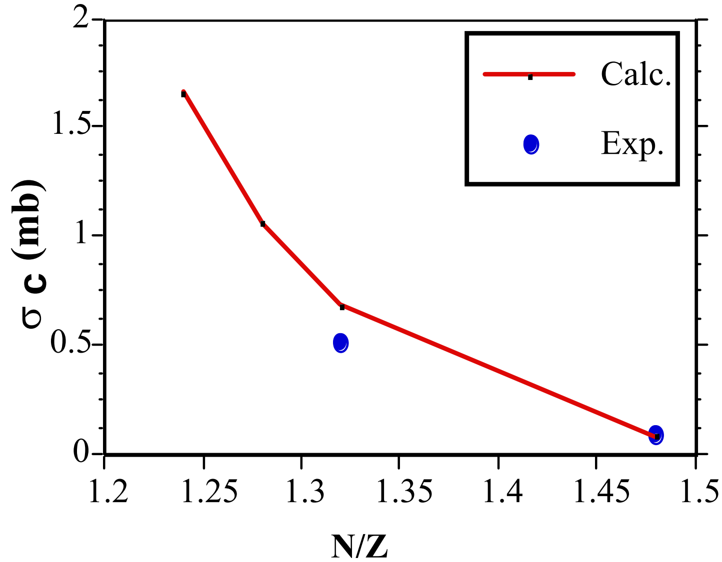

Figure 1. Carbon emission in ^{4}He + ^{116,124}Sn. Data from Re

large detector array INDRA in conjunction with a Micro Channel Plate (MCP) two-dimensional position sensitive timing detector. The MCP will be placed at the entrance of the INDRA detector to provide, with the beam, a timing trigger and a beam quality analyzer. If possible the MCP signal will be used to provide timing with the forward angle (< 12^0) INDRA detector telescopes. Adding timing channels to the forward angle telescopes will provide time of flight spectra that should be able to produce one mass unit resolution for Z~6. The use of INDRA will be extremely useful to measure the IMF angular distribution from ~2^0 to 100^0 with a very low threshold. In addition we will be able to monitor the elastic scattering at forward angles to provide absolute normalization to the data. Light particle multiplicities associated with IMF will provide an extremely valuable piece of data to study possible isospin effects in compound nuclei and study primary vs. secondary emission effects on the IMF's (see ref [1] and [2]). The angular granularity will be also adequate to provide a reasonable measurement of particle unstable IMF like ^{8}Be

Using a ^{40}Ca target of a thickness of 500 μg/cm^2, a beam intensity of 10^4p/s and the predicted angular distribution for Z=6 at 400 MeV ^{74}Kr +^{40}Ca, the expected counting rate is about 20cts/hr at 8^0 and 50cts/hr at 40^0. We request a total of 15 UT of running time for the radioactive beams of ^{74}Kr and 15 UT for ^{78}Kr as well. The requested bombarding energies are: for ^{74}Kr 5.4 MeV/nucleon and for ^{78}Kr 4,5 and 6 MeV/nucleon.

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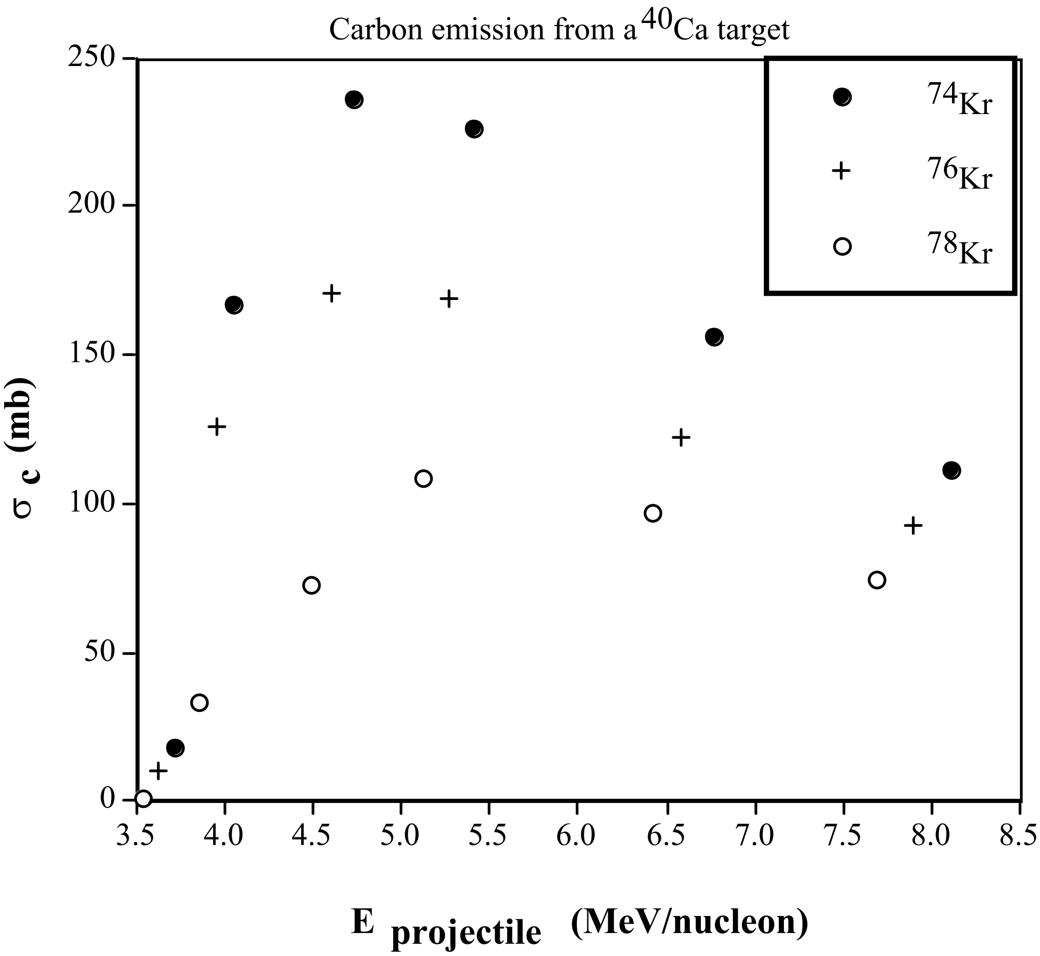

Figure 2. Cross section for the emission of C isotopes as a function of E/nucleon. Calculations are done with the code BUSCO for beams of ^{74}Kr, ^{76}Kr, and ^{78}Kr on a ^{40}Ca target .

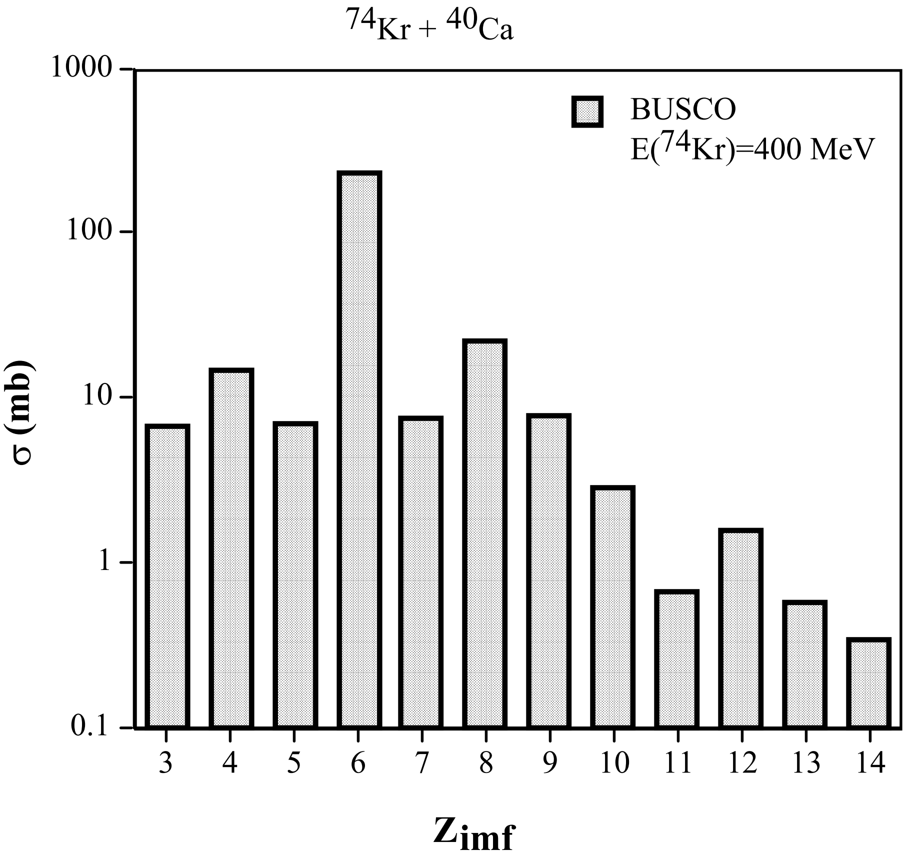

Figure 3. Angle integrated cross section for the emission of IMF for the ^{74}Kr + ^{40}Ca system at a bombarding energy of 400 MeV.