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PARTICLE EMISSION AS A PROBE FOR DYNAMICS OF FISSION OF HEATED NUCLEI*

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New data on neutron, proton and alpha particle multiplicity measured for the reactions ^{58}Ni (340 MeV) + ^{112,118,124}Sn, ^{20}Ne (160 MeV) + ^{162}Er, ^{40}Ar (243 MeV) + ^{142}Nd, and ^{58}Ni (320 MeV) + ^{124}Sn are presented. The results are compared with new model calculations. New results on proton induced very asymmetric division of ^{238}U at intermediate energies are discussed. A short description of experimental set-up HENDES for investigation of fusion-fission processes is given.

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1 Introduction

Understanding of dynamical processes governing nuclear matter is still far from complete. There is no coherent model to explain the mechanism of nuclear reactions much beyond what was already known, for example, from optical model or from statistical model predictions. Perhaps it

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was this lack of a major break through that, in the past, has diminished the interest in nuclear reaction research. However, as the quest for evermore-exotic nuclei reaches the fringes of the chart of nuclei, the lack of knowledge in the field of nuclear reactions becomes a serious obstacle. Production of radioactive ion beams (RIB) of high intensity, synthesis of super heavy elements, or population of exotic isotopes far from the stability line are just some of the topics that urgently need solutions. Having similar problems in mind, we have initiated nuclear reaction program at the cyclotron facility at the Department of Physics of the University of Jyväskylä. The main emphasis of our program is on the study of fusion- fission reactions using correlated measurements of light particles with fission fragments. We believe that particle emission is the most direct way to extract the information on the dynamical processes taking place following collision of heavy nuclei during their de-excitation and decay. For instance, particles emitted at different stages of fission process carry information on the temperature and on the time scale of nuclear processes. One can say that they work as a thermometer and a clock. By measuring several kinds of particles simultaneously one has several independent clocks and thermometers gauging the same process. This substantially increases the reliability of the measurement and of the subsequent interpretation of the data. Naturally, in addition to the measurements, we conduct thorough model analysis of the results. For that purpose, we have developed a modified version of the statistical model that includes dynamical hindrance of fission that depends on nuclear dissipation. We hope that, by applying modern equipment and improved model calculations, we can make a meaningful contribution towards the solving of at least some of the important problems of fission research.

2 Description of HENDES

HENDES stands for High Efficiency Neutron Detection System [1,2]. It consists of a set of fission fragment detectors, neutron detectors and light charged particle (LCP) detectors assembled in and around reaction chamber. As this set-up is constantly evolving, we would like to describe here shortly its main features. The device has been built and is operated by a joint Finnish-Russian-German collaboration since 1994 and is located at the K=130 cyclotron in Jyväskylä, Finland. Inside the thin stainless steel spherical reaction chamber of 0.8m diameter, there are two large stop detectors - position sensitive avalanche counters (PSAC) - and one or two start detectors. When two start detectors are used they are placed on the opposite sides of the target, each in front of the corresponding PSAC. Presence of a fast coincidence between the two PSACs and at least one of the start detectors is the required trigger condition. Our start detectors are mostly parallel plate avalanche counters but we have also used, with good success, micro channel plate detectors. They provide reference for all time-of-flight measurements. The remaining space inside the chamber is taken by various LCP detectors; mostly PIN diodes but also, depending on the application, by Si(Li) detectors, CsI(Tl) scintillators, proportional counters and so on.

Position sensitive neutron detectors (PSND), filled with NE213 liquid scintillator, are located outside the chamber at about 60cm from the target. Each PSND has 1m long active length and delivers 10 to 20cm position resolution; depending on neutron energy. Currently, two detector types are in use: cylindrical, with 6 cm diameter and 2.6 liter volume [3] and rectangular with 10 x 10 cm base and 10 liter volume [4]. There is a big flexibility as to the number and placement of PSNDs. However, there is seldom need for more than 8 detectors. To accommodate more and to prevent increased cross-talk one would have to increase the distance from the target thus ending up with only a small net gain in efficiency but with considerably more complex set-up. Similar arguments apply to the number of PSAC detectors. Even if there is a provision for at least 5, we seldom use more than 2 PSACs to leave space for LCP detectors and to minimize neutron scattering and interaction by reducing the amount of material inside the chamber.

3 HI induced fusion-fission reactions

After successful investigation of the reaction ^{180}Hf(^{40}Ar, fission) at beam energies E_{lab} = 180 - 249 MeV [5,6], we have started a comprehensive study of Ni induced fusion- fission reaction on Sn isotopes. The reasons for this choice are quite obvious. The abundance of stable Sn isotopes allows us to reach not only very neutron deficient compound systems but also those close to the stability line. At the same time, while Coulomb forces in the entrance channel remain the same, fission barrier height and light charged particle binding energy change significantly. Also, our calculations predict that, in addition to neutron emission, we should observe high multiplicity of protons and alpha particles. This is the necessary condition to make our approach of multiple clocks and thermometers possible.

While being more interesting, Ni + Sn reactions pose a more serious experimental challenge. The major difficulty results from the relative symmetry between beam and target nuclei. Naturally, fusion-fission is not the only reaction channel that is open; and certainly it is not the dominant one. At the bombarding energy of around 6 MeV per nucleon, in addition to elastic and quasi-elastic processes, we also have a whole range of deep inelastic reactions, including fast fission. Unfortunately, for this beam- target combination, these competing processes can not be easily distinguished from the proper (slow) fission of the compound nucleus. The only way to sort out the influence of the other reactions is by changing parameters of entrance channel leading to the same compound nucleus and the same excitation energy. For instance, to reach ^{182}Pt at about 105 MeV excitation energy, one can use the following reactions:

- ^{58}Ni + ^{124}Sn, E_{lab} = 320 MeV
- ^{40}Ar + ^{142}Nd, E_{lab} = 243 MeV
- ^{20}Ne + ^{162}Er, E_{lab} = 160 MeV

For each of them the contribution of deep inelastic and fast fission will be different. Therefore, it should be possible to extract time scale for the compound nucleus fission and for fast fission. As the excitation energy will remain constant, the data should also yield the dependence of particle multiplicity on the mean introduced angular momentum.

Recently, we have measured all these reactions as well as ^{58}Ni + ^{112,118,124}Sn at E_{Ni} = 340 MeV and ^{58}Ni + ^{112}Sn at E_{Ni} = 320 MeV. Although the data is not yet fully analyzed and some measurements need to be repeated, we would like to present here our preliminary results.

To get an indication of the emission source, during the analysis all particle spectra are kinematically separated into the ones emitted from the source moving with the velocity of the compound nucleus and those emitted from each of the fully accelerated fission fragment. There are later called pre- and post-scission particles respectively. Since the separation is strictly based on kinematics, we have no way to determine at which point of fission process particle emission took place. This can only be answered by calculations. As the multiplicity of pre-scission particles depends on the excitation energy and lifetime of the compound system, it is a good indicator of the time scale of the fission process (the clock) while the slope of the energy spectra provides

Table I. Preliminary values of the observed neutron, proton, and α- particle multiplicity. The minus sign indicates that the collected statistics was not enough for a meaningful analysis.

Projectile	^{58}Ni	^{58}Ni	^{58}Ni	^{58}Ni	^{58}Ni	^{40}Ar	^{20}Ne
Energy	340	340	340	320	320	243	160
Target	^{112}Sn	^{118}Sn	^{124}Sn	^{112}Sn	^{124}Sn	^{142}Nd	^{162}Er
Compound	^{170}Pt	^{176}Pt	^{182}Pt	^{170}Pt	^{182}Pt	^{182}Pt	^{182}Pt
M_n^{pre}	0.42(10)	1.59(10)	2.33(30)	0.41(20)	1.30(20)	2.45(20)	3.85(30)
M_n^{post}	2.65(20)	2.97(20)	2.86(20)	2.01(25)	2.80(30)	3.37(30)	2.28(20)
M_n^{tot}	3.07(22)	4.56(22)	5.19(36)	2.42(32)	4.10(36)	5.82(36)	6.13(36)
M_p^{pre}	-	-	-	2.1	1.9	0.22	0.19
M_p^{post}	-	-	-	<0.1	<0.1	<0.1	<0.1
M_α^{pre}	0.87(20)	0.82(21)	0.74(19)	0.52	0.44	0.12	0.14
M_α^{post}	0.06(5)	0.06(5)	0.07(4)	<0.1	<0.1	<0.1	<0.1

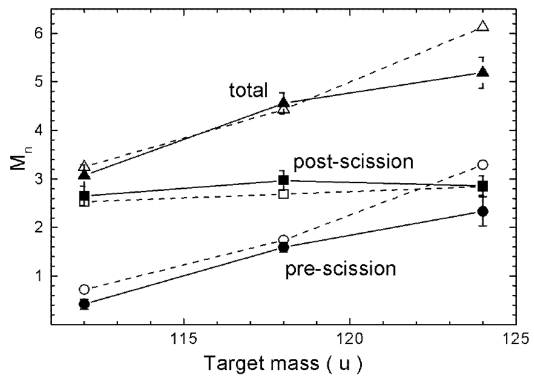

Fig. 1. Pre-, post-scission, and total neutron multiplicities from 340 MeV ^{58}Ni induced fusion-fission reaction on ^{112,118,124}Sn. Solid symbols with error bars indicate measured data. The calculated values are shown with open symbols. The connecting lines are to guide the eye only.

information of nuclear temperatures (the thermometer). Table I summarizes our preliminary experimental results.

There is a reasonably good agreement of the measured values with our model calculations [6]. The calculations were made using the new version of time-dependent statistical model which includes the main dynamical effects in fission: retardation of the fission degree of freedom; emission of light particles during the saddle-to-scission transition; de-excitation process of fission fragments. The reduced friction coefficient is parameterized as a function of the excitation energy to describe consistently the pre-scission characteristics and evaporation residue cross-sections.

Figure 1 shows the comparison of experimental (solid symbols) and calculated (open symbols) neutron multiplicities measured in the reaction 340 MeV ^{58}Ni on ^{112,118,124}Sn.

The measured post-scission values overlap perfectly with the predicted values. The pre-scission multiplicity for ^{112}Sn and for ^{118}Sn is also in agreement with the calculated value, how-

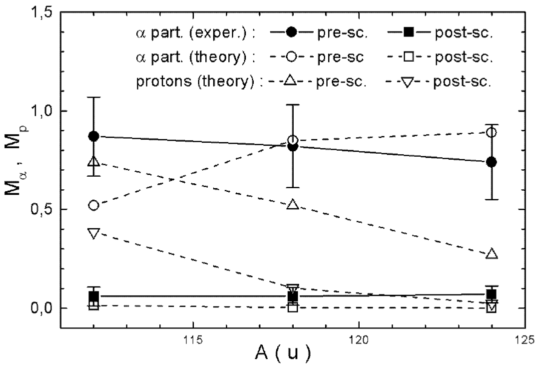

Fig. 2. Pre-, and post-scission multiplicities of protons and alpha particles from 340 MeV ^{58}Ni induced fusion-fission reaction on ^{112,118,124}Sn. Solid symbols with error bars indicate measured data. The calculated values are shown with open symbols. The connecting lines are to guide the eye only.

ever, the measured pre- scission multiplicity for ^{124}Sn is smaller (by about one unit) than the calculated value. If it is a real effect, such a drop of neutron multiplicity should be balanced by increased LCP multiplicity to fulfill energy conservation. As it can be seen from Figure 2, it is not the case.

Alpha particle multiplicity does not show any abnormality for ^{124}Sn target. It agrees well with our model predictions. The only discrepancy is for ^{112}Sn and it is reasonably within the accuracy of the experiment. Proton data was not taken at that time due to temporary lack of suitable detectors.

Figures 3 and 4 show, respectively, neutron and LCP multiplicities compared to the calculated values for the ^{182}Pt compound nucleus populated with the same excitation energy in three different reactions. The multiplicities were plotted as a function of effective fissility parameter x_{eff}:

$$x_{eff} = (4Z_P Z_T/(A_P^{1/3} A_T^{1/3}(A_P^{1/3} + A_T^{1/3}))/(Z^2/A)_{crit}$$

The agreement of measured and calculated neutron multiplicities for ^{20}Ne and ^{40}Ar induced reactions is excellent but there is a big discrepancy for the ^{58}Ni values. Similar situation is for LCP data (see Figure 4). Even if the experimental points have substantial uncertainties, there is a huge and unexpected jump in proton pre-scission multiplicity observed with ^{58}Ni beam. All the other values are reproduced reasonably well by the calculations.

There are several possible explanations of this discrepancy. First of all one can question the validity of experimental results. Indeed, we would like to repeat Ni irradiation to verify our measurements. However, the present results seem sufficiently self-consistent to be taken seriously. The increased multiplicity of charged particles is well compensated by the drop in neutron multiplicity. This balance is not only qualitative but also quantitative: the drop in total kinetic energy taken by neutrons is compensated by higher than expected share of kinetic energy carried out by LCP. It is therefore quite likely that with 320 MeV ^{58}Ni beam we do not yet obtain equilibrium of the compound nucleus. Instead, particle emission takes place from the highly deformed, rotating system. Such a system would have increased LCP emission resulting from the lowering of the Coulomb barrier at the extremities. We may get a better agreement

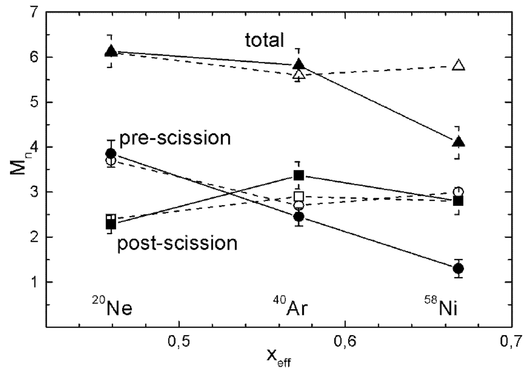

Fig. 3. Pre-, post-scission, and total neutron multiplicities from 3 different reactions leading to the same compound nucleus ^{182}Pt at the same excitation energy of 105 MeV: ^{20}Ne (160 MeV) + ^{162}Er, ^{40}Ar (243 MeV) + ^{142}Nd, and ^{58}Ni (320 MeV) + ^{124}Sn. Solid symbols with error bars indicate measured data. The calculated values are shown with open symbols. The connecting lines are to guide the eye only. The values are plotted as a function of the effective fissility parameter.

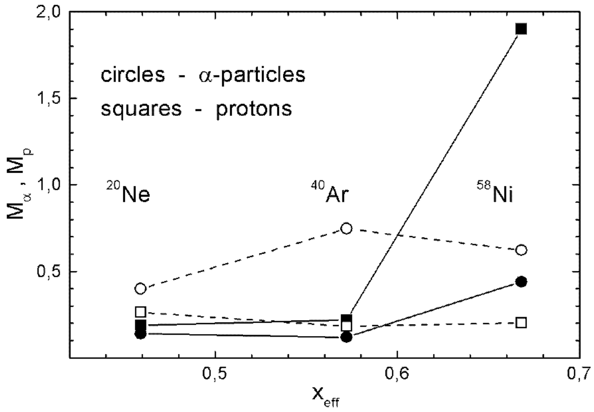

Fig. 4. Pre-scission multiplicity of protons and alpha particles from 3 different reactions leading to the same compound nucleus ^{182}Pt at the same excitation energy of 105 MeV: ^{20}Ne (160 MeV) + ^{162}Er, ^{40}Ar (243 MeV) + ^{142}Nd, and ^{58}Ni (320 MeV) + ^{124}Sn. Solid symbols indicate measured data. The calculated values are shown with open symbols. The connecting lines are to guide the eye only. The values are plotted as a function of the effective fissility parameter.

by modifying or updating the data on ^{58}Ni + ^{124}Sn reaction. Perhaps it would also improve our description of pre-scission neutron multiplicity on Figure 1 and change the value of the average angular momentum brought to the compound system as plotted in Figures 3 and 4.

At the higher bombarding energy of 340 MeV, particle emission conforms well to our calculations. It will be worthwhile to investigate closer the energy dependence of the fusion-fission process around this energy.

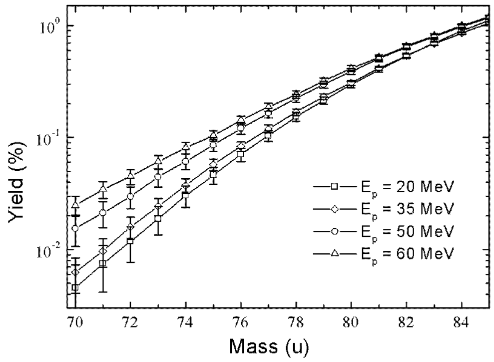

Fig. 5. Fission fragments mass yields in the super asymmetric mass region for the reaction ^{238}U(p,f) measured at 4 proton energies: 20, 35, 50, and 60 MeV

4 Search for super-asymmetric fission mode

The main limitation in the study of exotic, neutron-reach nuclei produced through fission, lies in very small yields. For instance, measured fragment mass distribution of fission products from ^{235}U(n_{th},f) [7] shows 4 orders of magnitude drop in the yield between mass 80 and mass 70. To search, in that mass range, for new isotopes and to investigate their properties one needs much higher yields. Hence, the renewed interest in fission mass distributions, especially for the extreme mass division. If a major super-asymmetric fission mode would ever be found for some beam/target combination, it could give an enormous boost to the way we produce exotic, neutron- reach nuclei. Unfortunately, by so far, all the earlier claims have been found to result from experimental artifacts that disappear under stringent analysis and/or sufficient statistics [8].

Available experimental data seem to indicate that the very asymmetric fission modes of heavy nuclei are prohibited in low energy fission. Better yields are achieved at moderate excitation energies. Indeed, an experiment at IGISOL facility in Jyväskylä has shown [9] that for proton induced fission on ^{238}U the drop in yield between mass 80 and 70 is only two orders of magnitude as opposed to 4 orders of magnitude that was observed in thermal neutron induced fission [7].

As HENDES is very well suited for efficient measurements of fission fragment mass distributions with mass resolution of up to 3 a.m.u. (FWHM), we have decided to verify the results obtained by our colleagues at IGISOL and extend the search for super-asymmetric fission modes to proton and deuteron induced fission on uranium and thorium targets at beam energies available at K=130 cyclotron in Jyväskylä. Preliminary analysis of the proton experiment confirms the IGISOL results. In addition, no appreciable change in the yield with the increase of proton energy from 20 to 50 MeV has been noticed. At mass 70 the yield at 50 MeV is not more than factor of 2 higher from the 20 MeV value (see Figure 5).

Thanks to the relatively high efficiency of HENDES we were able to accumulate sufficient data to investigate dependence of neutron multiplicity emitted from fission fragments (post-scission multiplicity) as a function of the mass number of the fragment for the ^{238}U(p,f) reaction. Figure 6 shows this dependence measured for 4 proton energies: 20, 35, 50 and 60 MeV. It is interesting to notice that the 50 MeV and the 60 MeV curves lie practically on top of each other.

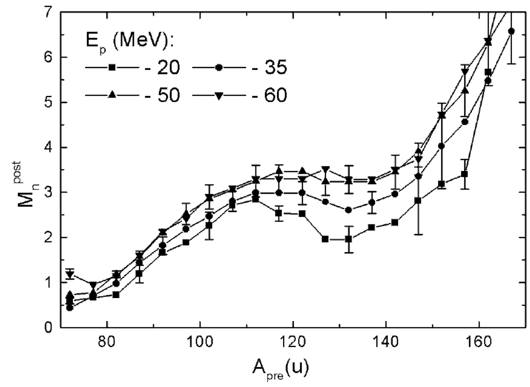

Fig. 6. Post-scission neutron multiplicity as a function of fragment mass prior to the particle emission. Measurements were done for the reaction ^{238}U(p,f) at 4 proton energies: 20, 35, 50, and 60 MeV.

It would indicate that with 50 MeV protons we have already reached the saturation. It would be very interesting to extend this curve further into the asymmetric mass region but it would require substantially longer measurements.

In the latest experiments we have measured fission fragment mass distribution and neutron multiplicities from deuteron induced fission of ^{238}U. With the aid of LCP telescopes we have also looked for the ^{238}U(d,pf) mode to get some indication on mass distribution from fast neutron induced fission. Further experiments are planned at IGISOL facility in Jyväskylä and at other European laboratories.

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