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Abstract. We performed an experiment to search for a signature of a long living component in the collision of ^{238}U + ^{238}U between 6.09 and 7.35A MeV. The experiment was performed at GANIL using the spectrometer VAMOS, tuned for observing reactions with kinematics similar to fusion-fission events. Theoretical calculations indicate that if a long living component would exist for this reaction, the most probable fission channel of such a giant system would be via the emission of quasi-lead nuclei. We detected events of such a category in the focal plane of VAMOS. These events present an excitation function growing as a function of the bombarding energy.

Keywords: fission, giant system
PACS: 25.85.-w, 25.90.+k

INTRODUCTION

The study of very heavy collision systems started in the late 70s when beams in the U region with energies above the Coulomb barrier became available at the linear accelerator of GSI. Soon, research on very heavy systems split mainly into two principal directions: the search for superheavy elements and the physics of superstrong electromagnetic fields. In both cases a di-nuclear system consisting of the two colliding nuclei is transiently created during the collision. In these earlier experiments, the emphasis has been put on the investigation of the decay channels of the di-nuclear system (production of superheavies) or on particle creation in the strong electromagnetic fields. Detailed studies of the properties of the di-nuclear system have not been performed.

For superheavy di-nuclear systems like U+U the fission barrier is no longer existing due to the strong Coulomb repulsion. Due to the absence of the fission barrier one would expect that the lifetime of the di-nuclear system is very short (about 10^{-22} s). However, the neutrons and protons are embedded in the nuclear potential, and hence they are moving in a potential with a strong barrier. Even protons, which are unbound by about 5 MeV in such a system, when evaluated by a liquid drop model, feel a much higher coulomb barrier of about 35 MeV. Therefore, the individual nucleons will move in this potential pocket, and will flow from one U core to the other, thus forming the giant composite system (see [1]). Thereby, in such a model, energy from the collective movement can be transformed into excitation energy via nuclear friction.

These considerations motivated us to search for a signature of such long lived giant system and, in particular, for “trigger" events to study their properties.

DECAY CHANNELS

The above described nuclear friction effect suggests three important consequences:

1) If practically all relative collective motion has been transformed into internal excitation energy of the giant di-nuclear system, the emitted particles, in particular the fission fragments, are emitted with very low kinetic energy at the scission point. They should thus emerge out of the collision with their Coulomb barrier energy. In the language of deep inelastic scattering, this corresponds to reactions with the largest possible negative Q-values.

2) The lifetime of the di-nuclear system might be significantly longer than 10^{-22} s.

3) The decay of the system should be governed by statistical decay probabilities.

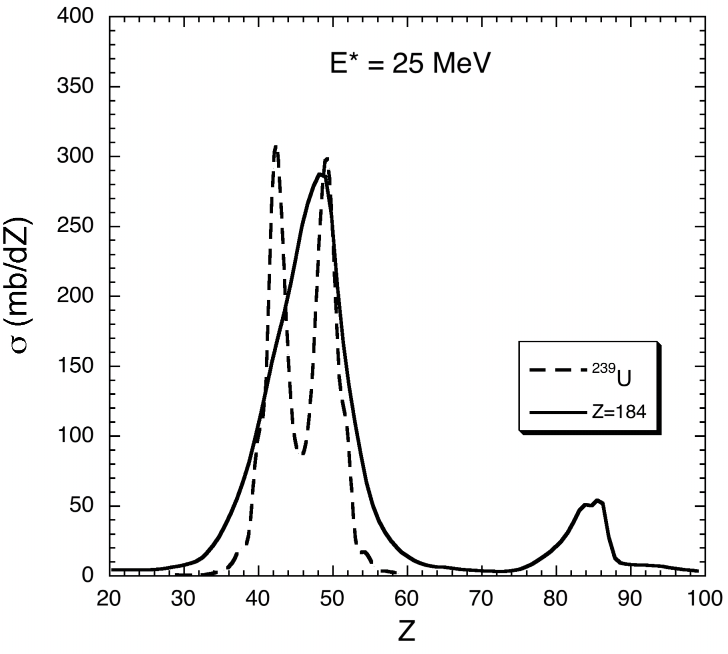

FIGURE 1. Calculated elemental yields after decay of ^{239}U at 25MeV excitation anergy, and of the giant system ^{476}184 at 25MeV excitation energy.

According to item 3) one can calculate the statistical branching ratios to different exit channels. If the excitation energy of the di-nuclear system is moderate, shell corrections should be important. In this case one expects an asymmetric fission, with preferential emission of nuclei close to the doubly magic nucleus ^{208}Pb. This should be similar to the well known low excitation energy fission of e.g. ^{239}U, where a pronounced double bump is observed, related to the doubly magic nucleus ^{132}Sn. The idea that ^{208}Pb may play an important role in fission of transuranium nuclei was raised frequently, and is partially experimentally proven [2, 3, 4, 1, 5]. In order to check this idea for this extremely heavy system, we performed a statistical calculation in a micro-canonical approach that treats fission and light particle emission in the same manner [6, 7]. The result is shown in Fig. 1. As a control of the model calculation, the fission of ^{239}U at 25 MeV, is also shown. A population cross section of 1 barn has been assumed.

For ^{239}U at 25 MeV excitation energy, the well known double humped fission is obtained. The same parametrisation of the model has been used to calculate the yields from the composite ^{476}184. Besides the fission products from U and transuranium elements, a strong and isolated peak in the yield distribution is obtained around the lead region. The excitation energy of 25 MeV corresponds to an incident energy of about 7A MeV, depending on binding energy estimates. No heavy residues above the lead region are obtained, in agreement with very low cross section limits experimentally established for transuranium elements (see [8] and references therein).

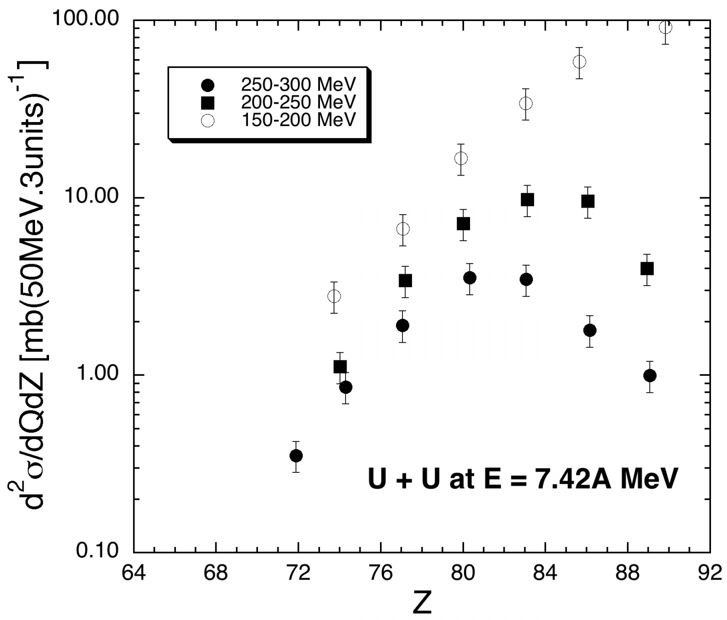

FIGURE 2. Double differential cross section of deep inelastic reaction residues as a function of Z for consecutive Q-bins [3].

The peak in the lead region will be well separated only in the system U+U, while in other systems such as Pb+Pb, Au+Pb, etc. it will be very difficult to isolate it from quasielastic or deep inelastic processes. Experimental results supporting the above described hypotheses can be found in [3]. In this experiment [3], inclusive one particle measurements were performed for the charge, the kinetic energy and the angular distributions of the reaction products from ^{238}U+ ^{238}U at 7.42A MeV. Relatively large mass transfers have been found for deep inelastic reactions with the largest Q-values. Indications for this behaviour are visible on Fig. 2 (from [3]). In this figure, one can see for the most negative Q-values a maximum in the elemental yield around Z = 82 which is in agreement with the considerations above. As a consequence, the deep inelastic reaction products usually consist of one partner with a nuclear charge number significantly lower than 92 and the corresponding partner in the transuranium region. While the lighter partner is surviving with cross sections up to the range of several mb, the produced transuranium isotopes, which in most cases undergo spontaneous fission, are predicted to survive with cross sections of nb or less. In experiments of Schaedel et al., nuclei up to Z=100 have been observed directly in U+U collisions [9]. The same is obtained in calculations performed by Zagrebaev et al. [10]

Lifetimes of giant di-nuclear systems

There are only scarce experimental data investigating the lifetime of superheavy di-nuclear systems. J. Stroth et al. have investigated the collision system U+Au at 8.65A MeV [11]. So called “ternary events" where the Au-nucleus survives and the U-nucleus is fissioning after the collision, have been discussed. Contact times have been deduced from delta-electron spectra as well as from deflection functions (from rotation angle of the di-nuclear system) and the longest contact times have been found for reactions with the most negative Q-values. Within statistics and the discussion of a possible systematic error, contact times of up to 10^{-20} s have been deduced from the data. Rehm et al. investigated the reaction ^{206}Pb + ^{110}Pd and found nuclear contact times somewhat above 10^{-20} s for reactions with a large mass flow between both nuclei. Very recently, reaction times have been measured by the blocking technique in single crystals for the system ^{238}U + Ni at 6.6A MeV and a surprisingly high cross-section of the composite systems with Z = 120 living more than 10^{-18} s has been found [13]. Further publications deal "only" with long lifetimes of excited nuclei in the Uranium region. In the reaction ^{238}U + Si at 24A MeV long lifetimes for excited U-nuclei before scission have been found by Goldenbaum et al., [14] using the crystal blocking technique. Especially for excitation energies below 250 MeV, lifetimes larger than 3 10^{-19} s were obtained. Similar results for lower excitation energies investigating the K-vacancy production probability are reported by Molitoris [15] as well as by Wilschut [16]. Molitoris et al. deduced lower limits for the lifetime before scission of 4 10^{-18} s and more recently Wilschut found lifetimes of excited U of the order of 10^{-18} s. Concerning superheavy di-nuclear systems, several theoretical works have been carried through, some of them very recently, which suggest expected lifetimes in the 10^{-20} s range. With an overdamped Langevin equation with standard parameters, Abe [17] obtained a lifetime on the order of even 10^{-19} s for the composite system U+U. In a recent publication, applying a constrained molecular dynamics model [18] similarly long lifetimes have been obtained for the system Au+Au. Calculations have been performed for incident energies from 5A to 35A MeV and especially for energies around 10A MeV lifetimes reaching up to 10^{-19} s have been found. In a recent publication by Zagrebaev et al., the collision systems U+U, Th+Cf and U+Cm have been investigated and lifetimes longer than 10^{-20} s are predicted [10]. In an earlier work of Yamaji et al. with a time dependant Schroedinger equation a lifetime of the order of 10^{-20}s was obtained for U+U at E_{cm} around 850 MeV [19].

In summary, a series of experimental and theoretical results show that nuclear systems without fission barrier (di-nuclear systems or U-like nuclei excited above the barrier) reveal lifetimes orders of magnitude longer than expected from the liquid drop model, which can most likely be explained by nuclear friction.

EXPERIMENTAL SET-UP

As discussed above, reference [3] contains promising indications for the formation and the decay of the giant system $^{476}184$. In this reference, measurements at only one incident energy have been performed, not enough to be conclusive, and the detection device was a simple ionisation chamber. We proposed to improve these data using up-to-date high resolution devices for the detection of the heavy residues in the region around Pb. At GANIL, the VAMOS spectrometer, with a detection system especially designed for the identification of heavy nuclei was used in this new experiment. In this contribution we present preliminary mass identification results for 5 bombarding energies, ranging from 6.09 to 7.35A MeV.

The ^{238}U beam was produced by the ECR-4M of GANIL with charge states varying from 30^+ to 33^+, depending on the final energy of the beam. The beam was accelerated by the cyclotrons C0 and CSS1 of GANIL up to the energies 6.09, 6.49, 6.91 and 7.35A MeV. The fifth energy (7.1A MeV) was obtained by degrading the beam energy just before the alpha-shaped spectrometer. Intensities of about 0.5 pnA impinged UF_4 or metallic U targets of about 400 μg/cm^2 placed in front of the VAMOS spectrometer. VAMOS was placed at 35 degrees covering an angular aperture of +/- 7 degrees in both the horizontal and vertical planes. The spectrometer was used in a "pure-quadrupole" mode. Just behind the two VAMOS quadrupoles, two secondary electron detectors (SED) were used for time of flight measurements. Two drift chambers and one ionization chamber allowed for trajectory reconstruction as well as ΔE measurements, for Z identification. Finally, the scattered particles were stopped by a Si detection wall (300μm thick). Germanium detectors as well as another Si detector in kinematic coincidence with VAMOS was also present in the experiment. Experimental data corresponding to the latter detectors is still under analysis.

PRELIMINARY RESULTS

We present the mass distributions obtained in the focal plane of VAMOS as a function of bombarding energy. The masses were obtained using time of flight between the first SED detector and the radio-frequency signal of the cyclotrons, corresponding to a flight path of about 4 m. In order to avoid superposition between two different beam bursts the second SED detector at about 1m from the first one helped on the construction of the time-of-flight. Time-of-flight and the energy obtained in the final Si detector were used to determine the fragment mass for each event.

The mass calibration obtained so far was checked using targets of ^{208}Pb and natural Sn. The mass resolution in the present stage of the analysis is of the order of 3% FWHM for the U scattered particles. Note that we did not use the dispersion of the dipole, which

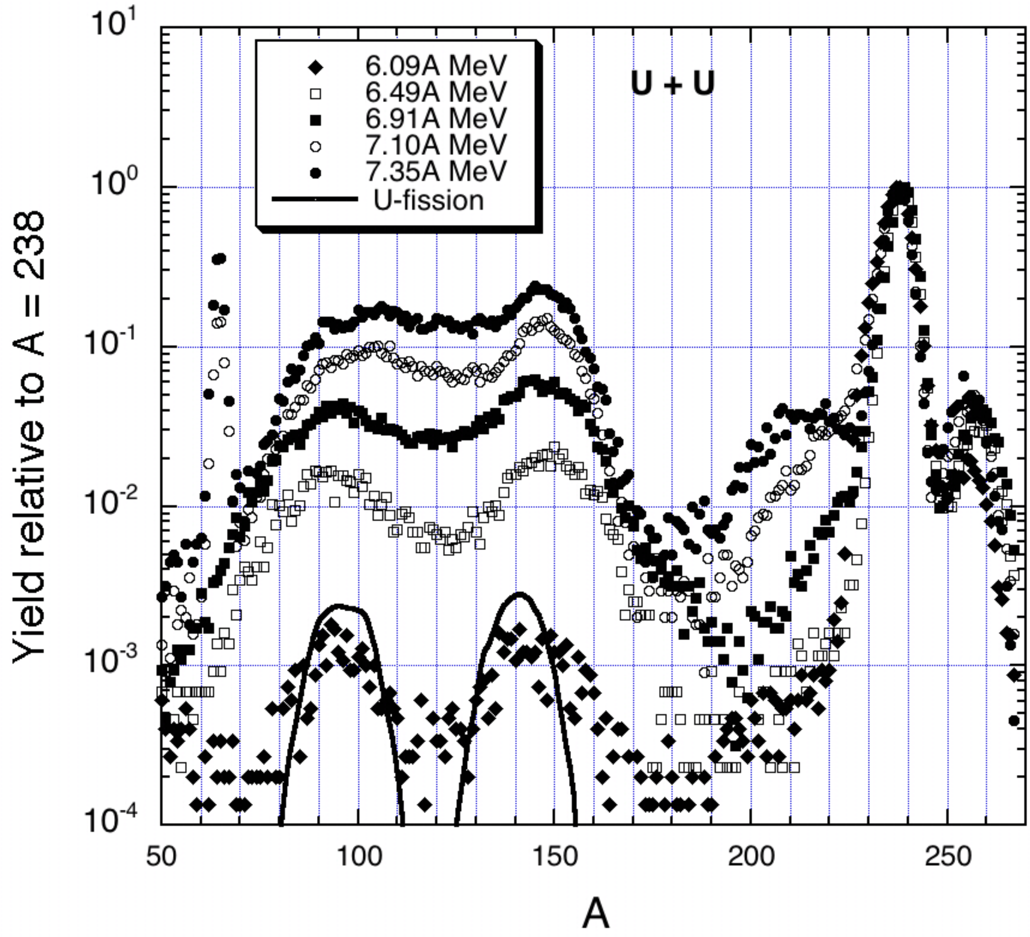

FIGURE 3. Mass identification spectra for different energies compared with re-normalized ^{238}U spontaneous fission. See text for interpretation.

could in principle improve the mass resolution, but would need perfect separation of charge states. The resolution can be improved in the future by applying corrections for the energy losses in the drift and ionization chambers. No correction or condition were done up to now. The mass spectrum obtained so far is shown in Fig. 3 for 5 different bombarding energies. From left to right, one can see peaks corresponding to:

- A = 65, corresponding to a ^{65}Cu contamination of the uranium beam for the energies 7.1 and 7.32A MeV
- A double bump for $70 < A < 170$ corresponding to fission fragments from uranium. This can be compared with relative spontaneous fission yields from ^{238}U (solid line) [20]
- At around A = 208, corresponding to quasi-lead fragments with intensity varying as a function of energy
- A = 238, corresponding to uranium ions from elastic and inelastic scattering

- At around A = 256, corresponding to a channeling effect in the silicon detector. This kind of effect is well described in [21]. Note that this is *not* a real mass, but a detector defect which simulates a heavier mass.

From figure 3 one can see clearly a *bump* in the region of quasi-lead products, which enhances significantly as a function of energy. The excitation function of this mass region is shown in Figure 4. The energy dependence of the *lead-like* production cross section in this reaction is one of the expected clues for the formation of a long-living giant system . However, it is not a proof for the existence of such long-living giant system. The completion of the excitation function - to higher energies - as well as the analysis of the angular distributions of these fragments should provide more ingredients to establish the existence or not of such a long living giant system.

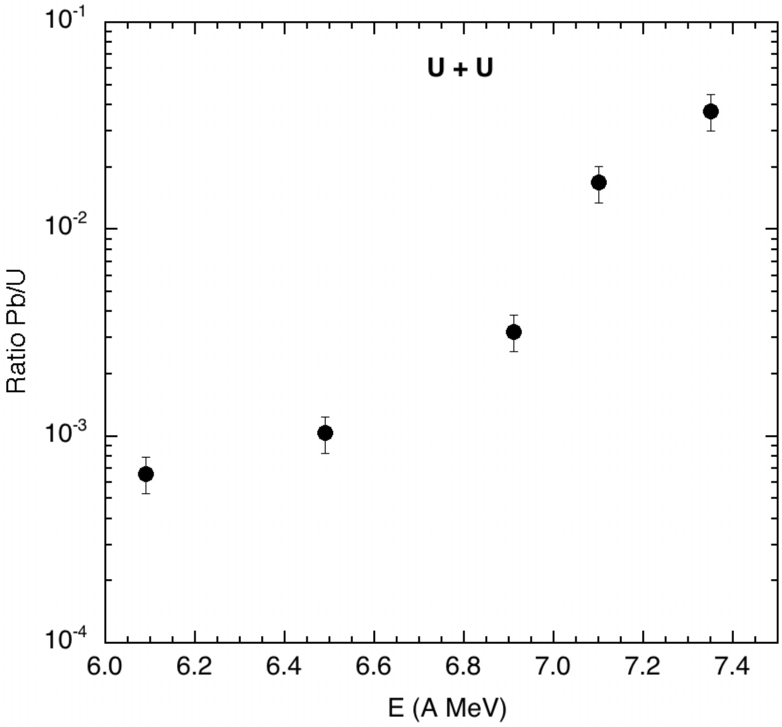

FIGURE 4. Excitation function of *lead-like* fragments normalized to quasi-elastic uranium yield.

SUMMARY

We performed an experiment to search for a long living component in the collision of $^{238}U + {}^{238}U$ between 6.09 and 7.35A MeV. The experiment was performed at GANIL using the spectrometer VAMOS, tuned for observing reactions with kinematics similar to fusion-fission events. Theoretical calculations indicate that if a long living component would exist for this reaction, the most probable fission channel of such a giant system would be via the emission of quasi-lead nuclei. Preliminary results show a relative increase of the yield for such events in the focal plane of VAMOS. These events present an excitation function growing as a function of the bombarding energy, as expected. The evolution of the excitation function towards higher energies as well as the fragment angular distribution should provide for additional constraints to establish the existence of such a giant system. If confirmed, we can use these events as trigger to study the physics of such a system.

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