

## Study of binary fragmentation and compound nucleus fission in the reaction $^{50}\text{Ti} + ^{208}\text{Pb}$

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The dynamics of binary fragmentation and fusion-fission in the Super-Heavy mass region has been widely studied because of its influence on the Super-Heavy Elements (SHE) formation. In the past, the evolution with the bombarding energy of the fission dynamics for the  $^{288}116$  and  $^{312}124$  nuclei produced via different projectile - target combinations was investigated at the TANDEM-ALPI facility of the Laboratori Nazionali di Legnaro. No SHE residues have been observed so far for the studied entrance channels. On the other hand, the fission path of some heavy-ion fusion reactions for which SHE formation was experimentally reported, has not been investigated in full detail. We report in this contribution preliminary results for the binary fragmentation and neutron emission of the reaction  $^{50}\text{Ti} + ^{208}\text{Pb}$  at 294 MeV. The “cold fusion” of  $^{50}\text{Ti}$  on  $^{208}\text{Pb}$  was used at GSI for the synthesis of the Z=104 (Rf) element.

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1

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## 1. Introduction

The synthesis of Super-Heavy Elements (SHE) is one of the frontiers of Nuclear Physics. SHE production has been achieved in heavy-ion fusion reactions with  $^{48}\text{Ca}$  projectiles on actinide targets (warm fusion) [1] as well as with neutron rich projectile beams like  $^{48,50}\text{Ti}$ ,  $^{54}\text{Cr}$ ,  $^{58}\text{Fe}$ ,  $^{62,64}\text{Ni}$  and  $^{70}\text{Zn}$  on Pb or Bi targets (cold fusion) [2]. In this way, elements from  $Z=104$  to  $Z=112$  have been synthesized.

The production cross section of a Super-Heavy nucleus as an evaporation residue (ER) can be written as:  $\sigma_{\text{ER}} = \sigma_{\text{CAP}} \times P_{\text{CN}} \times P_{\text{surv}}$ , where  $\sigma_{\text{CAP}}$  is capture cross section of the two colliding ions in the attractive potential pocket,  $P_{\text{CN}}$  is the probability of forming an equilibrated compound nucleus (CN) and  $P_{\text{surv}}$  is the survival probability against fission of the CN. As a consequence there is only a narrow bombarding energy window giving the optimum SHE production cross section [3]. Furthermore, only a very small fraction (about  $10^{-7}$ ) of the CN cross section leads to ER formation in the SHE region due to the fact that fission barrier of Super-Heavy nuclei is very low compared to the excitation energy of the system. The fission properties of a Super-Heavy nucleus in its ground state can be inferred through the study of binary fragmentation reactions as a function of the bombarding energy, provided that compound nucleus fission can be separated from non-compound processes. Fragment mass – Total Kinetic Energy correlations can be used to follow the evolution of the reaction mechanism from Deep Inelastic Collisions to Quasi-Fission and Fusion-Fission [4]. Pre-scission neutron multiplicities can provide a clock for the fission time scale [5]. Such kind of studies for elements  $Z=116, 124$  populated through the reactions  $^{56}\text{Fe}, ^{80}\text{Se} + ^{232}\text{Th}$  and  $^{80}\text{Se} + ^{208}\text{Pb}$  at various bombarding energies have been performed in past experiments [6,7]. No Super-heavy residues have been observed so far for these three systems. It should be therefore of great interest to perform a binary fragmentation and neutron emission study of a target – projectile combination for which evaporation residues have been detected. The  $^{50}\text{Ti} + ^{208}\text{Pb}$  reaction was used to synthesize the Rf element ( $Z=104$ ) but a detailed study of its fragmentation dynamics is still not available. Recently, a paper was published [8] in which the CN formation probability was estimated from Fission Fragment angular distribution up to a center of mass energy  $E_{\text{cm}}$  of about 200 MeV. The need of neutron detection for a complete study of the fission dynamics for this system was also pointed out in the same paper.

In this contribution we report on preliminary results for the  $^{50}\text{Ti} + ^{208}\text{Pb}$  reaction at 294 MeV bombarding energy for which fragment-fragment and fragment-fragment-neutron correlations have been measured.

## 2. Experimental Details

The experiment has been carried out at the Laboratori Nazionali di Legnaro (Italy). A 294 MeV  $^{50}\text{Ti}$  beam of 0.5 pA intensity was delivered by the TANDEM+ALPI accelerator complex impinging on a  $^{208}\text{Pb}$  target composed by a stack of two  $500 \mu\text{g}/\text{cm}^2$  thick self-supporting foils. The emitted binary fragments were detected in coincidence by two Time of Flight (TOF) arms based on Multi Channel Plates (MCP) detectors. Each arm consists of a compact Start detector

and a position sensitive Stop detector. The flight path of each arm is 18 cm and the distance from the target of the start detector is about 7 cm. The two arms are positioned at  $\theta_{\text{lab}} = \pm 65^\circ$  covering an angular range of about  $\Delta\theta = \pm 10^\circ$ . The coincidence between the TOF arms allows for a complete kinematical reconstruction of the binary event determining mass and kinetic energy of the two fragments. Details of the performances of this device can be found in ref. [9]. Neutrons were detected in 24 BC501 liquid scintillator 5"× 5" cylindrical cells. Neutron detectors were placed around the scattering chamber at a distance of about 2 m from the target position. Neutron energy was measured by the TOF with respect to the MCP start signal. The absolute TOF was determined using the prompt  $\gamma$ -ray peak as a reference. The detectors signals were directly sent to VME digitizers 1 Gs/s sampling rate, 10 bit resolution for the MCP timing signals and 250 Ms/s, 12 bit for MCP position and neutron detector signals. The sampled waveforms have been registered event by event and off-line processed using a custom developed ROOT-based software in order to extract the parameters of interest like TOF, energy and pulse shape for n- $\gamma$  discrimination. The different triggers for the Acquisition System were selected using custom trigger box module. The selected triggers for the acquisition were:

- 1) Double coincidences between Start and Stop detectors of each MCP TOF arm
- 2) Triple coincidences between Start and Stop detectors of each MCP TOF arm and at least one neutron detector.

### 3.Data Analysis and Preliminary Results

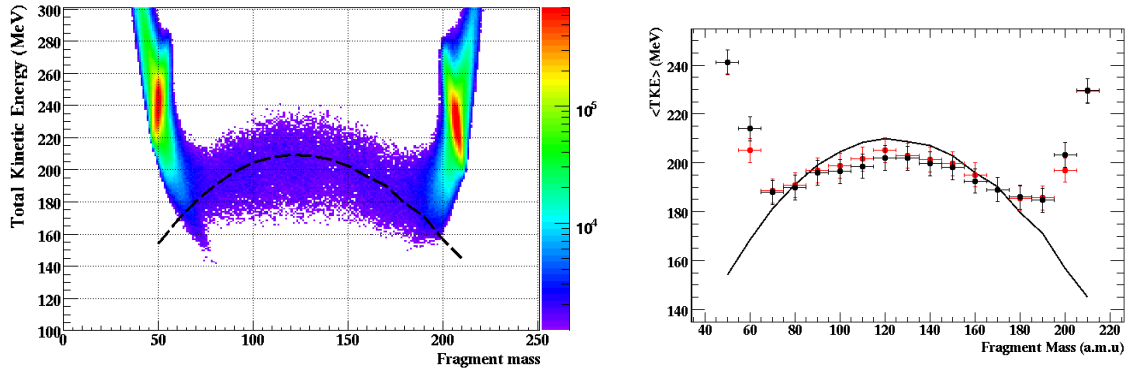
The goal of the data analysis was to obtain fragment mass and kinetic energy distributions and correlations between the binary events with and without a neutron coincidence requirement. Furthermore, multi-source fit of the neutron spectra in coincidence with binary fragments can provide pre and post scission neutron multiplicity for different mass splitting giving information on the timescale of the fission process.

The calibration of the time of flight spectrum of each TOF arm was achieved using the elastic scattering events. The polar ( $\theta$ ) and azimuthal ( $\phi$ ) angles of each Stop detector were calibrated using the image of the edges of the detector and the positions of a known reference grid. The velocity vectors of the fragments were determined using the TOF and the position information ( $\theta$  and  $\phi$ ). Proper corrections were applied for the energy loss of the fragments in the target and in the entrance aluminized mylar foil of the Start detector of each TOF arm. From the measured velocities, the provisional fragment masses and energies were deduced assuming binary kinematics, linear momentum and mass conservation relationships. The final values were then obtained starting from the provisional ones in an iterative procedure until convergence. Details of this procedure can be found in refs. [9,10].

#### 3.1 Fragment Mass and Total Kinetic Energy (TKE) Correlations

In the left panel of Fig. 1 we show the experimental two-dimensional scatter plot of the Center-of-mass Total Kinetic Energy (TKE) versus the fragment mass for binary events detected in coincidence in the two TOF arms. It is seen that the scatter plot is dominated by events close to the target and projectile masses which correspond to elastic, quasi-elastic and deep-inelastic collisions. The Quasi-Fission and Fusion-Fission events are located in the

intermediate region between  $A \sim 80$  and  $A \sim 180$ . Fusion-Fission is believed to take place mainly in the symmetric mass splitting region  $A = 129 \pm 20$  a.m.u.

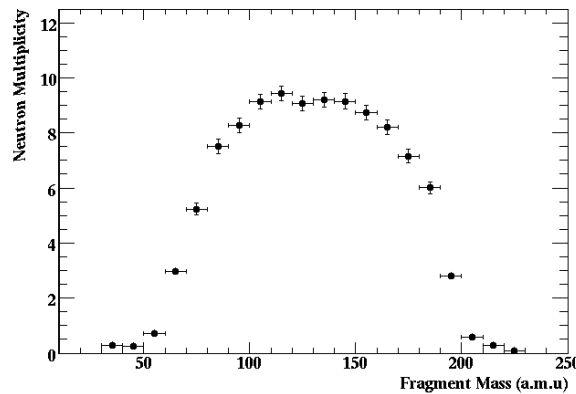


**Figure 1:** Left Panel: Total Kinetic Energy – Mass fragment scatter plot. The dashed line is the average TKE from the Viola Systematics [11]. Right Panel: Variation of the measured  $\langle TKE \rangle$  with the fragment mass compared to the predicted values from Viola systematics (solid line). The points in red were obtained asking the coincidence with neutron detectors

In the right panel of Fig. 1 the experimental average TKE, is reported as a function of the fragment mass for 10 a.m.u bins and is compared with the predicted value from the Viola systematics [11]. From the figure one can observe that the experimental values are not very far from the systematics in the  $80 < A < 180$  mass region being slightly lower with respect to the expectations. In particular, in the symmetric mass splitting region, the measured value is lower by about 10 MeV with respect to the Viola one. This fact could be ascribed to the contribution of deep Quasi-Fission events as discussed in refs. [12,13]. The coincidence with neutrons does not significantly affect the experimental  $\langle TKE \rangle$  value, as reported in the right panel of Fig. 1.

### 3.2 Neutron Emission

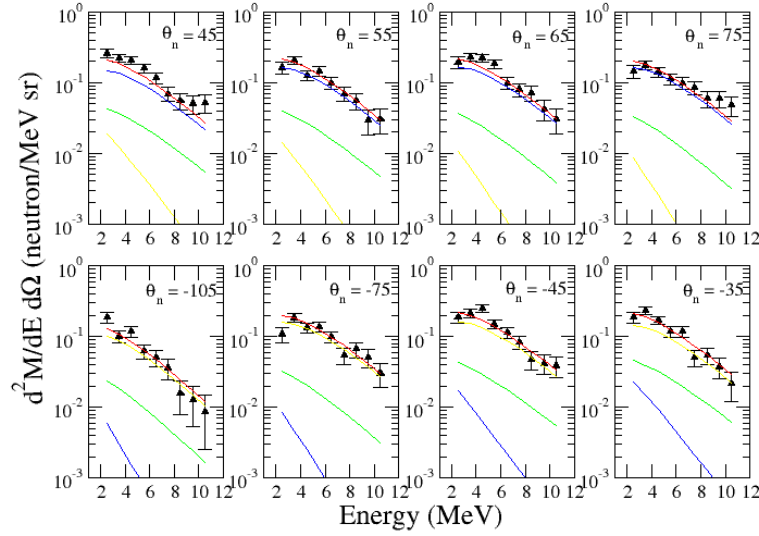
As a first attempt, we extracted a rough average total neutron multiplicity ( $\nu_{tot}$ ) by dividing the two fragment mass distributions in coincidence with neutrons and in singles.



**Figure 2:** Total neutron multiplicity as a function of the fragment mass extracted from the mass distributions in singles and in coincidence with neutrons. For details see the text

A correction for the neutron detection efficiency was applied considering the geometrical solid angle coverage and an average intrinsic efficiency taken by Monte Carlo calculations for the experimental neutron identification threshold. The estimated total neutron multiplicity is reported in Fig. 2 as a function of the fragment mass. As expected, the higher neutron multiplicity is seen in the symmetric mass splitting region and is very low in the quasi- and deep-inelastic region. The extracted average total neutron multiplicity in the symmetric splitting is about 9.

A more refined analysis can be carried out considering the neutron spectra in coincidence with different mass splits. Pre- ( $v_{\text{pre}}$ ) and post-scission ( $v_{\text{post}}$ ) neutron multiplicity can be extracted with a simultaneous fit to all the spectra assuming the emission from a compound nucleus and two symmetric fission fragments according to the procedure described in ref. [14]. Preliminary results are shown in Fig. 3 for the symmetric mass cut ( $A=129\pm 20$  a.m.u.).



**Figure 3:** Measured neutron spectra for different  $\theta$  in coincidence with fragment masses in the  $A=129\pm 20$  a.m.u. window. Preliminary multisource fits to the spectra are also shown. Red line correspond to the total neutron emission. Green, blue and yellow lines are the CN and the two symmetric fission fragments contributions respectively.

We obtain a pre-scission multiplicity  $v_{\text{pre}} = 2.3 \pm 1.0$  and a post-scission multiplicity  $v_{\text{post}} = 7.1 \pm 1.0$ . The total multiplicity  $v_{\text{tot}} = v_{\text{pre}} + v_{\text{post}}$  is in agreement with our rough estimate from the mass distribution ratio discussed at the beginning of this subsection.

As done in refs. [6,7], one can try to evaluate an average overall cost for neutron emission from the deduced  $v_{\text{tot}}$  and the measured  $\langle \text{TKE} \rangle$ . The available excitation energy for a given mass split can be written as  $E_{\text{av}} = E_{\text{cm}} + Q_{\text{gg}} - \langle \text{TKE} \rangle$ , where  $E_{\text{cm}}$  is the available energy in the center of mass, and  $Q_{\text{gg}}$  is the Q-value for the selected exit channel with respect to the projectile and target. For the symmetric splitting  $E_{\text{av}} = 133$  MeV that gives an average overall energy cost for the emission of a single neutron of about 14 MeV. This overall “neutron cost” also includes the emission of  $\gamma$ -rays along the de-excitation cascade [15] and is in agreement with the value found in a previous paper [16] in which the fission of  $^{260}\text{Rf}$  formed in the  $^{28}\text{Si} + ^{232}\text{Th}$  reaction

at 340 MeV bombarding energy was studied. From the average cost for neutron emission and the post-scission neutron multiplicity one can estimate an available energy at scission of about 100 MeV to be compared with the effective Q-value for symmetric fission  $Q_{\text{eff}} = Q_{\text{fiss}} - \langle \text{TKE} \rangle = 72$  MeV, where  $Q_{\text{fiss}}$  is the symmetric fission Q-value.  $Q_{\text{eff}}$  is the available energy for the fission when the CN is populated in its ground state. Thus, we can estimate a neutron multiplicity for spontaneous fission  $\nu_{\text{sf}} \sim 5$ . This value is consistent with systematics of spontaneous and neutron induced fission on heavy nuclei [5] and with the value of  $\nu_{\text{sf}}$  quoted in previous works [6,7] for the Super-Heavy nuclei  $Z=116$  and  $Z=124$ .

#### 4. Conclusions and Perspectives

We have performed an experimental study of the binary fragmentation of the  $^{50}\text{Ti} + ^{208}\text{Pb}$  reaction at 294 MeV bombarding energy by measuring fragment-fragment and fragment-fragment-neutron correlations. The average value of the measured fragment TKE is slightly lower with respect to the systematics.

The mass distribution width of the dissipative events is large with respect to the width that can be associated only to the Fusion-Fission dynamics [4]. This fact is in agreement with recent measurements performed at the Australian National University's Heavy-Ion Accelerator Facility [17] mapping the evolution of the fission dynamics with bombarding energy for a wide variety of entrance channels.

Preliminary values of neutron multiplicities ( $\nu_{\text{pre}}$ ,  $\nu_{\text{post}}$ ,  $\nu_{\text{tot}}$ ) extracted from multisource fit to the neutron spectra in coincidence with the symmetric mass splitting are in agreement with earlier measurements and indicate a spontaneous fission neutron multiplicity  $\nu_{\text{sf}} \sim 5$  for the  $^{258}\text{Rf}$  nucleus.

Multisource fit to the neutron spectra in coincidence with asymmetric mass splitting windows are in progress to map the evolution of the dynamics with the mass of the emitted fragments. Selection of events in different TKE windows could be also useful for mapping the evolution of the dynamics as a function of the fragment mass. Comparison with dynamical and statistical models are also in progress to interpret the data.

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