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Production of n-rich Nuclei along the Closed Shell N=126 in the collision ^{136}Xe + ^{208}Pb @E_{lab}=870 MeV

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Abstract. Multi-nucleon transfer reactions are nowadays the only known mean to produce neutron-rich nuclei in the *Terra Incognita*. The closed-shell region N=126 is crucial for both studying shell-quenching in exotic nuclei and the r-process, being its last "waiting-point". The choice of suitable reactions is challenging and a favorable case is ^{136}Xe+^{208}Pb, near the Coulomb barrier, because their neutron shell-closures play a stabilizing role, favoring the proton-transfer from lead to xenon. TOF-TOF data were analyzed to reconstruct the mass-energy distribution of the primary fragments. Preliminary results of an experiment held at Laboratori Nazionali di Legnaro with PRISMA, aimed at A and Z identification of the products, will be shown.

1. Introduction

The exploration of the the unknown regions of the Segré map and the potential discovery of the *Island of Stability* represents one of the most interesting challenges in nuclear physics and astrophysics. In order to reach these goals, the production of super-heavy species and half-lives and masses measurement are extremely important and would contribute to the discussion about the quenching of shell effects in nuclei with large neutron excess. Fusion reactions with neutron-rich radioactive nuclei and neutron capture are unfeasible channels, because of the low intensity of the currently available Radioactive Ion Beams and the insufficient neutron fluxes from working nuclear reactors. Multinucleon transfer reactions and *Quasi-Fission* process, employing stable beams, look more feasible, with cross sections of the order of mb or μb. Emblematic is the collision ^{136}Xe+^{208}Pb at energies close to the Coulomb barrier. In this case, both nuclei have a closed neutron shell (N=82 and N=126) and, thus, proton transfer from Pb to Xe might be favorable, allowing the exploration of the closed shell N=126, corresponding to the last known "waiting point" of the r-process. The Q-value distribution around zero for such transfers would result in slightly excited fragments, having in this way a greater survival probability. M-TKE distributions of the binary products can be measured using simple kinematic analysis (TOF-TOF data). The results of a preliminary experiment [1] show possible transfers up to about 20 nucleons. Furthermore, there is a good agreement with cross section calculations in the region of interest (A∼200, Qgg∼0) and the yield is even underestimated [2] by a factor 2 in the region of asymmetric mass division.

2. Production of Nuclear Species in the *Terra Incognita*

To fill the "blank region" in the Segré map, the multi-nucleon transfer process in low-energy collisions of heavy ions has been proposed [2]. It is well known that in *Deep-Inelastic* collisions of heavy ions the energy of relative motion is quickly transformed into the internal excitation of the fragments which afterwards de-excite by evaporation of light particles (mostly neutrons). At a first glance, this does not seem of any help for the production of neutron-rich nuclei. However, if the colliding energy and the reaction Q-value are rather low, the primary fragments might not be very much excited and will descend to their ground states after evaporation of few neutrons, thus remaining far from the stability line. Moreover, it has been shown experimentally that even at low bombarding energies (close to the Coulomb barrier) the cross sections for transfer of several protons and neutrons are still rather high [3], and this kind of reactions could be considered as an alternative way for the production of exotic nuclei.

The satisfactory agreement between experimental data and calculation [2], within the model [5] proposed by Zagrebaev and Greiner, gave confidence in obtaining reliable cross section estimations of near-barrier multinucleon transfer reactions producing heavy neutron-rich species. It is clear that an appropriate choice of colliding partners is important for the production in a specific region and shell-closures effects play a very important role in the mass rearrangement both in *Fusion-Fission* and DI processes, possibly inducing the production of neutron-rich nuclei.

3. Predictions of the Dynamical Model

This semi-classical model proposes a dynamical description of a nuclear reaction depending only on some *bulk* degrees of freedom (*DoF*) which can provide a realistic picture of collective behavior and mass transfer. All the remaining *DoF* are treated as a heat bath. The equations (Langevin, eq. 1) describe the time evolution in terms of the variables and their conjugate momenta. The mechanism for transferring energy between the collective degrees of freedom and the heat bath is dissipation by viscosity and a stochastic term is used to take into account fluctuations.

$$\mu \ddot{q} = -\frac{\partial V}{\partial q} - \gamma \dot{q} + \sqrt{\gamma T}\,\Gamma(t). \tag{1}$$

The choice of proper *DoF*s is crucial to describe simultaneously several competitive mechanisms such as DI and QF and estimate the cross sections. The other key ingredient of the model is clearly the potential energy depending on the chosen set of degrees of freedom.

There is a link between the reaction channel, shell-effects and observables such as the fragment mass and Total Kinetic Energy (Fig. 1). The potential energy (often referred to as "potential landscape") shows valleys corresponding to a higher binding energy, therefore to shell closures. These valleys are related to mass divisions that can be associated to specific *loci* in the M-TKE distribution and specific reaction mechanisms, showing how these two observables can be of paramount importance from the experimental point of view.

It is interesting to note that QF may lead to an almost symmetric mass division that would be indistinguishable, in the M-TKE distribution, from the symmetric mass division that can arise from FF. In order to disentangle the two mechanisms it is necessary to look at other observables, such as gamma emission.

An example of calculation conducted within this model is shown in Fig. 2, a M-TKE distribution of fragments from the reaction ^{238}U+^{248}Cm. It is noticeable the possibility of asymmetrizing massive transfer, from light to heavy partner, leading to super-heavy nuclei: the masses inside the circle in figure are in a region close to the center of the Island of Stability.

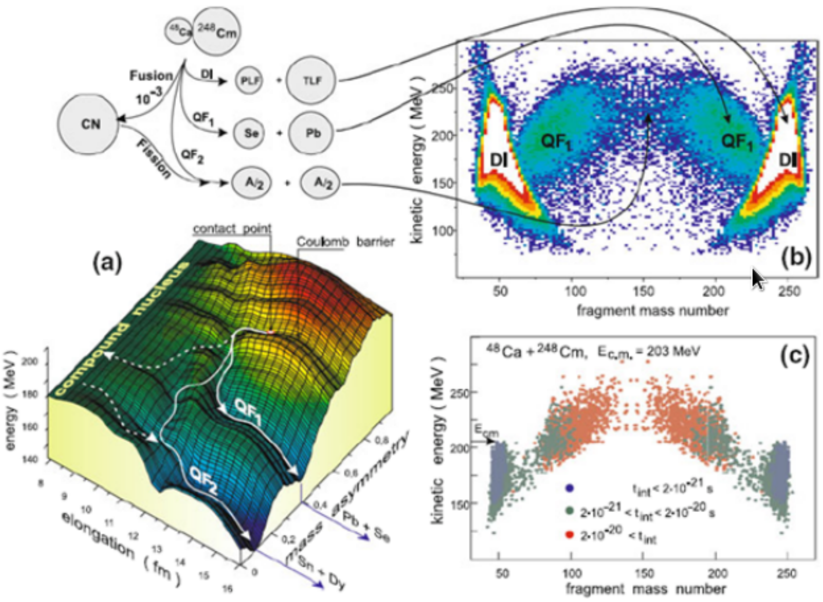

Figure 1. a) the solid lines show the QF trajectories going to the Pb and Sn valleys in the potential landscape. The dashed curves correspond to FF. Experimental b)and calculated c) M-TKE distribution of reaction fragments in collision at 203 MeV center-of-mass energy. Different colors in c) indicate the interaction time of different events. QF and FF cannot be disentangled by means of just mass and TKE (from [4, 5])

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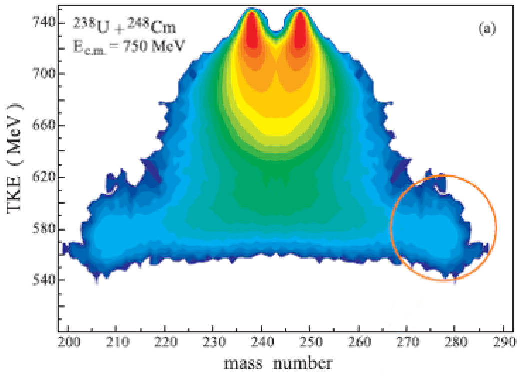

Figure 2. M-TKE distribution of ^{238}U+^{248}Cm, calculated within the model [4]. Asymmetrizing transfers result in super-heavy products. The circle corresponds the center of the Island of Stability.

4. Xe+Pb Reaction and the Closed-Shell N=126

The basic idea is to exploit stable beams and start from the case of the closed shell N=126. The study of the multinucleon transfer at low energies in the reaction ^{136}Xe+^{208}Pb assumes a great importance: if the model is able to predict, at a good extent, the cross sections, there will be more confidence in searching for superheavy element formation in the multinucleon transfer between massive nuclei and this mechanism would prove to be an important candidate for the production of elements, not reacheable by other known mechanisms. The choice falls on xenon

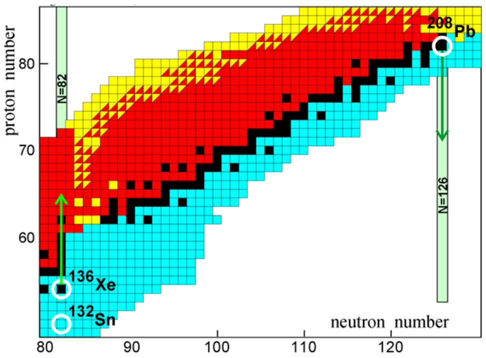

Figure 3. The favorable proton transfer from Pb to Xe allows the exploration of the region N=126. The TLF would slide into the Terra Incognita, keeping its neutron core: an example may be ^{202}Os [5].

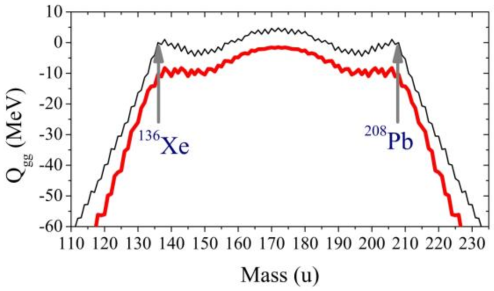

Figure 4. Q-value distribution for transfers in ^{136}Xe+^{208}Pb. In red the mean values, in black the maximum ones [1]. Values around zero for symmetric configurations and negative for asymmetric ones.

and lead because of their neutron shell-closure (N=82 and N=126): both have a closed shell neutron core and, if this stabilizing effect persists while descending into the *Terra Incognita*, the proton transfer from target to projectile could be favorable [1]. It could allow the exploration of the region with N=126 as shown in Fig. 3. An example of produceable species may be ^{202}Os [5].

The Q-value distribution (Fig. 4), which averages around zero in the symmetric mass region [2, 1] and the low bombarding energies may result in poorly exited fragments with greater survival probability against neutron evaporation or fission. Since the Total Kinetic Energy Loss and excitation energy are given by

$$TKEL = E_{cm} - TKE \tag{2}$$

$$E^* = TKEL + Q_{gg}, \tag{3}$$

and being $Q_{gg} \sim 0$, the TKEL trend equals to a good degree the excitation of the primary fragments. The bombarding energy of 870 MeV, near the Coulomb barrier ($V_C = 421.5\, MeV$, in Bass parametrization [7]) would then keep low the excitation of the fragments.

5. Mass Reconstruction

To extract the requested mass-TKE distribution of primary fragments, a time of flight spectrometer is used. By measuring the TOF of two fragments in coincidence and their position on stop detectors, their velocity vector can be evaluated, assuming that it would not be affect heavily by particle evaporation. The application of conservation laws such as energy (eq. 2, 3), momentum (5) and mass number (4) allows the kinematic reconstruction of the event and, in particular, the observables of interest.

$$M_{tar} + M_{proj} = \quad M_1 + M_2 \tag{4}$$

$$M_{proj}\vec{V_{proj}} = \quad M_1\vec{V_1} + M_2\vec{V_2} \tag{5}$$

The experimental apparatus used to study the reaction ^{136}Xe+^{208}Pb @LNL consists of the magnetic spectrometer *PRISMA* coupled with a *Bragg chamber* detector. Fig. 5 shows a schematic drawing of the two arms placed at 45° and 52°, respectively.

The TOF-TOF measurements are taken at the position-sensitive entrance detectors, a MCP in PRISMA arm and a PPAC in Bragg arm, used for full kinematic reconstruction: evaluation of angles, flight paths, velocities and, eventually, mass and energy.

The atomic number of one of the fragments can be evaluated with the use of a $\Delta E - E$ telescope-like ionization chamber at the focal plane, the reconstruction of the trajectory of one of the fragments (PRISMA arm) passing through well known magnetic fields (a dipole and a quadrupole) or the Bragg peak analysis (Bragg chamber arm).

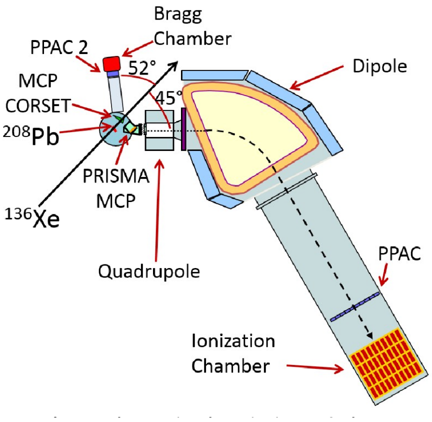

Figure 5. PRISMA at 45° and Bragg-arm at 52° with respect to the beam. The first consists of a MCP, quadrupole and dipole magnets, a PPAC in the focal plane and a $\Delta E - E$ telescope-like ionization chamber. The Bragg-arm has a MCP start and a PPAC stop, with a Bragg chamber behind the latter.

The preliminary analysis focused on the kinematic reconstruction, including the design and application of an algorithm of energy correction due to the losses in target and start detector which takes into account the change of charge state of the ions [6].

The observables $V_{\parallel}$ and $V_{\perp}$, projections of velocity vectors onto the reaction plane and on an orthogonal axis, are the key to search for full momentum transfer binary events, since for them $V_{\parallel} = V_{cm}$, $V_{\perp} = 0$. The possibile cases are shown in the Kinematic Diagram in Fig. 6:

(a) $V_{\parallel} = V_{cm}$, a FMT binary event for which the mass reconstruction is well interpreted;

(b) $V_{\parallel} > V_{cm}$, sequential fission (usually) of the TLF occurs and the secondary fragment emitted forward is detected, leading to a misinterpretation of the velocities;

(c) $V_{\parallel} < V_{cm}$, the secondary fragment emitted backward is detected.

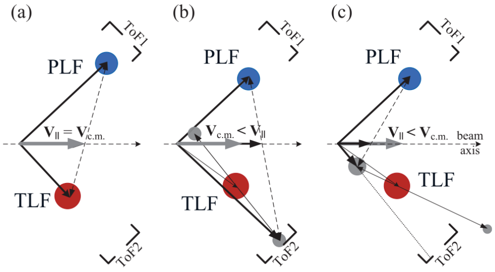

Figure 6. Kinematic Diagram [1]. (a) a FMT binary event; (b) sequential fission of TLF, the secondary fragment emitted forward is detected; (c) fragment emitted backward is detected.

In Fig. 7, the experimental $V_{\parallel}$ - $V_{\perp}$ distribution shows a peak corresponding to FMT binary events, which can be selected by application of a narrow gate around $V_{\parallel}/V_{cm} \sim 1$ and $V_{\perp} \sim 0$,

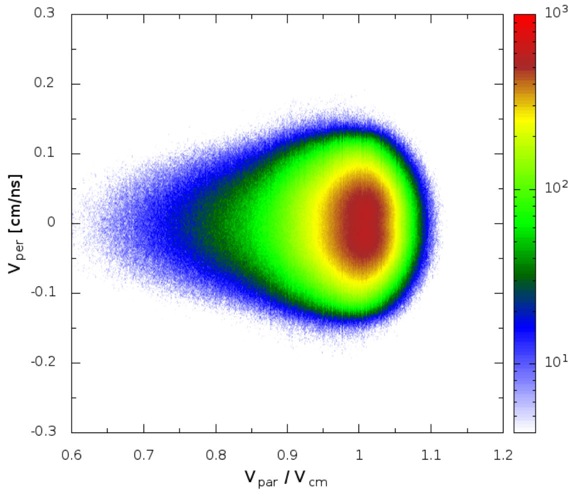

Figure 7. $V_{||}$ - $V_{\perp}$ experimental distribution of ^{136}Xe+^{208}Pb reaction. A gate around $V_{||}/V_{cm} \sim 1$ and $V_{\perp} \sim 0$, must be applied in order to discard sequential fission events.

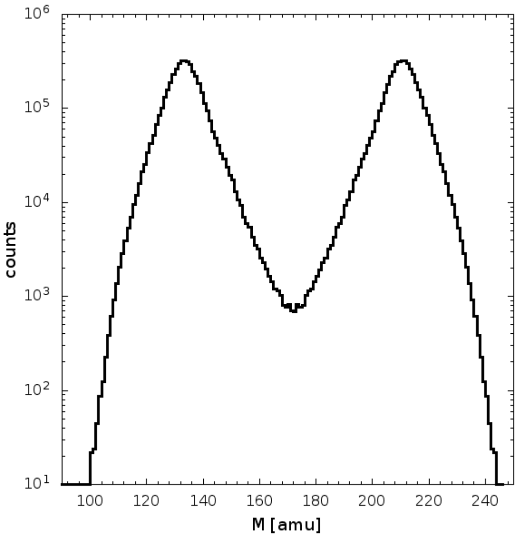

Figure 8. Preliminary results of ^{136}Xe+^{208}Pb reaction. The peaks are around the masses of Xe and Pb. There are cases of asymmetrizing transfers ending up in fragments heavier than target.

discarding sequential fission. The preliminary results of Fig. 8 show the mass of primary fragments obtained after the application of a gate on the $V_{||}$ - $V_{\perp}$ matrix.

The mass distribution (Fig. 8) is double hampered. The two peaks are centered around the masses of projectile and target. Mass transfers from heavier partner to lighter one lead to a symmetric configuration of the output fragments and populate the masses between xenon and lead but it is clearly visible the possibility of transfers in the other way, increasing the mass asymmetry and leading to species heavier than the target.

6. Conclusions

The observed shell-effect persistence of the *magic numbers* N=82,126 makes the multinucleon transfer channel really interesting for the production in the *Terra Incognita* and, in this specific case, in the region with N=126, of great importance for a better understanding of the r-process.

When TLFs havier than Pb are produced, Q_{gg} is negative and lowers the excitation energy. This means that mass transfers from xenon projectiles to lead target end up in fragments with greater survival probability against neutron evaporation. Since masses way grater than 200 amu have been produced, this is an exciting result, showing how this reaction channel is to be chosen as a candidate in the attempt of producing heavy, *surviving*, neutron-rich nuclei, not reachable by other methods. Though the analysis is only at a preliminary stage, this is an important result and the experimental program is going to continue with reactions between heavier partners, like Xe+Cm and also implying lighter partners in order to search the same stabilizing effects in smaller closed shells such as N=28,82. The further step will be the application of techniques for the atomic number evaluation and, in the near future, the exploitation of radioactive ion beams.

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