New ideas on the production of heavy and superheavy neutron rich nuclei

Valery Zagrebaev\textsuperscript{a} and Walter Greiner\textsuperscript{b}

\textsuperscript{a}Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Moscow region, Russia

\textsuperscript{b}Frankfurt Institute for Advanced Studies, J.W. Goethe-Universität, Germany

A new way is proposed to discover and examine unknown neutron-rich heavy and superheavy (SH) nuclei at the “north-east” part of the nuclear map. These nuclei can be produced neither in fusion reactions nor in fragmentation processes widely used nowadays for production of new nuclei. The present limits of the upper part of the nuclear map are very close to stability while the unexplored area of heavy neutron-rich nuclides to the east of the stability line (also those located along the neutron closed shell \(N = 126\)) is extremely important for nuclear astrophysics investigations and, in particular, for the understanding of the r-process of astrophysical nucleo-genesis. A novel idea is proposed for the production of these nuclei via low-energy multi-nucleon transfer reactions using a gain given by the shell effects. The estimated yields of neutron-rich nuclei are found to be rather high in such reactions and several tens of new nuclides can be produced, for example, in near-barrier collision of \(^{136}\text{Xe}\) with \(^{208}\text{Pb}\). This finding may spur new studies at heavy ion facilities and should have significant impact for future experiments.

1. MOTIVATION

The study of exotic nuclei located far from the stability line has been of increased interest from experimental and theoretical points of view. Nowadays, nuclei far from stability are accessible for experimental study in almost any region of the nuclear map. The only exception is the north-east part where a vast “blank spot” is still unexplored, see Fig. 1. This area of the nuclear map can be reached neither in fusion–fission reactions nor in fragmentation processes, while the heavy neutron-rich nuclides is extremely important for nuclear astrophysics investigations and, in particular, for the understanding of the r-process of astrophysical nucleo-genesis. The study of the structural properties of nuclei along the closed neutron shell \(N = 126\) \((Z < 80)\) would also contribute to the present discussion of the quenching of shell effects in nuclei with large neutron excess.

The island of stability in the SH mass region is another still unreachable part of the nuclear map. Due to the “curvature” of the stability line, in the fusion reactions of stable nuclei we may produce only proton rich isotopes of heavy elements. That is the main reason for the impossibility to reach the center of the island of stability \((Z \sim 114, 120\) and \(N \sim 184\)) in fusion reactions with stable projectiles. As can be seen from Fig. 1, there is also a gap between the SH nuclei produced in the “hot” fusion reactions with \(^{48}\text{Ca}\) and the continent. This gap does not allow one to depart from known nuclei when
we attribute the charge and mass numbers to the new SH elements produced in the “hot” fusion reactions. It also hinders one from obtaining a clear view of the properties of SH nuclei in this region. It is rather difficult to fill this gap in fusion reactions of stable nuclei. All the three problems may be solved by using multi-nucleon transfer reactions at near barrier collisions of heavy nuclei.

Figure 1. Top part of the nuclear map. The r-process path is shown schematically and the three problems are indicated: How to reach the island of stability, how to fill the gap and how to explore the blank spot of the nuclear map?

2. MULTI-NUCLEON TRANSFER REACTIONS

Several models have been proposed and used for the description of mass transfer in deep inelastic heavy ion collisions, namely, the Focker-Planck [1] and master equations [2], the Langevin equations [3] and more sophisticated semiclassical approaches [4,5]. We employ here the model of low-energy collisions of heavy ions proposed in [6]. This model is based on the Langevin-type dynamical equations of motion. The distance between the nuclear centers $R$, dynamic surface deformations $\beta_1$ and $\beta_2$ and the neutron and proton asymmetries, $\eta_N = (2N - N_{CN})/N_{CN}$ and $\eta_Z = (2Z - Z_{CN})/Z_{CN}$, are the most relevant degrees of freedom for the description of deep inelastic scattering and fusion-fission reactions. The use of the neutron and proton asymmetry parameters allows one to describe properly neutron and proton transfers and obtain the yields of different isotopes of a given element (including extremely neutron rich ones) [7]. The potential energy is calculated within the double-folding procedure at initial (diabatic) reaction stage and within the extended version of the two-center shell model [8] in the adiabatic reaction stage. Thus, we use a time-dependent potential energy, which after contact gradually transforms from a diabatic potential energy into an adiabatic one: $V(R, \beta, \eta_N, \eta_Z; t) = V_{\text{diab}}[1 - f(t)] + V_{\text{adiab}}f(t)$. Here $t$ is the time of interaction and $f(t)$ is a smoothing function satisfying the conditions $f(t = 0) = 0$ and $f(t >> \tau_{\text{relax}}) = 1$, $\tau_{\text{relax}}$ is the adjustable parameter $\sim 10^{-21}$ s. The diabatic and adiabatic potentials depend on the same variables and are equal to each others for well separated nuclei. Thus, the total potential energy, $V(R, \beta, \eta_N, \eta_Z; t)$, provides quite smooth driving forces $-\partial V/\partial q_i$. 
For all the variables, with the exception of the neutron and proton asymmetries, we use the usual Langevin equations of motion with the inertia parameters, $\mu_R$ and $\mu_\beta$, calculated within the Werner-Wheeler approach. For the mass and charge asymmetries the inertialess Langevin type equations have been derived from the master equations for the corresponding distribution functions. The double differential cross-sections of all the processes are calculated as follows

$$\frac{d^2\sigma_{N,Z}(E, \theta)}{d\Omega dE} = \int_0^\infty b db \frac{\Delta N_{N,Z}(b, E, \theta)}{N_{tot}(b)} \frac{1}{\sin(\theta)\Delta\theta\Delta E}.$$ (1)

Here $\Delta N_{N,Z}(b, E, \theta)$ is the number of events at a given impact parameter $b$ in which a nucleus $(N, Z)$ is formed with kinetic energy in the region $(E, E + \Delta E)$ and center-of-mass outgoing angle in the region $(\theta, \theta + \Delta\theta)$. Expression (1) describes the mass, charge, energy and angular distributions of the primary fragments formed in the binary reaction. Subsequent de-excitation cascades of these fragments via emission of light particles and gamma-rays in competition with fission are taken into account explicitly for each event within the statistical model leading to the final distributions of the reaction products.

3. RESULTS AND DISCUSSION

Figure 2. Left panel: Landscape of the cross sections ($\mu_b$, numbers near the curves) for the production of primary heavy fragments in collisions of $^{136}$Xe with $^{208}$Pb at $E_{c.m.} = 450$ MeV. Right panel: Yield of nuclei with neutron closed shell $N = 126$. Open symbols and dashed curve indicate the yield of the nuclei in high energy proton removal process. For the production of heavy neutron rich nuclei located along the neutron closed shell $N = 126$ (probably it is the last “waiting point” in the r-process of nucleosynthesis) we propose to explore the multi-nucleon transfer reactions in low-energy collisions of $^{136}$Xe with $^{208}$Pb. The idea is to use the stabilizing effect of the closed neutron shells in both nuclei, $N = 82$ and $N = 126$. The proton transfer from lead to xenon might be rather favorable here because the light fragments formed in such a process are well bound (stable nuclei) and the reaction $Q$-values are almost zero, for example, $Q( ^{136}$Xe + $^{208}$Pb $\rightarrow ^{142}$Nd
+ $^{202}$Os) = $-8.3$ MeV. The landscape of the calculated cross sections for the yield of the primary reaction fragments in low-energy collision of $^{136}$Xe with $^{208}$Pb is shown in Fig. 2. At the right panel the yields of nuclei with the closed neutron shell $N = 126$ produced in this reaction and in high-energy collisions of $^{208}$Pb with beryllium target (T. Kurtukian Nieto, PhD Thesis, 2007) are also shown. As can be seen from Fig. 2 several tens of new nuclides in the region of $Z = 70 \div 80$ can be produced with a cross section of 1 microbarn. Note, that a possibility for the production of new heavy isotopes in the multi-nucleon transfer reactions with neutron-rich calcium and xenon beams has been discussed in [9].

![Graph of cross sections](image-url)

Figure 3. Yield of primary and survived isotopes of SH nuclei produced in collisions of $^{238}$U with $^{248}$Cm at 800 MeV center-of-mass energy. Dashed line shows the expected locus of transfer reaction cross sections without the shell effects.

The calculated cross sections for formation of neutron-rich SH nuclei in low-energy collisions of $^{238}$U with $^{248}$Cm target are shown in Fig. 3. These SH nuclei are located very close to the center of the island of stability and cannot be produced in any fusion reactions with stable projectiles and long-lived targets. These are the shell effects which give us a significant gain as compared to a monotonous exponential decrease of the cross sections with increasing number of transferred nucleons.

REFERENCES