Universitatea din
București
Virtute et Sapientia

UNIVERSITATEA DIN BUCUREȘTI

MIKHAIL ITKIS

Doctor Honoris Causa

MIKHAIL ITKIS

DOCTOR HONORIS CAUSA

The pathway toward the production of superheavy elements crosses with the one of an in-depth study of the fission and quasifission processes. Quasifission affects the probability of forming a compound nucleus after capture and fission plays a decisive role during the cooling of the compound nucleus. To search for optimal reactions to produce superheavy elements in fusion reactions and to provide an estimate of their production cross section measurements of the capture and fusion cross sections along with the survival probabilities are a mandatory task. Here an overview of the impact of fission and quasifission over the synthesis of superheavy elements is discussed along with the need to perform measurements over a wide range of masses and energies.

Mikhail Itkis

Laudatio | Mikhail Itkis

Professor **Mikhail Grigorievich Itkis** is a prominent and remarkable personality of Nuclear Physics, his activities having a substantial impact on the development of the Nuclear Physics, Experimental Heavy Ion Physics, sustained by his prestigious and major contributions to the field development in Russian Federation, and in the world.

Professor **Mikhail Grigorievich Itkis** was awarded the title of **Doctor in Physics** (Candidate of Sciences) in 1974, at the Institute of Nuclear Physics, Kazakhstan Academy of Sciences, under the supervision of Professor V. N. Okolovich. In 1985 he obtained the title of **Doctor of Physics and Mathematics** (Doctor Docent) at the Radium Institute of Sankt Petersburg. Since 1988 dr. Mikhail **Grigorievich Itkis** is a full Professor at the Institute of Nuclear Physics of Kazakhstan Academy of Science.

Between 1967 and 1992, after graduating the Faculty of Physics of the Moscow State University, he had different scientific positions at the Institute of Nuclear Physics, Kazakhstan Academy of Sciences (Engieneer, as Senior Researcher, Head of scientific department), and obtained significant scientific results.

In 1993 he was elected Deputy Director of the Flerov Laboratory of Nuclear Reactions, at the Joint Institute of Nuclear Research Dubna (Russia). Considering the prestigious experimental results obtained at this laboratory of the JINR Dubna, in 1997 Professor **Mikhail Grigorievich Itkis** was elected Director of the Flerov Laboratory of Nuclear Reactions. He coordinated the research activities of this important laboratory of the JINR Dubna until 2006. Since 2006, Professor **Mikhail Grigorievich Itkis** is **Vice-Director** of the Joint Institute for Nuclear Research Dubna. **It is important to emphasize here that** Professor **Mikhail Grigorievich Itkis was during 2010-2011** the **Interim Director of this prestigious international institute of Nuclear Physics.**

The major filds of interest of Professor **Mikhail Grigorievich Itkis** are **nuclear fission and heavy** and **superheavy nuclei physics.**

In the field of Nuclear Fission the main problems studied where spontaneous fission of heavy nuclei, fission modes, fission from the isometric state of nucleus (spin and shape isomers), spontaneous emission of clusters, fission into three fragments, sequential fission, beta-delayed fission of neutron deficient isotopes of heavy elements; fission and quasi-fission of exotic nucle;, angular, mass, and energy distributions of fragments, pre- and post-equilibrium neutron emission.

Among the major aspects of the **heavy and superheavy nuclei Physics** studied by Professor **Mikhail Grigorievich Itkis** in his scientific activity we mention: synthesis of new heaviest elements; reactions of synthesis and decay properties of the heaviest nuclei; electromagnetic and chemical separation and detection of evaporation residues. Also, he was involved in the design and construction of kinematic separators of recoil nuclei. Profesor Mikhail G. Itkis participated actively in the experiments on the synthesis of elements with atomic numbers 112–118, measurements of production cross sections of heavy and superheavy nuclei, the influence of nuclear shells on the stability of heavy and superheavy nuclei, as well as in the development of methods for identification of superheavy elements.

The exquisite results obtained by Professor **Mikhail Grigorievich Itkis**, were published in more than 200 papers in ISI journals, and were recognized by the scientific community by lot of awards. We can mention here the following:

(i) Flerov Prize – awarded by the JINR in 2003
(ii) Alexander von Humboldt Prize – awarded by Alexander von Humboldt Foundation, Bonn, Germany, in 2005
(iii) Laureate of the State Prize of the Russian Federation in Science and Technology, in 2010
(iv) Gold Medal of Bulgarian Academy of Sciences, in 2016.

Professor **Mikhail Grigorievich Itkis** received during his scientific activity the title of **Honorary Doctor of „J.W.Goethe" University of Frankfurt am Main, Germany**, in 2009, as well as the title of
Honoray Professor of Tver State University, Russia

The importance of the scientific contributions of Professor **Mikhail Grigorievich Itkis** is also significant to a number of Romanian physicists that worked on similar problems related to these research fields: Academician Aureliu Sandulescu, Dorin Poenaru and their collaborators.

As Vice-Director of the Joint Institute for Nuclear Research, Professor **Mikhail Grigorievich Itkis** contributes his great efforts to realize the mega-science project at JINR – the Nuclotron based Ion Collider fAcility (NICA) – a search for those rare and fundamental processes at extreme conditions in the micro-world, which will allow us to understand the origin of the creation of Universe as well. Also, Professor **Mikhail Grigorievich Itkis** contributes his best for transforming JINR in an open international scientific center dedicated to a wide cooperation with the national and international scientific centers, and also for the training of young generation of physicists and specialists.

The scientific activity of Professor **Mikhail Grigorievich Itkis** has been published in many prestigious Physics journals. As it was mentioned previously, up to now he published over **200 papers** in ISI quoted journals, having the **Hirsh Index** of **42**, and recognized by over **8000 citations**. Therefore, Professor **Mikhail Grigorievich Itkis** is one of the most productive personalities in the Experimental Nuclear Physics and Heavy Ion Physics.

Professor **Mikhail Grigorievich Itkis** was in his entire scientific carrier an active participant in solving of the problems of the scientific community. Therefore, he was elected in different positions in the international associations of the physicists. He is member of the Nuclear Physics European Collaboration Committee (NuPECC) since 2015 year.

During the time, Professor **Mikhail Grigorievich Itkis collaborated at different experiments with Romanian physicists, including large the experiments from JINR, and other international laboratories.** In these collaborations Romanian physicists from „Horia Hulubei" National Institute for Nuclear Physics and Engineering and the Faculty of Physics, University of Bucharest were involved, and as a result of this collaboration a large number of papers have been published in prestigious Physics journals.

Professor **Mikhail Grigorievich Itkis** permanently sustained the Nuclear and Particle Physics research in Romania.

As an important member of a number of international collaborations, Director of the Flerov Laboratory of Nuclear Reactions, Vice-Director of the JINR Dubna, Professor **Mikhail Grigorievich Itkis** permanently encouraged the presence of the Romanian physicists in these collaborations and institutions. Therefore, Romanian physicists, researchers and professors, visited, had work stages, and presented seminars here. During the time, a number of Ph.D. students had the opportunity to work in the frame of different collaborations from these institutes, too. Professor **Mikhail Grigorievich Itkis** and his groups have actively contributed, during the time, at the organization of summer schools and conferences in Nuclear and Particle Physics field, and by the high scientific standard of the invited lectures and works presented here contributed significantly at the scientific prestige of these schools and conferences in Nuclear and Particle Physics.

Entire scientific and administrative activity of Professor **Mikhail Grigorievich Itkis** is characterized by a great and profound creativity, scientific intuition, permanently focused on fundamental concepts, simple but essential for the understanding of the physical phenomena and processes. **His fundamental and profound contribution to the development of the Nuclear Physics and Heavy Ion Physics is related to the unique combination of deeply theoretical understanding and remarkable intuition with experimental skills.**

Awarding of the title of *Doctor Honoris Causa* of the University of Bucharest to Professor **Mikhail Grigorievich Itkis** represents a **symbolic recognition of his great scientific merits** and a **new step** forward to enhance **the scientific and teaching collaborations between the University of Bucharest, the Russian Universities and JINR Dubna, between the scientists from Romania and Russia, as well as from Romania and the entire world.**

Dean,
Associate Professor Dr. Petrică Cristea

Curriculum vitae | Mikhail Itkis

PERSONAL:

Born December 7, 1942 in Taldy Kurgan region, Kazakhstan, USSR
Citizen of Russia.

WORK ADDRESS:

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ACADEMIC EDUCATION:

M.Sc. Moscow State University , physics – **1966**
Ph.D. Institute of Nuclear Physics , KazakhstanAcademy of Sciences – **1974**
Doctor of Physics and Mathematics – **1985**
Professor – **1988**

MAIN POSITIONS HELD:

1967–1992 Institute of Nuclear Physics, KazakhstanAcademy of Sciences; **Ingeneer, Senior Researcher, Head of scientific department.**
1993–1996 Join Institute for Nuclear Research, Flerov Laboratory of Nuclear Reactions, Dubna, Russia; **Deputy Director**.
1997–2006 Join Institute for Nuclear Research, Flerov Laboratory of Nuclear Reactions, Dubna, Russia; **Director**.
2006–2010 Join Institute for Nuclear Research, Dubna, Russia; **Vice-Director**.
2010–2011 Join Institute for Nuclear Research, Dubna, Russia; **Director at interim**.
2011–present Join Institute for Nuclear Research, Dubna, Russia; **Vice-Director**.

HONOURS, AWARDS AND PROFESSIONAL SOCIETY MEMBERSHIPS:

Awards:

Flerov Prize, JINR, **2003**.
Alexander von Humboldt Prize, Alexander von Humboldt Foundation, Bonn, Germany, **2005**
Laureate of the State Prize of the Russian Federation in science and technology, **2010**
Gold Medal of Bulgarian Academy of sciences, **2016**

Honours:

Honoury Doctor of Goethe University of Frankfurt, Germany, 2009

Honoury Professor of Tver State University, Russia

Member:

Member of the Nuclear Physics European Collaboration Committee (NuPECC)

RESEARCH INTERESTS AND ACTIVITIES:

Heavy and superheavy nuclei research: synthesis of new heaviest elements; reactions of synthesis and decay properties of the heaviest nuclei; electromagnetic and chemical separation and detection of evaporation residues. Design and construction of kinematic separators of recoil nuclei. Experiments on the synthesis of elements with atomic numbers 112–118; measurements of production cross sections of heavy and superheavy nuclei; the influence of nuclear shells on the stability of heavy and superheavy nuclei; development of methods for identification of superheavy elements.

Nuclear fission: spontaneous fission of heavy nuclei; fission modes; fission from the isometric state of nucleus (spin and shape isomers); spontaneous emission of clusters; fission into three fragments, sequential fission; beta-delayed fission of neutron deficient isotopes of heavy elements; fission and quasi-fission of exotic nuclei; angular, mass and energy distributions of fragments, pre- and post-equilibrium neutron emission.

Autor and co-autor of over 200 peer reviewed articles.

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Articol | Mikhail Itkis

Fission and quasifission toward the superheavy mass region

M.G. Itkis[3]

June 2019

Abstract. The pathway toward the production of superheavy elements crosses with the one of an in-depth study of the fission and quasifission processes. Quasifission affects the probability of forming a compound nucleus after capture and fission plays a decisive role during the cooling of the compound nucleus. To search for optimal reactions to produce superheavy elements in fusion reactions and to provide an estimate of their production cross section measurements of the capture and fusion cross sections along with the survival probabilities are a mandatory task. Here an overview of the impact of fission and quasifission over the synthesis of superheavy elements is discussed along with the need to perform measurements over a wide range of masses and energies.

Keywords: Fission, Quasifission, Superheavy elements

1. Introduction

The major aim of this review is to discuss on the importance of studying fission and quasifission processes in connection with the research fission to the production of superheavy elements (SHE) via heavy-ion fusion reactions. This importance is justified by the fact that in the long reaction chain which brings to the formation of SHE two bifurcations must be crossed. Picturing the time evolution of the reaction as shown in Fig. 1 [1, 2], in the first one, after contact or capture, the formation of a compound nucleus (CN) has to overcome the competition with the quasifission process; in the second one, if a compound nucleus is formed, it has to survive its own fission to become an evaporation residue. The crossing of each of these two bifurcations relies on the competition with very strong processes. Quasifission (QF) and CN fission (CNF) are indeed so strong that approximately one out of 10^6 decay paths ends up in an evaporation residue. The understanding of the features of quasifission and fission is therefore crucial to search for the optimal conditions to ignite SHE production and to estimate evaporation residues cross sections. In the following, few issues connected to the properties of quasifission and fi will be discussed in some detail along with a possible strategy to pick out the optimal entrance reaction channels to produce elements heavier than *Og*.

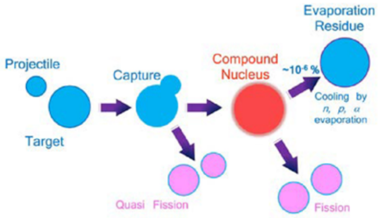

Figure 1. Schematic picture of the present knowledge of the process chain leading to SHE in heavy ion fusion reactions.

2. The SHE production cross section

As schematically shown in Fig. 1, the formation of SHE is pictured to occur in three sequential, independent steps: contact or capture, CN formation, survival of the CN to fi Consequently, the evaporation residues cross section σ_{ER} is the product of three terms [2, 3]: the capture cross section $\sigma_{capture}$, the probability of forming a CN (P_{CN}) after contact, and the probability that it survives against fi ($W_{survival}$), namely:

$$\sigma_{ER} = \sigma_{capture} \times P_{CN} \times W_{survival} \tag{1}$$

Experimentally, $\sigma_{capture}$ is defined as the sum of the QF, CNF and ER cross sections:

$$\sigma_{capture} = \sigma_{QF} + \sigma_{CNF} + \sigma_{ER} \tag{2}$$

Both capture cross section and fusion probability depend on the bombarding energy and angular momentum. The survival probability is a property of the CN and depends on its excitation energy and angular momentum, whereas the fusion probability depends strongly on the reaction entrance channel. The separation of the SHE reaction chain into three steps is clearly an oversimplification. However, the three-step concept is very helpful from the experimental point of view which only gives observables in the fi stage of a reaction. Accurate measurements of the above cross sections are very desirable to estimate the production rate of SHE and are of crucial importance to setup experiments for their production.

At present, both cold and hot fusion reactions have been used to produce SHE [3]. Cold and hot fusion reactions are characterized by strongly diff t entrance channels. In cold reactions, where fusion occurs near the reaction threshold, ^{208}Pb or ^{209}Bi target nuclei are bombarded with projectiles heavier than Ca to form compound nuclei with low excitation energy (about 10÷20 MeV). One neutron emission is enough to produce evaporation residues. Hot fusion reactions involve actinide target nuclei, larger entrance channel mass asymmetry, and lead to evaporation residues with excitation energy between 30 and 60 MeV, which results in higher neutron evaporation. Besides this, there are profound different in the production cross section as shown in Fig. 2.

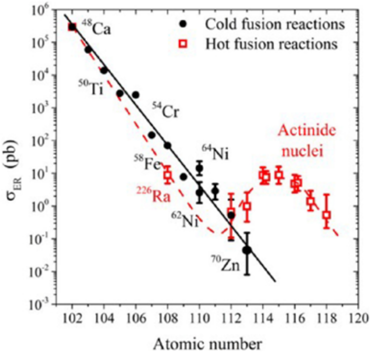

Figure 2. Cross sections of 1n-evaporation channel in the cold fusion reactions of ^{208}Pb and ^{209}Bi target nuclei with different projectiles (labelled in the figure) and cross sections of 3n and 4n-channels in the hot fusion reactions of ^{48}Ca as a function of compound nucleus atomic number. The lines are drawn as guide for the eye (adapted data from Oganessian Yu Ts [4]).

It is quite evident that hot fusion reactions involving ^{48}Ca are more suitable to produce SHE with Z>112. The fast monotonic decrease of the ER cross sections with increasing charge of SHE synthesized in the cold fusion reactions must be compared with the rise of the cross sections measured in hot reactions leading to heavier SHE. The change in the trend occurs at Z=112. There are several reasons for this drastic change which spans several orders of magnitude. A comprehensive overview of such reasons is given from the trend of the calculated cross section proposed in Ref. [2] and shown in Fig. 3. The dashed lines describe the trend for the capture, fusion and evaporation residues cross sections in the cold fusion reactions induced by several projectiles on ^{208}Pb. The solid lines refer to the same observables but for the hot fusion reactions induced by ^{48}Ca on several actinides. There are several major differences. Besides the differences of about one order of magnitude in the capture cross sections, the most striking feature is in the gap between σ_{cont} and the compound nucleus cross section σ_{CN} and the evaporation residues cross section σ_{ER}. These remarkably different trends for the cold and hot cases mean a different balance between the probabilities to pass the bifurcation points above.

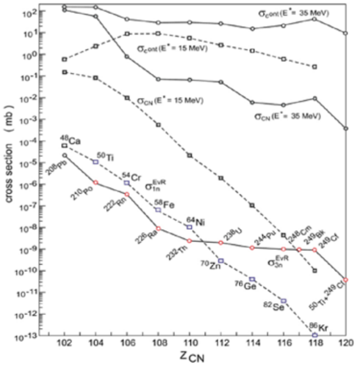

Figure 3. Calculated contact (capture), fusion and evaporation residue cross sections in the cold ^{208}Pb induced (rectangles joined by dashed lines, projectiles are shown) and in hot ^{48}Ca induced (circles joined by solid lines, targets are shown) fusion reactions. The cross sections are calculated at beam energies corresponding to 15 MeV (cold fusion, 1n channel) and 35 MeV (hot fusion, 3n channel) excitation energies of the compound nuclei (reprinted figure with permission from Zagrebaev V I and Greiner W [2]).

Fission and quasifission toward the superheavy mass region

The gap between σ_{cont} and σ_{CN} gives the measure of what is the fate of the reaction at the fi bifurcation point. In the case of a cold reaction, for instance, to produce element Z=116, one out of 10^8 paths ends up into a CN whereas one out of 10^4 in the case of hot reactions. This is a dramatic gain in favor of hot reactions. This big lost in the flow for cold reactions is due to the competition with the QF channel which is comparatively less strong in the hot case because the entrance channel mass asymmetry is lower and the target nuclei are usually deformed in their ground state.

Continuing in the timeline, the survival of the formed CN comes into play. As expected from the lower excitation energy, the cold fusion reaction case gives rise to a larger survival probability, about 10^{-3}, whereas in the hot reactions this probability is about 10^{-7} for the 3n channel. Combining these two numbers, the outcome is a total gain of three orders of magnitude in the production cross section in favor of hot reactions. This result is mainly due to the fact that in hot reactions the compound nuclei are located closer to the island of stability, and the N/Z values, even after evaporating 3 neutrons, remains large enough to make the fi barrier sufficiently higher for the compound nuclei to survive fi with larger probability. This is not the case for the nuclei involved in cold reactions which, despite the lower excitation energy, undergo fi with larger probability after losing one neutron being on the most neutron deficient side.

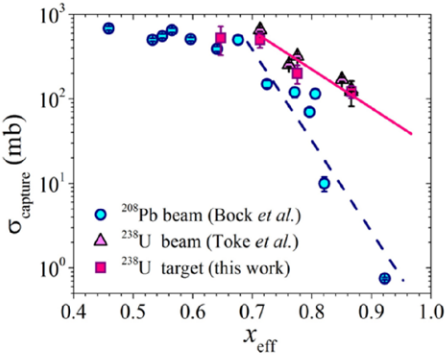

Figure 4. The capture cross section as a function of the effective fissility parameter for the reactions with ^{208}Pb and ^{238}U nuclei at interaction energies of $E_{c.m.}/E_{Bass}$ = 1.1÷1.2, where $E_{c.m.}$ is the center of mass energy and E_{Bass} is the Bass barrier. The lines are a guide for the eye (reprinted figure with permission from Kozulin E M *et al* [7]; data from ^{208}Pb beam are from Bock R *et al* 1982 *Nucl. Phys.* A **388** 334; data for ^{238}U beam are from Tõke J *et al* 1985 *Nucl. Phys.* A **440** 327. Data for ^{238}U target are from Kozulin E M *et al* [7]).

The relative balance between the competition with QF, which affects P_{CN}, and the survival against fi explains why all the elements above Z=113 where synthesized via hot fusion reactions and gives the guidelines on how to search for reactions and mechanisms to produce heavier nuclei. It is therefore clear that in choosing the reactions to produce SHE it is advisable to maximize all the three factors, namely, $\sigma_{capture}$, P_{CN} and $W_{survival}$. Consequently, independent measurements of $\sigma_{capture}$, P_{CN} and $W_{survival}$ over a large span of reactions are of paramount importance to understand the individual contributions to σ_{ER}. These measurements are indeed even more relevant considering that the models known to predict these quantities differ dramatically between each other [5] and accurate predictions of σ_{ER} are crucial for the design of new experiments which may last many months.

Many models predict quite well the trend of $\sigma_{capture}$ in hot and fusion reactions. From the experimental point of view, the same theoretical trend of $\sigma_{capture}$ is also observed as in Fig. 3. One recent compilation of old and new data [7] is shown in Fig. 4 where capture cross sections are reported as a function of the effective fi y parameter x_{eff}, a scaling parameter which allows to highlight an empirical trend of the capture cross sections over many systems [8]. It is defined as:

$$x_{eff} = \frac{4\mathrm{ZpZt}\{A_T^{1/3} A_T^{1/3} (A_P^{1/3} A_T^{1/3})\}}{(Z^2/A)_{crit}} \qquad (3)$$

$$X_{CN} = (Z^2/A) \, / \, (Z^2 \, / \, A)_{crit} \qquad (4)$$

$$(Z^2 \, / \, A)_{crit} = 50.883\,(1 - 1.7826\, I^2)\; A = A_p + A_T \quad Z = Z_p + Z_T \quad (5)$$

When compared with the fi y parameter of the compound system x_{CN}, it is clear that x_{eff} is a kind of generalization of x_{CN} because it includes the dependence on the mass and charge of the projectile and target nuclei, an indirect way to embed the mass asymmetry of the entrance channel.

In the case of hot fusion reactions on ^{238}U the cause of the less steep dropping of the capture cross section in Fig. 4 has been searched into the ground state deformation of the target nuclei [3]. To maximize σ_{ER}, once more the hot fusion reactions offer an important advantage.

3. The fusion cross section

One essential step in the search for optimal reactions to synthesize SHE is to measure P_{CN} or fusion cross sections. This task is particularly important because no satisfactory model exists to predict the behavior of P_{CN} [5, 6]. Furthermore, the measurement of P_{CN} is not an easy and fully understood task because QF events overlap with pure CNF events and make the counting of true fusion events blurred. As we will discuss now, a detailed knowledge of the QF and CNF processes is therefore mandatory and is still a matter of open questions.

The basic task in the measurement of the fusion cross section consists in counting the number of events which arise from the complete fusion of the projectile and target nuclei. In the light/medium mass nuclei, evaporation residues and fi fragments are the most copious events. The sum of them gives rise to the experimental fusion cross section:

$$\sigma_{fusion} = \sigma_{CNF} + \sigma_{ER} \qquad (6)$$

When more massive nuclei are involved at energies around the Coulomb barrier, because of the substantial increase of the Coulomb repulsion the QF arises as the most important process counteracting complete fusion [3]. QF gives rise to a binary reaction without forming a compound nucleus. The mass distribution is predominantly asymmetric but events extend up to the symmetric region of the mass distribution. The counting of pure fusion-fission events, if any, is therefore polluted by the occurrence of non-compound events in the same mass region or at its tails. One such example is given in Fig. 5.

The potential energy surface (PES) for the ^{48}Ca + ^{248}Cm reaction leading to the superheavy composite system ^{296}116 as a function of elongation and mass asymmetry (collective variables) is shown in Fig. 5(a). After just overcoming the Coulomb barrier and reaching the contact point, the intermediate nuclear system can follow different trajectories (drawn schematically, without others, some of which may end up in the same binary channel, also known as "fission channel", hollowed by the shell effects (magic numbers) with or without forming a compound nucleus. The symmetric QF_2 path merges with the one following CNF and causes the pollution. The corresponding mass-energy distribution in Fig. 5(b) shows loci that can be readily connected to the valleys originated by the shell corrections. This interpretation of the QF process also manifests one of the proofs of its strong connection with shell closures. Another very remarkable evidence of the involvement of the shell closures is the occurrence of the inverse QF [11] and of large mass transfers in damped collisions [12].

The amount of pollution between CNF and QF events is rather strongly related to some entrance channel features of the reaction. For instance, QF grows with growing mass symmetry or with the $Z_P \cdot Z_T$ products of the charges of the projectile and target, respectively [3]. Such an example is given in Fig. 6, from which it is fairly evident the dependence of the relative contribution of CNF and QF in the symmetric mass range on the entrance channel mass asymmetry and on the product $Z_P \cdot Z_T$ [13]. Furthermore, it has been demonstrated, by sophisticated TDHF calculations, that an interplay between the orientation of the prolate deformed target with shell effects in the fragments exists [14, 15]. In particular, calculations show that collisions with the tip of the deformed target produce QF whereas collisions with the side are the ones that may result into fusion [14, 15]. Other important implications of the mutual orientation between the projectile and deformed target symmetry axis have been recently investigated by Saiko and Karpov [16] by using a multidimensional Langevin approach over a large mass range. Additional insights on nuclear dynamics in heavy ion collisions and its dependence on the entrance channel properties are proposed by Adamian [17] and Kalandarov [18] based on the dinuclear system (DNS) concept, and by Simenel [19] on the basis of an in-depth TDHF model.

Since QF is a multi-facet process, still not completely identified, for which no reliable theory exists yet, semi-empirical methods have been developed on purpose to isolate the CNF component from the QF one. In order to achieve this separation several techniques have been developed based on the analysis of different experimental observables of fission fragments [3], namely, angular distributions, width of mass distributions, mass and energy distributions, mass and angular distributions. One of the main procedures used for decomposing fission and fragments into CNF and QF is to compare the experimental properties of fission and fragments for reactions

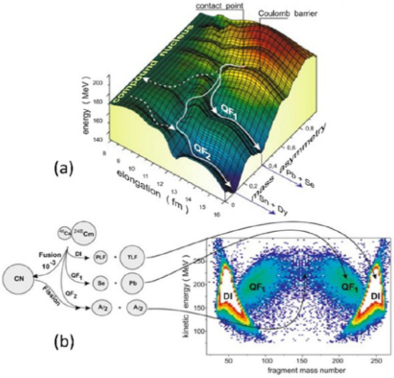

Figure 5. (a) Potential energy surface for the nuclear system formed in ^{48}Ca + ^{248}Cm collision (reprinted figure with permission from Zagrebaev V I and Greiner W [9]). The solid lines with arrows show schematically the quasi-fission trajectories going to the lead and tin valleys. The dashed curves correspond to fusion (CN formation) and fission processes. (b) Mass-energy distribution of reaction fragments in collision of ^{48}Ca with ^{248}Cm at 203 MeV center-of-mass energy (experimental data from [10]).

leading to the formation of the same composite system but having different entrance channel properties, either with experimental fission systematics [58], or with theoretical predictions in the frame of the liquid drop model (LDM) [7], or the transition state model [21] or modern multidimensional calculations [3, 22, 23, 24, 25, 26, 27].

In the lack of a comprehensive theoretical model it is necessary to proceed empirically by searching for correlations between observables and extrapolating the systematics to unknown regions. One such example is given in Fig. 7. On the left, the Total Kinetic Energy (TKE) distributions for the fragments with masses $A_{CN}/2\pm 20$ u for the reactions ^{36}S, ^{48}Ca, ^{48}Ti, and ^{64}Ni+^{238}U [7, 28, 30, 31, 32] are shown. Clearly, the TKE distributions change markedly showing nearly Gaussian shape in the case of ^{36}S and ^{48}Ca ions and two-humped shape for the reactions with ^{48}Ti and ^{64}Ni. One may speculate about the presence of other processes together with the CN fission

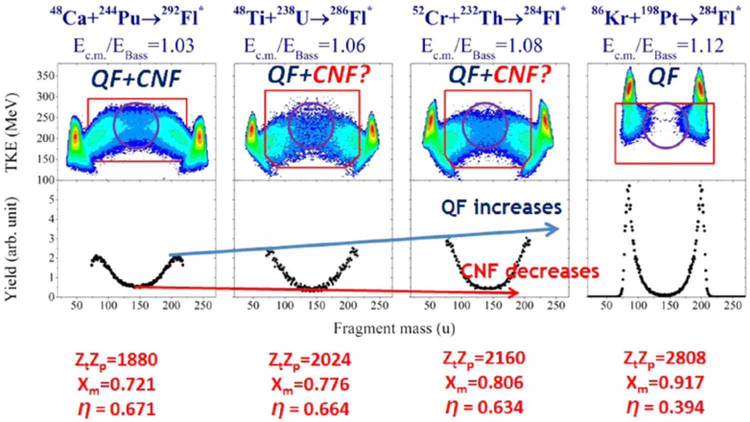

Figure 6. (top) The mass-energy matrices of binary fragments formed in several reactions candidate to the formation of composite systems with Z = 114 at energies above the Bass barrier. (bottom) mass distributions as a function of mass of fission- like fragments inside the contour lines shown on the mass-energy matrices (adapted from Kozulin E M *et al* [13]). Also shown are the changes in product $Z_P \cdot Z_T$, in the mean fissility parameter x_m (see definition later) and in the entrance mass asymmetry $\eta = (A_T - A_P)/(A_T + A_P)$.

the symmetric mass region. The disentanglement of possibly three components is based on the fact that different paths in the PES, as shown in Fig. 7 (right), have different TKE. If it is assumed that the mass-symmetric fragments may be formed by three different modes (CN fission, symmetric QF and a tail of the asymmetric QF process), to evaluate the contribution of the CN-fission process in the symmetric mass region the TKE distributions can be decomposed as a sum of three Gaussians. One of them is associated to the CN-fission process (filled region in Fig. 7(left)). To constraint the fi of three Gaussians to some physical ground, the means and variances can be fi considering some systematic properties. For the CN component, the fission systematics can be mean and variance of this component. For the QF components, additional information can be gained from systems where it is fairly known that only QF occurs in the symmetric mass region. For instance, in the case of the ^{58}Fe + ^{208}Pb reaction [28] where the asymmetric QF is the main process, even in the symmetric mass region of fragments, it is found that the variance of TKE for QF does not depend on the mass of the QF fragments. Attributing the lower energy component to QF$_{asym}$ and the higher energy one to QF$_{sym}$, in the fi procedure the variance of the QF$_{asym}$ components can be kept fixed.

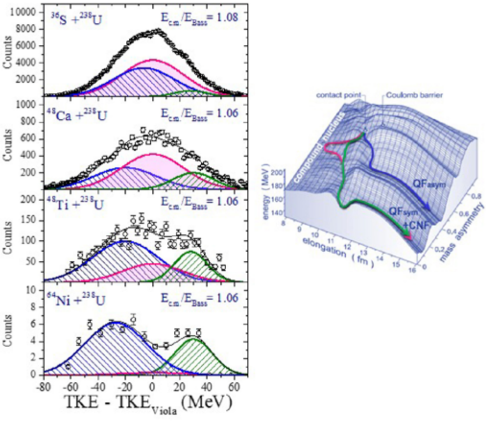

Figure 7. Total Kinetic Energy distributions of fragments with masses $A_{CN}/2\pm20$ u for the reactions ^{36}S, ^{48}Ca, ^{48}Ti, and ^{64}Ni + ^{238}U at energies above the Coulomb barrier. The filled region corresponds to the TKE distribution for CN fission. The dashed and dashed-dotted curves are associated with asymmetric and symmetric QF, respectively (reprinted figure with permission from Kozulin E M *et al* [7]).

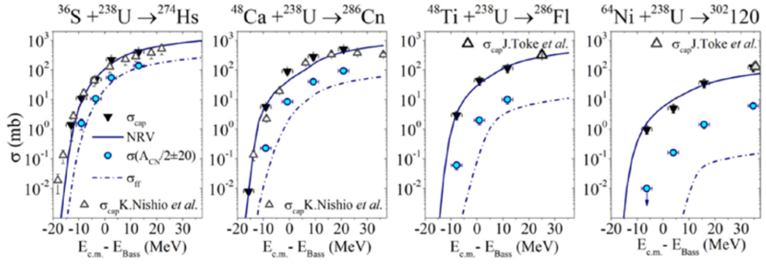

Figure 8. The solid triangles are the cross sections for fission-like fragments in the reactions ^{36}S, ^{48}Ca, ^{48}Ti, and ^{64}Ni + ^{238}U and the open triangles are the cross sections for fission-like fragments. The solid lines are the empirical model calculations. The circles are the cross sections for fragments with masses $A_{CN}/2\pm20$ u, and the dashed- dotted lines are the estimated CN-fission cross sections. E_{Bass} is the Bass barrier (reprinted figure with permission from Kozulin E M *et al* [7] for details).

From the analysis above on the fusion events, the fusion cross section can be extracted by means of an integration over 4π considering an angular distribution of the type $1/sin(\theta_{c.m.})$. This is clearly an important approximation, but the only hypothesis possible since no information was obtained for the data in [7] about the angular distribution both in fission and capture events. The fusion cross sections are shown in Fig. 8 along with the capture cross sections. One can notice the drastic drop in the capture cross section going from ^{36}S to ^{64}Ni. This in an important result in view of the search of reactions to produce superheavy elements heavier than *Og* by using projectiles heavier than ^{48}Ca.

4. The fusion probability

Once the fusion cross section is extracted, the fusion probability P_{CN} entering equation (1) can be estimated. P_{CN} is defined as the probability for CN formation from the configuration of two nuclei in contact. Being σ_{ER} typically negligible with respect to σ_{CN} (only a few picobarns for the reactions in Fig. 8) P_{CN} is the ratio between the number of events attributed to CN fission and the fission events all together.

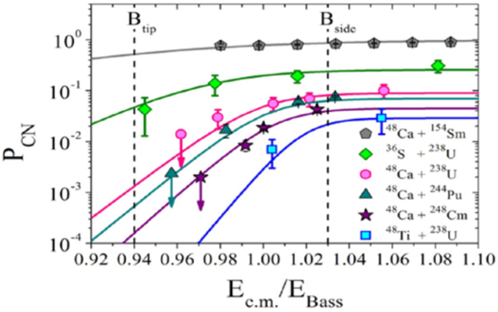

Figure 9. The fusion probabilities below and above Bass barrier obtained from the analysis of mass-energy distributions of fission-like fragments for the reactions with strongly deformed target nuclei: $^{48}Ca + ^{154}Sm$, $^{36}S + ^{238}U$, $^{48}Ca + ^{238}U$, ^{244}Pu, ^{248}Cm and $^{48}Ti + ^{238}U$ (reprinted figure with permission from Kozulin E M *et al* [7]).

Fig. 9 shows the trend of the fusion probability versus the center of mass energy below and above the Bass barrier [7] for a number of reactions [7, 28, 30, 31, 33]. There are few interesting features in this plot. The target nuclei in Fig. 9 are all deformed in the ground state. This means that there are two Coulomb barriers, one, named B_{tip}, when the collision occurs between the spherical projectile and the tip of the target nucleus, the other, named B_{side}, when the collision occurs with the side of the target nucleus. By definitions B_{tip} and B_{side} are the minimum and the maximum Coulomb barrier, respectively. For energies below B_{side}, side collisions are below barrier, and this explains the lower probability for $E_{c.m.} < B_{side}$. Above B_{side}, P_{CN} saturates as expected for all reactions. This means that not only the choice of the system is important to maximize the fusion cross section, but also the choice of the bombarding energy is crucial. Another observation is that if the reactions on ^{238}U are considered, increasing the mass and charge of the projectile results in a drop of P_{CN} of about 2 orders of magnitude at energies above B_{side}. Last comment concerns with the fact that for all the reactions in Fig. 9 a trend is observed that may be brought back to some common empirical algebraic relationship. In the lack of reliable quantitative models for P_{CN}, to identify an empirical relation and some scaling parameter to predict P_{CN} for a given reaction would be a great progress. Zagrebaev and Greiner [29] indeed proposed the following energy dependence:

$$P_{CN}(E_{c.m.}) = (P^0_{CN})/\{1 + exp\,[\alpha\,(\beta - E_{c.m.}/E_{Bass})]\} \qquad (7)$$

P^0

which is overlapped to the data in Fig. 9. P^0_{CN}, α, and β are empirical constants.

$_{CN}$ is the fusion probability above the barrier, β is the effective barrier for CN formation, and α is responsible for the sub-barrier suppression of fusion probability. Of course, each of the curves in Fig. 9 corresponds to different fission parameters. Therefore equation (7) is still not the empirical law searched for.

However, if the data above the Bass barrier are plotted against the recently identified scaling parameter [8]:

$$x_m = 0.75x_{eff} + 0.25x_{CN} \qquad (8)$$

as shown in Fig. 10, the following empirical law, also proposed in Ref. [29]:

$$P^0_{CN}(E_{c.m.}) = 1/\left\{1 + exp\left(\frac{x_m - \xi}{T}\right)\right\} \qquad (9)$$

reproduces surprising well the data for cold and hot reactions. x_{eff} is the effective fissility parameter (eq. 3) and x_{CN} (eq. 4) is the liquid drop model fissility parameter. The values of the fission parameters are the following [29]:

Reactions with Pb: $\tau = 0.0067 \pm 0.0007$; $\xi = 0.776 \pm 0.007$;

Reactions with actinide nuclei: $\tau = 0.0226 \pm 0.0006$; $\xi = 0.721 \pm 0.002$.

This new scaling parameter x_m, termed as „mean” fissility, seems to embed the main features of the entrance channels, such as the products $Z_P \cdot Z_T$ and the mass asymmetry. However, the main difference in the trend of P^0 reactions is to be searched in the orientation during the collision of the target with the projectile being important as the target nuclei are deformed in the case of hot fusion reactions (orientation effect) in Fig. 10. This feature cannot be included in a scaling parameter and hence the difference in the trends of P^0 between the two types of reactions.

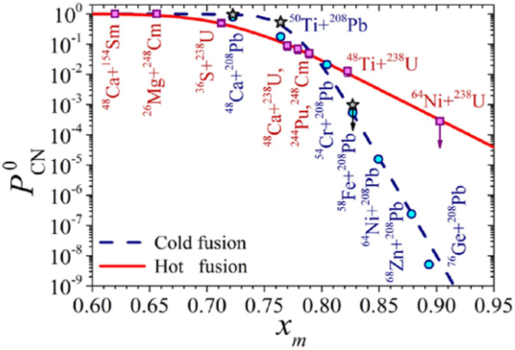

Figure 10. Fusion probability in cold (spherical target nuclei) and hot fusion (strongly deformed target nuclei) reactions at energies above the Coulomb barrier versus the mean fissility parameter of the reaction. The circles are the fusion probabilities calculated for cold fusion reactions [29] (reprinted figure with permission from Kozulin E M *et al* [7]).

5. The survival probability

The last term in equation (1) is the survival probability of the CN against fission. It is defined experimentally as $W_{survival} = \sigma_{ER}/(\sigma_{ER} + \sigma_{CNF})$. If experimental data are not available it can be written in a form that explicitly uses the neutron and fission partial decay widths Γ_n and Γ_f:

$$W_{survival} = P_{xn}(E^*_{CN}) \prod \left(\frac{\Gamma_n}{\Gamma_n + \Gamma_f}\right)_{i,E^*_{CN}} \qquad (10)$$

Where P_{xn} is the probability of emitting x neutrons. The index Ω runs on the number of emetted neutrons and E^*_{CN} is the excitation energy of the CN. The ratio Γ_n/Γ_f can be computed through the statistical model as:

$$\frac{\Gamma_n}{\Gamma_f} = \frac{4A_{CN}^{2/3} a_f \, (E^*_{CN} - B_n)}{ka_n \left[2a_f^{1/2}(E^*_{CN} - B^*_f)^{1/2} - 1\right]} exp\, [2a_n^{1/2}(E^*_{CN} - B_n)^{1/2} - 2a_f^{1/2}(E^*_{CN} - B^*_f)^{1/2}] \quad (11)$$

where $B^*_f = B_f(E^*_{cn}) = B_f \, exp\,(-\frac{E^*_{CN}}{E_D}), a_n = A_{CN}/10, a_f = 1.1\, a_n, E_D = 0.4A_{CN}^{4/3}/a_n$, $k = 0.98\, MeV$.

This equation implies that to arrive to an estimate of σ_{ER} some knowledge of the fi barrier is needed as well. This is a critical point because the values of fi barriers rely on models [34, 35, 36, 37, 38, 39, 40, 41]. Differences between predictions vary from 0.5 up to 2 MeV. This translates in survival probabilities that can differ up to one order of magnitude from model to model. Conversely, if the ratio Γ_n/Γ_f or σ_{ER} is measured the fi barrier can be estimated. Indeed, this is still not enough because other ingredients of the model need to be fi as the neutron binding energy B_n, a_f and a_n and the dumping of B_f as the excitation energy is raised. All of this means that the uncertainties in the estimates of $W_{survival}$ play an important role. Furthermore, equation (11) for Γ_n/Γ_f is an approximation and a much more complex statistical model of particle evaporation and fi should be invoked along with dynamical effects such as nuclear viscosity [9, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51]. All the above gives support to the necessity of measuring $W_{survival}$ over a wide range of masses and energies to establish a larger and larger set of data on which to test the different models [5, 46].

6. Perspectives

From the analysis presented here, it is clear that the synthesis of superheavy elements has to face many challenges. Since the predictive power of the current models is quite limited, experimental campaigns should be designed to increase substantially the amount of data available on the fusion process, especially on the front of heavier target nuclei. Understandingly, this is not an easy task because heavier target nuclei such as Cm, Bk or Cf are diffi to make and to handle. From the trend of the capture and fusion cross sections, we can conclude that further progress in the fi of synthesis of superheavy nuclei can be achieved using hot fusion reactions between actinide nuclei and Ti, Fe or Cr isotopes. Of course, for planning experiments on the synthesis of superheavy nuclei of up to Z=122, new research and more precise quantitative data obtained from the processes of FF and QF of these nuclei in reactions with Ti, Fe and Cr ions are needed. A worldwide effort in many laboratories, such as FLNR (Russia), JAEA (Japan), ANU (Australia) or ATLAS (USA), is indeed actively pursued in order to measure independently capture, fusion and survival cross sections over a broad spectrum of projectile target combinations.

Above all, the biggest challenge is to be able to detect evaporation residues with cross sections of the order of the pico or sub-pico barn. This task requires a major jump in the presently available intensity for stable beams and an update of the technology for targets and for detection. These are indeed the aims of the SHE factory being under construction at the FLNR at JINR in Dubna and soon to be ready to operate.

In the complex framework of the current superheavy research it is still not clear what is the role that radioactive ion beams (RBIs) could play in the future. Some recent review articles discuss capture and fusion cross sections in reactions induced by RIBs or weakly bound nuclei from the experimental [52] and theoretical [53] points of view and contradictory results have been highlighted. Experimental data seem to confirm that when neutron-rich projectiles are used a raise in the capture cross section is observed [54] and possibly new neutron-rich heavy nuclei can be produced.

The lack of experimental data on this topic is related to the limited availability of facilities that can produce and re-accelerate neutron-rich RIBs. Whereas there are many under construction (i.e. ACCULINNA2 (Russia), SPES (Italy), SPIRAL2 (France) or FRIBS (USA)) there are some smaller facilities such as the EXOTIC beam line at LNL (Legnaro, Italy) [55] which can produce fairly clean and intense RIBs of ^{8}Li, ^{7}Be, ^{15}O or ^{17}F with which preliminary studies, such as those in [57, 56, 58] in the fi channel, can be performed on the proton-rich side of the nuclides' chart. Same type of studies could be performed at the ACCULINNA2 as well. These types of facilities can indeed produce very valuable data while waiting for the bigger facilities to be completed.

7. Acknowledgments

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