Nuclei: superheavy–superneutronic–strange–and of antimatter

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Nuclei: superheavy–superneutronic–strange–and of antimatter[1]

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Abstract. The extension of the periodic system into various new areas is investigated. Experiments for the synthesis of superheavy elements and the predictions of magic numbers are reviewed. Further on, investigations on hypernuclei and the possible production of antimatter-clusters in heavy-ion collisions are reported. Various versions of the meson field theory serve as effective field theories at the basis of modern nuclear structure and suggest structure in the vacuum which might be important for the production of hyper- and antimatter.

1. Introduction

I am happy to be here and congratulate my friend and collaborator for more than 30 years, Prof. Aurel Sandulescu, on occasion of his 80-th birthday. After developing the fragmentation theory with Werner Scheid based on the two–center shell model we predicted together with Dorin Poenaru **cluster radioactivity**. As a term it entered the **Encyclopedia Britannica**. Indeed, it is one of the most outstanding discoveries in Nuclear Physics. Looking through Rumanian history of Physics I compare it with Proca's work. I will summarize here the work on the extension of the Periodic System, into which my work with Aurel Sandulescu is embedded.

There are fundamental questions in science, like e. g. "How did life emerge?" or "How does our brain work?" and others. However, the most fundamental of those questions is "How did the world originate?". The material world has to exist before life and thinking can develop. Of particular importance are the substances themselves, i. e. the particles the elements are made of (baryons, mesons, quarks, gluons), i. e. elementary matter. The vacuum and its structure is closely related to that. We want to report on these questions, beginning with the discussion of modern issues in nuclear physics.

The elements existing in nature are ordered according to their atomic (chemical) properties in the **periodic system**, which was developed by Dmitry Mendeleev and Lothar Meyer. The heaviest element of natural origin is uranium. Its nucleus is composed of $Z = 92$ protons and a certain number of neutrons ($N = 128$–150). They are called the different uranium isotopes. The transuranium elements reach from neptunium ($Z = 93$) via californium ($Z = 98$) and fermium ($Z = 100$) up to lawrencium ($Z = 103$). The heavier the elements are, the larger are their radii and their number of protons. Thus, the Coulomb repulsion in their interior increases, and they undergo fission. In other words: the transuranium elements become more unstable as they get

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[1] A similar talk I have given and published in The European Physical Journal D (2012).

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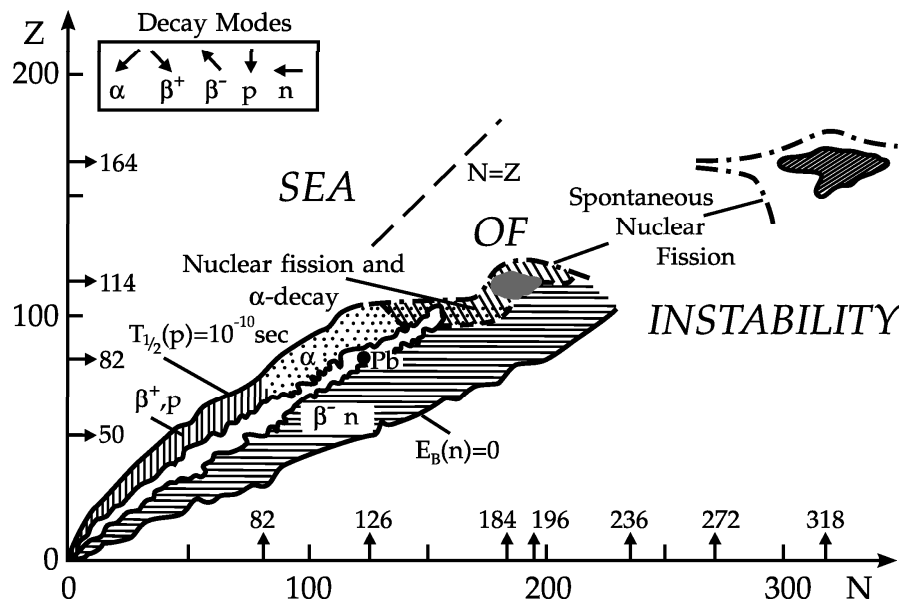
Figure 1. The periodic system of elements as conceived by the Frankfurt school in the late sixties. The islands of superheavy elements (Z = 114, N = 184, 196 and Z = 164, N = 318) are shown as dark hatched areas.

bigger. In the late sixties, the dream of the superheavy elements arose. Theoretical nuclear physicists around S. G. Nilsson (Lund) and from the Frankfurt school [1, 2] predicted that so-called closed proton and neutron shells should counteract the repelling Coulomb forces. Atomic nuclei with these special **"magic" proton and neutron numbers** and their neighbours could again be rather stable. These magic proton (Z) and neutron (N) numbers were thought to be Z = 114 and N = 184 or 196. Typical predictions of their life-times varied between seconds and many thousand years. Figure 1 summarizes the expectations at the time. One can see the islands of superheavy elements around Z = 114, N = 184 and 196, respectively, and the one around Z = 164, N = 318.

2. Cold Valleys in the Potential
The important question was how to produce these superheavy nuclei. There were many attempts, but only little progress was made. It was not until the middle of the seventies that the Frankfurt school of theoretical physics together with foreign guests (R. K. Gupta (India), A. Sandulescu (Romania), D. Poenaru (Romania)) [3] theoretically understood and substantiated the concept of bombarding double magic lead nuclei with suitable projectiles, which had been proposed intuitively by the Russian nuclear physicist Y. Oganessian [4]. The two-center shell model, which is essential for the description of fission, fusion and nuclear molecules, was developed in 1969–1972 by W. Greiner and his students U. Mosel [1] and J. Maruhn [5]. It showed that the shell structure of the two final fragments was visible far beyond the barrier, where the nucleus undergoes fusion. The collective potential energy surfaces of heavy nuclei, which were calculated in the framework of the two-center shell model, exhibit pronounced valleys [6].

These valleys provide promising doorways to the fusion of superheavy nuclei for certain projectile-target combinations (Fig. 2). If projectile and target approach each other through those **"cold" valleys** [3, 7], they get only minimally excited and the barrier, which has to be overcome (fusion barrier) is lowest (as compared to the neighbouring projectile-target
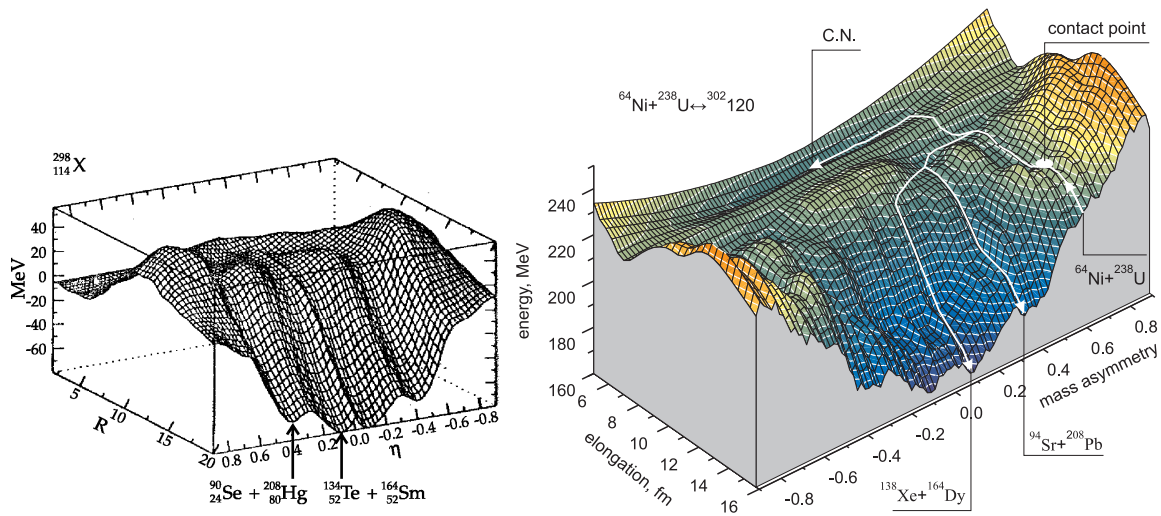
Figure 2. Left: The collective potential energy surface of ^{184}114 calculated within the two center shell model by J. Maruhn *et al.* shows clearly the cold valleys, which reach up to the barrier and beyond. R denotes the distance between the centers for fragments containing A_1 and A_2 nucleons, while $\eta = (A_1 - A_2)/(A_1 + A_2)$ is the mass asymmetry parameter. Right: Collective potential energy surface of the element ^{302}120. (C. N. stands for compound nucleus).

combinations). In this way, the correct projectile- and target-combinations for fusion were predicted. Indeed, Gottfried Münzenberg and Sigurd Hofmann and their group at GSI [8] have followed this approach. With the help of the SHIP mass-separator and the position sensitive detectors, which were especially developed by them, they produced the pre-superheavy elements Z = 106, 107, . . . 112, each of them with the theoretically predicted projectile-target combinations, and only with these.

Everything else failed. This is an impressive success, which crowned the laborious construction work of many years. The last but one example of this success, was the discovery of element 112 and its long α–decay chain. The Dubna group produced the six isotopes of Z = 113–118 by bombarding ^{244}Pu–^{248}Cf with ^{48}Ca [9]. This is also a cold valley reaction (in this case due to the combination of a spherical and a deformed nucleus), as predicted by Gupta, Sandulescu and Greiner in 1977 [3]. There exist also cold valleys for which both fragments are deformed [7], or have non-axial orientations [10], but these have not been verified experimentally. The cold valleys also play an important role in nuclear fission giving rise to asymmetric and superasymmetric [11, 12] fission and to cluster radioactivity [13].

## 3. Shell structure in the superheavy region
Decay properties and stability of heaviest nuclei with $Z \leq 132$ were recently studied within the macro-microscopical approach for nuclear ground state masses and phenomenological relations for the half-lives with respect to α-decay, β-decay and spontaneous fission [14]. It was found (see Fig. 3) that the β-stable isotopes ^{291}Cn and ^{293}Cn with a half-life of about 100 years are the longest-living superheavy nuclei located on the first island of stability. Because of their short half-lives the search in nature of superheavy nuclei may be performed only in cosmic rays. Under terrestrial conditions a measurable amount of superheavies is unlikely to exist. Note, that fusion reactions lead to the proton-rich nuclei. The heaviest synthesized nuclei with Z = 118 is situated already quite close to the border of 1 μs half-life. It means that the synthesis and detection of nuclei with $Z > 120$ produced in fusion reactions may be difficult at existing experimental
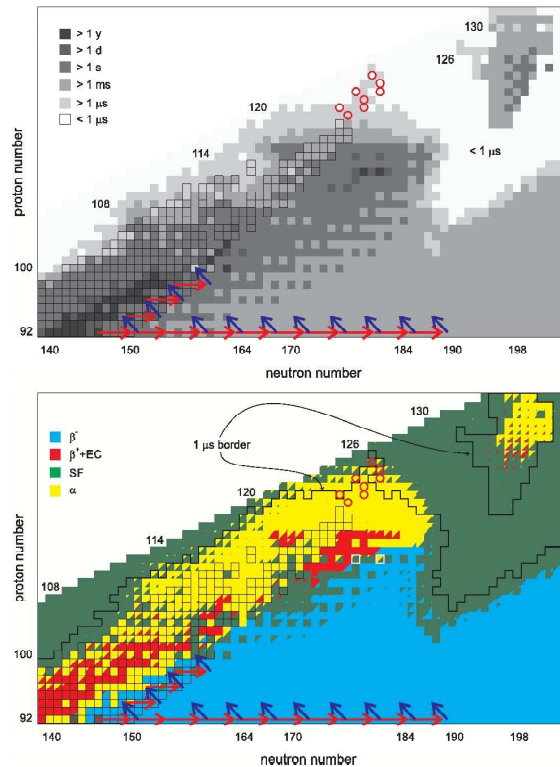
Figure 3. Half-lives (top) and decay modes (bottom) of nuclei in the upper part of the nuclear map. The circles show the nuclei with $Z = 119 - 124$, which may be synthesized in $3n$ channel of fusion reactions ^{50}Ti $+^{249}$ Bk,^{249} Cf and ^{54}Cr,^{58} Fr $+^{248}$ Cm,^{249} Bk,^{249} Cf. Outlined squares on the lower panel correspond to the experimentally known nuclei. The most stable Copernicium isotopes are ^{291}Cn and ^{293}Cn. Schematic view of slow (terminated at the short-lived fission Fermium isotopes) and fast neutron capture processes with subsequent β^- decays are shown by the arrows.

facilities due to their short half-lives (shorter than 1 μs). This prediction should be taken into account while planning new experiments and experimental setups. One may see as well that the nearest neutron-rich isotopes of superheavy elements with $111 \leq Z \leq 115$ to those synthesized recently in Dubna in ^{48}Ca-induced fusion reactions are found to be β^+-decaying. This fact may significantly complicate their experimental identification. However, existence of this area of β^+-decaying nuclei gives us a possibility to reach the center of the island of stability. One of the way to produce ^{291}Cn is the triple β^+ (or EC) decay of ^{291}115 which in turn could be, for example, synthesized after α-decay of ^{295}117 in the reaction ^{48}Ca $+^{249}$ Bk $\rightarrow^{295}$ 117 + 2n. The proposed method of reaching the island of stability hopefully may be realized in future with the progress in experimental techniques. We found as well the second area of stability of superheavy nuclei (still with shorter half-lives) situated in the region of $Z \sim 124$ and $N \sim 198$. It is separated from the "continent" by the "gulf" of short-living nuclei with half-lives shorted than 1 μs.

Studies of the shell structure of superheavy elements in the framework of the meson field theory and the Skyrme-Hartree-Fock approach have recently shown that the magic shells in the superheavy region are very isotope dependent [3]. Additionally, there is a strong dependence
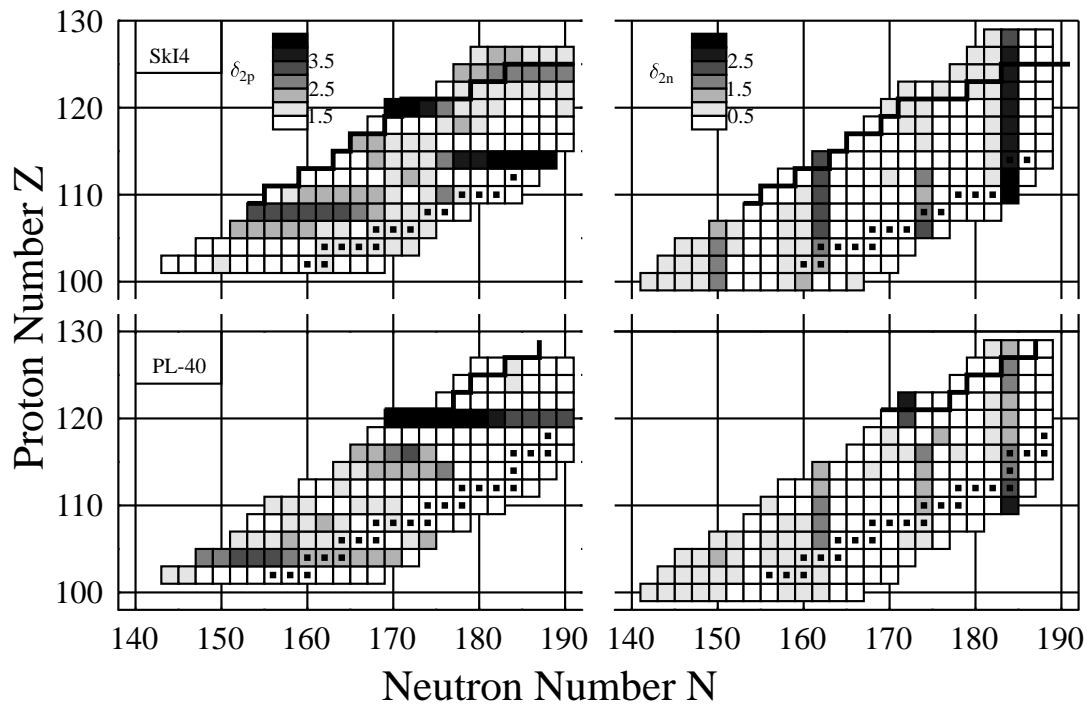
Figure 4. Grey scale plots of proton gaps (left column) and neutron gaps (right column) in the N-Z plane for deformed calculations with the forces SkI4 and PL- 40. Besides the spherical shell closures one can see the deformed shell closures for protons at $Z = 104$ (PL-40) and $Z = 108$ (SkI4) and the ones for neutrons at $N = 162$ for both forces.

on the parameter set and the model. Some forces hardly show any shell structure, while other predict the magic numbers $Z = 114$, 120 and 126. Using the heaviest known even-even nucleus Hassium $^{264}_{156}108$ as a criterium to find the best parameter sets in each model, it turns out that PL-40 and SkI4 produce best its binding energy. However, these two forces make conflicting predictions for the magic number in the superheavy region: SkI4 predicts $Z = 114$, 120 and PL-40 $Z = 120$. Most interesting, $Z = 120$ **as magic proton number seems to be as probable as** $Z = 114$. Calculations of deformed systems within the two models [15] reveal again different predictions: Though both parametrizations predict $N = 162$ as the deformed neutron-shell closure, the deformed proton-shell closures are $Z = 108$ (SkI4) and $Z = 104$ (PL-40) (see Fig. 4). Calculations of the potential energy surfaces [15] show single humped barriers; their heights and widths strongly depend on the predicted magic number. Furthermore, recent investigations in a chirally symmetric mean-field theory (see also below) result also in the prediction of these two magic numbers [16, 17]. The corresponding magic neutron numbers are predicted to be $N = 172$ and to a lesser extend $N = 184$. Thus, this region provides an open field of research. The charge distribution of the $Z = 120, N = 184$ nucleus indicates a hollow inside. This may suggest that it might be essentially a fullerene consisting of 60 α–particles and one binding neutron per alpha. The cold valleys in the collective potential energy surface are basic for understanding this exciting area of nuclear physics! It is a master example for understanding the **structure of elementary matter**, which is so important for other fields, especially astrophysics, but even more so for enriching our "Weltbild", i.e. the status of our understanding of the world around us.
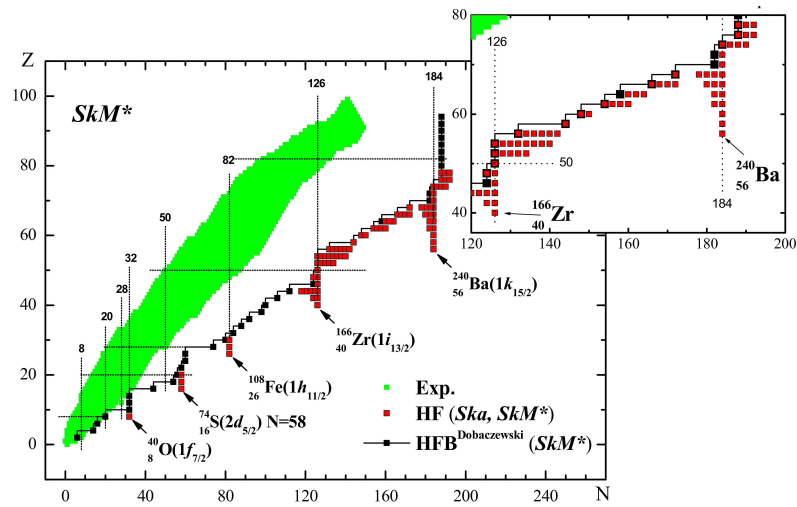
Figure 5. Fragment of the neutron drip line and elements (red squares) that are stable against one neutron emission [18]. One can see the formation of stability peninsulas along neutron magic numbers.
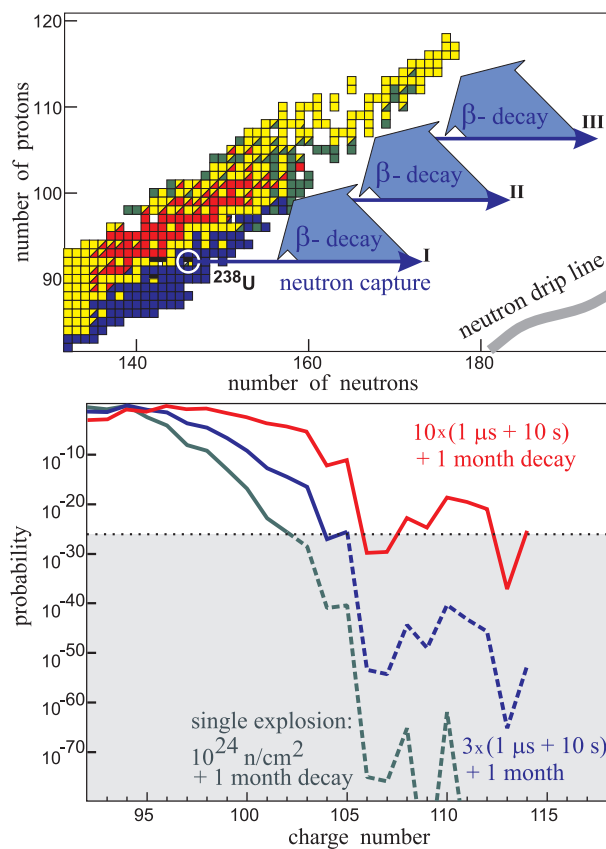
Figure 6. Schematic picture for multiple neutron irradiation of initial ^{238}U material (top) and probability for formation of heavy nuclei (bottom) in such process (one, three and ten subsequent explosions). Dotted line denotes the level of few atoms.
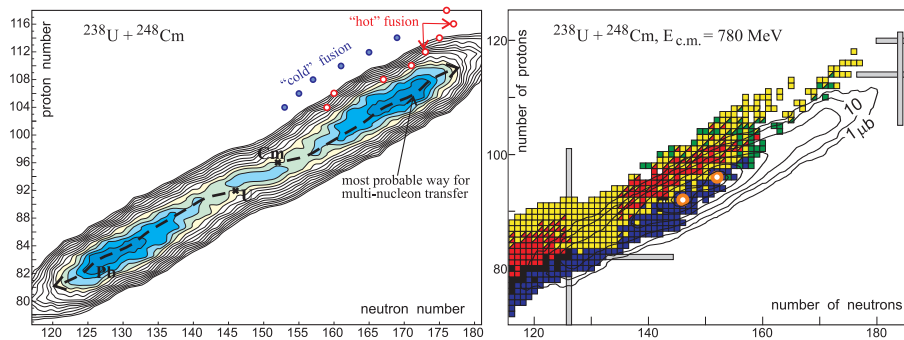
Figure 7. Landscape of potential energy surface (on the left) and the cross sections (microbarns, logarithmic scale) for production of primary fragments (on the right) in collision of ^{238}U with ^{248}Cm.
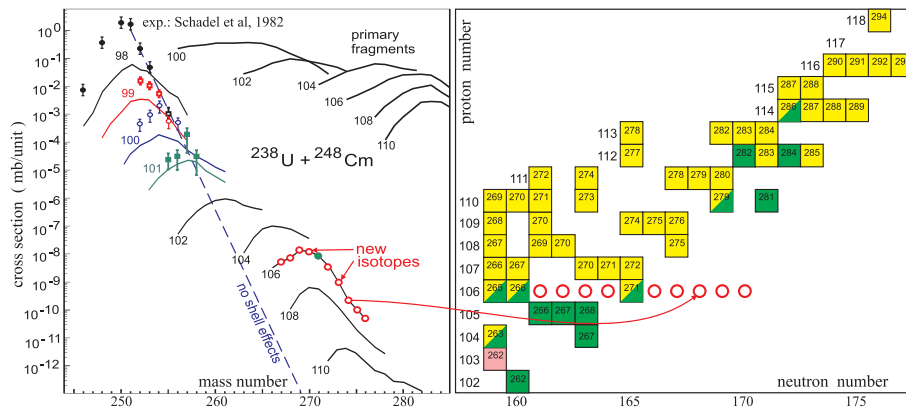
Figure 8. Yield of primary and survived isotopes of SH nuclei produced in collisions of ^{238}U with ^{248}Cm at 800 MeV center-of-mass energy. Dashed line shows the expected locus of transfer reaction cross sections without the shell effects.

The investigation of the neutron drip line by extended Hartree-Fock+BCS calculations led to a surprise: extremely neutron rich nuclei along the magic neutron numbers become stable against one-and two-neutron separation [18], see Fig. 5. The standard production of superheavy nuclei by fusing two smaller stable nuclei leads automatically to neutron poor isotopes near the proton drip line (therefore the lifetime of the produced superheavies is so small). Only a few superheavy atoms are produced this way. This leads us directly to the question of how superheavies with larger neutron numbers (and therefore having larger lifetimes: up to thousands of years) can be produced. One also wants to produce such long–living superheavies in macroscopic quantities (milligrams, grams,...) so that they can eventually be used technically. This can be done either by double (or multiple) underground atomic bomb explosions or by pulsed reactors with very high neutron flux ($\simeq 10^{21}$ neutrons/ sec cm^2) see [19, 20] and Figs. 3 and 6.

The idea to take advantage of the shell effects for the production of SH nuclei in the multi-nucleon transfer processes of low-energy heavy ion collisions was proposed in [21]. The shell effects are known to play an important role in fusion of heavy ions with actinide targets driving the nuclear system to the quasi-fission channels into the deep lead and tin valleys and, thus, decreasing the fusion probability. On the contrary, in the transfer reactions the same effects may lead to enhanced yield of SH nuclei. It may occur if one of heavy colliding nuclei, say ^{238}U, gives
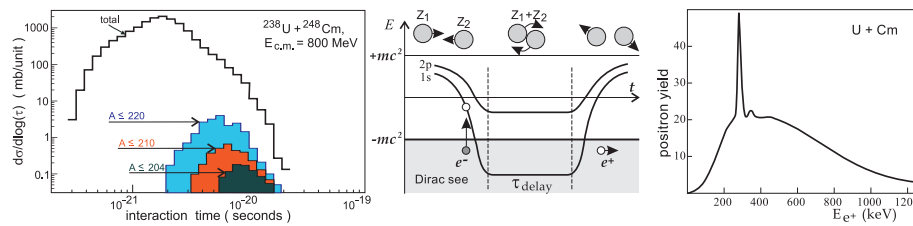
Figure 9. Reaction time distribution (left panel) and spontaneous positron formation (middle panel) in supercritical electric field of long-lived giant quasi-atom formed in collision of U+Cm; the right panel shows the energy distribution of the positron yield.

away nucleons approaching to double magic ^{208}Pb nucleus, whereas another one, say ^{248}Cm, accepts these nucleons becoming superheavy in the exit channel the so called "inverse" (anti-symmetrizing) quasi-fission process. The potential energy surface of the giant nuclear system formed in collision of ^{238}U and ^{248}Cm nuclei is shown in Fig. 7. In low-energy damped collisions of heavy ions just the potential energy surface regulates to a great extent the evolution of the nuclear system driving it to the minimal values of potential energy in the multidimensional space of collective variables. In the course of nucleon exchange the most probable path of the nuclear system formed by ^{238}U and ^{248}Cm lies along the line of stability with formation of SH nuclei which have many more neutrons as compared with those produced in the "cold" and "hot" fusion reactions. Due to fluctuations even more neutron rich isotopes of SH nuclei may be formed in such transfer reactions. The calculated cross sections for formation of primary fragments in low-energy collisions of ^{238}U with ^{248}Cm target are shown in Fig. 7 by the counter lines in logarithmic scale. As can be seen, the superheavy nuclei located very close to the center of the island of stability may be produced in this reaction with rather high cross section of one microbarn. This region of the nuclear map cannot be reached in any fusion reaction with stable projectiles and long-lived targets. Of course, the question arises whether these excited superheavy primary fragments may survive. 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. 8 for final survived fragments. 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.

We found that the nuclear system consisting of two very heavy nuclei may hold in contact rather long in some cases [22]. During this time the giant nuclear system moves over the multidimensional potential energy surface with almost zero kinetic energy (result of large nuclear viscosity). The reaction time distribution is shown in Fig. 9 for the ^{238}U+^{248}Cm collision. With increase of the energy loss and mass transfer the reaction time becomes longer and its distribution becomes more narrow. The lifetime of a giant composite system more than 10^{-20} s is quite enough to expect positron line structure emerging on top of the dynamical positron spectrum due to spontaneous e^+e^- production from the supercritical electric fields as a fundamental QED process ("decay of the vacuum", Fig. 9) [23]. Formation of the background positrons in these reactions forces one to find some additional trigger for the longest events. For the considered case of ^{238}U+^{248}Cm collision at 800 MeV center-of-mass energy, the detection of the surviving nuclei in the lead region at the laboratory angles of about 25° and at the low-energy border of their spectrum (around 1000 MeV for Pb) could be a real trigger for longest reaction time.

It was recently found that low-energy collision of actinides may lead to quite an exotic process of three-body clusterization, the so-called true ternary quasifission, leading to formation of two
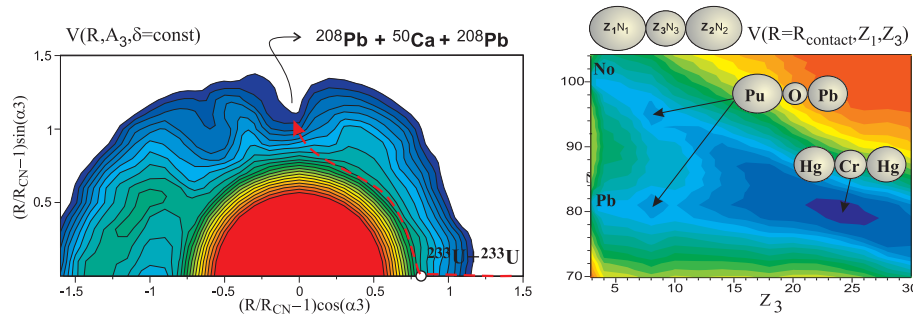
Figure 10. (Left panel) Potential energy (macroscopic plus shell corrections) for ternary quasifission of giant nuclear system formed in ^{233}U+^{233}U collision, depending on elongation and mass of third fragment ($\alpha_3 = \pi \cdot A_3/100$, where A_3 is the mass number of the third fragment). (Right panel) Landscape of potential energy of three-body contact configurations of giant nuclear system formed in collision of ^{238}U+^{238}U.

lead-like fragments and some heavy third particle in between [24]. This type of processes is quite possible because the shell effects significantly reduce the potential energy of the three-cluster configurations with two strongly bound lead-like fragments. In Fig. 10 the landscape of the potential energy surface is shown for a three-body clusterization of the nuclear system formed in collision of U+U. It is seen (left panel) that the shell correction at contact configurations makes a very deep minimum for the "lead-calcium-lead" ($A_3 = 50$) clusterization. In the right panel the potential energy is shown as a function of three variables, Z_1, Z_3 (charges of the first and third fragments) and system elongation R (minimized over the neutron numbers) at fixed (equal) deformations of the fragments being in contact. As can be seen, the giant nuclear system, consisting of two touching uranium nuclei, may split into the two-body exit channel with formation of lead-like fragment and complementary superheavy nucleus (the so-called anti-symmetrizing quasifission process which may lead to an enhanced yield of SH nuclei in multi-nucleon transfer reactions [21]). Beside the two-body Pb–No clusterization and the shallow local three-body minimum with formation of light intermediate oxygen-like cluster, the potential energy has the very deep minimum corresponding to the Pb-Ca-Pb–like configuration (or Hg-Cr-Hg) caused by the $N = 126$ and $Z = 82$ nuclear shells. The extreme clustering process of formation of two lead-like doubly magic fragments in collisions of actinide nuclei is a very interesting subject for experimental study. Such measurements, in our opinion, are not too difficult. It is sufficient to detect two coincident lead-like ejectiles (or one lead-like and one calcium-like fragments) in U+U collisions to conclude unambiguously about the ternary fission of the giant nuclear system.

4. Extension of the periodic system into the field of hyper- and antimatter

Nuclei that are found in nature consist of nucleons (protons and neutrons) which themselves are made of u (up) and d (down) quarks. However, there also exist s (strange) quarks and even heavier flavours, called charm, bottom, top. The latter has just recently been discovered. Let us stick to the s quarks. They are found in the "strange" relatives of the nucleons, the so-called hyperons ($\Lambda, \Sigma, \Theta, \Omega$). The Λ–particle, e. g., consists of one u, d and s quark, the Θ–particle even of an u and two s quarks, while the Ω (sss) contains strange quarks only.

If such a hyperon is taken up by a nucleus, a **hyper-nucleus** is created. Hypernuclei with one hyperon have been known for 20 years [25]. Several years ago, Carsten Greiner, Jürgen Schaffner and Horst Stöcker [26] theoretically investigated nuclei with many hyperons, **hypermatter**, and

found that the binding energy per baryon of strange matter is in many cases even higher than that of ordinary matter (composed only of u and d quarks). This leads to the idea of extending the periodic system of elements in the direction of strangeness.

One can also ask for the possibility of building atomic nuclei out of **antimatter**, that means searching e. g. for anti-helium [27], anti-carbon, anti-oxygen. Figure 11 depicts this idea. Due to charge conjugation symmetry, antinuclei should have the same magic numbers and the same spectra as ordinary nuclei. However, as soon as they get in touch with ordinary matter, they annihilate with it and the system explodes. Now the important question arises, how these strange matter and antimatter clusters can be produced. First, one thinks of collisions of heavy nuclei, e. g. lead on lead, at high energies (energy per nucleon $\geq$200 GeV). Calculations with the URQMD-model of the Frankfurt school show that through **nuclear shock waves** [28] nuclear matter gets compressed to 510 times of its usual value, $\rho_0 \simeq 0.17$ fm^{-3}, and heated up to temperatures of $kT \simeq 200$ MeV. As a consequence, about 10 000 pions, 100 Λ's, 40 Σ's and Θ's and about as many antiprotons and many other particles are created in a single collision. It seems conceivable that it is possible in such a scenario for some Λ's to get captured in a nuclear cluster. This happens indeed rather frequently for one or two Λ–particles; however, more of them get built into nuclei with rapidly decreasing probability only. This is due to the low probability for finding the right conditions for such a capture in the phase space of the particles: the numerous particles travel with all possible momenta (velocities) in all directions. The chances for hyperons and antibaryons to meet get rapidly worse with increasing number. In order to produce multi–Λ–nuclei and antimatter nuclei, one has to look for a different source.

In the framework of the meson field theory, the energy spectrum of baryons has a peculiar structure, depicted in upper part of Fig. 12. It consists of an upper and a lower continuum, as it is known for electrons (see, e. g. Ref.[29]). Of special interest in the case of the baryon spectrum is the potential well, built of the scalar and the vector potential, which rises from the lower continuum. Naftali Auerbach and collaborators noticed this first [30]. It is known since P. A. M. Dirac (1930) that the negative energy states of the lower continuum have to be occupied by particles (electrons or, in our case, baryons). Otherwise our world would be unstable, because the "ordinary" particles are found in the upper states which can decay through the emission of photons into lower lying states. However, if the "underworld" is occupied, the Pauli-principle will prevent this decay. Holes in the occupied "underworld" (Dirac sea) are antiparticles.

The occupied states of this underworld, including up to 40 000 occupied bound states of the lower potential well, represent the **vacuum**. The peculiarity of this strongly correlated vacuum structure in the region of atomic nuclei is that — depending on the size of the nucleus — more than 20 000 up to 40 000 (occupied) bound nucleon states contribute to this polarization effect. Obviously, we are dealing here with a **highly correlated vacuum**. Pronounced shell structure can be recognized [31]. Holes in these states have to be interpreted as bound antinucleons (antiprotons, antineutrons). If the primary nuclear density rises due to compression, the lower well increases while the upper decreases and soon is converted into a repulsive barrier. This compression of nuclear matter can only be carried out in relativistic nucleus-nucleus collision with the help of shock waves, which have been proposed by the Frankfurt school (see W. Scheid et al., Ref. [32]) and which have since then been confirmed extensively (see, e. g. Ref. [33]). These **nuclear shock waves** are accompanied by heating of the nuclear matter. Indeed, density and temperature are intimately coupled in terms of the hydrodynamic Rankine–Hugoniot equations. Heating as well as the violent dynamics cause the creation of many holes in the very deep (measured from $-M_B c^2$) vacuum well. These numerous bound holes resemble antimatter clusters which are bound in the medium; their wave functions have large overlap with antimatter clusters. When the primary matter density decreases during the expansion stage of the heavy–ion collision, the potential wells, in particular the lower one, disappear.

The bound antinucleons are then pulled down into the (lower) continuum. In this way
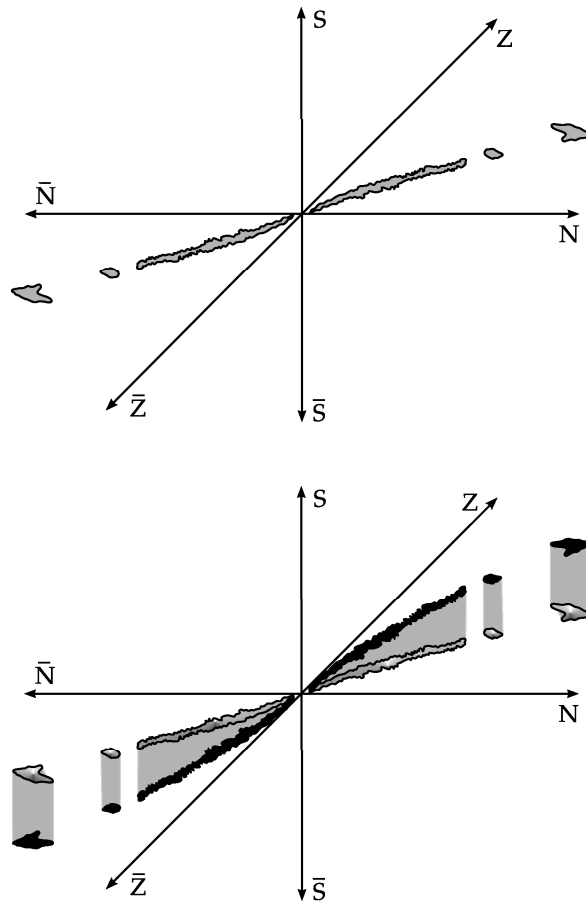
Figure 11. The extension of the periodic system into the sectors of strangeness $S, \overline{S}$ and antimatter $\overline{ZN}$. In the upper part of the figure only the stable valley in the usual proton (Z) and neutron (N) plane is plotted, however, extended into the sector of antiprotons and antineutrons. In the second part of the figure it has been indicated, how the stable valley winds out of the Z-N-plane into the strangeness sector. The same can be observed for the antimatter sector.

antimatter clusters may be set free. Of course, a large part of the antimatter will annihilate on ordinary matter present in the course of the expansion. However, it is important that this mechanism for the production of antimatter clusters out of the highly correlated vacuum does not proceed via the phase space. The required coalescence of many particles in phase space suppresses the production of clusters, while it is favoured by the direct production out of the highly correlated vacuum. In a certain sense, the highly correlated vacuum is a kind of cluster vacuum (vacuum with cluster structure). The shell structure of the vacuum levels (see Fig. 12) supports this latter suggestion. Fig. 13 illustrates this idea. Recently the STAR Collaboration at RHIC observed Anti–^{4}He with production rate in excess of coalescent nucleosynthesis production [27].

The mechanism is similar for the production of multi-hyper nuclei $(\Lambda, \Sigma, \Theta, \Omega)$. Meson field theory predicts also for the Λ energy spectrum at finite primary nucleon density the existence of upper and lower wells. The lower well belongs to the vacuum and is fully occupied by Λ's.

Dynamics and temperature then induce transitions ($\Lambda\overline{\Lambda}$ creation) and deposit many Λ's in
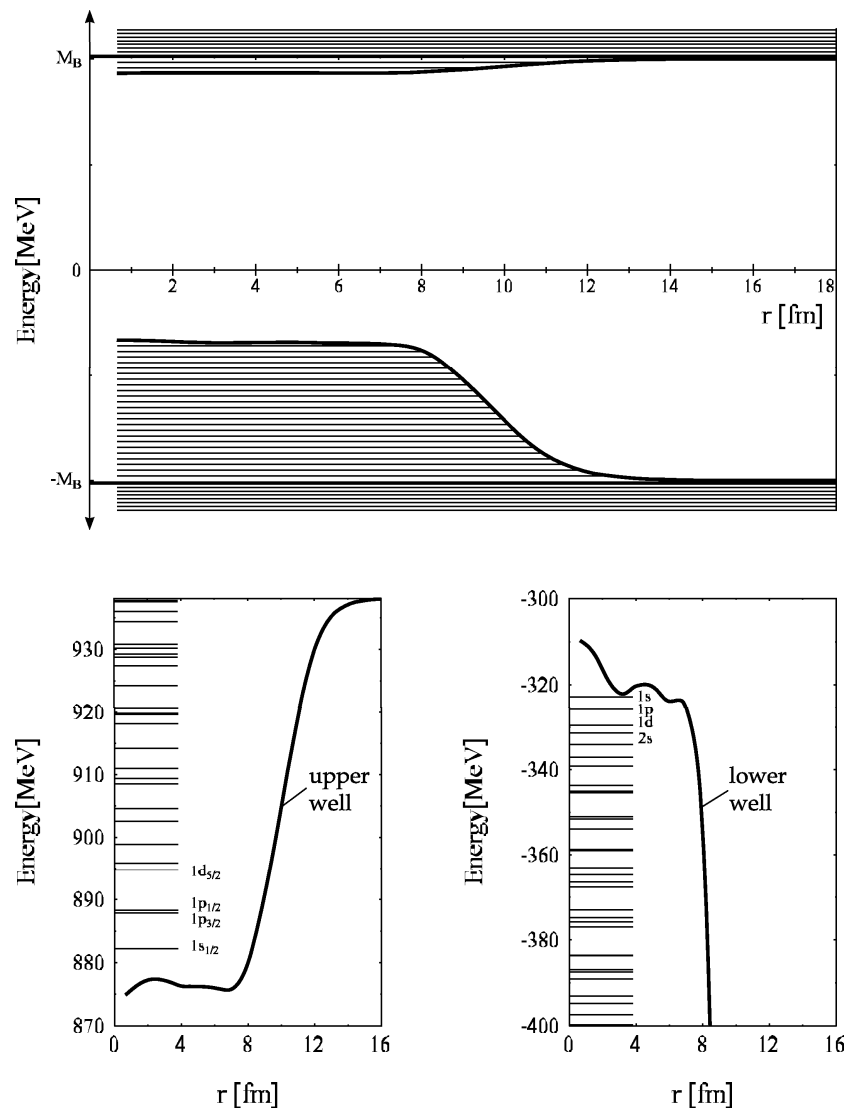
Figure 12. Baryon spectrum in a nucleus (upper panel). Below the positive energy continuum exists the potential well of real nucleons. It has a depth of 50-60 MeV and shows the correct shell structure. The shell model of nuclei is realized here. However, from the negative continuum another potential well arises, in which about 40 000 bound particles are found, belonging to the vacuum. A part of the shell structure of the upper well and the lower (vacuum) well is depicted in the lower figures.

the upper well. These numerous bound Λ's are sitting close to the primary baryons: in a certain sense a giant multi–Λ hypernucleus has been created. When the system disintegrates (expansion stage) the Λ's distribute over the nucleon clusters (which are most abundant in peripheral collisions). In this way multi–Λ hypernuclei can be formed. Of course this vision has to be worked out and probably refined in many respects. This requires a much more and thorough investigation in the future. It is particularly important to gain more experimental information on the properties of the lower well by (e, p) or (e, p) and also $(\overline{p}_c p_b, \, p_c \overline{p}_b)$ reactions at high energy ($\overline{p}_c$ denotes an incident antiproton from the continuum, p_b is a proton in a bound
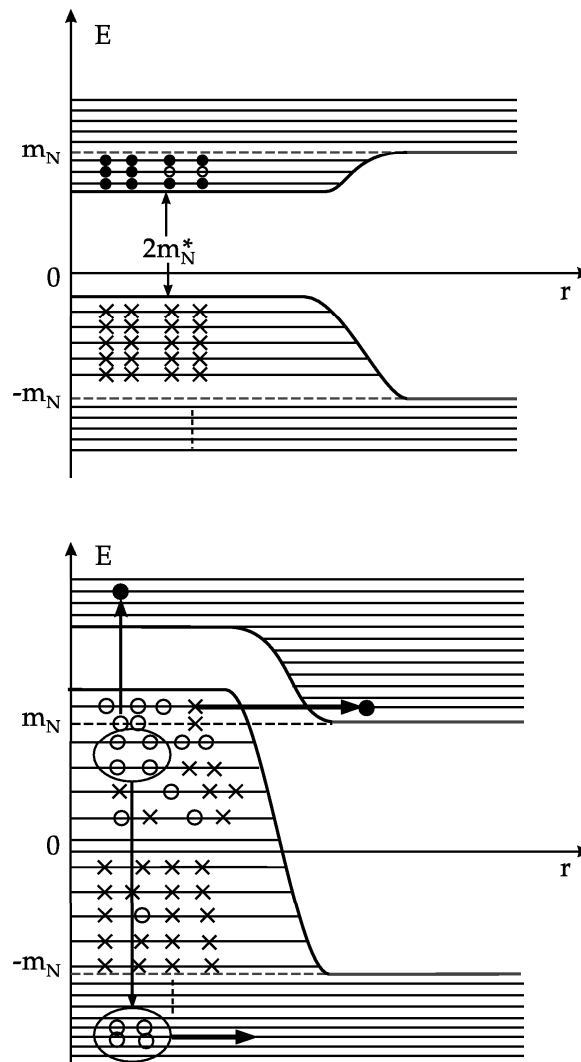
Figure 13. Due to the high temperature and the violent dynamics, many bound holes (antinucleon clusters) are created in the highly correlated vacuum, which can be set free during the expansion stage into the lower continuum (upper panel). In this way, antimatter clusters can be produced directly from the vacuum. The horizontal arrow in the lower part of the figure denotes the spontaneous creation of baryon-antibaryon pairs, while the antibaryons occupy bound states in the lower potential well. Such a situation, where the lower potential well reaches into the upper continuum, is called supercritical. Four of the bound holes states (bound antinucleons) are encircled to illustrate a "quasi-antihelium" formed. It may be set free (driven into the lower continuum) by the violent nuclear dynamics.

state; for the reaction products the situation is just the opposite). Also the reaction (p, p' d), (p, p' ^{3}He), (p, p' ^{4}He) and others of similar type need to be investigated in this context. The systematic studies of antiproton scattering on nuclei can contribute to clarify these questions. Various effective theories, e. g. of the Walecka-type on the one side and theories with chiral invariance on the other side, have been constructed to describe dense strongly interacting matter [4]. It is important to note that they seem to give different strengths of the potential wells and also different dependence on the baryon density.

According to chirally symmetric meson field theories, the antimatter–cluster production and multi–hypermatter–cluster production out of the highly correlated vacuum takes place at approximately the same heavy-ion energies as compared to the predictions of the Dürr-Teller-Walecka type meson field theories. This in itself is a most interesting, quasi-fundamental question to be clarified. In the future, the question of the nucleonic substructure (form factors, quarks, gluons) and its influence on the highly correlated vacuum structure has to be studied. The nucleons are possibly strongly modified in the correlated vacuum: the Δ resonance correlations are probably important. Is this highly correlated vacuum state, especially during the compression, a preliminary stage to the quark-gluon cluster plasma? To which extent is it similar or perhaps even identical with it?

5. Concluding remarks – outlook

Study of nuclear properties and mechanisms of nuclear reactions in the region of superheavy nuclei remains one of the most challenging problems. In particular, the center of island of stability waits for its discovery, that requires new methods (reactions), which may be used for synthesis of neutron-rich superheavy nuclei. The extension of the periodic system into the sectors of hypermatter (strangeness) and antimatter is of general and astrophysical importance. Indeed, microseconds after the big bang, the new dimensions of the periodic system we have touched upon, certainly have been populated in the course of the baryo- and nucleo-genesis. In the early history of the universe, even higher dimensional extensions (charm, bottom, top) may have played a role, which we did not pursue here. It is an open question, how the depopulation (the decay) of these sectors influences the structure and composition of our world today. Our conception of the world will certainly gain a lot through the clarification of these questions.

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