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DEVELOPMENTS IN FISSION, FUSION, CLUSTER RADIOACTIVITY AND THE EXTENSION OF THE PERIODIC SYSTEM OF ELEMENTS*

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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. Different ways of nuclear decay are discussed like cluster radioactivity, cold fission and cold multifragmentation, including the recent discovery of the triple fission of ^{252}Cf and long–living three–cluster–nuclear molecules. Furthermore, the possibility of production of clusters of hypermatter and antimatter in high energy heavy–ion collisions is envisaged. A perspective for the future is given.

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1 Introduction

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 elements. On this I want to report today.

The elements existing in nature are ordered according to their atomic (chemical) properties in the **periodic system** which was developed by 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 instable as they get bigger.

In the late sixties the dream of the superheavy elements arose. Theoretical nuclear physicists around S.G. Nilsson (Lund) [1] and from the Frankfurt school [2, 3, 4] predicted that so-called

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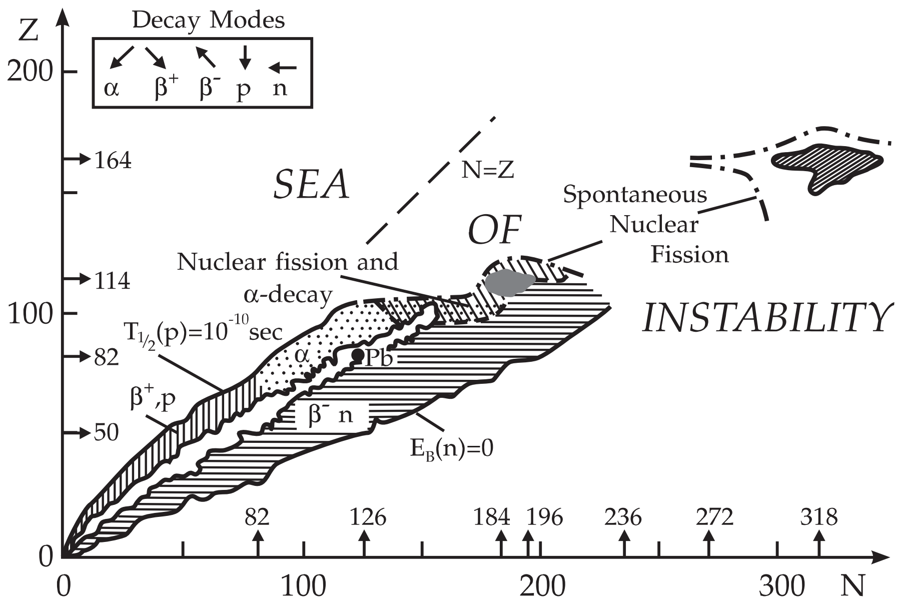

Fig. 1. The periodic system of elements as conceived by the Frankfurt school in the late sixties. The islands of superheavy elements ($Z = 114$, $N = 184$, 196 and $Z = 164$, $N = 318$) are shown as dark hatched areas.

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. Fig. 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)) [5] theoretically understood and substantiated the concept of bombarding of double magic lead nuclei with suitable projectiles, which had been proposed intuitively by the Russian nuclear physicist Y. Oganessian [6]. The two-center shell model, which is essential for the description of fission, fusion and nuclear molecules, was developed in 1969-1972 together with my then students U. Mosel and J. Maruhn [7]. It showed that the shell structure of the two final fragments was visible far beyond the barrier into the fusioning nucleus. The collective potential energy surfaces of heavy nuclei, as they were calculated in the framework of the two-center shell model, exhibit pronounced valleys, such that 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**, they get only minimally excited and

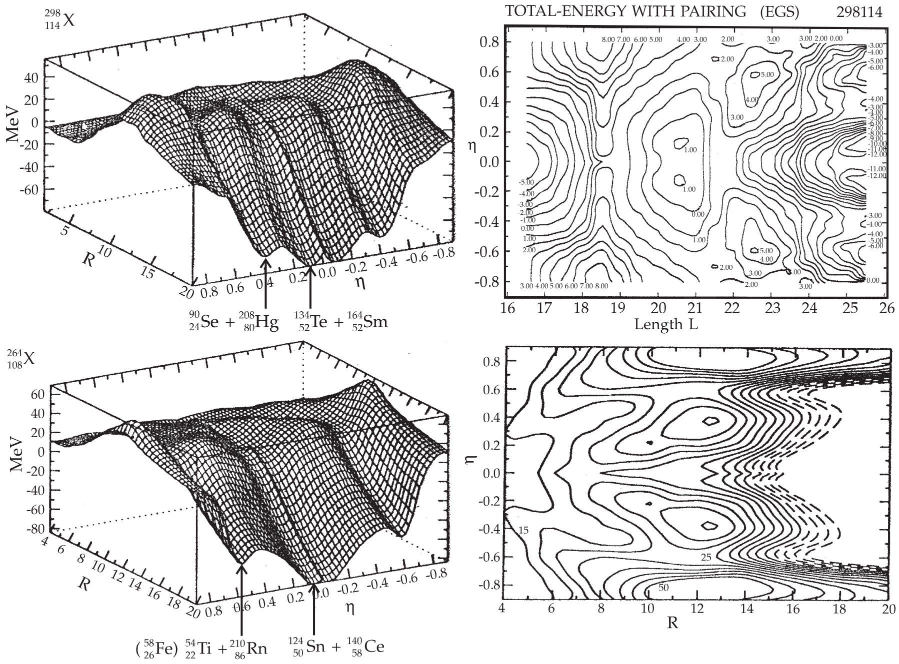

Fig. 2. The collective potential energy surface of $^{264}108$ and $^{184}114$, calculated within the two center shell model by J. Maruhn et al., shows clearly the cold valleys which reach up to the barrier and beyond. Here R is the distance between the fragments and $\eta = (A_1 - A_2)/(A_1 + A_2)$ denotes the mass asymmetry: $\eta = 0$ corresponds to a symmetric, $\eta = \pm 1$ to an extremely asymmetric division of the nucleus into projectile and target. If projectile and target approach through a cold valley, they do not "constantly slide off" as it would be the case if they approach along the slopes at the sides of the valley. Constant sliding causes heating, so that the compound nucleus heats up and gets unstable. In the cold valley, on the other hand, the created heat is minimized. The colleagues from Freiburg should be familiar with that: they approach Titisee (in the Black Forest) most elegantly through the Höllental and not by climbing its slopes along the sides.

the barrier which has to be overcome (fusion barrier) is lowest (as compared to neighbouring projectile-target combinations). In this way the correct projectile- and target-combinations for fusion could be predicted. Indeed, Gottfried Münzenberg and Sigurd Hofmann and their group at GSI (P. Armbruster, ...) [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 $Z = 106, 107, \dots 112$, each of them with the theoretically predicted projectile-target combinations, and only with these. Everything else failed. This is an impressing success, which crowned the laborious construction work of many years. The last example of this success, the discovery of element 112 and its long α-decay chain, is shown in Fig. 3.

3 Shell structure in the superheavy region

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 super-

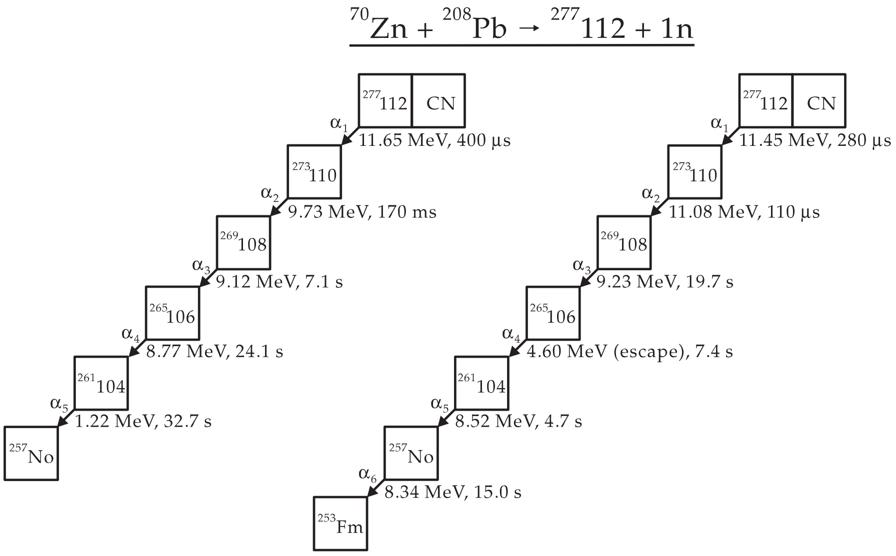

Fig. 3. The fusion of element 112 with ^{70}Zn as projectile and ^{208}Pb as target nucleus has been accomplished for the first time in 1995/96 by S. Hofmann, G. Münzenberg and their collaborators. The colliding nuclei determine an entrance to a "cold valley" as predicted as early as 1976 by Gupta, Sandulescu and Greiner. The fused nucleus 112 decays successively via α emission until finally the quasi-stable nucleus ^{253}Fm is reached. The α particles as well as the final nucleus have been observed. Combined, this renders the definite proof of the existence of a $Z = 112$ nucleus.

heavy region are very isotope dependent [9] (see Fig. 4). **According to these investigations** $Z = 120$ **being a magic proton number seems to be as probable as** $Z = 114$. Additionally, recent investigations in a chirally symmetric mean–field theory (see also below) result also in the prediction of these two magic numbers [31, 32]. Thus, this region provides an open field of research. R.A. Gherghescu et al. have calculated the potential energy surface of the $Z = 120$ nucleus. It utilizes interesting isomeric and valley structures (Fig. 5).

The determination of the chemistry of superheavy elements, i. e. the calculation of the atomic structure — which is in the case of element 112 the shell structure of 112 electrons due to the Coulomb interaction of the electrons and in particular the calculation of the orbitals of the outer (valence) electrons — has been carried out as early as 1970 by B. Fricke and W. Greiner [10].

4 Asymmetric and superasymmetric fission - Cluster radioactivity

The potential energy surfaces, which are shown prototypically for $Z = 114$ in Fig. 2, contain even more remarkable information that I want to mention cursorily: if a given nucleus, e. g. uranium, undergoes fission, it moves in its potential mountains from the interior to the outside. Of course, this happens quantum mechanically. The wave function of such a nucleus, which decays by tunneling through the barrier, has maxima where the potential is minimal and minima where it has maxima. This is depicted in Fig. 6.

The probability for finding a certain mass asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2)$ of the fission

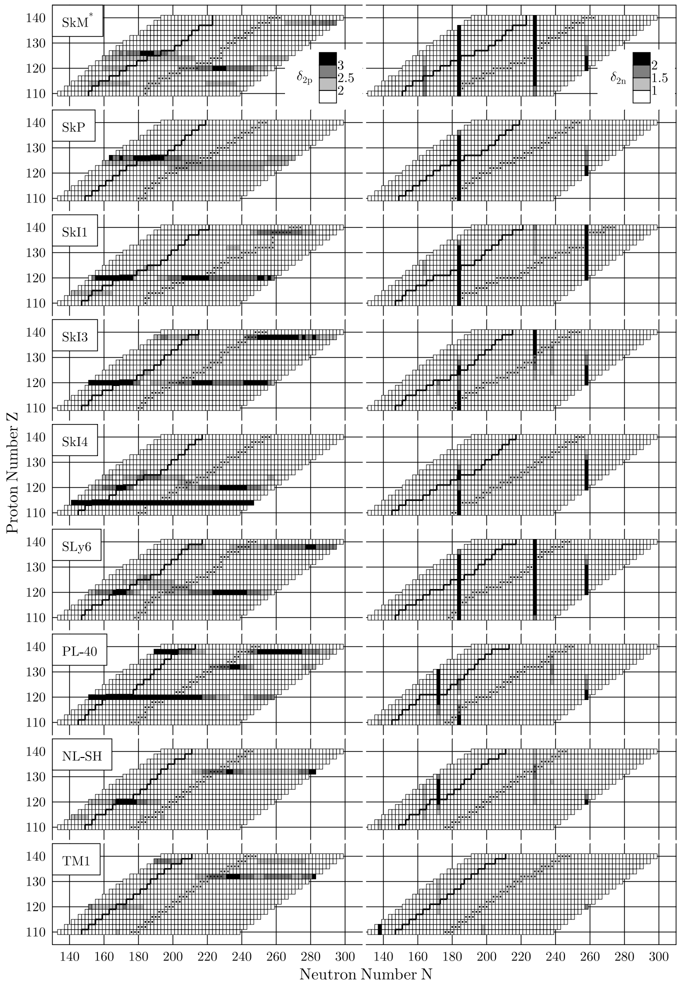

Fig. 4. Grey scale plots of proton gaps (left column) and neutron gaps (right column) in the *N*-*Z* plane for spherical calculations with the forces as indicated. The assignment of scales differs for protons and neutrons, see the uppermost boxes where the scales are indicated in units of MeV. Nuclei that are stable with respect to β decay and the two-proton dripline are emphasized. The forces with parameter sets SkI4 and PL-40 reproduce the binding energy of $^{264}_{156}108$ (Hassium) best, i.e. $|\delta E/E| < 0.0024$. Thus one might assume that these parameter sets could give the best predictions for the superheavies. Nevertheless, it is noticed that PL-40 predicts only $Z = 120$ as a magic number while SkI4 predicts both $Z = 114$ and $Z = 120$ as magic numbers. The magicity depends — sometimes quite strongly — on the neutron number. These studies are due to Bender, Rutz, Bürvenich, Maruhn, P.G. Reinhard et al. [9].

is proportional to $\psi^*(\eta)\psi(\eta)d\eta$. Generally, this is complemented by a coordinate dependent scale factor for the volume element in this (curved) space, which I omit for the sake of clarity. Now it becomes clear how the so-called **asymmetric** and **superasymmetric** fission processes come into being. They result from the enhancement of the collective wave function in the cold

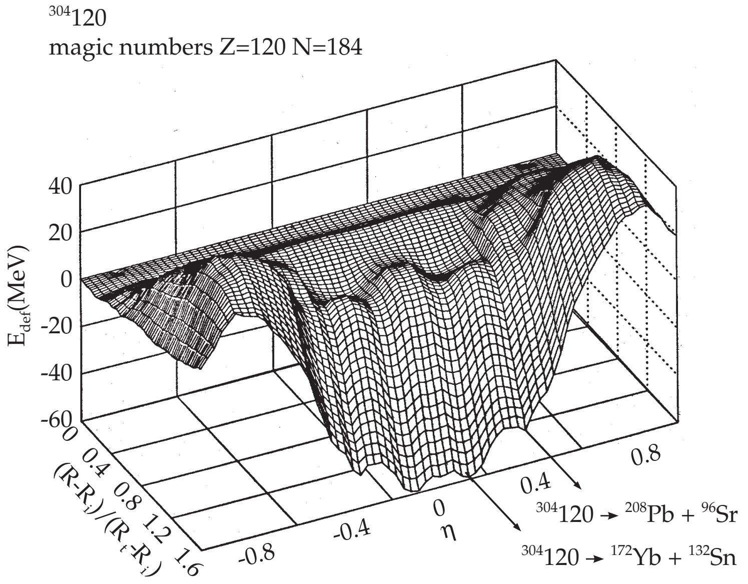

Fig. 5. Potential energy surface as a function of reduced elongation $(R-R_i)/(R_t-R_i)$ and mass asymmetry η for the double magic nucleus $^{304}120$.

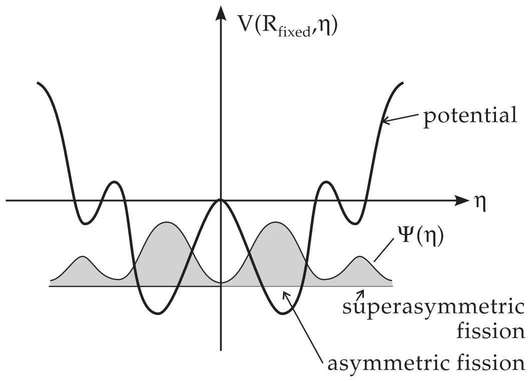

Fig. 6. The collective potential as a function of the mass asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2)$. A_i denotes the nucleon number in fragment i. This qualitative potential $V(R_{\text{fixed}}, \eta)$ corresponds to a cut through the potential landscape at $R = R_{\text{fixed}}$ close to the scission configuration. The wave function is drawn schematically. It has maxima where the potential is minimal and vice versa.

valleys. And that is indeed, what one observes. Fig. 7 gives an impression of it.

For a pronounced mass asymmetry ($\eta \approx 0.8 - 0.9$) there exist very narrow valleys. They are

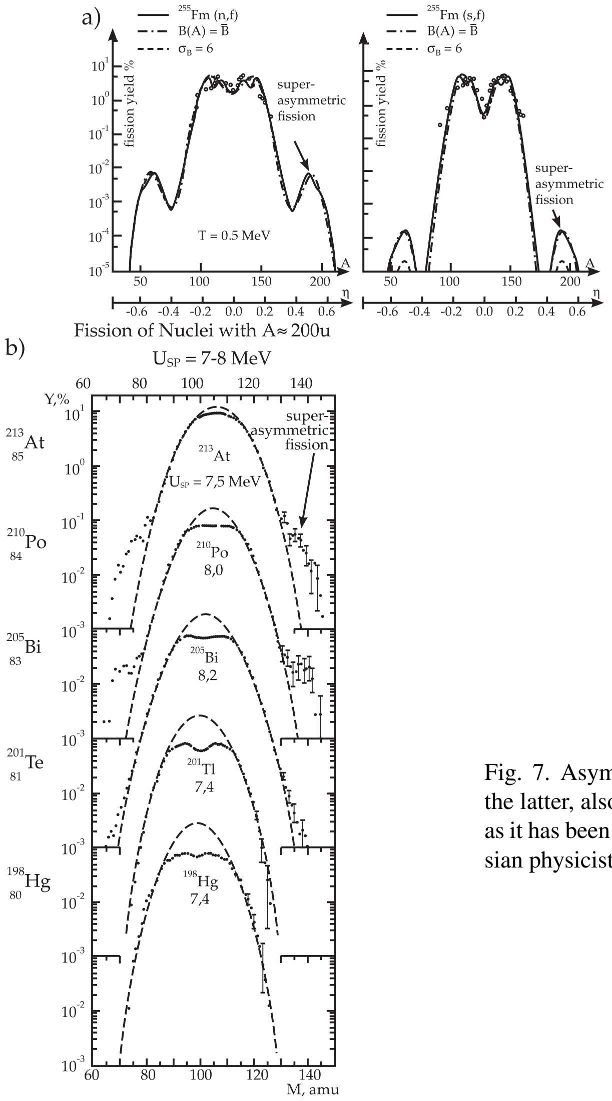

Fig. 7. Asymmetric (a) and symmetric (b) fission. For the latter, also superasymmetric fission is recognizable, as it has been observed only a few years ago by the Russian physicist Itkis — just as expected theoretically.

not as clearly visible in Fig. 2, but they have interesting consequences. Through these narrow valleys nuclei can emit spontaneously not only α-particles (helium nuclei) but also ^{14}C, ^{20}O, ^{24}Ne, ^{28}Mg, and other nuclei. Thus, we are lead to the **cluster radioactivity** (Poenaru, Sandulescu, Greiner [11]).

By now this process has been verified experimentally by research groups in Oxford, Moscow, Berkeley, Milan and other places. Accordingly, one has to revise what is learned in school: there are not only 3 types of radioactivity (α-, β-, γ-radioactivity), but many more. Atomic nuclei can also decay through spontaneous cluster emission (that is the "spitting out" of smaller nuclei like carbon, oxygen,...). Fig. 8 depicts some nice examples of these processes.

The knowledge of the collective potential energy surface and the collective masses $B_{ij}(R,\eta)$,

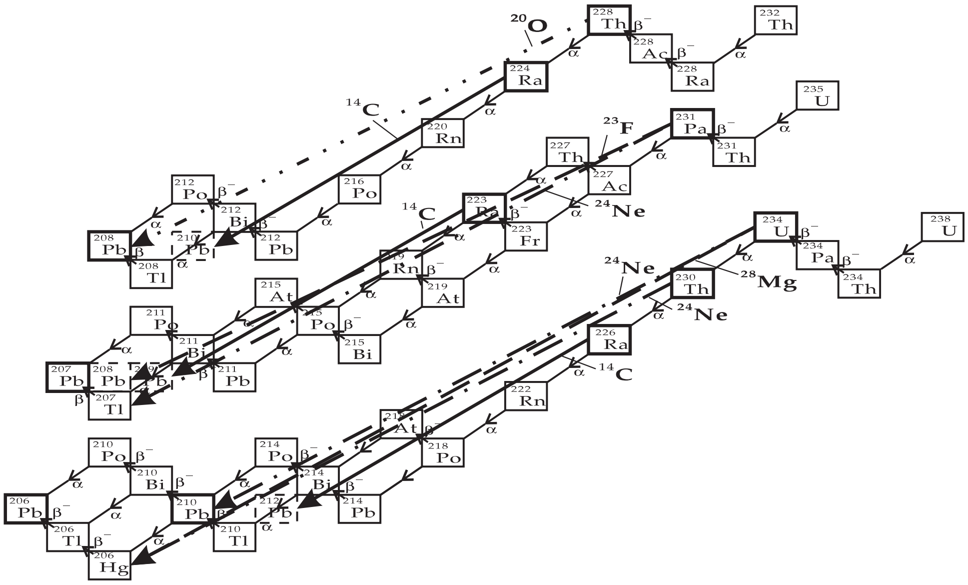

Fig. 8. Cluster radioactivity of actinide nuclei. By emission of ^{14}C, ^{20}O, … "big leaps" in the periodic system can occur, just contrary to the known α, β, γ radioactivities, which are also partly shown in the figure.

all calculated within the Two-Center-Shell-Model (TCSM), allowed H. Klein, D. Schnabel and J. A. Maruhn to calculate lifetimes against fission in an "ab initio" way [12].

Utilizing a WKB-minimization for the penetrability integral

$$\begin{aligned} \mathcal{P} = e^{-\mathrm{I}}, \quad \mathrm{I} &= \min_{\forall\,\mathrm{paths}} \frac{2}{\hbar} \int_S \sqrt{2m(V(R,\eta)-E)}\,\mathrm{d}s \\ &= \min_{\forall\,\mathrm{paths}} \frac{2}{\hbar} \int_0^1 \sqrt{\underbrace{2mg_{ij}}_{B_{ij}}(V(x_i(t)-E)\frac{\mathrm{d}x_i}{\mathrm{d}t}\frac{\mathrm{d}x_j}{\mathrm{d}t}}\,\mathrm{d}t \end{aligned} \tag{1}$$

where $\mathrm{d}s^2 = g_{ij}\mathrm{d}x_i\mathrm{d}x_j$ and g_{ij} — the metric tensor — is in the well-known fashion related to the collective masses $B_{ij} = 2mg_{ij}$, one explores the minimal paths from the nuclear ground state configuration through the multidimensional fission barrier (see Fig. 9).

The thus obtained fission half lives are depicted in the lower part of Fig. 9. Their distribution as a function of the fragment mass A_2 resembles quite well the asymmetric mass distribution. Cluster radioactive decays correspond to the broad peaks around $A_2 = 20,\ 30\ (200,\ 210)$. The confrontation of the calculated fission half lives with experiments is depicted in Fig. 10. One notices "nearly quantitative" agreement over 20 orders of magnitude, which is – for an ab-initio calculation – remarkable!

Finally, in Fig. 11, we compare the lifetime calculation discussed above with one based on the Preformation Cluster Model by D. Poenaru et al. [13] and recognize an amazing degree of similarity and agreement.

The systematics for the average total kinetic energy release for spontaneously fissioning isotopes of Cm and No is following the Viola trend, but ^{258}Fm and ^{259}Fm are clearly outside. The

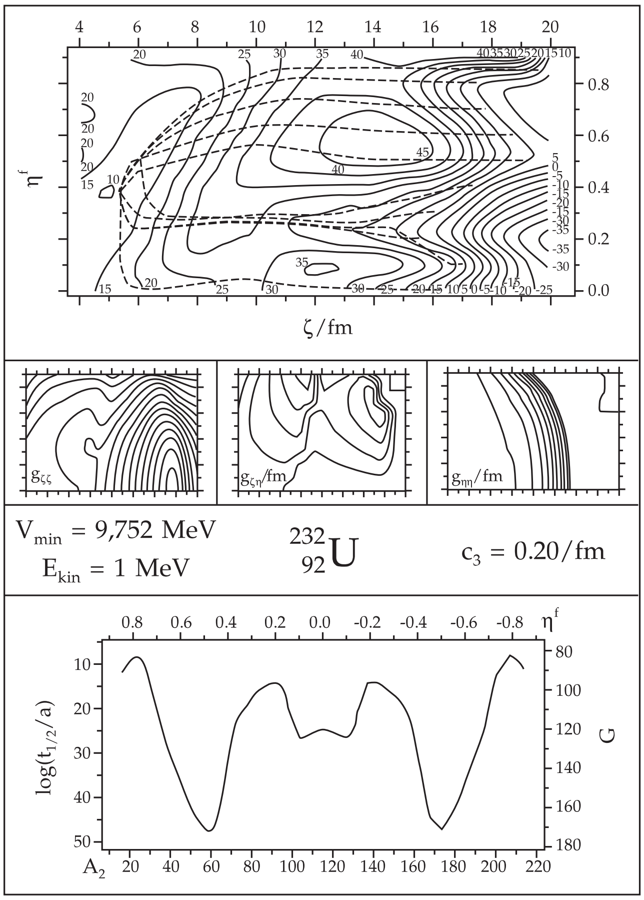

Fig. 9. The upper part of the figure shows the collective potential energy surface for $^{232}_{92}U$ with the ground state position and various fission paths through the barrier. The middle part shows various collective masses, all calculated in the TCSM. In the lower part the calculated fission half lives are depicted.

situation is similar also for ^{260}Md, where two components of fission products (one with lower and one with higher kinetic energy) were observed by Hulet et al. [14]. The explanation of these interesting observations lies in two different paths through the collective potential. One reaches the scission point in a stretched neck position (i.e. at a lower point of the Coulomb barrier - thus lower kinetic energy for the fragments) while the other one reaches the scission point practically in a touching-spheres-position (i.e. higher up on the Coulomb barrier and therefore highly energetic fragments) [15]. The latter process is cold fission; i.e., the fission fragments are in or close to their ground state (cold fragments) and all the available energy is released as kinetic energy. Cold fission is, in fact, typically a cluster decay. The side-by-side occurrence of cold and normal (hot) fission has been named bi-modal fission [15].

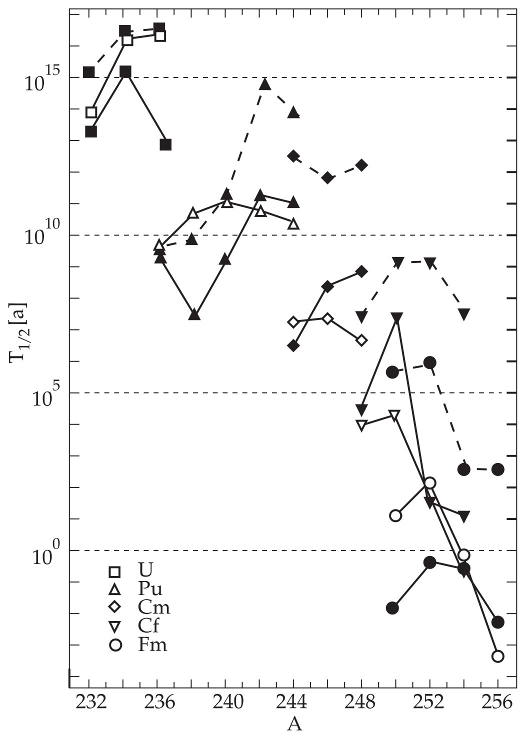

Fig. 10. Fission half lives for various isotopes of $Z = 92$ (□), $Z = 94$ (△), $Z = 96$ (◇), $Z = 98$ (∇) and $Z = 100$ (∘). The open symbols represent the experimental values. The full symbols with full and dashed lines correspond to calculations with different choices of the barrier parameter in the Two Center Shell Model ($c_3 \approx 0.2$ and 0.1 respectively).

5 Fission observed with the Gamma-sphere: Long living nuclear molecules

There has now been put forward a fantastic idea [16] in order to study cold fission (cluster decays) and other exotic fission processes (ternary-, multiple fission in general) very elegantly: By measuring with e. g. the Gamma–sphere characteristic γ-transitions of individual fragments in coincidence, one can identify all these processes in a direct and simple way (Fig. 12). First confirmation of this method by J. Hamilton, V. Ramaya et al. worked out excellently [17]. This method has high potential for revolutionizing fission physics! With some physical intuition one can imagine that **triple** - and **quadruple** fission processes and even the process of **cold multifragmentation** will be discovered - absolutely fascinating! We have thus seen that fission physics (cold fission, cluster radioactivity, ...) and fusion physics (especially the production of superheavy elements) are intimately connected.
Indeed, very recently, triple fission of

$$
\begin{aligned}
{}^{252}\mathrm{Cf} &\rightarrow {}^{146}\mathrm{Ba} + {}^{96}\mathrm{Sr} \quad + {}^{10}\mathrm{Be} \\
&\rightarrow {}^{112}\mathrm{Ry} + {}^{130}\mathrm{Sn} + {}^{10}\mathrm{Be} \\
&\rightarrow \ldots
\end{aligned}
$$

has been identified by measuring the various γ–transitions of these nuclei in coincidence (see Fig. 13). Even though the statistical evidence for the ^{10}Be line is small ($\approx$ 50 events) the various coincidences seem to proof that spontaneous triple fission out of the ground state of ^{252}Cf with the

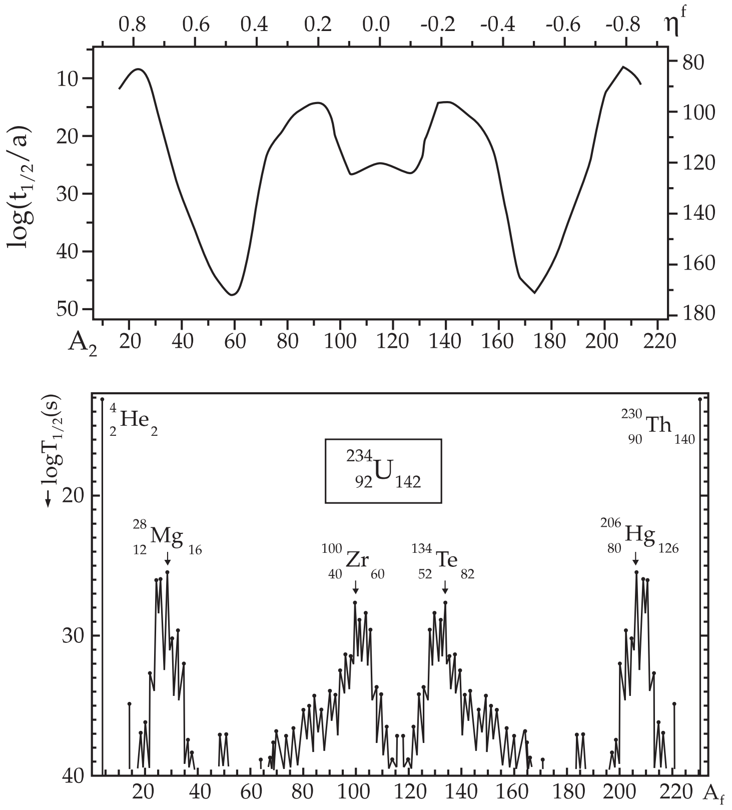

Fig. 11. Comparison of the fission half lives calculated in the fission model (upper figure – see also Fig. 4) and in the Preformation Cluster Model [13]. In both models the deformation of the fission fragments is not included completely.

heavy cluster ^{10}Be as a third fragment exists. Also other triple fragmentations can be expected. One of those is also denoted above. In fact, there are first indications, that this break–up is also observed. The most amazing observation is, however, the following: The cross coincidences seem to suggest that one deals with a simultaneous three–body breakup and not with a cascade process. For that one expects a configuration as shown in Fig. 14. Consequently the ^{10}Be will obtain kinetic energy while running down the combined Coulomb barrier of ^{146}Ba and ^{96}Sr and, therefore, the 3368 keV line of ^{10}Be should be Doppler-broadened. Amazingly, however, it is not and, moreover, it seems to be about 6 keV smaller than the free ^{10}Be γ–transition. If this turns out to be true, the only explanation will be that the gamma is emitted while the nuclear molecule of the type shown in Fig. 14. holds. The molecule has to live longer than about 10^{-12} sec. The nuclear forces from the ^{146}Bo and ^{96}Sn cluster to the left and right from ^{10}Be lead to a softening of its potential and therefore to a somewhat smaller transition energy. Thus, if experimental results hold, one has discovered long living ($\approx 10^{-12}$ sec) complex nuclear molecules. This is fantastic! Of course, I do immediately wonder whether such configurations do also exist in e.g. U + Cm soft encounters directly at the Coulomb barrier. This would have tremendous importance

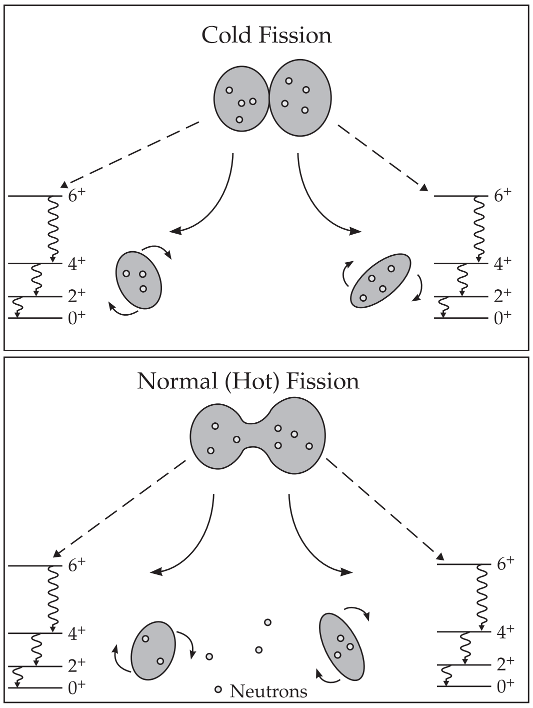

Fig. 12. Illustration of cold and hot (normal) fission identification through multiple γ-coincidences of photons from the fragments. The photons serve to identify the fragments.

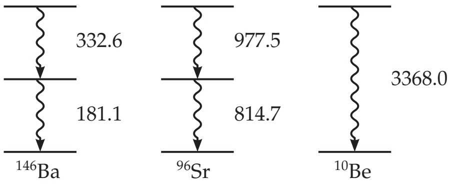

Fig. 13. The γ–transitions of the three fission products of ^{252}Cf measured in coincidence. Various combinations of the coincidences were studied.

for the observation of the spontaneous vacuum decay [19], for which ”sticking giant molecules” with a lifetime of the order of 10^{-19} sec are needed. The nuclear physics of such heavy ion collisions at the Coulomb barrier (giant nuclear molecules) should indeed be investigated!
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.

6 Extension of the periodic system into the sections 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 flavors, called charm, bottom, top. The latter has just recently been discovered. Let us

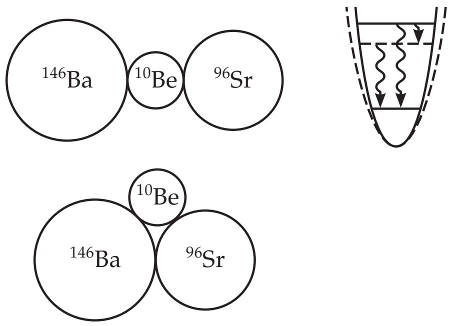

Fig. 14. Typical linear cluster configuration leading to triple fission of ^{252}Cf. The influence of both clusters leads to a softening of the ^{10}Be potential and thus to a somewhat smaller transition energy. Recent theoretical investigations indicate that the axial symmetry of this configuration is broken (lower left hand figure).

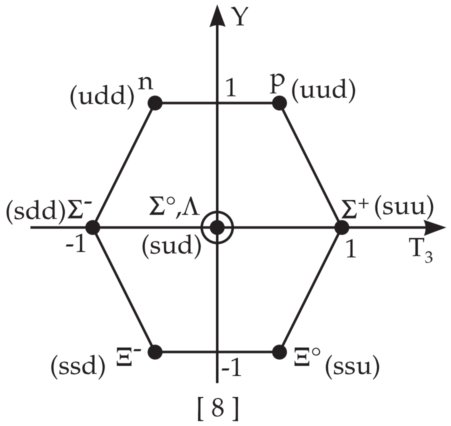

Fig. 15. Important baryons are ordered in this octet. The quark content is depicted. Protons (p) and neutrons (n), most important for our known world, contain only u and d quarks. Hyperons contain also an s quark. The number of s quarks is a measure for the strangeness.

stick to the s quarks. They are found in the ”strange” relatives of the nucleons, the so-called hyperons (Λ, Σ, Ξ, Ω). The Λ-particle, e. g., consists of one u, d and s quark, the Ξ-particle even of an u and two s quarks, while the Ω (sss) contains strange quarks only. Fig. 15 gives an overview of the baryons, which are of interest here, and their quark content.

If such a hyperon is taken up by a nucleus, a **hyper-nucleus** is created. Hyper-nuclei with one hyperon have been known for 20 years now, and were extensively studied by B. Povh (Heidelberg) [20]. Several years ago, Carsten Greiner, Jürgen Schaffner and Horst Stöcker [21] 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, anti-carbon, anti-oxygen. Fig. 16 depicts this idea. Due to the 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

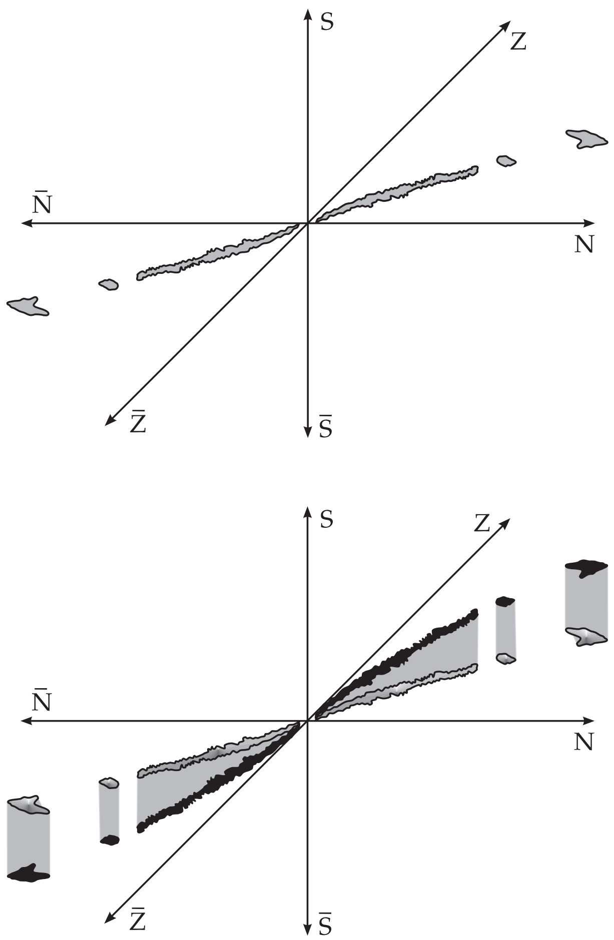

Fig. 16. The extension of the periodic system into the sectors of strangeness (S, $\bar{S}$) and antimatter ($\bar{Z}$, $\bar{N}$). The stable valley winds out of the known proton (Z) and neutron (N) plane into the S and $\bar{S}$ sector, respectively. The same can be observed for the antimatter sector. 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.

show that through **nuclear shock waves** [22–24] nuclear matter gets compressed to 5–10 times of its usual value, $\rho_0 \approx 0.17\,\mathrm{fm}^3$, and heated up to temperatures of $kT \approx 200$ MeV. As a consequence about 10000 pions, 100 Λ's, 40 Σ's and Ξ'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 by 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 every possible momenta (velocities) in all directions. The chances for hyperons and antibaryons to meet gets rapidly

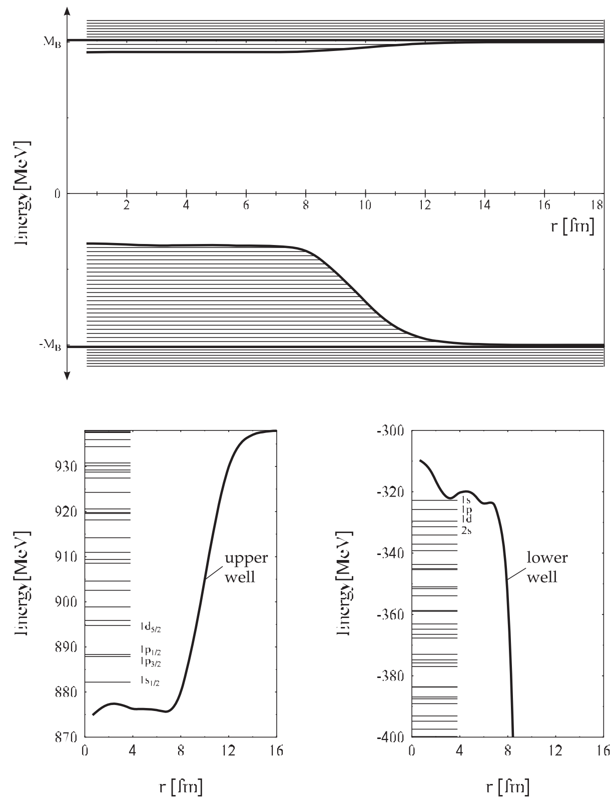

Fig. 17. Baryon spectrum in a nucleus. Below the positive energy continuum exists the potential well of real nucleons. It has a depth of 50-60 MeV and shows the correct shell structure. The shell model of nuclei is realized here. However, from the negative continuum another potential well arises, in which about 40000 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.

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 meson field theory the energy spectrum of baryons has a peculiar structure, depicted in Fig. 17. It consists of an upper and a lower continuum, as it is known from the electrons (see e. g. [19]). 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. 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 40000 occupied bound states of the lower potential well represent the **vacuum**. The peculiarity of this strongly correlated vacuum

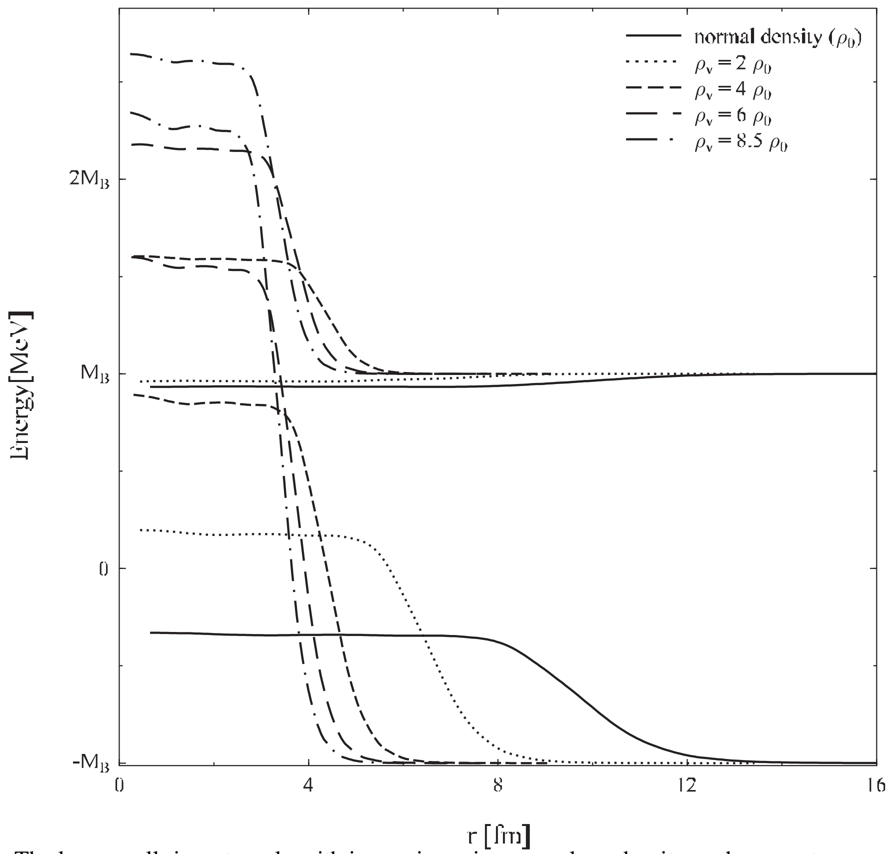

Fig. 18. The lower well rises strongly with increasing primary nucleon density, and even gets supercritical (spontaneous nucleon emission and creation of bound antinucleons). Supercriticality denotes the situation, when the lower well enters the upper continuum.

structure in the region of atomic nuclei is that — depending on the size of the nucleus — more than 20000 up to 40000 (occupied) bound nucleon states contribute to this polarization effect. Obviously, we are dealing here with a **highly correlated vacuum**. A pronounced shell structure can be recognized [25, 26]. 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 (Fig. 18). 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 [22, 23] and which have since then been confirmed extensively (for references see e.g. [27]). 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 $-M_Bc^2$) 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,

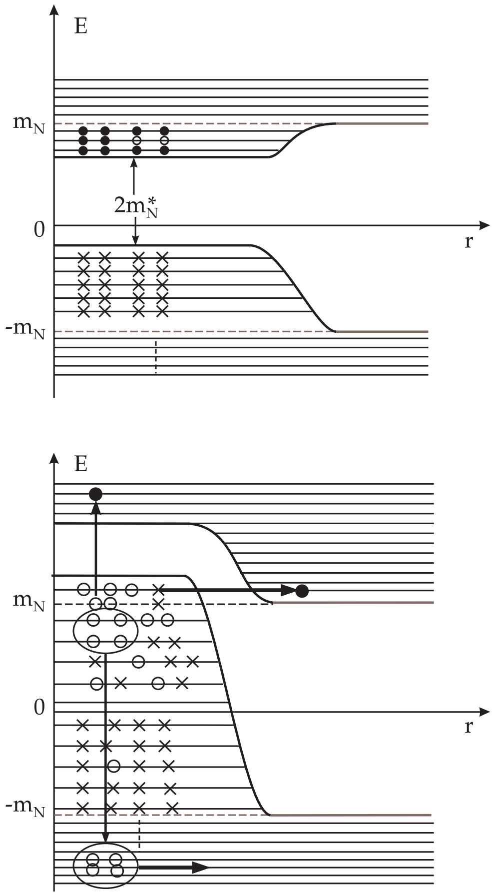

Fig. 19. Due to the high temperature and the violent dynamics, many bound holes (antinucleon clusters) are created in the highly correlated vacuum, which can be set free during the expansion stage into the lower continuum. In this way, antimatter clusters can be produced directly from the vacuum. The 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.

the potential wells, in particular the lower one, disappear.

The bound antinucleons are then pulled down into the (lower) continuum. In this way 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. 17) supports this latter suggestion. Fig. 19illustrates this idea.

The mechanism is similar for the production of multi-hyper nuclei (Λ, Σ, Ξ, Ω). 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 ($\Lambda\bar{\Lambda}$ creation) and deposit many Λ's in 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 means 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, e' p) or (e, e' p p') and also ($\bar{p}_c p_b$, $p_c \bar{p}_b$) reactions ($\bar{p}_c$ denotes an incident antiproton from the continuum, p_b is a proton in a bound state; for the reaction products the situation is just the opposite) [28]. 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 scattering of antiprotons on nuclei can contribute to clarify these questions. Problems of the meson field theory (e. g. Landau poles) can then be reconsidered. An effective meson field theory has to be constructed. Various effective theories, e. g. of Walecka-type on the one side and theories with chiral invariance on the other side, seem to give different strengths of the potential wells and also different dependence on the baryon density [29]. The Lagrangians of the Dürr-Teller-Walecka-type and of the chirally symmetric mean field theories look quite differently. We exhibit them — without further discussion — in the following equations:

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{BM} + \mathcal{L}_{vec} + \mathcal{L}_0 + \mathcal{L}_{SB}$$

Non-chiral Lagrangian:

$$\begin{aligned}
\mathcal{L}_{kin} &= \frac{1}{2}\partial_\mu s \partial^\mu s + \frac{1}{2}\partial_\mu z \partial^\mu z - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
\mathcal{L}_{BM} &= \sum_B \overline{\psi}_B [i\gamma_\mu\partial^\mu - g_{\omega B}\gamma_\mu\omega^\mu - g_{\phi B}\gamma_\mu\phi^\mu - g_{\rho B}\gamma_\mu\vec{\tau}_B\vec{\rho}^\mu - \frac{1}{2}e\gamma_\mu(1+\tau_B)A^\mu - m_B^*]\psi_B \\
\mathcal{L}_{vec} &= \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{2}m_\rho^2\rho_\mu\rho^\mu + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu \\
\mathcal{L}_0 &= -\frac{1}{2}m_s^2 s^2 - \frac{1}{2}m_z^2 z^2 - \frac{1}{3}bs^3 - \frac{1}{4}cs^4
\end{aligned}$$

Chiral Lagrangian:

$$\begin{aligned}
\mathcal{L}_{kin} &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\partial_\mu\zeta\partial^\mu\zeta + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
&\quad -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
\mathcal{L}_{BM} &= \sum_B \overline{\psi}_B [i\gamma_\mu\partial^\mu - g_{\omega B}\gamma_\mu\omega^\mu - g_{\phi B}\gamma_\mu\phi^\mu - g_{\rho B}\gamma_\mu\vec{\tau}_B\vec{\rho}^\mu - \frac{1}{2}e\gamma_\mu(1+\tau_B)A^\mu - m_B^*]\psi_B \\
\mathcal{L}_{vec} &= \frac{1}{2}m_\omega^2\frac{\chi^2}{\chi_0^2}\omega_\mu\omega^\mu + \frac{1}{2}m_\rho^2\frac{\chi^2}{\chi_0^2}\rho_\mu\rho^\mu + \frac{1}{2}m_\phi^2\frac{\chi^2}{\chi_0^2}\phi_\mu\phi^\mu \\
\mathcal{L}_0 &= -\frac{1}{2}k_0\chi^2(\sigma^2+\zeta^2) + k_1(\sigma^2+\zeta^2)^2 + k_2(\frac{\sigma^4}{2}+\zeta^4) + k_3\chi\sigma^2\zeta \\
&\quad - k_4\chi^4 + \frac{1}{4}\chi^4\ln\frac{\chi^4}{\chi_0^4} + \frac{\delta}{3}\ln\frac{\sigma^2\zeta}{\sigma_0^2\zeta_0^2} \\
\mathcal{L}_{SB} &= -\left(\frac{\chi}{\chi_0}\right)^2\left[m_\pi^2 f_\pi\sigma + (\sqrt{2}m_K^2 f_K - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi)\zeta\right]
\end{aligned}$$

The non-chiral model contains the scalar-isoscalar field s and its strange counterpart z, the vector-isoscalar fields ω_μ and ϕ_μ, and the the ρ-meson ρ_μ as well as the photon A_μ. For more details see [29]. In contrast to the non-chiral model, the $SU(3)_L \times SU(3)_R$ Lagrangian contains the dilation field χ introduced to mimic the trace anomaly of QCD in an effective Lagrangian at tree level (For an explanation of the chiral model see [29, 31]).

The connection of the chiral Lagrangian with the Walecka-type can be established by the substitution $\sigma = \sigma_0 - s$ (and similarly for the strange condensate ζ). Then, e.g. the difference in the definition of the effective nucleon mass in both models (non-chiral:$m_N^* = m_N - g_s s$, chiral:$m_N^* = g_s \sigma$) can be removed, yielding:

$$m_N^* = g_s \sigma_0 - g_s s \equiv m_N - g_s s \tag{2}$$

for the nucleon mass in the chiral model.

Nevertheless, if the parameters in both cases are adjusted such that ordinary nuclei (binding energies, radii, shell structure,...) and properties of infinite nuclear matter (equilibrium density, compression constant K, binding energy) are well reproduced, the prediction of both effective Lagrangians for the dependence of the properties of the correlated vacuum on density and temperature is remarkably different. This is illustrated to some extent in Fig. 20. Accordingly, the chirally symmetric meson field theory predicts much higher primary densities (and temperatures) until the effects of the correlated vacuum are strong enough so that the mechanisms described here become effective. In other words, 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 considerably higher 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. Moreover, 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 polarized in the correlated vacuum: the Δ resonance correlations in the vacuum 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? It is well known for more than 10 years that meson field theories predict a phase transition qualitatively and quantitatively similar to that of the quark-gluon plasma [30] — see Fig. 21.

7 Concluding remarks - outlook

The extension of the periodic system into the sectors 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. Of course, for the creation of the universe, even higher dimensional extensions (charm, bottom, top) come into play, which we did not pursue here. It is an open question, how the de-population (the decay) of these sectors influences the distribution of elements of our world today. Our conception of the world will certainly gain a lot through the clarification of these questions.

For the Gesellschaft für Schwerionenforschung (GSI), which I helped initiating in the sixties, the questions raised here could point to the way ahead. Working groups have been instructed by the board of directors of GSI, to think about the future of the laboratory. On that occasion, very

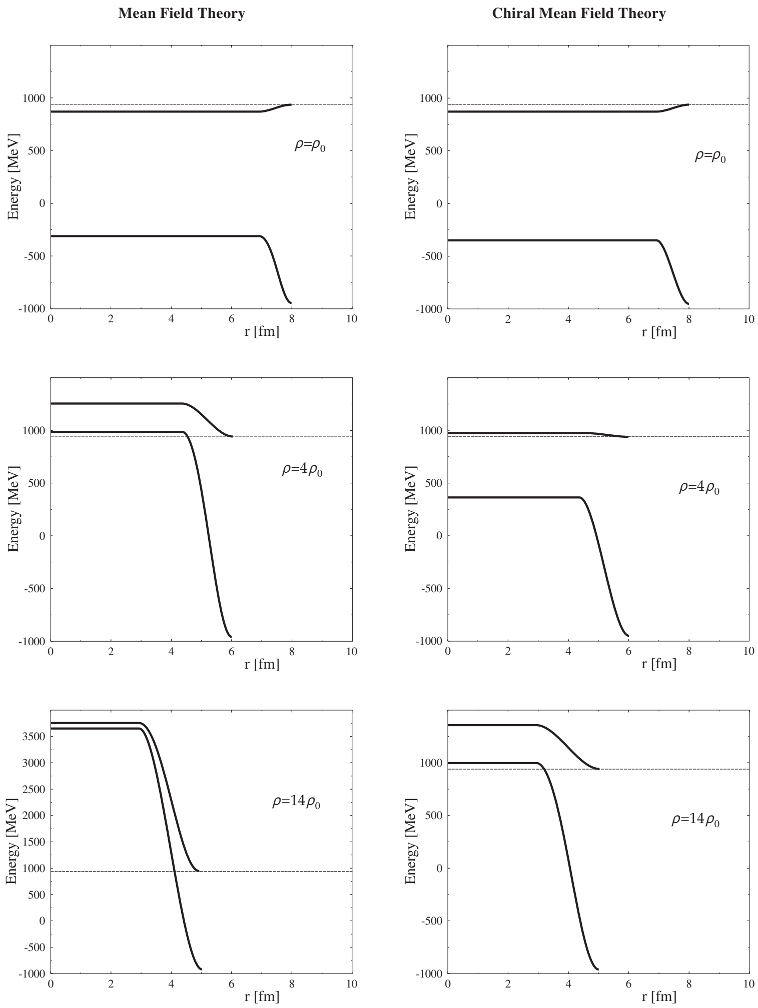

Fig. 20. The potential structure of the shell model and the vacuum for various primary densities $\rho = \rho_0$, $4\rho_0$, $14\rho_0$. At left the predictions of ordinary Dürr-Teller-Walecka-type theories are shown; at right those for a chirally symmetric meson field theory as developed by P. Papazoglu [29, 31].

concrete (almost too concrete) suggestions are discussed — as far as it has been presented to the public. What is missing, as it seems, is a **vision on a long term basis**. The ideas proposed here, the verification of which will need the **commitment for 2–4 decades of research**, could be such a vision with considerable attraction for the best young physicists. The new dimensions of the periodic system made of hyper- and antimatter cannot be examined in the "stand-by" mode at CERN (Geneva); a dedicated facility is necessary for this field of research, which can in future serve as a home for the universities. The GSI — which has unfortunately become much too self-sufficient — could be such a home for new generations of physicists, who are interested in the **structure of elementary matter**. GSI would then not develop just into a detector laboratory

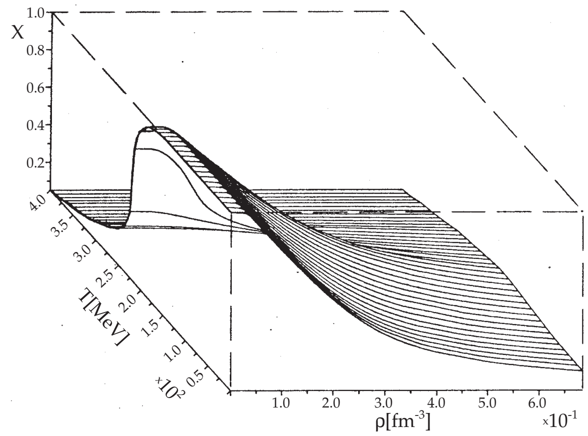

Fig. 21. The strong phase transition inherent in Dürr-Teller-Walecka-type meson field theories, as predicted by J. Theis et al. [30]. Note that there is a first order transition along the ρ-axis (i.e. with density), but a simple transition along the temperature T-axis. Note also that this is very similar to the phase transition obtained recently from the Nambu-Jona-Lasinio-approximation of QCD [33].

for CERN, and as such become obsolete. I can already see the enthusiasm in the eyes of young scientists, when I unfold these ideas to them — similarly as it was 30 years ago, when the nuclear physicists in the state of Hessen initiated the construction of GSI.

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