Nuclear Shells in the Superheavy Region within Meson Field Theory

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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 with modern meson field theories are reviewed. Furtheron, different channels of nuclear decay are discussed including cluster radioactivity, cold fission, and cold multifragmentation. A perspective for future research is given.

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 particles the elements are made of (baryons, mesons, quarks, gluons), i.e. elementary matter. The vacuum and its structure is closely related to that. On this I want to report today. I begin 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 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[2–4] 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 lifetimes 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 $Z = 164$, $N = 318$. 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))[6] 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.[7] 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.[8] 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 (Figure 2). If projectile and target approach each other through those **"cold" valleys**, they get only minimally excited and the barrier which has to be overcome (fusion barrier) is lowest (as compared to neighbouring projectile-target combinations).

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2. Cold Valleys in the Potential

In this way the correct projectile and target combinations for fusion were predicted. Indeed, Gottfried Münzenberg and Sigurd Hofmann and their group at GSI[9] 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 before last example of this success, the discovery of element 112 and its long α-decay chain, is shown in Figure 3. Very recently the Dubna-Livermore group produced two isotopes of $Z = 114$ element by bombarding ^{244}Pu with ^{48}Ca and also $Z = 116$ by ^{48}Ca + ^{248}Cm (Figure 4). Also these are cold-valley reactions (in this case due to the combination of a spherical and a deformed nucleus), as predicted by Gupta, Sandulescu, and Greiner[10] in 1977. There exist also cold valleys for which both fragments are deformed,[11] but these have yet not been verified experimentally. The $Z = 118$ isotope claimed to be fused with the cold valley reaction[13] ^{86}Kr + ^{208}Pb by Ninov et al.[14] could not be reproduced in later experiments.

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-

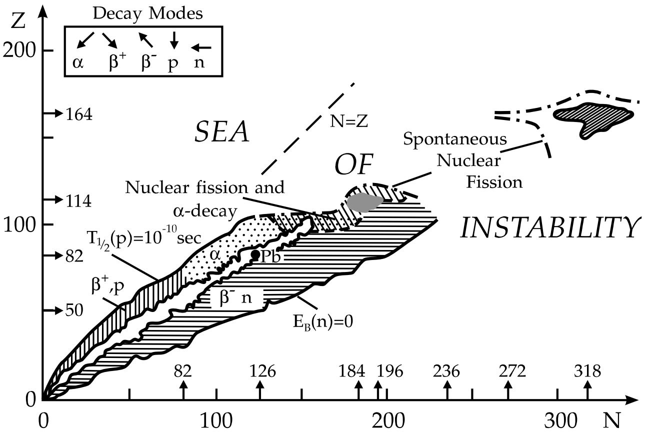

Figure 1. The periodic system of elements as conceived by the Frankfurt school in the late sixties. The islands of superheavy elements ($Z = 114$, $N = 184$, 196 and $Z = 164$, $N = 318$) are shown as dark hatched areas.

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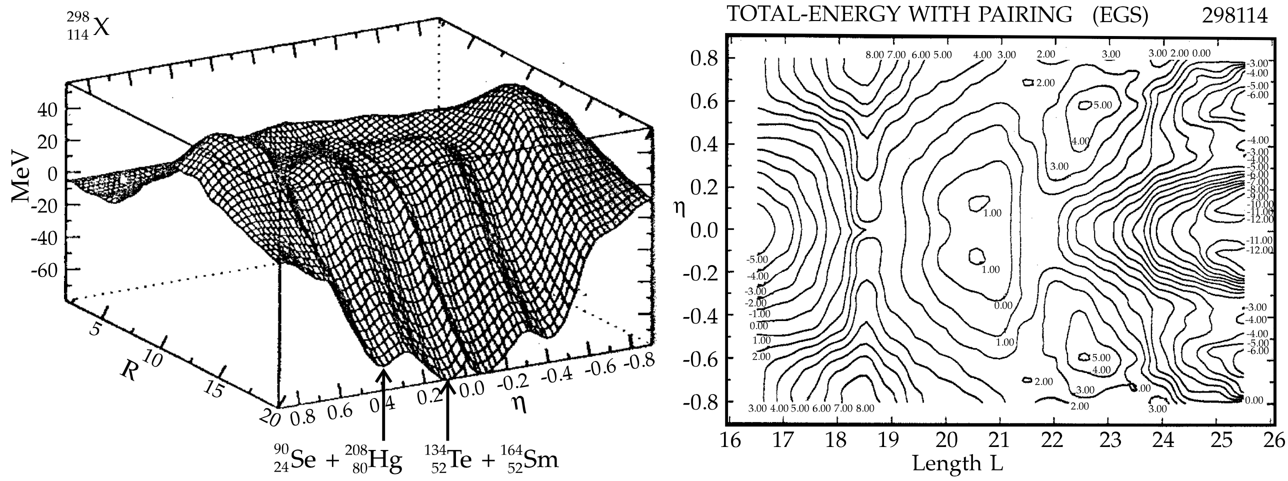

Figure 2. The collective potential energy surface of ^{184}114, calculated within the two center shell model by J. Maruhn et al., shows clearly the cold valleys which reach up to the barrier and beyond. Here R is the distance between the fragments and $\eta = \frac{A_1 - A_2}{A_1 + A_2}$ denotes the 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.

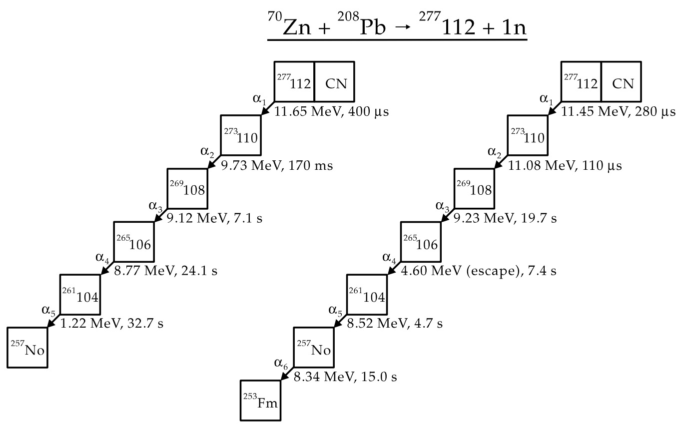

Figure 3. The fusion of element 112 with ^{70}Zn as projectile and ^{208}Pb as target nucleus has been accomplished for the first time in 1995/96 by S. Hofmann, G. Münzenberg, and their collaborators. The colliding nuclei determine an entrance to a "cold valley" as predicted as early as 1976 by Gupta, 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.

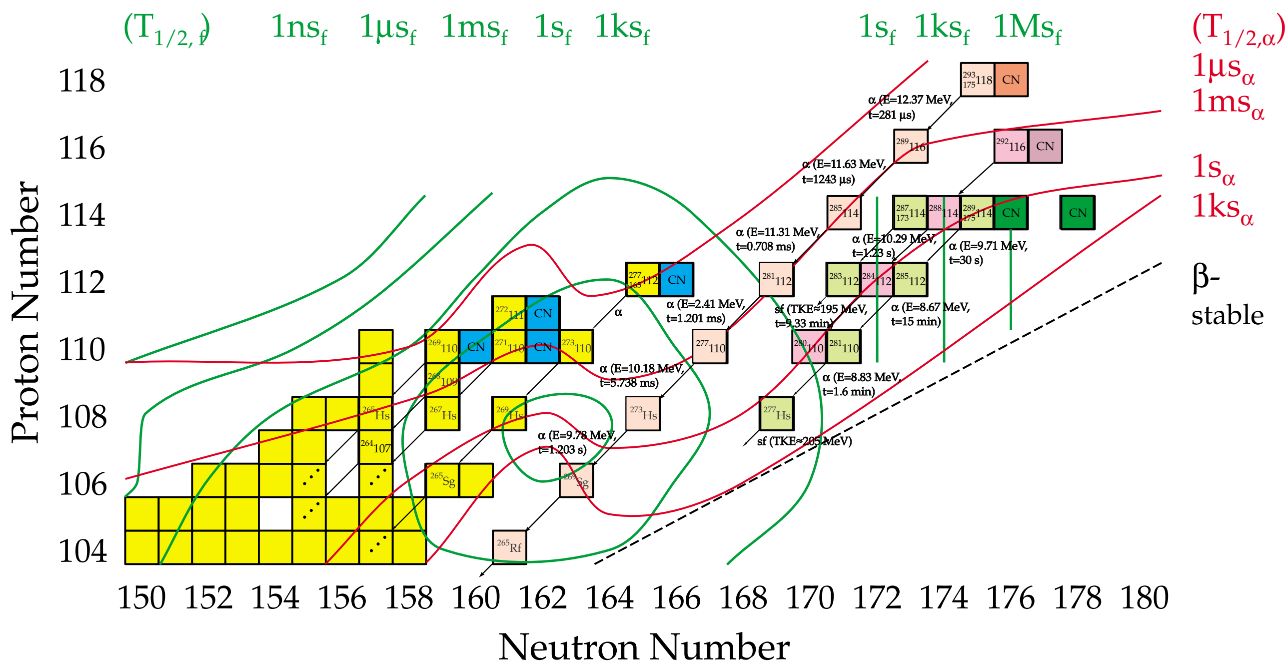

Figure 4. The $Z = 106$–112 isotopes were fused by the Hofmann-Münzenberg (GSI) group. The two $Z = 114$ isotopes and the $Z = 116$ isotope were produced by the Dubna-Livermore group. It is claimed that three neutrons are evaporated. Obviously the lifetimes of the various decay products are rather long (because they are closer to the stable valley), in crude agreement with early predictions[3,4] and in excellent agreement with the recent calculations of the Sobiczewski group.[12] The $Z = 118$ isotope claimed to be fused by V. Ninov et al. at Berkeley could not be reproduced in later experiments.

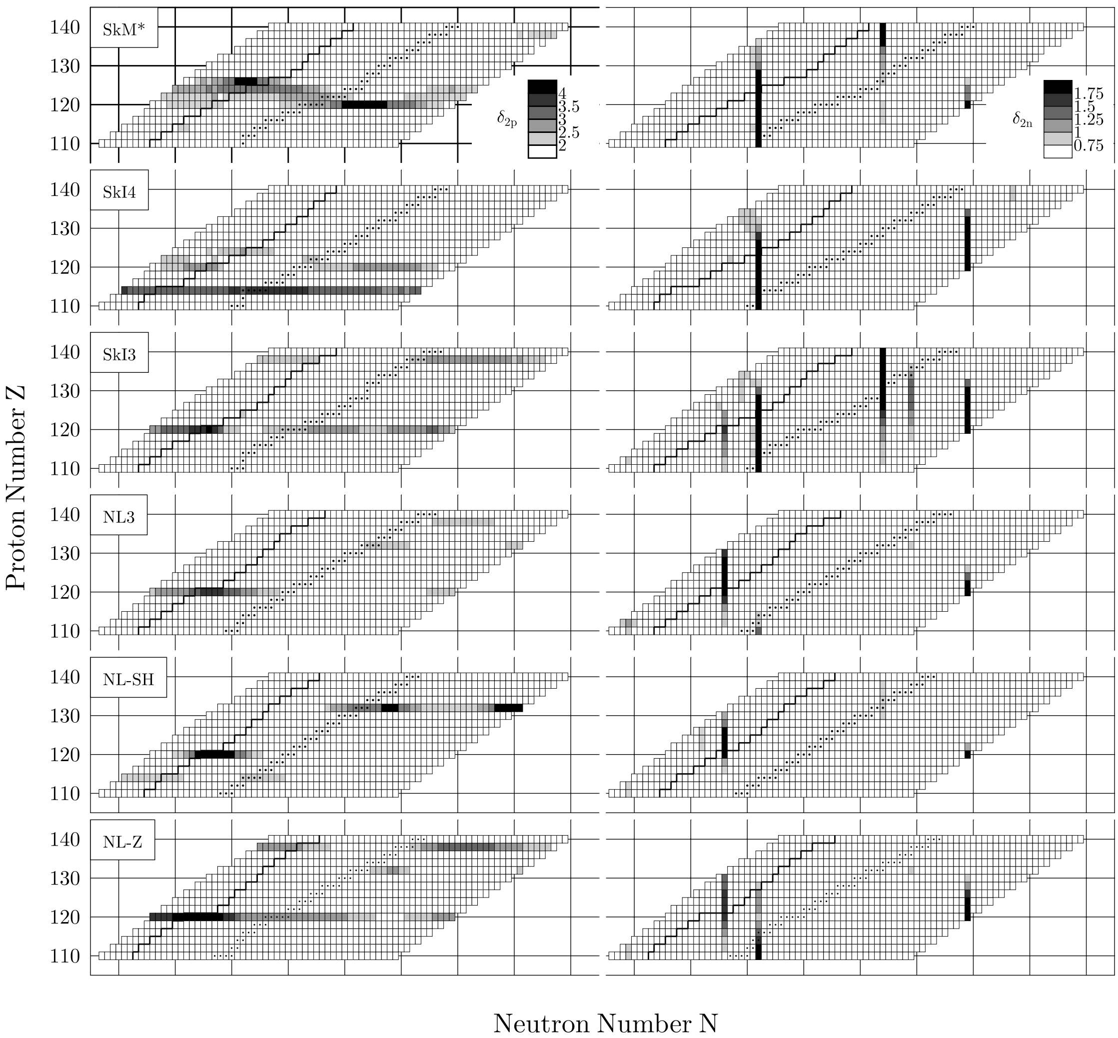

Figure 5. Grey scale plots of proton gaps (left column) and neutron gaps (right column) in the *N*–*Z* plane for spherical calculations with the forces as indicated. The assignment of scales differs for protons and neutrons, see the uppermost boxes where the scales are indicated in units of MeV. Nuclei that are stable with respect to β decay and the two-proton dripline are emphasized. The forces with parameter sets SkI4 and NL-Z 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 NL-Z 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.[15]

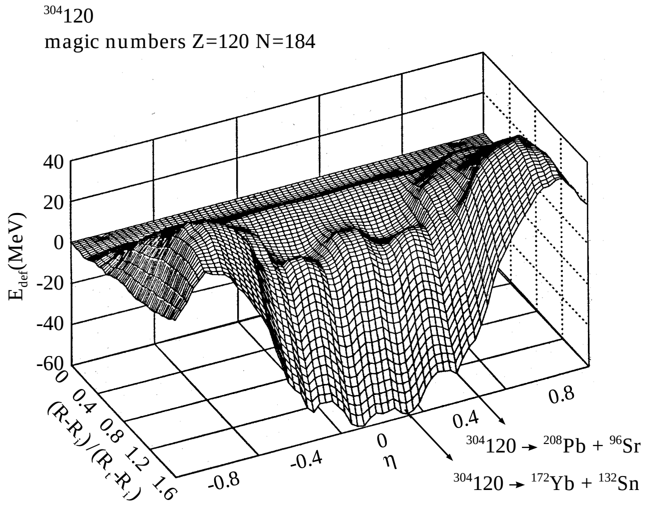

Figure 6. Potential energy surface as a function of reduced elongation $(R - R_i)/(R_t - R_i)$ and mass asymmetry η for the double magic nucleus $^{304}120_{184}$.

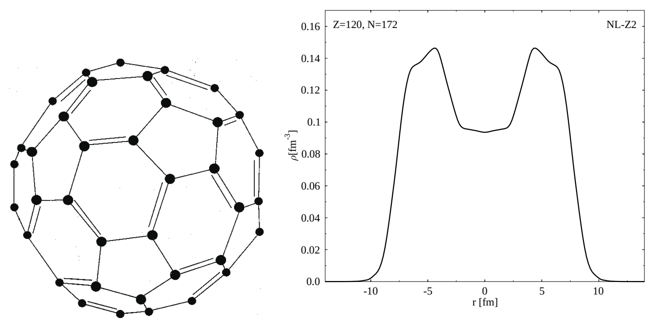

Figure 7. Typical structure of the fullerene ^{60}C. The double bindings are illustrated by double lines. In the nuclear case the Carbon atoms are replaced by α particles and the double bindings by the additional neutrons. Such a structure would immediately explain the semi-hollowness of that superheavy nucleus, which is revealed in the mean-field calculations within meson-field theories. The radial density of the nucleus with 120 protons and 172 neutrons, as emerging from a meson-field calculation with the force NL-Z2 is shown on the right side. Note that the semi-bubble structure is mostly pronounced for this nucleus. When going to higher neutron numbers, this structures becomes less and less.

Fock approach have recently shown that the magic shells in the superheavy region are very isotope dependent[5,15] (see Figure 5). **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 result also in the prediction of these two magic numbers,[42,44] see also below. The corresponding magic neutron numbers are predicted to be $N = 172$ and — as it seems to a lesser extend —

$N = 184$. 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 (Figure 6). The charge distribution of the $Z = 120$, $N = 184$ nucleus, calculated with mean-field models, indicates a hollow inside. This leads us to suggest that it might be essentially a fullerene consisting of 60 α particles and one additional binding neutron per alpha. This is illustrated in Figure 7. The protons and neutrons of such a superheavy nucleus are distributed over 60 α particles and 60 neutrons (forgetting the last 4 neutrons). The potential energy surfaces of superheavy elements, as they emerge from selfconsistent calculations within mean-field models in axial symmetry, exhibit some interesting features.[24]

Nuclei in the vicinity of the nucleus with $Z = 108$ protons and $Z = 162$ have prolate ground-states and barriers. Going upward in proton and neutron numbers, one encounters transitional systems with two shallow minima, one on the oblate, one on the prolate side. Nuclei with proton numbers $Z = 120$ and neutron numbers $N = 178 \ldots 184$ exhibit no pronounced deformation. Mean-field forces predict either a clear spherical shape or a rather soft potential energy surface around zero deformation with small wiggles. For these nuclei, however, triaxial degrees of freedom might become important and change the picture considerably.

The barriers correspond to a simple-humped structure for almost all forces. Isomeric states appear in the reflection-symmetric solutions but disappear when allowing for shapes including odd multipole moments. Globally, barriers calculated with Skyrme-forces appear to be up to twice as high as the ones emerging from RMF calculations. This effect has already been seen in former studies.[23] It indicates the need for a deeper understanding of these selfconsistent approaches. One might further ask how collective motions of these spherical superheavy elements might look like. We will take a first look at these aspects in the following section.

4. Vibrational Modes in Spherical Superheavy Nuclei

We consider vibrational collective properties of the putative double magic SH nucleus $^{292}120$ as predicted by the RMF axial-symmetric model and compare them with those of the well-known double magic heavy nucleus ^{208}Pb (Ref. 25). As one can see in Figure 8, the nucleus ^{208}Pb has a pronounced harmonic behaviour, at least for the three vibrational states, i.e. 0^+, 2^+, and the triplet 0^+, 2^+, 4^+. In contrast to that the SHE $^{292}120$, computed also with the force NL-Z2, exhibits a clear prolate-oblate asymmetry and consequently the sequence of states follows a

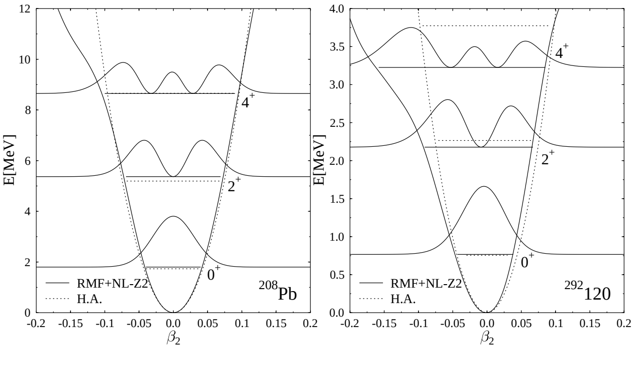

Figure 8. Potential well and first three vibrational states of the potential, calculated in the frame of the RMF model with NL-Z2 force (RMF + NL-Z2) and in the Harmonic approximation (HA) for two nuclei. The wave functions of the states are also shown. The left panel represents the case of ^{208}Pb where the harmonic approximation works quite well. The right panel shows the putative double-magic nucleus $^{292}120$ for which the anharmonic distortions in the potential are inducing a sensitive departure of the collective level spacing from the equidistant harmonic behaviour.

non-equidistant behaviour. This result was expected because the SHE are less stable (calculations give barriers up to 5 times smaller when the first symmetric barrier of $^{292}120$ is compared with that of ^{208}Pb). Therefore the departure of the deformation energy curve from the harmonic oscillator well will be larger.

It is important to stress that in view of the width and height of the potential well in the β_2 coordinate, no more than two phonon states exist. Clearly, the future observation of such β-vibrational states will yield further useful information about the structure of these nuclei. Also the sensitivity of this structure to the underlying effective forces is interesting.

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.[16] Hartree-Fock-Dirac calculations yield rather precise results.

5. Asymmetric and Superasymmetric Fission — Cluster Radioactivity

The potential energy surfaces, which are shown prototypically for $Z = 114$ in Figure 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.

The probability for finding a certain mass asymmetry $\eta = \frac{A_1 - A_2}{A_1 + A_2}$ of the fission 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 valleys. And that is indeed, what one observes. For large mass asymmetry ($\eta \approx 0.8,\ 0.9$) there exist very narrow valleys. They are not as clearly visible in Figure 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 led to the **cluster radioactivity** (Poenaru, Sandulescu, Greiner[17]).

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, ...). Figure 9 depicts some examples of these processes.

The knowledge of the collective potential energy surface and the collective masses $B_{ij}(R, \eta)$, 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.[18] The discussion of much more very interesting new physics cannot be pursued here. We refer to the literature.[19–22, 26–28]

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.

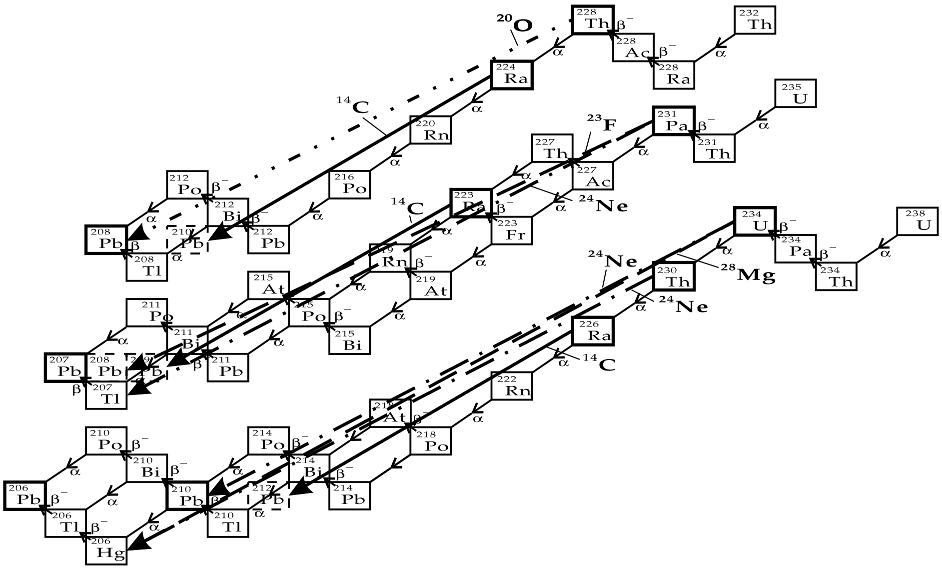

Figure 9. Cluster radioactivity of actinide nuclei. By emission of ^{14}C, ^{20}O, ..., "big leaps" in the periodic system can occur, just contrary to the known α, β, γ radioactivities, which are also partly shown in the figure.

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 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.

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).[31] Several years ago, Carsten Greiner, Jürgen Schaffner, and Horst Stöcker[32] 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. Figure 10 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 ≥ 200 GeV). Calculations with the URQMD-model of the Frankfurt school show that through **nuclear shock waves**[33–35] nuclear matter gets compressed to 5–10 times of its usual value, $\rho_0 \approx 0.17$ 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 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 within the mean-field approximation the energy spectrum of baryons in a nucleus has a peculiar structure, depicted in Figure 11. It consists of an upper and a lower continuum, as it is known from the electrons (see e.g. Reference 30). The upper well represents the nuclear shell model potential. It describes the overall structure throughout the

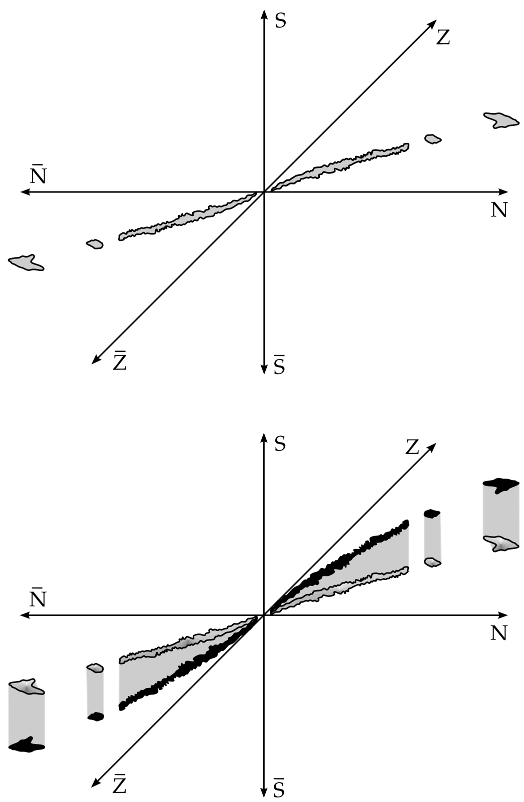

Figure 10. The extension of the periodic system into the sectors of strangeness (S, $\bar{S}$) and antimatter ($\bar{Z}$, $\bar{N}$). The stable valley winds out of the known proton (Z) and neutron (N) plane into the S and $\bar{S}$ sector, respectively. The same can be observed for the antimatter sector. 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. This is due to an additional term proportional to $(\frac{A}{A} - \frac{S_0}{A})^2$ in the mass formula.

nuclear table very well.

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. This has been extensively discussed in the context of QED of strong fields (overcritical fields, decay of the vacuum from a neutral one into a charged one[30]).

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 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.[36–38] 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 (Figure 12). 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[33,34] and which have since then been confirmed extensively (for references see e.g. Reference 39). These **nuclear shock waves** are accompanied by heating of the compressed nuclear matter. Indeed, density and temperature are correlated in

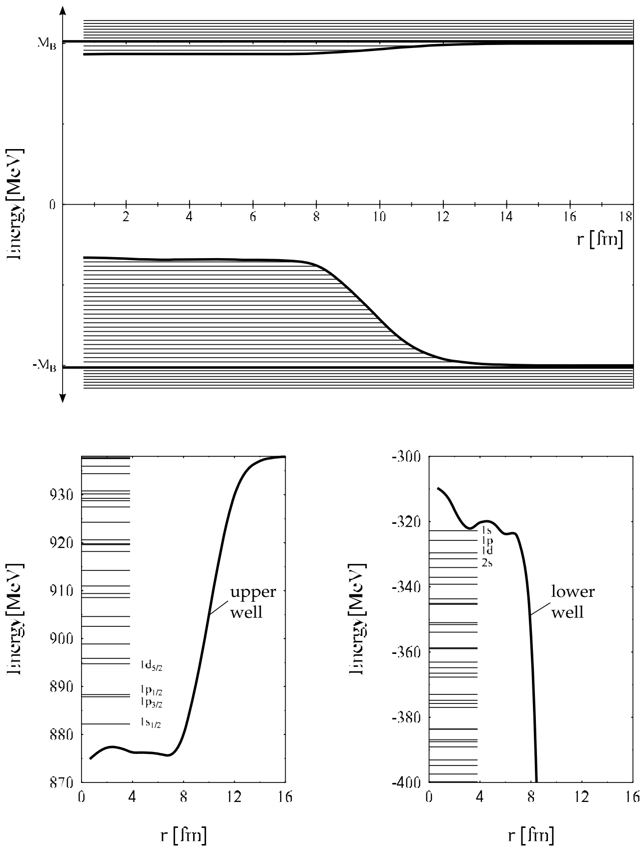

Figure 11. Baryon spectrum in a nucleus. Below the positive energy continuum exists the potential well of real nucleons. It has a depth of 50–60 MeV and shows the correct shell structure. The shell model of nuclei is realized here. However, from the negative continuum another potential well arises, in 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.

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 and an equal number of particles (baryons) in the upper continuum. This is analogous to the dynamical $e^+ e^-$ pair creation in heavy ion collisions.[39]

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 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 Figure 11) supports this latter suggestion. Figure 13 illustrates 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 $\underline{\Lambda}$'s. Dynamics and temperature then induce transitions (e.g. $\Lambda\bar{\Lambda}$ creation) and deposit many Λ's in the upper well. These numerous bound Λ's (and similarly other hyperons) 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. Also clusters of hyperons alone (Λ, Σ, ...) seem possible and quasistable[5,32] and the Bethe-Weizsäcker mass formula requires at least one additional term proportional to $(f_S - f_{S_0})^2$, where f_S/A is the strangeness content in a hypernucleus.

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

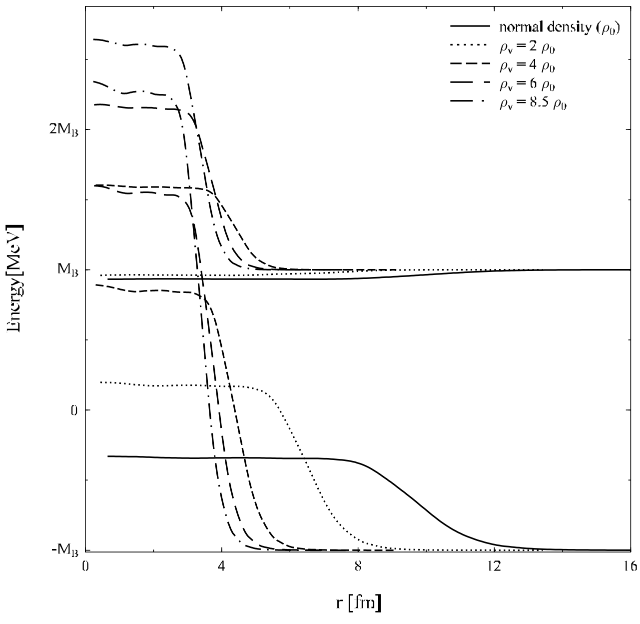

Figure 12. The lower well rises strongly with increasing primary nucleon density, and even gets supercritical (spontaneous nucleon emission and creation of bound antinucleons). Supercriticality denotes the situation, when the lower well enters the upper continuum.

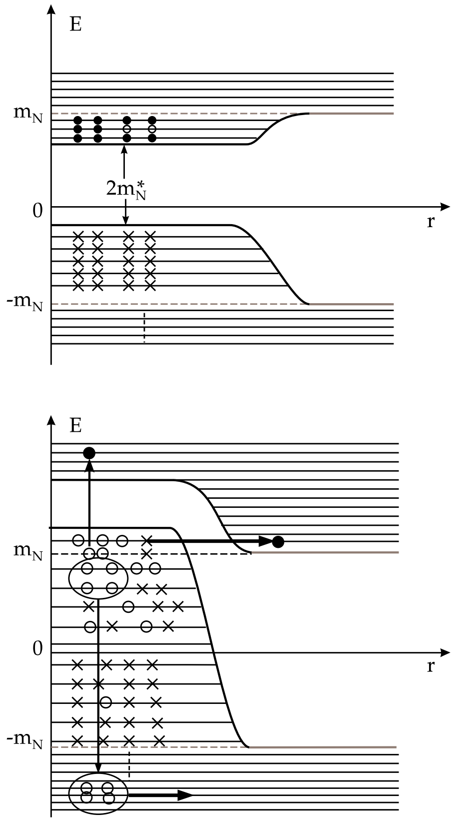

Figure 13. Due to the high temperature and the violent dynamics, many bound holes (antinucleon clusters) are created in the highly correlated vacuum, which can be set free during the expansion stage into the lower continuum. In this way, antimatter clusters can be produced directly from the vacuum. The 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.

more experimental information on the properties of the lower well by $(e,e'p)$ or $(e,e'pp')$ and also $(\bar{p}_c p_b,\, p_c\bar{p}_b)$ reactions at high energy ($\bar{p}_c$ 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).[40] Also the reaction $(p,p'd)$, $(p,p'^3\mathrm{He})$, $(p,p'^4\mathrm{He})$ 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: Time-like momentum transfer is required here! The Nambu-Jona-Lasigno (NJL) model seems to give much smaller lower wells, but does not describe the shell model potentials. Studies of I. Mishustin, L. Satarov et al. to improve the NJL model for applications to nuclear and baryon-meson sectors are on the way.

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.[41] The Lagrangians of the Dürr-Teller-Walecka-type and of the chirally symmetric mean field theories look quantitatively quite differently. We exhibit them — without further discussion — in the following equations:

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

Non-chiral Lagrangian:

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

Chiral Lagrangian:

$$\begin{aligned}
\mathcal{L}_{\rm kin} &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\partial_\mu\zeta\partial^\mu\zeta + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
&\quad - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \\
\mathcal{L}_{\rm BM} &= \textstyle\sum_B \overline{\psi}_B\big[i\gamma_\mu\partial^\mu - g_{\omega B}\gamma_\mu\omega^\mu - g_{\phi B}\gamma_\mu\phi^\mu \\
&\quad - g_{\rho B}\gamma_\mu\tau_B\rho^\mu - e\gamma_\mu\frac{1}{2}(1+\tau_B)A^\mu - m_B^*\big]\psi_B\ , \\
\mathcal{L}_{\rm vec} &= \frac{1}{2}m_\omega^2\frac{\chi^2}{\chi_0^2}\omega_\mu\omega^\mu + \frac{1}{2}m_\rho^2\frac{\chi^2}{\chi_0^2}\rho_\mu\rho^\mu + \frac{1}{2}m_\phi^2\frac{\chi^2}{\chi_0^2}\phi_\mu\phi^\mu \\
&\quad + g_4^4(\omega^4 + 6\omega^2\rho^2 + \rho^4)\ , \\
\mathcal{L}_0 &= -\frac{1}{2}k_0\chi^2(\sigma^2+\zeta^2) + k_1(\sigma^2+\zeta^2)^2 + k_2\Big(\frac{\sigma^4}{2}+\zeta^4\Big) \\
&\quad + k_3\chi\sigma^2\zeta - k_4\chi^4 + \frac{1}{4}\chi^4\ln\frac{\chi^4}{\chi_0^4} + \frac{\delta}{3}\ln\frac{\sigma^2\zeta}{\sigma_0^2\zeta_0}\ , \\
\mathcal{L}_{\rm SB} &= -\left(\frac{\chi}{\chi_0}\right)^2\left[m_\pi^2 f_\pi\sigma + \left(\sqrt{2}m_K^2 f_K - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right)\zeta\right].
\end{aligned}$$

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 ρ-meson ρ_μ as well as the photon A_μ. For more details see Reference 41. In contrast to the non-chiral model, the $SU(3)_L\times SU(3)_R$ Lagrangian contains the dilaton 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 References 41, 42).

The connection of the chiral Lagrangian with the Walecka-type one 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:

$$m_N^* = g_s\sigma_0 - g_s s \equiv m_N - g_s s$$

for the nucleon mass in the chiral model. Nevertheless, if the parameters in both cases (e.g. g_s, g_ω, g_ρ, m_s, b, c in the non-chiral case) 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 similar as long as the same mesons are considered. 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[43] — see Figure 14.

7. Concluding Remarks — Outlook

The extension of the periodic system into the sectors hypermatter (strangeness) and antimatter is of general and astrophys-

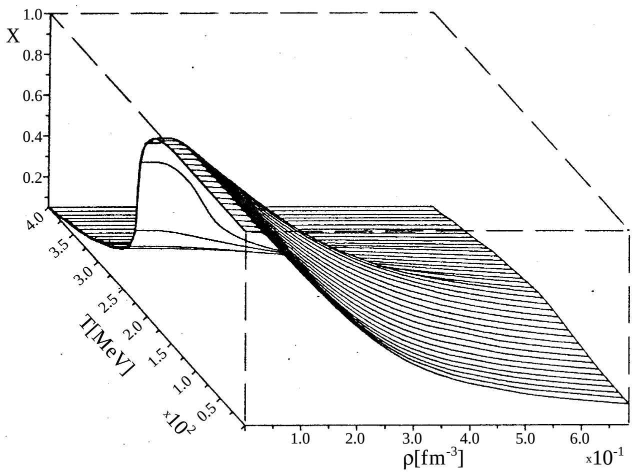

Figure 14. The strong phase transition inherent in Dürr-Teller-Walecka-type meson field theories, as predicted by J. Theis et al.[43] Note that there is a first order transition along the ρ-axis (i.e. with density), but a simple transition along the temperature T-axis. Note also that this is very similar to the phase transition obtained recently from the Nambu-Jona-Lasinio approximation of QCD.[45]

ical 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 depopulation (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 concrete (almost too concrete) suggestions are discussed — as far as it has been presented to the public. What is necessary, 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 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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