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SUPERHEAVY NUCLEI AND BEYOND: HYPERMATTER AND ANTIMATTER

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Paper devoted to honour the memory of Professor Nikola Cindro

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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. 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.

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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 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 developped by Mendeleev and 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 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 $Z = 164$, $N = 318$.

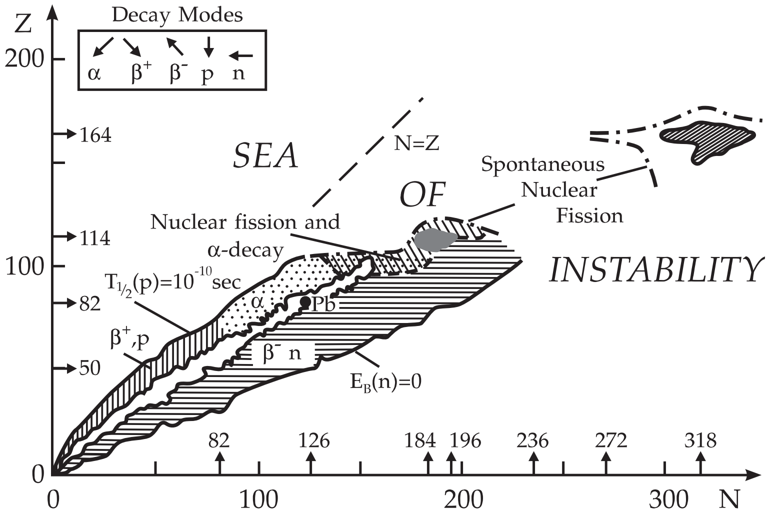

Fig. 1. The periodic system of elements as conceived by the Frankfurt school in the late sixties. The islands of superheavy elements ($Z = 114$, $N = 184$, 196 and $Z = 164$, $N = 318$) are shown as dark hatched areas.

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)) [3] 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 [4] The two-center shell model, which is essential for the description of fission, fusion and nuclear molecules, was developped 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 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** [3,6], they get only minimally excited and the barrier, which has to be overcome (fusion barrier) is lowest (as compared to the neighbouring projectile-target 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 [7] have followed this approach. With the help of the SHIP mass-separator and the position sensitive detectors, which were especially developped by them, they produced the pre-superheavy elements $Z = 106, 107, \ldots 112$, 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. Very recently the Dubna–Livermore group produced two isotopes of $Z = 114$ element by bombarding ^{244}Pu with ^{48}Ca [8]. This is

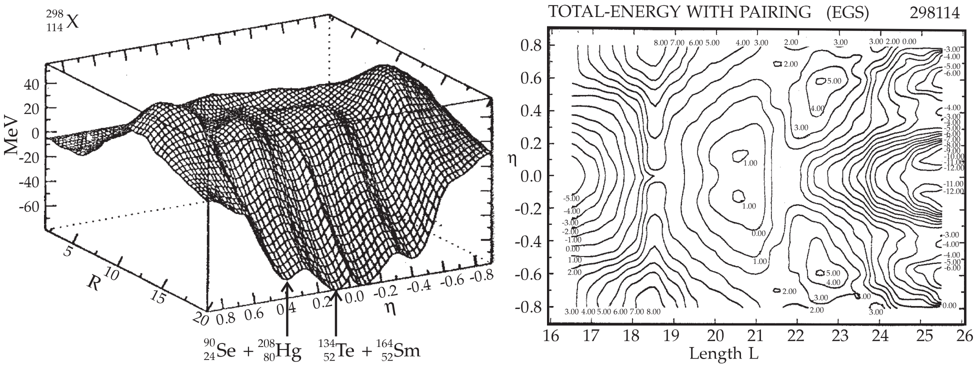

Fig. 2. The collective potential energy surface of $^{184}114$, calculated within the two center shell model by J. Maruhn et al., shows clearly the cold valleys which reach up to the barrier and beyond. Here R is the distance between the fragments and $\eta = (A_1 - A_2)/(A_1 + A_2)$ denotes the mass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

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 [6], or have non-axial orientations [9], but these have yet not been verified experimentally.

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 superheavy region are very isotope dependent [3] Additionally, there is a strong dependence 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 [10] 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. 3). Calculations of the potential energy surfaces [10] show single humped barriers, their heights and widths strongly depending on the predicited magic number. Further on,

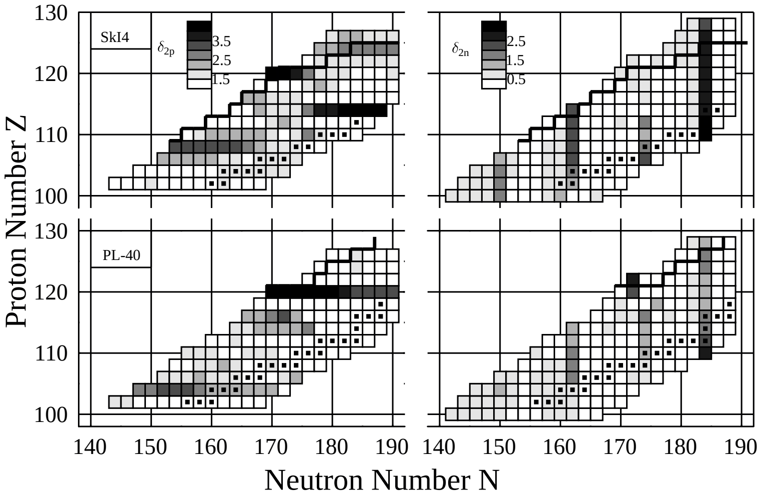

Fig. 3. Grey scale plots of proton gaps (left column) and neutron gaps (right column) in the N-Z plane for deformed calculations with the forces SkI4 and PL-40. Besides the spherical shell closures one can see the deformed shell closures for protons at $Z = 104$ (PL-40) and $Z = 108$ (SkI4) and the ones for neutron at $N = 162$ for both forces.

recent investigations in a chirally symmetric mean-field theory (see also below) result also in the prediction of these two magic numbers [11,12]. The corresponding magic neutron numbers are predicted to be $N = 172$ and – seemingly 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 leads us to 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.

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 (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. Hypernuclei with one hyperon have been known for 20 years now, and were extensively studied by B. Povh (Heidelberg) [13]. Several years ago, Carsten Greiner, Jürgen Schaffner and Horst Stöcker [14] 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 4 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 show that through **nuclear shock waves** [15] 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,

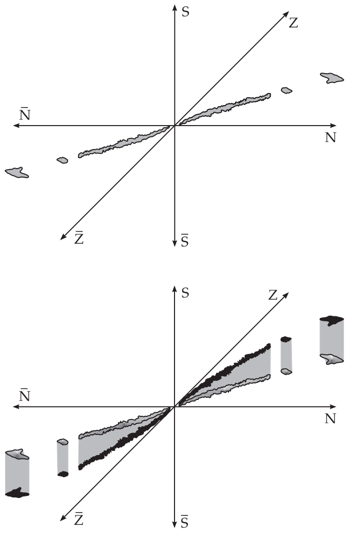

Fig. 4. The extension of the periodic system into the sectors of strangeness $(S, \bar{S})$ *and antimatter* $(\bar{Z}, \bar{N})$. *The stable valley winds out of the known proton* (Z) *and neutron* (N) *plane into the* S *and* $\bar{S}$ *sector, respectively. The same can be observed for the antimatter 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.*

about 10 000 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 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 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 the meson field theory, the energy spectrum of baryons has a peculiar structure, depicted in Fig. 5. It consists of an upper and a lower continuum, as it is known for electrons (see, e. g. Ref. [16]). 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 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**. A pronounced shell structure can be recognized [17]. 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

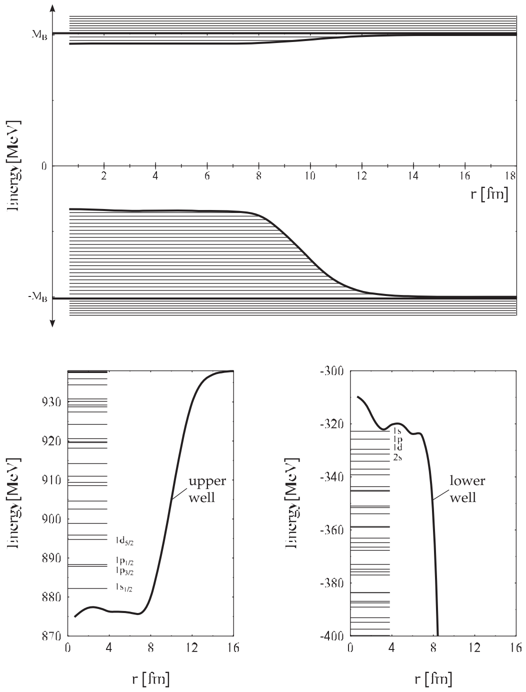

Fig. 5. Baryon spectrum in a nucleus. Below the positive energy continuum exists the potential well of real nucleons. It has a depth of 50-60 MeV *and shows the correct shell structure. The shell model of nuclei is realized here. However, from the negative continuum another potential well arises, in which about 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.*

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. [18]) and which have since then been confirmed extensively (see, e. g. Ref. [19]). 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 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. 5) supports this latter suggestion. Fig. 6 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 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 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, e′ p) or (e, e′ p p′) and also ($\bar{\mathrm{p}}_\mathrm{c}\mathrm{p}_\mathrm{b}$, $\mathrm{p}_\mathrm{c}\bar{\mathrm{p}}_\mathrm{b}$) reactions at high energy ($\bar{\mathrm{p}}_\mathrm{c}$ 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). 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?

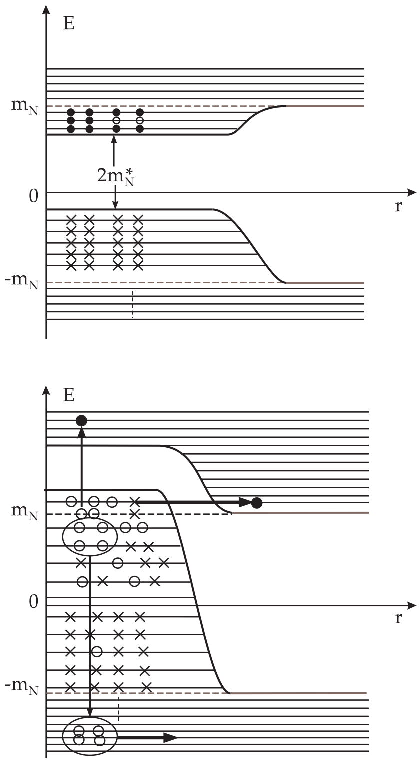

Fig. 6. Due to the high temperature and the violent dynamics, many bound holes (antinucleon clusters) are created in the highly correlated vacuum, which can be set free during the expansion stage into the lower continuum. In this way, antimatter clusters can be produced directly from the vacuum. The 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.

5. Concluding remarks - outlook

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.

Nikola Cindro was a dear friend of mine over several decades. I discussed with him many times the physics of superheavy elements and he followed these investigations with interest. I will miss him!

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SUPERTEŠKE JEZGRE I DALJE: HIPERMATERIJA I ANTIMATERIJA

Proučava se proširenje periodičkog sustava u nova područja. Razmatraju se eksperimenti tvorbe superteških elemenata i predviđanja magičnih brojeva. Izvješćuje se o istraživanjima hiperjezgri i mogućoj tvorbi nakupina antimaterije u sudarima teških iona. Razne inačice mezonske teorije polja služe kao efektivne teorije polja koje su osnova suvremene teorije građe jezgri, te nagovještaju građu vakuuma koja može biti važna za tvorbu hiper- i antimaterije.