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Frontier Topics in Nuclear Physics

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PREFACE

This volume contains the lectures and contributions presented at the NATO Advanced Study Institute (ASI) on "Frontier Topics in Nuclear Physics", held at Predeal in Romania from 24 August to 4 September 1993. The ASI stands in a row of 23 Predeal Summer Schools organized by the Institute of Atomic Physics (Bucharest) in Predeal or Poiana-Brasov during the last 25 years.

The main topics of the ASI were cluster radioactivity, fission and fusion. the production of very heavy elements, nuclear structure described with microscopic and collective models, weak interaction and double beta decay, nuclear astrophysics, and heavy ion reactions from low to ultrarelativistic energies. The content of this book is ordered according to these topics.

The ASI started with a lecture by Professor Greiner on the "Present and future of nuclear physics", showing the most important new directions of research and the interdisciplinary relations of nuclear physics with other fields of physics. This lecture is printed in the first chapter of the book.

Cluster radioactivity means the spontaneous emission of carbon, fluorine or other light nuclei out of very heavy nuclei. This new field of nuclear physics began its development in the Institute of Atomic Physics in Bucharest 15 years ago when lifetimes for cluster radioactivity were theoretically predicted. Today cluster radioactivities are measured at various laboratories in the world. The recent theoretical and experimental aspects of cluster radioactivity were thoroughly presented in lectures and contributions at the ASI and are collected together with those of cold fission and fusion in the second chapter of this volume.

Another major point of the ASI were the lectures on nuclear structure presented in chapters III (Heavy elements) and IV (Nuclear structure). This important field is presently experiencing a renaissance which is supported by new experimental techniques such as the crystal-ball spectrometers and by refined theoretical models including cluster and continuum states. The search for new elements with charge numbers larger than 109 is now based on new estimates of the nuclear stability against alpha-decay and fission.

The double beta decay allows to fix an upper bound of the neutrino mass. The newest results of double beta decay of ^{76}Ge, obtained in the Gran Sasso experiment, are given in chapter V on weak interaction and double beta decay.

The last three chapters of the book are mainly devoted to nuclear rections and heavy ion collisions in connection with astrophysics (chapter VI), heavy ion physics (chapter VII) and miscellaneous physics (chapter VIII). Out of the topics of these lectures we like to point to investigations of resonance structures in cross sections seen in light and medium heavy ion collisions, which are essential for our understanding of the formation of nuclear molecules and of the cosmological (astrophysical) synthesis of light nuclei.

The atmosphere of the ASI was very exciting and stimulating. We were very satisfied with the excellent and pedagogically presented lectures and the very interesting contributions of the ASI-students. The lectures were very lively, especially because of the interesting questions, new suggestions and ideas raised by the participants.

The ASI had a very high educational, scientific and political rank in Romania. In the opening session on 24 August 1993 Professor Sandulescu welcomed the President of the Romanian Senate, Professor Dr. O. Gherman, the Romanian Minister of Science and Technology, Professor Dr. D. Palade, the President of the Romanian Academy, Professor Dr. M. Draganescu, the Vice-President of the Romanian Academy, Professor Dr. R. Grigorovici, the Director of the Unesco-Office in Bucharest, Professor Dr. I. Vaideanu and the Director of the Institute of Atomic Physics in Bucharest, Professor Dr. G. Pascovici. We are grateful to them for their interest in the ASI and their addresses to the participants.

The NATO-ASI was awarded and generously supported by the Scientific and Environmental Affairs Division of the NATO. It was also supported by the UNESCO, the Romanian Ministry of Science and Technology, the Romanian Academy, the Institute of Atomic Physics in Bucharest, the Romanian Physical Society and, last but not least, by the German Ministry of Research and Technology through the Romanian-German collaboration contract. We express our deep gratitude to these institutions for their financial help.

The Romanian scientific secretaries, Dr. M.I. Cristu and Dr. S. Stoica, and the technical secretaries have done an extremely valuable and very difficult job with great success during these days. We are obliged and thankful to them for their very efficient work.

Finally, we thank Dipl.-Phys. Stefan Hofstetter very much for his very excellent collaboration in editing this volume.

Giessen, January 1994

Aurel Sandulescu

Werner Scheid

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I.

Present and Future of Nuclear Physics

(Introductory Lecture)

PRESENT AND FUTURE OF NUCLEAR PHYSICS

Walter Greiner

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The future of a science depends on its open fundamental problems. Therefore we have to ask: are there open fundamental tasks in nuclear physics? My answer is yes, and I will proof it by discussing several such fundamental issues in nuclear physics.

Be reminded that there are certain "Ur-Fragen" as e.g. how did our world begin, how were the present day elementary particles formed (lepton and baryon synthesis) and how the elements in nature built up (nuclear synthesis). Another "Ur-question" is how life has been formed, or how our brain functions.

It is presently believed that our world began with a big bang, a giant phase transition from a true vacuum into a Higgs minimum. This inflationary phase went extremely fast and was followed by the "ordinary" expansion of spacetime. During these very early stages our universe consisted of a phase of matter which we believe is similar to or identical with what we call a quark gluon plasma (QGP). It was originally visualized as hot and dense matter consisting of free quarks and gluons. But during the last couple of years D. Rischke showed by analysing the results of lattice gauge calculations that the QGP seems to be, actually, a cluster plasma, i.e. quarks and gluons are still dominantly coupled to colour singlets. Figure 1 illustrates these pictures. When such a plasma cools down ordinary particles like baryons, mesons etc. are formed. This is then the stage of baryon synthesis.

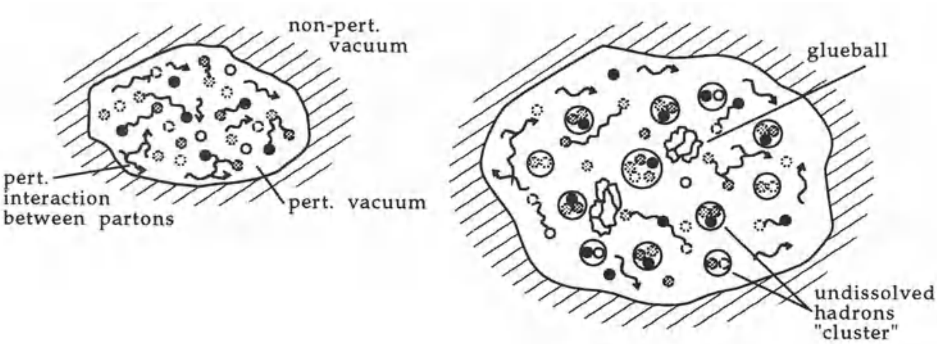

Figure 1. *The so-called gluon plasma seems to be a cluster plasma (second picture) where quarks and gluons still form color singlets. According to D. Rischke only 15% free quarks and gluons are present at the critical temperature T_c.*

Clearly, theoretical concepts like these have to be verified or falsified. Fortunately, through nuclear shock waves, proposed by Scheid and Greiner in 1969 and 1973 and studied theoretically in great detail by Stöcker, Maruhn and others [1], one has a mechanism at hand to compress and heat nuclear matter. It is the key to investigate nuclear matter, its phase transition and its equation of state. When it is compressed and heated, nucleons are excited into Δ's and other resonances, Δ-matter is created (Stöcker, Greiner, Scheid 1978 [2]). Some people renamed it recently "resonance matter" (Metag 1992). This, as well as meson condensates could cause a density isomer of the form shown in figure 2.

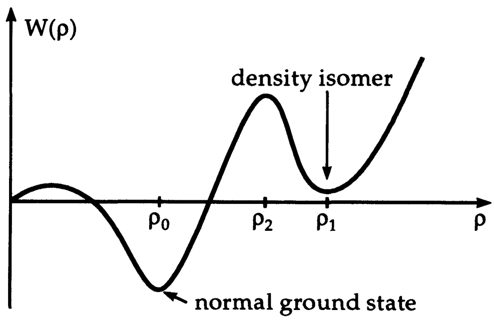

Figure 2. *Illustration of a density isomer in the equation of state (schematic). If the shock wave density reaches the instability window between ρ_1 and ρ_2 the shock will collapse (disperse due to negative pressure) and reappear again for $\rho_{shock} > \rho_1$*

How can it be discovered? Well, when reaching the negative pressure domain of such a density isomeric configuration, shock waves ("flow") should disappear (smear out) and reappear again after densities on the positive pressure side of the second minimum are reached. Such a possibility has already been discussed in the 70'ties (Stöcker,....Greiner 1976 [3]) and E. Schopper's early shock wave experiments (suffering of low statistics) seem to indicate such physics (fig. 3). It must be confirmed or disproved! Using medium heavy projectiles at the SIS at GSI and utilizing the Fopi-detector should enable us to comply.

According to Relativistic Quantum Molecular Dynamics (RQMD) high baryonic densities and temperatures are reached in Pb+Pb collisions at AGS-, CERN- and even RHIC energies. The so-called Bjorken-scenario, according to which the colliding nuclei should fly through each other more or less untouched (like two swarms of insects), is not valid. Instead nuclear matter is stopped to large extend at RHIC energies. Hence it will be the baryon rich quark gluon plasma which is formed. In Pb-Pb collisions at $\sqrt{s}$=200GeV/A about 8000 pions, 30 Λ's and 500 K^+K^- and $K_0\bar{K}_0$ pairs are produced at midrapidity (see fig. 4). This opens the door to generate completely new forms of nuclear matter:

a) In such a micro bang there is a good chance to form multi-pionic atoms, in which the **bosonic character** of the pions enters essentially. They would constitute new atoms, different form fermionic atoms. The π-π interaction will finally be responsible to limit the number of pions in an orbit. The problem is to obtain clusters (i.e. small nuclei) which can capture the pions and to find the location of these clusters in phase space together with the appropriate number of pions in their vicinity. The capture rate is then essentially given by folding the product of this quantity together with the pion capture cross section. b) Multi-Λ-hypernuclei and other Memos (Multiply Strange Exotic Mesonic Objects) are likely to be created. These

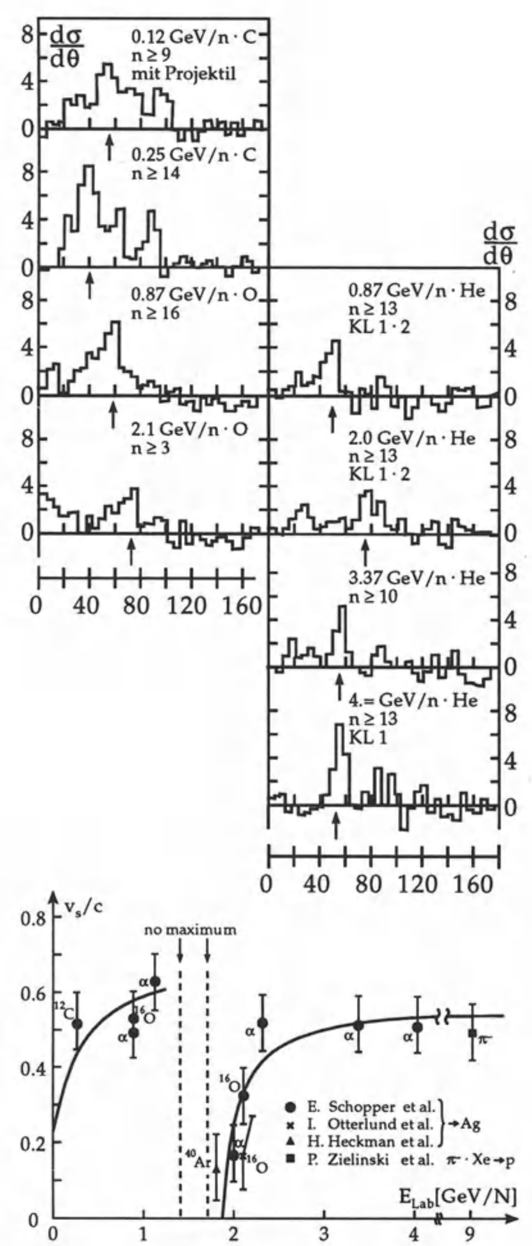

Figure 3. *Early data by E. Schopper show as a function of energy a flow-peak with irregular behaviour between 1200-1800 Mev/A. The shock velocity v_s/c deduced from these data (second figure) magnifies the irregularity. This could be the signature of a density isomere (phase transition to Δ-matter or some sort of meson condensate or both).*

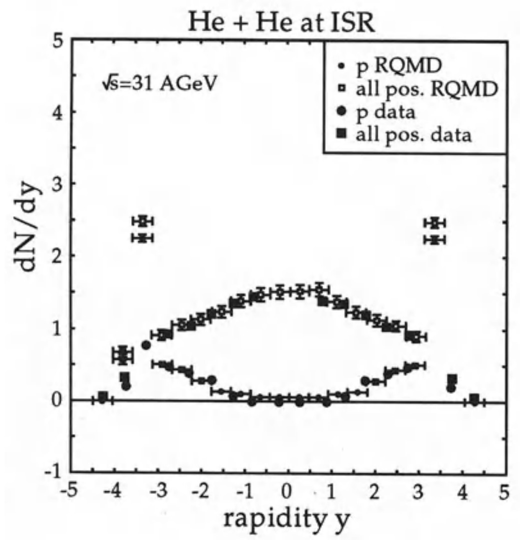

Figure 4. *4a. Transparency and stopping. Figure 4a) shows He+ He at* $s^{1/2} = 31$ *AGev (ISR), which is the up to now highest energy achieved for nucleus-nucleus collisions. The RQMD-calculations of T. Schönfeld yield a qualitatively very similar rapidity distribution as* $p + p$ *(respectively* $p + \bar{p}$*). This is not unexpected. Nevertheless the agreement of RQMD with data is impressive.*

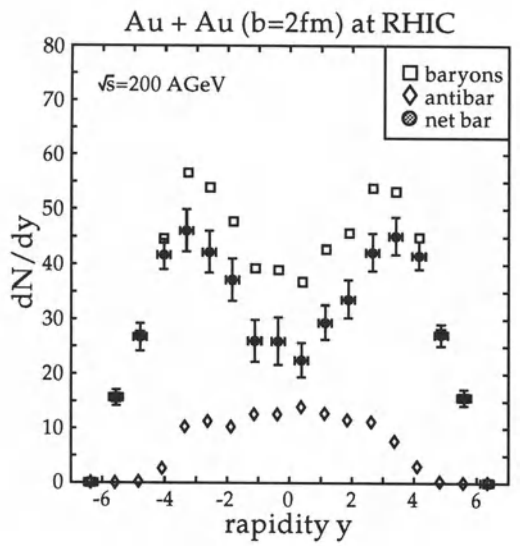

Figure 4. *4b: Figure 4b) shows the rapidity distribution for Au+Au at RHIC-energies* $s^{1/2}$ *= 200 AGeV. For nearly central collisions the impact parameter b=2 fm has been chosen. Obviously the nuclei do not stop, but there is also no baryon free region at y=0, as many people had expected. The analysis of these results show that mesons contribute about 1/4 to the stopping.*

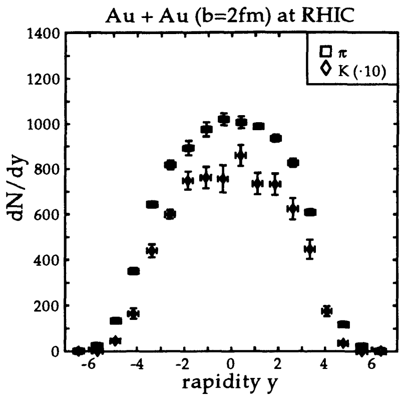

Figure 4. *4c: Figure 4c) shows the π 's produced (about 7400) and their rapidity distribution. There is now a plateau at midrapidity and therefore also no Bjorken-scenario. However, the maximum is broad; hence one is probably not too far from a Bjorken-scenario. The π 's peak at y=0; the baryons at y$\neq$0. Hence baryons collide preferentially with slow mesons. This accounts for the contribution $\Delta y_z \approx 0.6$ to baryon stopping. If there would be a meson plateau, one would have equal probability for a baryon to collide with slow and fast meson. In this case there would be no contribution to baryon stopping.*

exotic objects have been proposed and intensively studied by Carsten Greiner, J. Schaffner and Horst Stöcker. The dissolved form of the Memos is what has been called strangelet (Carsten Greiner and Horst Stöcker are the pioneers in these possibilities [4]). Tremendous research oppourtunity lies in this domain. For example, the periodic system of elements is generalized by not only having proton and neutron numbers as "degrees of freedom" but also the strangeness number. One might even generalize to negative p-n-axis, i. e. $\bar{p}$, $\bar{n}$, $\bar{\lambda}$-axis and enter into the sector of antimatter (anti-deuterons, anti-carbons, anti-hypernuclei etc.). Fig. 5 illustrates the general ideas of what might happen in a micro-bang. The periodic system of elements has suddenly reached new dimensions, which are breath-taking. The Memos's may exhibit exceptional properties: bound neutral (e. g. ${}^4\mathrm{M}^{2n}_{2\Lambda}$, ${}^{10}\mathrm{M}^{8n}_{2\Lambda}$, pure Λ-droplets like ${}^8\Lambda$) and negatively charged composite objects with positive baryon numbers (e. g. ${}^4\mathrm{M}^{2n}_{2\Sigma^-}$, ${}^6\mathrm{M}^{2n}_{2\Lambda,2\Xi^-}$) could be formed in rare events. Such negatively charged nuclei can easily be identified in a magnetic spectrometer. They could be considerably more abundant than antinuclei with the same A. The properties of these objects were studied by J. Schaffner, Carsten Greiner and H. Stöcker within the relativistic meson-baryon-field theory, which gives an excellent description of normal nuclear and single-Λ hypernuclear properties. They calculated the rich spectrum of such exotic objects, their stability and structure (J. Schaffner, C. Greiner, H. Stöcker, Metastable Exotic Multihypernuclear Objects...[5]). Also solutions for a large variety of bound short-lived nuclei (e. g. ${}^8\mathrm{M}^{2p2u}_{2\Lambda 2\Sigma^-}$) were found, which may decay strongly via the formation of cascade (Ξ) particles. Multi-Ξ-hpernuclei are also possible. It turns out that the properties of such exotic multihypernuclear objects reveal quite similar features as the strangelets, which were propsed as a (unique) signal for quark-gluon-plasma formation in heavy ion collision.

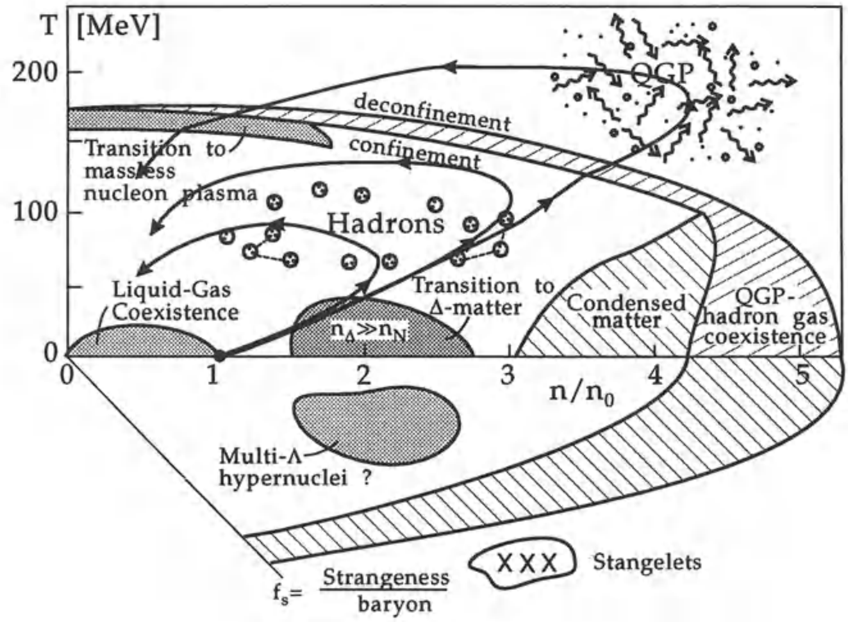

Figure 5. *Phase diagram of hadronic matter, including strangeness. In principle one could supplement this figure by a "negative density" axis and an anti-strangeness axis, which would then allow to include antimatter and its cluster effects in the diagram. Normal nuclear matter occurs at $T = 0$, $n/n_0 = 1$. Deconfinement into a so-called quark-gluon-plasma is expected at high T, n, f_s. Multi strange objects like multi-Λ-hypernuclei and strangelets (which are more or less the dissolved form of multi-Λ-hypernuclei) are also expected.*

Multi-Λ-hypernulei and Memos

The Lagrangian of the Relativistic Mean Field Theory (RMFT), which has been proven to give a very good description of normal nuclei [6], has the following structure:

$$\mathcal{L} = \mathcal{L}_{Dirac} + \mathcal{L}_\phi + \mathcal{L}_V + \mathcal{L}_R + \mathcal{L}_A$$

with additional terms for the hyperons Λ, Σ, and Ξ:

$$\begin{aligned}
\mathcal{L}_{Dirac}^{Hyp} &= \bar\psi_\Lambda(i\gamma^\nu\partial_\nu - m_\Lambda)\psi_\Lambda + \bar\psi_\Sigma(i\gamma^\nu\partial_\nu - m_\Sigma)\psi_\Sigma + \bar\psi_\Xi(i\gamma^\nu\partial_\nu - m_\Xi)\psi_\Xi \\
\mathcal{L}_\phi^{Hyp} &= -g_{\sigma\Lambda}\phi\bar\psi_\Lambda\psi_\Lambda - g_{\sigma\Sigma}\phi\bar\psi_\Sigma\psi_\Sigma - g_{\sigma\Xi}\phi\bar\psi_\Xi\psi_\Xi \\
\mathcal{L}_V^{Hyp} &= -g_{\omega\Lambda}V^\mu\bar\psi_\Lambda\gamma_\mu\psi_\Lambda - g_{\omega\Sigma}V^\mu\bar\psi_\Sigma\gamma_\mu\psi_\Sigma - g_{\omega\Xi}V^\mu\bar\psi_\Xi\gamma_\mu\psi_\Xi \\
\mathcal{L}_R^{Hyp} &= -\frac{1}{2}g_{\rho\Sigma}\vec{R}^\mu\cdot\bar\psi_\Sigma\vec\tau\gamma_\mu\psi_\Sigma - \frac{1}{2}g_{\rho\Xi}\vec{R}^\mu\cdot\bar\psi_\Xi\vec\tau\gamma_\mu\psi_\Xi \\
\mathcal{L}_A^{Hyp} &= -\frac{1}{2}eA^\mu\bar\psi_\Sigma(1+\tau_0)\gamma_\mu\psi_\Sigma - \frac{1}{2}eA^\mu\bar\psi_\Xi(1+\tau_0)\gamma_\mu\psi_\Xi
\end{aligned}$$

Variation of the fields yields within the mean field approach and in the no sea approximation, i.e. the sum of the densities runs only over the occupied states, four boson fields and three baryon field equations which can be solved numerically for the nuclear ground states.

The parameters of the meson fields and of the nucleon coupling are fitted to the properties of eight spherical nuclei. Calculations done with lower effective masses show instabilities

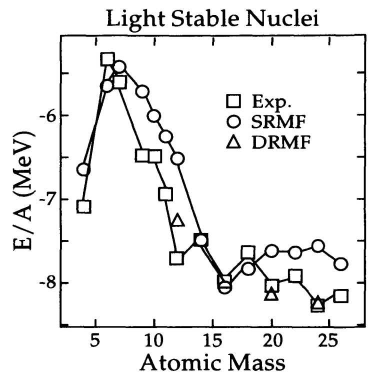

Figure 6. *The binding energy of light stable normal nuclei in spherical relativistic mean field model (SRMF) and in the deformed RMF (DRMF) compared to experimental data.* [5].

for highly dense nuclear systems as ^{12}C and unphysical behaviour in nuclear matter for a negative coefficient c in the standard nonlinear self-interaction of the effective scalar field. The determination of the various parameters is discussed in [5]. An appreciation of the accuracy of these calculations can be obtained from fig. 6, which shows the binding energies for normal light nuclei. In fig. 7 the single particle energies of single-Λ-hypernuclei in the Relativistic Mean Field Theory (RMFT) are compared to recent data. The binding energies of such nuclei are shown in fig. 8. Obviously the RMFT describes existing data rather well. The density distribution of the hyperons is shifted outwards relative to the nucleons according to their smaller binding energy (fig. 9). Thus an extended neutral Λ-halo appears which results in an enhanced interaction radius. Here "anomalons" [7] come in mind.

Early discussions about double-Λ-hypernuclei can be found in [8]. The multi-Λ-hypernuclei, the exotic objects as well as the possibility of their creation in heavy ion collisions came in [5], [6]. In figures 10 and 11 the binding energies of various spherical multi-Λ-hypernuclei are depicted as a function of the number of Λ's. Note that the binding energy increases when hyperons are added to normal nuclei [6], because a new degree of freedom is opened for which the Fermi energy is small for small number of Λ's. The argument is analogous to the discussion of the stability of strange quark matter [4]. All possible pairs of nucleons and hyperons can be sorted according to their strangeness number and their charge (both conserved in strong interactions). The pair with lowest mass is shown in the following tables 1 and 2. Three different baryons can be combined to six metastable configurations (e.g. $\Lambda\Xi^- n$ - see table 2). It is not possible to have more than three baryon species in a metastable configuration, because they will react immediately to form a configuration with two or three different baryons, if the mass difference cannot overcome by binding energy differences inside the bound system.