NUCLEAR MODELS: SHELL STRUCTURE AND THE EXTENSION OF THE PERIODIC SYSTEM

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Contents

Summary

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 $^{252}\mathrm{Cf}$. 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 as the basis of modern nuclear structure and suggest structure in the vacuum which might be important for the production of hyper- and antimatter. 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 are closely related to that. On this we want to report, beginning with the discussion of modern issues in nuclear physics.

The elements existing in nature are ordered according to their atomic (chemical) properties in the **periodic system** which was developed by Mendeleev and Lothat 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 ($Z = 100$) upto 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 become bigger.

In the late 1960s the dream of the superheavy elements arose. Theoretical nuclear physicists around S.G.Nilsson (Lund) and from the Frankfurt school predicted that the 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 neighbors 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 thousands of 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.

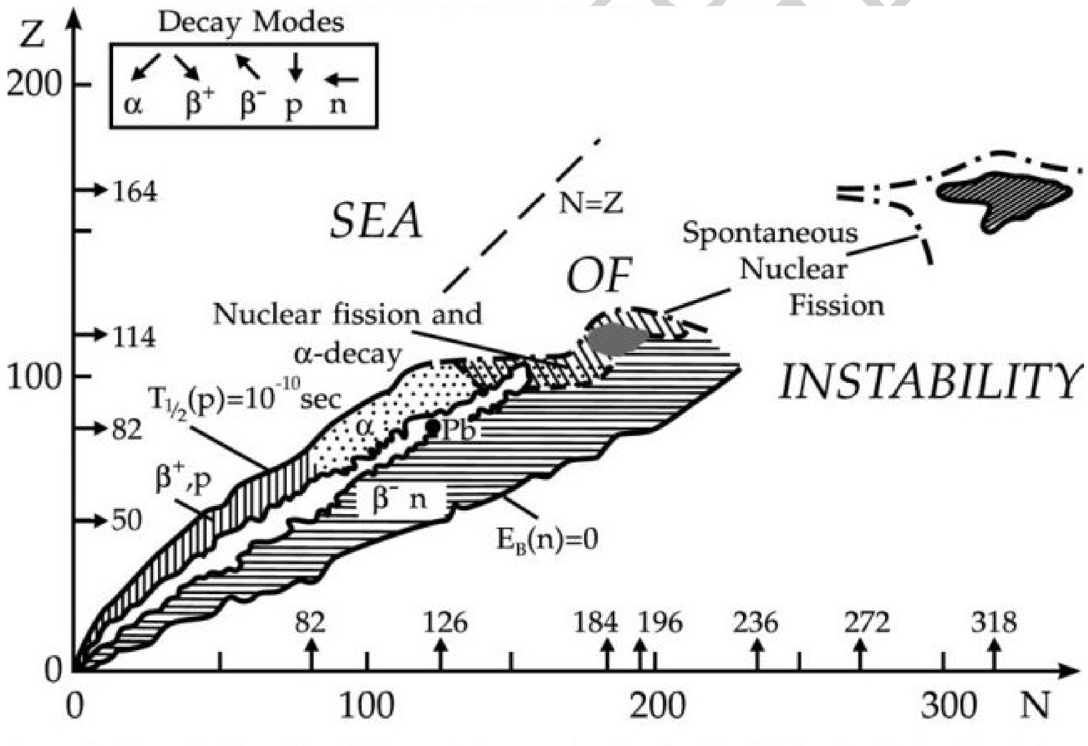

Figure 1: The periodic system of elements as conceived by the Frankfurt school in the late sixties. The islands of superheavy elements (Z = 114, N =184,196 and Z = 164, N =318) are shown as dark hatched areas.

2. Cold Valleys in the Potential

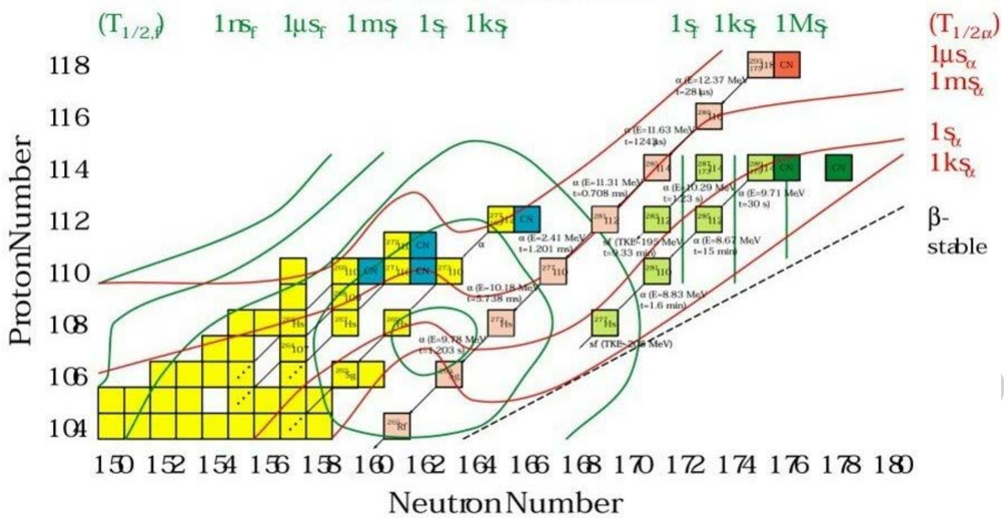

Figure 2: The Z = 106 – 112 isotopes were fused by the Hofmann-Münzenberg (GSI)-group. The two Z = 114 isotopes were produced by the Dubna-Livermore group. It is claimed that three neutrons are evaporated. Obviously the lifetimes of the various decay products are rather long (because they are closer to the stable valley), in crude agreement with early predictions and in excellent agreement with the recent calculations of the Sobicevsky-group.

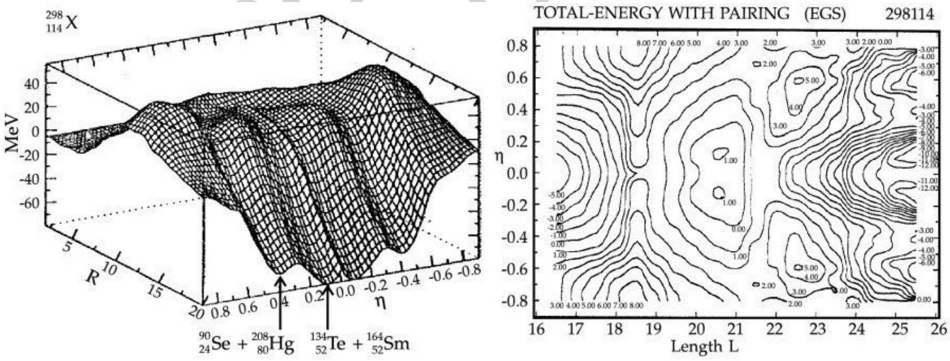

Figure 3: The collective potential energy surface of $^{264}108$ and $^{184}114$, calculated within the two center shell model by J. Maruhn et al., shows clearly the cold valleys which reach up to the barrier and beyond. Here R is the distance between the fragments and $\eta = \frac{A_1 - A_2}{A_1 + A_2}$ 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 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 1970s that the Frankfurt school of theoretical physics together with foreign guests (R.K. Gupta (India), A. Sandulescu (Romania)) 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. The two-center shell model, which is essential for the description of fission, fusion and nuclear molecules, was developed in 1969-1972 by W. Greiner and his students U.Mosel and J. Maruhn. 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. 3). 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 neighboring projectile-target combinations). In this way the correct projectile- and target-combinations for fusion were predicted. Indeed, Gottfried Münzenberg and Sigurd Hoffmann and their group at GSI 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 example before the last of this success, the discovery of element 112 and its long α-decay chain, is shown in Fig.4. Very recently the Dubna-Livermore-group produced two isotopes of Z = 114 element by bombarding $^{244}\mathrm{Pu}$ with $^{48}\mathrm{Ca}$ (Fig. 2). Also this is 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. There exist also cold valleys for which both fragments are deformed, but these have yet not been verified experimentally. The very recently reported Z = 118 isotope fused with the cold valley reaction $^{58}\mathrm{Kr}+^{208}\mathrm{Pb}$ by Ninov et al. yields the latest support of the cold valley idea.

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 (see Fig. 5). Additionally, there is a strong dependency on the parameter set and the model. Some forces hardly show any shell structure, while others predict the magic numbers Z = 114, 120, 126. Using the heaviest known gg-nucleus Hassium $^{264}_{154}108$ as a criterion to find the best parameter sets in each model, it turns out that PL-40 and SkI4 produce best its binding energy. These two forces though 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. Deformed calculations within two models reveal again different predictions. Though both parameterizations predict N=162 as the deformed neutron shell closure, the deformed proton shell closures are Z=108 (SkI4) and Z=104 (PL-40) (see Fig6). Calculations of the potential energy surfaces show single humped barriers, their heights and widths strongly depending on the predicted magic number. Furtheron, recent investigations in a chirally symmetric mean-field theory (see also below) result also in the predictions of these two magic numbers. 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 (Fig.7). 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 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 calculations of the orbitals of the outer (valence) electrons – has been carried out as early as 1970 by B. Fricke and W. Greiner. Hartree-Fock-Dirac calculations yield rather precise results.

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Biographical Sketches

Walter Greiner, was born October 1935. He received PhD. in 1961 from the University of Freiburg/ Brsg (Germany). During 1962-1964 he was Assistant Professor at the University of Maryland. Since 1964 he is C4-Professor in Theoretical Physics at the University of Frankfurt am Main (Germany) and Director of the Institut until 1996. He was a visiting professor at the Univ. of Florida State, Los Alamos Scientific Laboratory, Univ. of California, Berkeley, Oak Ridge National Laboratory, Univ. of Melbourne, Yale Univ., Vanderbilt Univ., Univ. of Arizona and more. His main activities are in Theoretical Nuclear Physics and Heavy Ion Physics, Field theory (Quantumelectrodynamics, Theory of Gravitation), Atomic Physics. Professor Greiner received in 1974 the Max-Born-Price and the Max-Born-Medal (Institute of Physics in London and Deutsche Physikalische Gesellschaft), 1982 the Otto-Hahn-Prize of the City of Frankfurt and the Dr. Honoris causa of the University of Witwatersrand (Johannesburg, South Africa). Since 1989 he is a Distinguished Member of the Lorand-Eötvös-Society (Hungary), since 1990 honorary professor at the University of Beijing (China), in 1991 he received Dr. Honoris causa of the University of Tel. Aviv (Israel) and of the University of Strasbourg (France), in 1992 Dr. honoris causa of the University of Bukarest and since 1993 he is a Distinguished Member of the Rumanian Academy of Sciences.

Joachim A. Maruhn, was born on May 15, 1945 in Frankfurt an Main (Germany). He received PhD. In 1973 from Frankfurt. During 1974-1977 he was a Research Associate and then Staff Scientist at the Oak Ridge National Laboratory (Tennessee, USA). Since 1977 he is Professor in Theoretical Physics at the University of Frankfurt. He held visiting professor positions at the Vanderbilt University (Nashville, USA) and the Michigan State University (Lansing, USA). Professor Maruhn’s main activities are: Theoretical Nuclear Physics and heavy Ion Physics, Theory of Fusion through Inertia (hydrodynamics and radiative transport), Computational Physics.

Thomas Bürvenich ,was born march 20 1973 in Langen (Hessen), Germany. He was a PhD student at the University of Frankfurt and defended by thesis march 2002. Since October 2002 he is a postdoctoral research associate in the Theoretical Division at Los Alamos National Laboratory. His field of research is theoretical nuclear physics, especially with relativistic mean-field models