# Superheavy nuclei and pion condensation

V. A. Karnaukhov and S. M. Polikanov

*Joint Institute for Nuclear Research*

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The conclusions of the theory of pion condensation are analyzed for a set of parameters that makes possible the existence of superdense nuclei with a larger binding energy than in the normal state, and in a wide range of mass numbers. (It is noted that the properties of superheavy nuclei in the superdense and normal states differ substantially, and that this difference must be taken into account in the experimental searches).

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1. In recent years, A. B. Migdal and co-workers have developed the theory of pion condensation in atomic nuclei (see, e.g., [1]; a survey of work on pion condensation is given in[2]). In accordance with this theory, nuclear matter, starting with a certain density $n_c$, becomes unstable to pion production. The result is a phase transition to a state with a pion condensate. The energy gain connected with the $\pi$ condensate can lead to the appearance of an anomalous bound state at a larger density $n_c$ (superdense nucleus). The theory makes no definite predictions with respect to the binding energy of the nucleus in this state: the calculation is extremely sensitive to the parameters, but these are not known as yet with sufficient accuracy. It is not excluded, however, that a superdense nucleus can have a much higher binding energy per nucleon ($\epsilon_s$) than the normal energy ($\epsilon_0$). This is precisely the case we consider here.

2. Let us dwell on the assumed properties of superdense nuclei:

a) the condition of $\beta$-stability of superdense nuclei corresponds to $\nu = Z/A \simeq 1/2$, where $Z$ is the charge and $A$ is the baryon number of the nucleus. More accurately, $\nu = (1/2)(1 - 3\times 10^{-3}A^{2/3})$ at $n_s = 5n_0$.[1] The $\beta$-stability line for medium and heavy superdense nuclei passes through $Z$ and $A$, which correspond to neutron-deficient "ordinary" isotopes.

b) The $\beta$-decay energy of radioactive superdense nuclei, at a given distance from the stability line, is approximately four times larger than for ordinary nuclei (at $n_s = 5n_0$).[1] If we disregard the possible difference between the matrix elements of the $\beta$ decay, then this corresponds to lifetimes that are shorter by a factor of approximately $10^3$.

c) The question of $\alpha$ decay of superdense nuclei has not been investigated.

In the case when $\epsilon_s$ greatly exceeds $\epsilon_0$, the $\alpha$ decay of anomalous isotopes will be energywise hindered, at least near the $\beta$-stability line.

d) Spontaneous fission is strongly hindered. According to the estimate by Migdal *et al.*[1]

$$\left(\frac{Z^2}{A}\right)_{\text{cr}} \approx 50\,\frac{\epsilon_s(\nu)}{\epsilon_0(\nu)}\ .$$

If $\epsilon_s$ greatly exceeds $\epsilon_0$, then the barrier for spontaneous fission of superdense nuclei is much higher than for a "normal" nucleus with the same value of $\nu$. Thus, the most important method of superdense-nucleus decay near the $\beta$-stability corridor is $\beta$ decay.

e) By virtue of the difference between $\epsilon_s$ and $\epsilon_0$, the mass defects of superdense nuclei can differ substantially from those for the "normal" nuclei. This can be used for mass separation of the superdense nuclei from the normal isotopes.[3,4] In the normal mass scale, the superdense nuclei can manifest themselves as isotopes with essentially non-integer values of $A$.

3. It is indicated in[1] that the possible range of stable superdense nuclei extends from $A \approx 200\ \epsilon_s/\epsilon_0$, i. e., at $\epsilon_s > \epsilon_0$ it includes the far transuranium elements. The conditions for the existence of stable superdense superheavy nuclei are entirely different than those for "ordinary" superheavy nuclei, where the stability is determined entirely by shell effects. Long-lived ("ordinary") superdense isotopes should be concentrated only near magic nuclei in the form of "islands," whose dimensions are determined by the "strength" of the shell. Superheavy superdense nuclei can occupy a much wider range of $Z$, and can exist where there are no "ordinary" superheavy nuclei. Taking this circumstance into account, in experimental searches for superheavy nuclei it is necessary to bear in mind the properties of the superdense modification of nuclei, mentioned in Sec. 2. In light of Sec. 2, particular interest attaches to search methods that are applicable to stable isotopes, namely $x$-fluorescence,[5] mass separation followed by activation analysis,[6] and laser fluorescence.[7]

4. In connection with all the foregoing, we make a remark concerning the work by Gentry *et al.*[5] and Stephan *et al.*[6] The former used the method of spectroscopy of proton-induced characteristic x rays to observe traces of element 126 in giant halos in mica found on Madagascar. Stephan *et al.*,[6] to verify this observation, carried out mass separation of approximately 2 grams of Madagascar monazite, the mineral of which the central part of the halo is made up. Neutron bombardment of the quartz collector of the mass separator yielded the mass spectrum of the separation products undergoing induced fission, in the range $A = 290$—$360$. It was thus demonstrated that the peaks expected for the elements 124—127 on the basis of different variants of the shell model do not exist, and it was concluded that the results of[5] are in error. We wish to call attention, however, to the presence in the mass spectrum of two statistically reliable peaks, which were not analyzed by the authors, namely approximately at the mass numbers 299.5 and 308.5. It is important to investigate the possible background causes for the appearance of these peaks. If it will be shown that they are not of background origin, then it becomes necessary to consider as an alternate explanation the hypothesis of superdense far-transuranium elements (we note that according to the formula given in Sec. 2(a), a stable isotope of element 126 corresponds to $A \approx 290$).

5. We consider now the question of artificially obtaining superdense superheavy elements. According to calculations by Migdal *et al.*,[1] carried out for nuclear matter, the region of negative pressures is reached at a density $n \approx 2n_0$. In real nuclei, the critical density depends apparently on $A$. A theoretical analysis shows that the dependence of $n_C$ on $A$ is quite weak.[8] At the same time, estimates carried out in[9] admits of a possible substantial decrease of

the critical density for heavy nuclei. In this case, the path to superdense nuclei via superheavy nuclei may turn out to be more accessible.

To attain double the density in the interaction of heavy ions, the energy nucleon must exceed the Fermi energy.[9] After the composite system goes through the critical point and the phase transition takes place, an excitation energy $E^* \approx E_k + (\epsilon_s - \epsilon_0)A$ is released, where $E_k$ is the kinetic energy of the interacting nuclei in the c. m. s. and $A$ is the total number of nucleons. If the difference $\epsilon_s - \epsilon_0$ is appreciable, the excitation energy becomes comparable with the binding energy of the nucleus (or may even exceed it). The decay of such a composite nucleus can have an "explosive" character with a large number of emitted nucleons and with formation of (superdense) fragments that are much lighter than the initial compound nucleus. Thus, in order to obtain a superdense nucleus of a fragment, the compound nucleus must have an appreciable excess of $A$, and this can be attained in the interaction of two heavy nuclei, say $^{238}U + ^{238}U$. Methods for the registration of superdense nuclei should take into account their unusual properties.

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