ON THE PROBLEM OF SYNTHEZIS OF SUPERHEAVY NUCLEI. A SHORT HISTORICAL REVIEW ON FIRST THEORETICAL PREDICTIONS AND NEW EXPERIMENTAL REALITY.

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In connection with successful synthesis of a superheavy nucleus with charge $\mathbf{Z = 114}$ and mass number $\mathbf{A = 288, 289}$ performed in Dubna [1] (see review paper [2]) it makes sense to recall theoretical studies in which for the first time it has been predicted.

The problem is closely related to the experimental fact: nuclei with $\mathbf{Z = 8,20,28,50,82}$ (for neutrons also $\mathbf{N = 126}$) are most stable to different decay modes. This phenomenon can be interpreted in the framework of the shell model [3] according to which the "magic" occupation numbers are those of one-particle levels in nuclei after which a considerable energy gap arises in the spectrum, and the binding energy gets maximal. Consequently, a theoretical prediction of the existence of superheavy nuclei beyond the periodic table should at least be based on calculations of one-particle proton and neutron spectra aimed at finding noticeable energy gaps in them.

To the mid sixties when this problem arose, it became clear that the widely used oscillator potential (the Nilsson scheme) is not valid for that purpose. Perhaps, the only merit of it is that the wave functions of one-particle states are rather simple. Physically, its essential drawback is that the potential approaches to infinity near the surface of a nucleus. As a result, the wave functions of one-particle spectrum exhibit a wrong behavior on the surface and periphery of a nucleus, i.e. in the region that essentially contributes to the probabilities of radiative transitions (the transition operator $\mathbf{r^{\lambda} Y_{\lambda\mu}(\theta,\varphi)}$, $\lambda = \mathbf{1,2,3,\ldots}$), elastic and inelastic scattering and to those of other reactions. These computations are by an order of magnitude larger or smaller than computations based on "correct" wave functions. A serious drawback of that scheme is a necessary change of parameters of the potential and spin-orbital interaction when passing to a higher shell. Therefore, no wonder that computations of the spectrum of heavy nuclei based on the extrapolation of those parameters to remote distances produced different magic values for $\mathbf{Z}$ and $\mathbf{N}$. For example, Nilsson et all [4] obtained $\mathbf{Z = 126}$ and $\mathbf{N = 164, 184}$. Obviously a scheme of that sort cannot be considered reliable, especially, for predictions.

A reasonable solution of the problem may be based on a realistic finite diffuse potential $\mathbf{V_N(r)}$ as a mean nuclear field and on the justified form of the spin-orbital interaction [6,7]:

$$\mathbf{V_{SO}} = \kappa(\vec{\mathbf{l}} \cdot \vec{\mathbf{S}}) \frac{\mathbf{1}}{\mathbf{r}} \frac{\mathbf{dV_N}}{\mathbf{dr}}, \tag{1}$$

and also with the charge distributed over a nucleus. The most apt form of that potential

$$\mathbf{V_N(r)} = -\mathbf{V_0}\left(\mathbf{1} + \exp\left(\frac{\mathbf{r - R_0}}{\mathbf{a}}\right)\right)^{-1}, \quad \mathbf{R_0 = r_0 A^{1/3}}, \tag{2}$$

was proposed by Saxon and Woods [8].

In paper [9] *(Kalinkin B.N., Grabovskii Ya., Gareev F.A. "On levels of mean field of nuclei", JINR preprint* ***P-2682****, 1966, the paper was submitted to publication in Acta Physica Polonica on April 6, 1966 and accepted on May 23, 1966)* we employed just this potential with parameters $\mathbf{V_0, r_0, a}, \kappa$ fixed from the data on low-lying levels of near-magic nuclei, on reactions of one-nucleon transfers, elastic, inelastic scattering, and on polarization effects [10-13]. We developed an original method for numerical solution of the Schroedinger equation with that potential and demonstrated its high accuracy.

On June 16, 1966 we submitted for publication as a JINR preprint **P-2793, 1966** and an article in the Phys.Lett. [5]: *A. Sobiczewski, F.A. Gareev, B.N. Kalinkin, "Closed shells for* $\mathbf{Z > 82}$ *and* $\mathbf{N > 126}$ *in a diffuse potential well", Phys. Lett. V.22, No 4(1966)500, received 22 July 1966, published 1 September 1966.*

In this paper, based on the method elaborated in [9], we calculated the proton and neutron energy levels versus A for $\mathbf{Z > 82}$ and $\mathbf{N > 126}$ for the Saxon-Woods potential with spin-orbital interaction. The results show that possible magic numbers are $\mathbf{Z = 114}$ and $\mathbf{N = 184}$. The computations were carried out with the parameters taken from ref. [8]. The solution turned out to be stable to variations of the parameters of the potential and spin-orbital interaction caused by a possible inaccuracy in their definition. No energy gap was observed in the system of levels around $\mathbf{Z = 126}$.

This paper has been the first publication in the available journals giving a clear statement on possible existence of a superheavy nucleus with $\mathbf{Z = 114}$; it presents both the method of solution and demonstrates the stability of the latter within the framework of a realistic potential with justified values of parameters.

The importance of use of justified values of parameters for $\mathbf{V_N(r)}$ and $\mathbf{V_{SO}(r)}$ obtained from the analysis of the data on low-lying levels of near-magic nuclei, on reactions of one-nucleon transfers, elastic, inelastic scattering, and on polarization effects [10-13] demonstrated by the results of [14]. The parameter $\mathbf{a}$ in the potential $\mathbf{V_N(r)}$ [14] has been used unjustified large magnitude (see for details [14]) which changed strongly spectrum of nuclei and lead to the magic number $\mathbf{Z = 126}$.

The JINR preprint **P-2793** was then distributed by N.I. Pyatov among participants of the Int. Symposium on Why and how should we investigate NUCLIDES FAR FROM THE STABILITY LINE, Lysekil, Sweden, August 21-27, 1966, where the considered problem was of common interest (Session IX: Nucleosynthesis; Chairman: W.J. Swiatecki).

In the report [15] by H. Meldner: *"Predictions of new magic regions and masses for superheavy nuclei from calculations with realistic shell model single particle hamiltonians", Proc. of the Intern. Lyseki Symposium, Sweden, August 21-27, 1966. Received 14 September 1966, published 18 October 1967, Ark. Fys. **36**(1967)593.*

H. Meldner informed that new magic numbers should be $\mathbf{Z = 114}$ and $\mathbf{N = 184}$ and at the end made the comment: *"Note added in proof. In the meantime the proton shell $\mathbf{Z = 114}$ has been found in independent investigations [13]"*. Reference [13] of that report is [13] Nilsson S.G., private communications, Strutinsky V.M., private communications, Sobiczewski A., Gareev F.A., Kalinkin B.N. (preprint).

So, when H. Meldner submitted his report on September 14, 1966, he already had our preprint. We consider also that our studies and studies by H. Meldner were carried out independently. However, we do not agree with G. Herrmann, the author of recent paper [16], from which it may be concluded that it was just H. Meldner who first predicted magic numbers $\mathbf{Z = 114}$ and $\mathbf{N = 184}$. Let us discuss this question in greater detail.

In [15], p. 595, H. Meldner reported:

*The same result was obtained in simpler calculations with local potentials two years ago [9] (in [9] see discussion on superheavy nuclei in W.D. Myers and W.J. Swiatecki, Nucl. Phys. **81**,1 (1966); or UCRL-11980(1965), based on calculations quoted there under ref. [23]).*

In paper by W.D. Myers and W.J. Swiatecki, Nucl. Phys. **81**,1 (1966), ref. [23] looks as follows:

[23] H. Meldner and P. Roper (Institut fur Theoretische Physik der Universitat Frankfurt/M.), personal communication (1965).

We quote a brief fragment from that paper (pp. 49, 50): *"In our mass formula we have included, for purposes of illustration, magic numbers at $\mathbf{Z = 126}$ and $\mathbf{N = 184, 258}$, see fig 19.(the latter numbers are obtained by following the sequence of major shells in harmonic oscillator potential with spin-orbit coupling). We do not wish to imply that there are grounds for believing that any of these magic numbers would show up in practice, and we use them only to illustrate that some of the consequences would be if a magic number turned out to be present in the general neighborhood of superheavy nuclei somewhat beyond the end of the periodic table. The actual values of the magic numbers might be different; for example, we have recently learned [23] that $\mathbf{Z = 114}$ $\mathbf{N = 184}$ is a* *possible candidate for a doubly magic nucleus... What we wish to point out is that if a (double) magic number exists, then an important consideration affecting the possible stability of the corresponding nucleus is the considerable increase in the barrier against fission and, consequently, in the spontaneous fission half-life.*

... In order to proceed in a realistic manner with discussion of the existence and location of possible islands of stability beyond the periodic table the first requirement is the availability of estimates for the location and strength of magic number effects in that region. When such estimates have become available (through single-particle calculations in realistic nuclear potentials) it will be possible to apply our semi-empirical treatment of nuclear masses and deformations to the predictions of the fission barriers of hypothetical superheavy nuclei..."

From the above quotations it follows that:

- First, W.D. Myers and W.J. Swiatecki in their calculations used the values of magic numbers obtained by other authors with the use of harmonic potential. Estimates on the basis of realistic potentials were not available for them at that time.
- Second, they obtained information on a possible realization of the double magic nucleus with $\mathbf{Z = 114}$, $\mathbf{N = 184}$ from a personal communication of H. Meldner and P. Roper who did not published them anywhere, which is verified by the absence of any reference to that work in the report [15].

It is obvious that personal communications cannot be reason of the priority. The priority requires official publications of results with the method they have been obtained, accuracy, and stability of the solution permitting verification of the results by any physicist.

It remains to declare that the report by H. Meldner [15] is his first official communication on possible existence of the nucleus with $\mathbf{Z = 114}$.

The following two reports are also devoted to realization of superheavy nuclei.

In the report [17]:

*C. Gustafson, I.L. Lamm, B. Nilsson, S.G. Nilsson, "Nuclear deformations in the rare-earth and actinide regions with excursions off the stability line and into the superheavy elements", Received 14 September 1966, published in Ark. Fys. **36**(1967)613* it is stated that *as a by-product of these computations it appears reasonable to forecast that the "magic" proton candidate is* $\mathbf{Z = 114}$ *and not* $\mathbf{Z = 126}$ *while for neutrons* $\mathbf{N = 184}$ *is a rather questionable "magic" number. These predictions remain valid also when a reasonable extrapolation is made in the values* μ *and* ξ *(Fig. 5, cf. ref. [8]) [8] Sobiczewski, Gareev and Kalinkin, to appear in Nucl. Phys.*

In the report [18]:

*V.M. Strutinsky, "Microscopic calculations of the nucleon shell effects in the deformation energy of nuclei", received 14 September 1966, published in Ark. Fys. **36**(1967)629.*

The behavior of deformation energy is studied for some heavy and superheavy nuclei with consideration for shell effects. Use is made for the "Nilsson scheme" (a traditional version). The most stable nucleus has been that with $\mathbf{126^{310}}$. Possible realization of a nucleus with $\mathbf{Z = 114}$ is not discussed.

Next "burst" of the activity in discussing the existence of superheavy nuclei took place at the International conference on the physics of heavy nuclei held at Dubna on October 13-19, 1966. There two reports were delivered [19,20]:

V.M. Strutinskii and Yu.A. Muzychka "Some shell effects in transuranium nuclei",

A.M. Friedman, "Calculations on the production of the next closed shell nucleus and other nuclei".

Based on a realistic potential, the authors conclude that $\mathbf{Z = 114}$ and $\mathbf{N = 184}$ are the most pronounced magic numbers in the region of superheavy nuclei. Also, both the reports do not refer to our work [5]. Proceedings of that conference were published on October 16, 1967.

Concluding a brief review of studies made in 1966 and devoted to the possibility of existence of a heavy nucleus with $\mathbf{Z = 114}$, we note once more that it has first been predicted in our work [5].

It is also important to recall that our method of solving the problem [5] was later verified by V.A. Chepurnov [21] who reproduced our results by direct numerical solution with a high accuracy. Also, we generalized it to a realistic nuclear field for strongly deformed nuclei [22-29]. Practical application of the generalized method in a lot of investigations on the spectroscopy of the rare-earth and transuranium group carried out at the BLTP, JINR in recent years (see, e.g., monographs [30,31]) has proved its high efficiency. Therefore, we may hope, it could be used for studying superheavy deformed nuclei of the island of stability whose actual synthesis begins just now.

Evidence for the island of stability to exist rather than a single superheavy nucleus, to our mind, comes from the logic of [5] the very fact of synthesis of the nucleus with the magic number of protons $\mathbf{Z = 114}$ and nonmagic number of neutrons $\mathbf{N = 175}$. If so, then stable should be both the doubly magic nucleus with $\mathbf{Z = 114}$ and $\mathbf{N = 184}$ (the island center) and the nucleus with the nonmagic number of protons $\mathbf{Z = 114}$ and magic number of neutrons $\mathbf{N = 184}$. Nuclei with $\mathbf{Z}$ and $\mathbf{N}$ near the above-mentioned combinations should also be stable [32].

So, the theoretical prediction of a superheavy nucleus with $\mathbf{Z = 114}$, formulated for the first time at Dubna [5], that has allowed a goal-directed experimental search has been testified by its actual synthesis also at Dubna many years later.

In conclusion, we note that the synthesis of superheavy nucleus $^{289}\mathbf{114}$ was further developed: new heaviest nuclides $^{288}\mathbf{114}$ and $^{284}\mathbf{112}$ were observed [34]. An attempt of synthesis of the superheavy nuclei was performed in Berkeley [33]. This attempt was commented in [34]:

"The synthesis of $^{293}\mathbf{118}$ *and its sequential* α*-particle emission to the daughter isotopes with* $\mathbf{Z = 116 - 106}$ *in the bombardment of* $^{208}\mathbf{Pb}$ *with* $\mathbf{2.3 \cdot 10^{18}}$ *449-MeV* $^{86}\mathbf{Kr}$ *ions using the Berkeley separator BGS was announced in April-May, 1999. Three decay chains were observed, each consisting of an implanted atom and six subsequent* α*-decays. Another experiment with this reaction was carried out at the same bombarding energy at GSI, in Darmstadt, using the separator SHIP. No correlated* α*-decay chains were observed yet, with a similar beam dose of* $\mathbf{2.9 \cdot 10^{18}}$ **Kr** *ions [35]".* Therefore, the results of analyzing this reaction is to be continued.

Thus, the experimental research of the island of stability for superheavy nuclei was started with a high activity.

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