ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E7-96-434

Yu.Ts.Oganessian

SYNTHESIS AND RADIOACTIVE PROPERTIES OF THE HEAVIEST NUCLEI

Submitted to Proceedings of the International Conference
on Nuclear Physics at the Turn of the Millennium
«Structure of Vacuum and Elementary Matter», Wilderness/George,
South Africa, March 10—16, 1996

1996

Introduction

The problem of synthesizing new elements has a long history.

Based on the few atoms produced in nuclear reactions it was demonstrated that the radioactive properties of heavy nuclei confirm the main prediction of the macro-microscopic theory regarding a huge effect of nuclear shells on the spontaneous fission probability. As a result of the fission barrier emergence, determined by the nuclear structure, partial s.f. half-lives of heavy nuclei turn to be by 12–20 orders of magnitude larger than the values predicted by the classical liquid drop model of nuclei.

As a result of high stability of spontaneous fission, isotopes of heaviest elements undergo α-decay with a half-life $10^{-3} \div 10^{1}$ s.

What was the progress of these investigations and what are the prospects?

1 Nuclear shells and stability of heavy nuclei

Macro-microscopic investigations of the potential energy surface of nuclei at large deformations established that microscopic corrections drastically change the potential energy surface associated with fission [1-5].

Theory explains in general a number of experimental facts, fission barrier heights, shape isomerism in actinoid nuclei, spontaneous fission half-lives ($T_{s.f.}$) of transactinoids, substantial variations in $T_{s.f.}$ in the region $N = 152$, etc., which have not found any explanation in the classical liquid drop models.

Similarly to any other theory it possesses a certain predictive power, in particular for prediction of masses and radioactive properties of yet unknown superheavy nuclei. Such predictions were made in a number of papers. We are presenting here recent data from papers by Patyk, Smolanczuk and Sobiczewski [6-8] where there have been calculated masses and fission barriers as well as partial half-lives T_{α} and $T_{s.f.}$ of even-even nuclei with $Z = 100–114$ and $N = 140–190$.

Figure 1 presents a contour map of shell corrections to energy as a function of proton and neutron numbers. Significant changes in $T_{s.f.}$ of nuclei far from the $N = 152$ shell are determined to a great extent by another shell with $N = 162$. It should be noted that both neutron shells are referred to deformed nuclei in contrast to double magic nuclei such as ^{208}Pb ($Z = 82$, $N = 126$) possessing a spherical shape in the ground state. The maximum stabilization against spontaneous fission is expected for the nucleus $^{270}108$ ($Z = 108$, $N = 162$) for which the predicted $T_{s.f.}$ may reach 10^4–10^9 s.

On the other hand, in the region of heavier nuclei, in the vicinity of the above-mentioned deformed shells, one finds closed spherical shells $Z \approx 114$ and $N = 180$–184. A larger amplitude of shell corrections for spherical superheavy nuclei leads to as large (if not even larger) restrictions for the spontaneous fission.

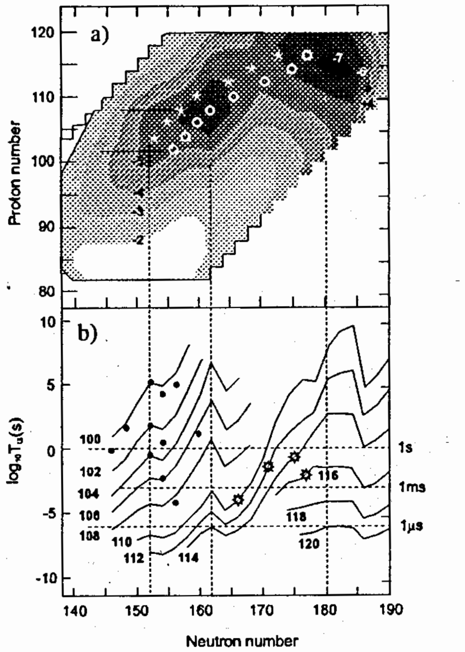

Figure 1. a) Contour map of the shell corrections to energy. Stars and cycles denote the heaviest nuclides produced in cold and hot fusion reactions, correspondingly.
b) Calculated α-decay half-lives (T_α). Black points – experimental data. Stars – T_α predicted for heaviest even-even isotopes of the elements 110, 112, 114 and 116 produced in hot fusion reactions with ^{48}Ca projectiles.

Upon the whole, such a non-trivial situation may lead to interesting consequences.

If one excludes spontaneous fission, than nuclei near the closed shells will undergo alpha and beta decays. The probabilities of these decays and, consequently, the half-life of superheavy nuclei will be determined by the masses of nuclei in their ground state. The latter may be calculated with the nuclear mass formula with the accuracy prevailing now at the description and extrapolation of nuclei masses on the basis of spectroscopic data.

It follows from calculations [8] that for a nucleus of $^{268}106$ ($N = 162$) T_α is equal to several hours (according to estimations by P.Moeller – several days) and for a nucleus of $^{298}114$ this value grows to several hundred years, possibly, thousands years! Really, we are talking here about very stable and very heavy nuclei. In case this is true, the nuclear structure expands significantly the limits of the Periodic

Table of Elements. This opens unique opportunities in neighboring sciences - atomic physics, inorganic chemistry which have a large experimental and theoretical basis.

Coming back to the issue of the spontaneous fission of superheavy nuclei, it is necessary to note the following circumstance.

The calculation of spontaneous fission half-life $T_{s.f.}$ in the dynamical way consists in the search for one-dimensional fission trajectory in a multi-dimensional deformation space, which minimizes the action integral corresponding to the penetration of the fission barrier. Although the calculated static barrier heights are about equal, differences in half-life estimates can be attributed to varying assumptions regarding the dynamical path through the fission and the consequent inertial mass.

In other words the complex structure of the potential surface and the variation of the inertial mass in the process of deformation may lead to different fission modes which are significantly different in time and, consequently, in their fission probability. Moreover, one and the same nucleus may have simultaneously two fission modes which was observed experimentally for heavy isotopes of actinide elements [9].

This situation becomes especially critical for the region of nuclei near deformed shells $Z = 108$ and $N = 162$. For example, Moeller et al. [10], taking ^{258}Fm as model for heavier nuclei. Assume that the path after the first barrier is short with the emerging fragments being nearly spherical and close to the doubly magic ^{132}Sn. On the other hand, Patyk et al. [6-7] calculate dynamical barriers that show a different path, higher inertial mass, and consequently much longer *SF* half-lives. This competition between static and dynamical features of the *SF* process which leads to so large differences in stability makes experiments that explore ground-state decay properties of nuclei around $N = 162$ and $Z = 108$ one of the most important tasks in heavy element research.

2 Reactions of synthesis

It is known, that the heaviest elements were synthesized in cold fusion reactions $^{208}Pb(HI,n)$. It has been experimentally observed that heavy ions with $A_I > 40$ undergo fusion with magic nuclei of ^{208}Pb deep in the subbarrier region, which lead to the formation of a compound nucleus with an excitation energy of 10–15 MeV. At such a small excitation the nuclear shell effects disappear, although not completely, which gives a certain stability to the system with respect to fission. The transition into the ground state occurs by emission of just one or two neutrons and γ rays [11,12].

The mechanism of such a process is not yet fully clear. This is evident, for example, in figure 2.

The process of ^{208}Pb nuclei fusion with ions of ^{16}O [13,14] and much heavier ions of ^{50}Ti, ^{58}Fe [15] or ^{64}Ni [16] falls under the general regularity of nuclei interaction at large distances. Despite a substantial growth of the Coulomb forces (from ^{16}O to ^{64}Ni the Coulomb energy grows nearly threefold) the threshold of the fusion reaction remains unchanged. This contradicts with numerous theoretical models of "extra-push" or "extra-extra-push" type in which the dynamic restrictions increase substantially the energy threshold of the fusion reaction [17-19].

At the same time, the decay of ^{224}Th can be satisfactorily described in the frame of statistical models but this cannot be achieved for heaviest compound nuclei.

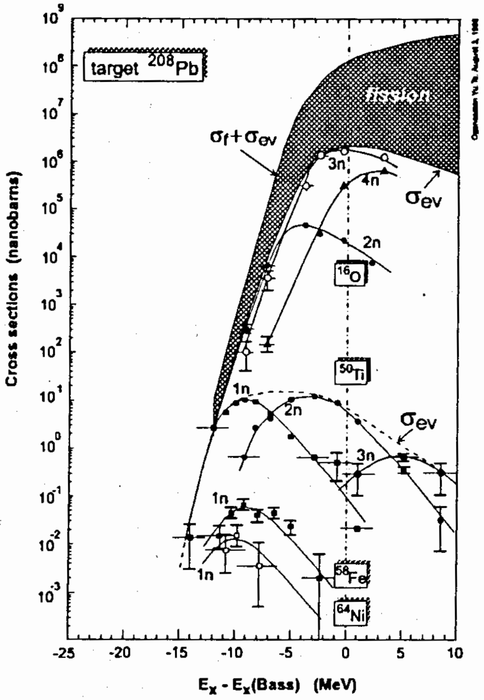

Figure 2. Cross sections σ_{xn} and $\sigma_{xn}+\sigma_f$ in the reaction $^{208}Pb + {}^{16}O$. In the bottom part of the figure one can see the cross sections σ_{xn} in the reactions $^{208}Pb + {}^{50}Ti$, ^{58}Fe and ^{64}Ni. The energy scale is presented as a difference $E_x - E_x$ (B_{Bass}). Solid lines are drawn through experimental points.

It is possible that in the cold-fusion reactions *(HI,n)* the emission of a neutron takes place at the stage of nuclear fusion and final compound nucleus decays further-on according to the laws of statistics.

We hope that the coming joint experiment FLNR-GSI studying the reaction $^{86}Kr + {}^{136}Xe \rightarrow {}^{222}Th$ together with our earlier data on the measurements of $\sigma_{EVR}(E_x)$ and $\sigma_f(E_x)$ in the reaction $^{208}Pb + {}^{16}O$ as well as the data on the mass and energy distribution of fission fragments $^{222-226}Th$ [20] will make the picture clearer.

The cross section of the cold fusion reaction for the heaviest elements is equal to only several pb which raises serious requirements to the luminosity of the experiment. The use of the ^{208}Pb target imposes a restriction on the value $(N-Z) \leq 48$ for $Z \leq 108$ which is somewhat away from the top of the predicted island of stability of the deformed shell $Z = 158$, $N = 162$.

In principle a significant growth in the number of neutrons in evaporation residues *(EVRs)* up to $N-Z = 54$ can be obtained in fusion reactions between heavy

actinide nuclei of the ^{244}Pu, ^{248}Cm type and projectiles such as ^{18}O, ^{22}Ne, ^{26}Mg. But in these reactions the excitation energy of the compound nucleus even at the Coulomb barrier is about 40 MeV (hot fusion).

Structural effects practically disappear at such a high excitation energy; their fission barrier is determined only by the macroscopic (liquid drop) component of the nucleus deformation energy $B_f \approx B_f(LD)$. It is well known that for transactinide nuclei $B_f(LD)$ is practically equal to zero. In the absence of a fission barrier the excited nucleus becomes totally unstable to fission which should lead to a strong decrease in the probability of its transition to the ground state via cascade evaporation of neutrons ($x \geq 4$). Under these conditions the survival of *EVRs* totally depends on the dynamic properties of the excited compound nucleus.

Investigation of excited nuclei fission dynamics by measuring the characteristics of pre-fission emission of gamma-quanta, neutrons and light charged particles was performed in numerous papers (see for example the overviews by Newton [21], Hilcher and Rossner [22].

We are most interested here in the region of heavy nuclei: $B_f(LD) \rightarrow 0$ with $E_x \approx$ 40–50 MeV and we are presenting here the experimental data obtained in collaboration with HMI (Berlin) for excited nuclei of *Cf–Fm* ($B_{LD} \approx$ 1.5-MeV) [23,24].

As is seen in figure 3a the contribution of pre-fission neutrons increases with the increase in excitation energy. The probability of pre-fission neutron emission can be calculated for the whole time interval of nucleus existence up to the moment of its splitting into two fragments. This time can be chosen as a parameter to obtain the best agreement with the experimental dependence $\nu_{pre}(E_x)$. For *Cf* nuclei $\tau_f \sim 3.5 \times 10^{-20}$ s.

Such experiments are used to measure the total number of neutrons emitted prior to reaching the scission point (pre-scission neutrons). A part of them had been emitted before the moment the nucleus reached the saddle point (pre-saddle neutrons). The number of pre-saddle neutrons can be defined from the excitation functions of the reaction $\sigma_{xn}(E_x)$ which determine the ratio of the widths Γ_n/Γ_f on each stage of compound nucleus deexcitation.

The values $\Gamma_n/\Gamma_{tot}(E_x)$ for nuclei with Z = 98 presented in figure 3b and cited from the data of

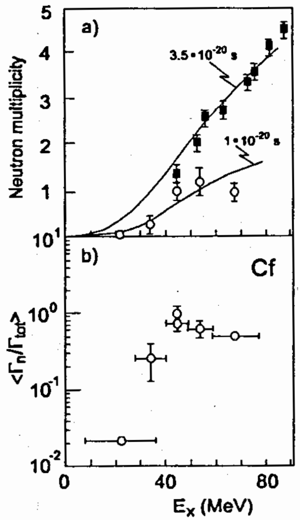

Figure 3. a) The number of pre-fission neutrons vs the excitation energy of ^{250}Cf nuclei. Black points: data of direct measurements of neutrons preceding the scission point (pre-scission neutrons). Open circles – pre-saddle neutrons obtained from the excitation functions of the *xn*-reactions;
b) Γ_n/Γ_{tot} *vs* E_x for ^{250}Cf.

Sikkeland et al. [25] testify to the fact that at $E_x \geq 40$ MeV the fission and neutron evaporation probabilities are comparable.

Note that for ^{250}Cf (E_x = 80 MeV) approximately 1/3 of the neutrons is emitted before reaching the saddle point.

At such a slow progress of deformation in the fission channel (viscous regime) even the heaviest nuclei with $B_{LD} \approx 0$ will have a finite probability of transition to the ground state through evaporation of neutrons. Quantitative data can be obtained only in direct experimental measurements of the evaporation residues formation cross sections for the heaviest excited nuclei.

The cross sections of the evaporation products formation in hot fusion reactions *(HI,5n)* for Z = 102–105 obtained in studies by Andreev et al., [26,27], new results obtained by Lazarev et al. [28,31] for nuclei with $Z \geq 104$ are presented in figure 4. The same figure presents as well the results obtained by Hoffman et al. [15,16,32] for nuclei with Z = 104–112 in cold fusion reactions (E_x = 10÷15 MeV). As is evident from figure 4 the cross sections of $\sigma(HI,n)$ and $\sigma(HI,5n)$ for compound nuclei with $E_x \sim$ 10 MeV (cold fusion) and E_x = 50 MeV (hot fusion) for the heaviest nuclei differ by approximately one order of magnitude in favour of the cold fusion reaction. This circumstance seems to be of importance in the problem of synthesizing heavier nuclei near the spherical shell Z = 114, N = 180–184.

The synthesis of nuclei with Z = 114–116 in cold fusion reactions using a ^{208}Pb target necessitates the increase of the ion mass to ^{76}Ge or ^{82}Se. The final products of the reaction *(HI,n)* will be isotopes of $^{283}114$ (N = 169) and $^{289}116$ (N = 173) located between the deformed and spherical shells. Note, that for the reaction $^{208}Pb(^{82}Se,n)^{289}116$ in the GSI experiments there was obtained the upper limit of the $\sigma_n \leq 5$ pb cross section [33].

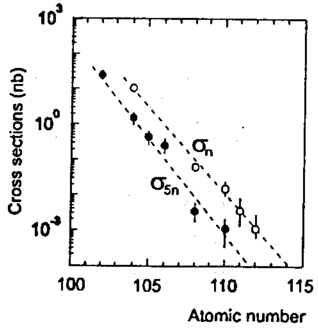

Figure 4. Cross sections of the reactions σ_n ($E_x \sim$ 10–15 MeV) – cold fusion and σ_{5n} (E_x = 50 MeV) – hot fusion depending on Z of the compound nucleus.

One can assume that at the synthesis of neutron-rich superheavy nuclei certain advantages can be attained in hot fusion reactions of the type ^{244}Pu, $^{248}Cm + {}^{48}Ca$.

Because of a large excess of neutrons in the nucleus of ^{48}Ca the excitation energy of the compound nucleus at the Coulomb barrier is equal to $E_x^{min} = B + Q \approx 35$ MeV. The most probable channels of the reaction *(^{48}Ca,xn)* corresponds to x = 3–4, which leads to the production of *EVR* with Z = 114, 116, N = 174,175 and N = 176, 177, respectively. The cross section of the reactions even at $E_i - B_c > 0$ can be larger than the one observed at the synthesis of isotopes of elements *108* and *110* in the reactions ^{238}U or $^{244}Pu(^{34}S,5n)$ at E_x = 50 MeV.

The cross sections of the production of nuclei with Z = 114 calculated by Y.Abe et al. [34] on stochastic approaches of nuclear dynamics, produce the maximum value of $\sigma_{xn} \sim$ 10 pb at $E_x \sim$ 30 MeV. Other preliminary calculations by B.Pustylnik [35] based on the statistical model and describing the experimental results on the production of *EVR* in hot fusion reactions up to Z = 110, point to a strong dependence of the cross section of *xn* channels on the value of the shell correction energy dependence. They also point to a substantial growth of σ_{xn} in the region of $E_x \sim$ 30 MeV (figure 5).

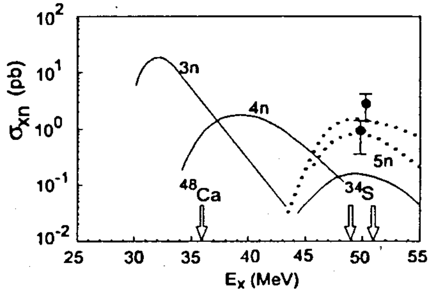

Figure 5. Calculated cross sections $\sigma_{xn}(E_x)$ in the reaction $^{244}Pu + {}^{48}Ca$. Broken curves - calculated cross sections $\sigma_{5n}(E_x)$ in the reactions $^{238}U + {}^{34}S$ and $^{244}Pu + {}^{34}S$. Points – experimental values. Arrows - excitation energy at the Coulomb barrier.

3 Observations of enhanced stability near closed deformed shells

Essentially, this was the underlying idea of a joint JINR (Dubna) – LLNL (Livermore) experiment on synthesis of *106* element heavy isotopes [29].

The ground-state decay properties of $^{266}106$ should be a quite sensitive probe of the theoretical predictions shown in figure 6a. If there is increased stability near N = 162 and Z = 108, the isotope $^{266}106$ should have a *SF*- or α-decay half-life of tens of seconds. Otherwise, $^{266}106$ should decay by *SF* with a half-life of ~100 μs, a $T_{s.f.}$ difference of ~10^5 or more. Thus a distinct signature for enhanced nuclear stability near N = 162 and Z = 108 would be the observation of the α decay of $^{266}106$ followed by the *SF* decay of the daughter nucleus $^{262}104$. A signature for the odd-A isotope $^{265}106$ would be the observation of its decay followed by decays of the known nuclides $^{261}104$ and $^{257}102$.

To produce $^{265}106$ and $^{266}106$ we used the complete fusion reaction $^{248}Cm + {}^{22}Ne$ at bombarding energies which are expected to provide maximum cross sections for the *4n* and *5n* evaporation channels.

In a 360-hour irradiation of the ^{248}Cm target with a ^{22}Ne total ion beam dose of $1.6 \cdot 10^{19}$ produced on the U-400 accelerator (FLNR) by means of the Gas Filled Recoil Separator (GFRS) there have been synthesized two new most neutron-rich isotopes of element *106* with masses 265 and 266.

Both the isotopes $^{265}106$ (N = 159) and $^{266}106$ (N = 160) undergo mostly the α-decay with energies E_α = 8.71 ÷ 8.91 and 8.63 ± 0.05 MeV correspondingly. The energy of α-decay of the even-even nucleus $^{266}106$ (Q_α = 8.76 MeV) determines its half-life T_α = 10–30 s.

Based on the six registered *(α,sf)* correlations to the α-decay of $^{266}106$ nucleus there was also determined the partial spontaneous fission half-life of the daughter nucleus $^{262}104$ (N = 158) $T_{s.f.} = 1.2^{+1.0}_{-0.5}$ s.

Radioactive properties of even-even isotopes of $^{262}104$ and $^{266}106$ give an indication of a substantial growth of heavy nuclei stability to spontaneous fission when approaching the closed shells Z = 108 and N = 162 (figure 6a,b).

The nuclei obtained in this experiment are in the process of an abrupt increase of stability to spontaneous fission like it has been predicted by macro-microscopic calculations by Patyk et al. [6,7]. Another spontaneous fission mode, characterized by a short way of tunneling through the fission barrier [10] and leading to a sharp decrease of $T_{s.f.}$ for $^{266}106$ is prohibited by more than 10^4 times.

The expected significant growth of T_α with the growing number of neutrons makes possible experiments studying the chemical properties of element 106 – *EkaW* [36,37].

Among all possible target-ion combinations leading to the production of a $^{270}108$ nucleus with closed shells Z = 108 and N = 160, the reaction $^{238}U(^{36}S,4n)^{270}108$ seems to be the most promising one.

Investigations of fusion reactions $^{206\text{-}208}Pb(^{34,36}S,2\text{-}4n)$ in the course of which there were synthesized new neutron-deficient isotopes of *Cf* demonstrated high sensitivity and selectivity of the kinematic separator to detection of evaporation residues [38]. Along with that, because of great expenditure for a rare isotope ^{36}S (the natural abundance – 0.015%) by a PIG-type ion source it would be most difficult to carry out such an experiment.

That is why in March–April 1994 experiments in

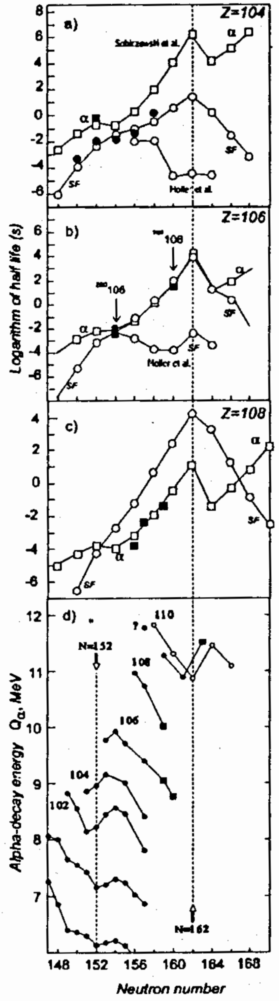

Figure 6. a,b,c) partial half-lives T_α and $T_{s.f.}$ for even-even isotopes with Z = 104, 106 and 108. Solid lines and open points – calculations. Black points – experiment.
d) $Q_\alpha(N,Z)$. Black points – experiment values, open points – calculations for isotopes with Z = 110.

Dubna were using a beam of a more abundant isotope ^{34}S enriched up to 90%.

At the irradiation of a ^{238}U target with a total ^{34}S-beam dose of $1.7\cdot10^{19}$, the position sensitive strip detectors of recoils registered 4*(α-α)* correlation events clearly pointing to the production of a new isotope of element *108* with a mass of 267 (E_α = 9.74–9.88 MeV, $T_\alpha = 19^{+29}_{-7}$ s) [30].

And finally, in September-December of 1995 there were carried out experiments on the synthesis of the heaviest isotope of element *110*. At the irradiation of ^{244}Pu target with ions of ^{34}S with a total doze of $2.5\cdot10^{19}$ there were discovered few events pointing to an α-decay of an odd isotope of $^{269}110$, produced in the reaction $(^{34}S,5n)$ [31].

The calculated and experimental values of partial periods T_α and $T_{s.f.}$ of isotopes of actinide elements Z = 104, 106 and 108 are represented in figure 6 (a,b,c) respectively. Upon the whole, experiments confirm not only qualitatively but also quantitatively the theoretical predictions of the stability of heavy nuclei.

The energy of α decays of heavy isotopes with Z = 104–110 produced in hot fusion reactions and that of lighter isotopes with Z = 104–112 in cold fusion reactions together with the earlier known data on nuclei with $Z \le 104$ are presented in figure 6d. At passing the level of a deformed shell Z = 102, N = 152, like it has been expected, one can observe a leap in the value of Q_α. Quantitatively, at passing the shell N = 152 the change in the decay energy of the two isotopes of element *102* with N = 151 and 153 is equal to $\Delta Q \sim 0.12$ MeV. Note, that this small value plays a large role in the stability of deformed nuclei of transuranium elements.

Analogous effect is observed at passing the shell N = 162 for Z = 110. Here the value $\Delta Q \sim 0.6$ MeV. This is a direct proof of the existence of shell N = 162 predicted by the theory. The shell correction turns to be even larger than the one predicted in calculations [6-8] for this region of nuclei.

Out of the data presented above one can make a number of conclusions.

The masses of the heaviest nuclides, their decay energies and the time of life are in good agreement with the predictions of the macro-microscopic theory, pointing to the significant role of the nuclear structure and first and foremost of nuclear shells for deformed superheavy nuclei.

For the known isotopes with Z = 106–112 the partial half-lives $T_{s.f.} > T_\alpha$. This circumstance is a direct indication to a decisive role of nuclear shells at the formation of the fission barrier and, consequently, in the stability of superheavy nuclei in the conditions when the liquid drop fission barrier $B^f_{LD} = 0$.

Neutron rich isotopes are most illustrative in this respect, since T_α grows sharply with the growth of the neutron number. Note, that these nuclei have been synthesized in hot fusion reactions.

4 Problems of synthesizing superheavy nuclei near closed spherical shells

The main provisions of the theory and the formalism of the calculation of specific properties of nuclei near the deformed shells can be applied to the region of heavier nuclei where a new growth of stability is expected which is due to the effect of spherical shells $Z = 114$, $N = 180–184$ [8].

In which way is it possible to obtain experimental proves of the existence of these superheavy and superstable nuclides?

Unfortunately, no combination of stable isotopes chosen as a target and an ion cannot form a compound nucleus with $Z = 110–114$ and $N = 180–184$.

That is why the essence of the problem is in the way to approach as close as possible the top of stability, i.e., how to produce heavy nuclei with $Z \sim 114$ with a maximum number of neutrons.

It is not difficult to understand that this can be achieved at the maximum excess of neutrons in the fusing nuclei with a minimum loss of neutrons in the process of compound nucleus deexcitation.

Figure 1b demonstrates that out of all possible reactions with extremely neutron rich ions of ^{48}Ca the maximum effect is achieved for nuclei with $Z = 114$ and $N = 174, 175$ produced in the fusion reaction $^{244}Pu(^{48}Ca,3\text{–}4n)^{289,288}114$.

How can one synthesize and identify these nuclides?

The fusion reactions kinematics of ^{244}Pu and ^{48}Ca very little differs from the one observed earlier in other reactions of the type $^{244}Pu + ^{34}S$ or $^{238}U + ^{40}Ar$. That is why the method of reaction products separation and registration used these last several years at GSI and FLNR can be applied in this case practically in full as well. In principle this approach ensures the luminosity of the experiment corresponding to the cross section ~1 pb or even less.

Identification of new nuclei is a more complicated issue. In all the earlier experiments after the α–decay of a new nuclide there was observed a chain of sequential α decays of already known isotopes, correlation with which determined Z and A of the nucleus synthesized. Now not only the initial nucleus is unknown but all the daughter decay products as well. That is why any event composed of sequential α decays with definite characteristics Q_α and T_α bears no direct information on the mass and charge of the initial nucleus. This means that one can not limit himself with just one experiment. At the same time the use of a very rare isotope of ^{48}Ca makes every experiment very expensive.

Further below a possible program of experiments on the synthesis of superheavy nuclei is suggested.

1. The experiment $^{232}Th(^{48}Ca,xn)^{280-x}110$ can be informative enough to determine the cross section of *EVR* formation in the reactions $(^{48}Ca,xn)$. At $x = 4$ in a short chain of α decays of nuclei $^{276}110 \xrightarrow{\alpha} {}^{272}108 \xrightarrow{\alpha} {}^{268}106$ the condition $T_{s.f.} >> T_\alpha$ is satisfied. The final even-even nucleus $^{268}106$ ($N = 162$) according to calculations [8] will have $Q_\alpha \doteq 8.0$ MeV and $T_\alpha \sim$ several hours. The isotope $^{264}104$ ($N = 160$) undergoing spontaneous fission with $T_{s.f.} \sim 10$ s will be its decay product. The $^{268}106$ nuclei can be extracted from the target by radiochemical methods: their consecutive $(\alpha - s.f.)$ decay can be registered with a high sensitivity. Taking into account the high intensity of the internal beam of the U-400 accelerator and the possibility of using a "thick target", one can achieve here a high sensitivity of the experiment ($\sigma_{min} \le 1$ pb).

2. The reaction $^{244}Pu(^{48}Ca,xn)^{292-x}114$ is most effective for the progress in the direction of a maximum excess of neutrons in the nucleus $Z = 114$. The largest cross section is expected for channels $x = 3,4$ (figure 5). Since the calculations of nuclear properties have been done for even-even isotopes it is interesting to consider the case $x = 4$.

In the chain $^{288}114 \xrightarrow{\alpha} {}^{284}112 \xrightarrow{\alpha} {}^{280}110$ the ratio $T_{s.f.} > T_\alpha$ is fulfilled for the initial nucleus. For the isotope $^{284}112$ it is already $T_{s.f.} \sim T_\alpha$, and for $^{280}110$ $T_{s.f.} < T_\alpha$. For a short chain $(\alpha - s.f.)$ or, in a better case of $(\alpha - \alpha - s.f.)$ a conclusion that a decay of a super heavy nucleus takes place here, is determined to a large extent by fission characteristics of $^{280}110$. The fission of such an exotic nucleus may have unusual properties (high kinematic energy of fragments, symmetrical mass distribution, manifestation of neutron shells $N = 82$, etc.). But at the implantation of the recoil nucleus into the front detector at a large depth the spectroscopy of fission fragments becomes rather problematic.

3. At the same time, if one uses as a target a lighter isotope ^{242}Pu leading to the production of the nucleus $^{286}114$ ($N = 172$), than the chain of consecutive α-decays gets longer until $Z = 104$. Note, that all the isotopes of the chain of daughter nuclei $112 \xrightarrow{\alpha} 110 \xrightarrow{\alpha} 108 \xrightarrow{\alpha} 106 \xrightarrow{\alpha} 104$ may be obtained in the reaction $^{238}U(^{48}Ca,xn)^{286-x}112$.

Thus, the first cycle of experiments on the synthesis of new superheavy nuclei includes the irradiation of ^{232}Th targets with a beam of ^{48}Ca (radiochemical extraction of the *EkaW* fraction and of-line detection of the decay of a $^{268}106$ nucleus) as well as the irradiation of ^{238}U and ^{244}Pu targets (in the on-line mode on kinematic separators).

Both the facilities – VASSILISSA (analog of SHIP at GSI) and the Dubna GFRS will be used in these experiments.

The Production of a ^{48}Ca ion beam

This is probably the key point of the problem of synthesizing new nuclei. The goal is to achieve the maximum intensity of the ^{48}Ca ion beam at the minimum expenditure of this rare and expensive isotope.

On the U-400 heavy ion cyclotron with an internal plasma source (PIG) there was obtained an ion beam of $^{48}Ca^{6+}$ with an intensity of about 0.1 pμA at the expenditure of the initial matter of ~3mg/h.

This result is unsatisfactory for long-term irradiations to achieve a beam dose of $\geq 10^{19}$.

To increase the intensity 5–10 times and decrease the expenditure of ^{48}Ca with a subsequent recuperation of the matter it is necessary to change radically the principle of production and acceleration of high charge ions.

In 1995–96 there was created an external ion source of ECR type and a channel of ion beam injection into the center of the U-400 accelerator. We assume that the new source ECR-4M will enable us to achieve an extracted beam intensity of ~0.5 pμA at the ^{48}Ca expenditure of ~0.5 mg/h (over 50% of the matter could than be extracted from the source chamber).

Supposedly, by the end of 1996 the technical part of this work will be completed and by mid 1997 we shall be able to start first experiments on the synthesis of superheavy elements.

Conclusion

Experimental investigations on the synthesis and study of properties of faraway transactinide elements confirm the predictions of macro-microscopic theory on the existence of closed shells in the region of heavy deformed nuclei. It has been demonstrated experimentally that nuclear structure plays a decisive role in the stability of superheavy nuclides.

Based on the experimental confirmation of the main provisions of the theory and after the introduction of a necessary correction into the calculation there have been predicted the properties of heavier nuclides in the region of spherical shells $Z = 114$ and $N = 180–184$. Here a substantial increase in the stability of nuclei is also expected.

All the nuclei synthesized by now, were obtained in fusion reactions with a formation of a compound nucleus, the transition of which to the ground state takes place with the emission of neutrons and gamma-rays.

Both the reactions of cold and hot fusion of nuclei can be used for the synthesis of new nuclei. Nevertheless, new experimental data on the fusion mechanism are required, since a number of theoretical descriptions of the fusion dynamics of complex nuclear systems need a substantial reviewing. One can assume that the reactions of the type ^{244}Pu, ^{248}Cm + ^{48}Ca are still within the current potential of the accelerators and experimental technique. This potential, nevertheless, is still to be implemented.

Acknowledgments

In the process of preparing this report I had interesting and fruitful discussions with my colleagues Yu.A.Lazarev, V.K.Utyonkov, A.Eremin, B.Pustylnik, M.Itkis, A.Popeko as well as with A.Sobiczevsky, Z.Hoffman, G.Muenzenberg, P.Moeller and Y.Abe. I would like to express my deepest gratitude to them.

I also think it to be my duty to thank the Alexander Humbold Fund which did not only allowed me to have intense contacts with my colleagues in Germany but stimulated also the cooperation between our Institutes.

I am grateful to E.Cherepanov and E.Schukina for their assistance in the preparation of this report and to V.Merzljakov for the translation of the Russian variant into English.

References

1. W.D. Myers and W.J. Swiatecki, *Nucl. Phys.* **81**, 1 (1966).
2. W.D. Myers and W.J. Swiatecki, *Ark. Fys.* **36**, 343 (1967).
3. M. Brack et al., *Rev. Mod. Phys.* **44**, 320 (1972).
4. V.V. Pashkevich, *Nucl. Phys.* A **169**, 275 (1971).
5. J.R. Nix, *Annu. Rev. Sci.* **22**, 65 (1972).
6. Z. Patyk et al., *Nucl. Phys.* A **533**, 132 (1991).
7. Z. Patyk and A. Sobiczewski, *Phys. Lett.* B **256**, 307 (1991).
8. R. Smolanczuk and A. Sobiczewski in *Proc. on XV Nucl. Phys. Conf. LEND-95*, St.Petersburg, April 18-22, 1995, World Sci., p.313.
9. E.K. Hulet et al., *Phys. Rev.* C **40**, 770 (1989).
10. P. Moeller, J.R. Nix and W.J. Swiatecki, *Nucl. Phys.* A **469**, 1 (1987); *Nucl. Phys.* A **492**, 349 (1989); P. Moeller and J.R. Nix, *Nucl. Phys.* A **549**, 84 (1992).
11. Yu.Ts. Oganessian, in *Classical and Quantum Mechanical Aspects in Heavy Ion Collision, Lecture Notes in Physics* (Springer, Heidelberg, v.33, 1975).

12. G. Münzenberg, *Rep. Progrl. Phys.* 51, 57 (1988).
13. Yu.Ts. Oganessian et al., *JINR Rapid Communications* No 1[75]-96, p.123.
14. To be published.
15. S. Hofmann et al., *Z. Phys.* A **350**, 277 (1995).
16. S. Hofmann et al., *GSI-Nachricten* 02-95 (Darmstadt, 1995), p.4.
17. J.P. Blocki et al., *Nucl. Phys.* A **459**, 145 (1986).
18. P. Fröbrich, *Phys. Lett.* B **215**, 36 (1988).
19. D. Berdichevsky et al., *Nucl. Phys.* A **499**, 609 (1989).
20. M. Itkis et al., in *Proc. on XV Nucl. Phys. Conf. LEND-95,* St.Petersburg, April 18-22, 1995, World Sci., p.177.
21. J.O. Newton, *Sov. J. Part. Nucl.* 21, 321 (1990).
22. D. Hilscher and H. Rossner, *Preprint HMI-92-P23* Hil.-1, Berlin, 1992.
23. D.J. Hinde et al., *Nucl. Phys.* A **472**, 318 (1987).
24. E.M. Kozulin et al., *JINR FLNR Sci. Rep. 1991-92,* JINR Rep. E7-93-57, Dubna, 1993, p.70.
25. T. Sikkeland, J. Maly and D.F. Lebeck, *Phys. Rev.* **169**, 1000 (1968).
26. A.N. Andreyev et al., *Z. Phys.* A **345**, 389 (1993).
27. A.N. Andreyev et al., *Z. Phys.* A **344**, 225 (1992).
28. Yu.A. Lazarev et al., in *Proc. of Intern. School-Seminar on Heavy Ion Physics*, Dubna, 1993 (JINR E7-93-274, Dubna, 1993), vol.2, p.497.
29. Yu.A. Lazarev et al., *Phys. Rev. Lett.* **73**, 624 (1994).
30. Yu.A. Lazarev et al., *Phys. Rev. Lett.* **75**, 1903 (1995).
31. Yu.A. Lazarev et al., *JINR Preprint* E7-95-552, Dubna, 1995, submitted to *Phys. Rev.* C (in press).
32. S. Hofmann et al., *Z. Phys.* A **354**, 229 (1996).
33. S.Hofmann in *Proc. on XV Nucl. Phys. Conf. LEND-95,* St.Petersburg, April 18-22, 1995, World Sci., p.305.
34. Y. Abe et al., *Preprint Yukawa Institute Kyoto YITR-95-18*, December 1995.
35. B.I.Pustylnik et al., *Nucl. Phys.* NP A **553**, 735 (1993).
36. S.N. Timokhin et al., *JINR Rapid Communications* No.4[61]-93, Dubna, 1993, p.60; *J. Radioanal. Nucl. Chem. Letters* **212**, 31 (1996).
37. M. Schädel et al., *GSI Scientific Report 1995*, GSI 96-1, Darmstadt, 1996, p.10.

Received by Publishing Department
on November 14, 1996.