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Subbarrier cold fusion reactions leading to superheavy elements(*)

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Summary. — The elements with $Z \geq 107$ were synthesized in cold fusion reactions based on Pb and Bi targets. Heavy ions undergo fusion with these target nuclei deeply in the subbarrier region. The analysis of the potential energy surface of colliding nuclei shows that a cloud of paired nucleons or massive clusters may be transferred from the projectile to the target.

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After the elements with $Z = 109$ [1] and $Z = 108$ [2] were discovered in 1982 and 1984, there were no reports on a successful synthesis of heavier elements during the next 10 years. The reason for such a situation was the dramatically decreasing production cross-sections. All elements with $Z \geq 107$ were firstly synthesized in the cold fusion reactions ^{208}Pb(HI,1n) and ^{209}Bi(HI,1n), which were shown by Oganessian [3] to be a feasible way of heavy element synthesis.

Possible explanations of such a behavior of the cross-section have been proposed by several authors: the macroscopic dynamical model by Swiatecki [4], the surface friction model by Fröbrich [5] and others. According to these models some extra energy above the entrance channel Coulomb barrier, the so-called "extra push", is needed to surmount the fusion barrier. During the fusion process part of the additional collision kinetic energy will be converted into heat. Thus, the excitation energy of a formed compound nucleus must be not less than many tens or hundreds of MeV and a SHE-nucleus cannot be obtained in a cold fusion reaction.

Figure 1 (left) shows the excitation energies of heavy compound nuclei calculated at the Bass barrier [6] using the models [4, 5] and mass tables [7]. In several investigations the existence of the "extra push"-like effects seemed to be confirmed.

A new series of the experiments aimed at synthesizing the elements heavier than $Z = 109$ was started at the end of 1994, and elements $Z = 110, 111$ [8] and 112 [9] were

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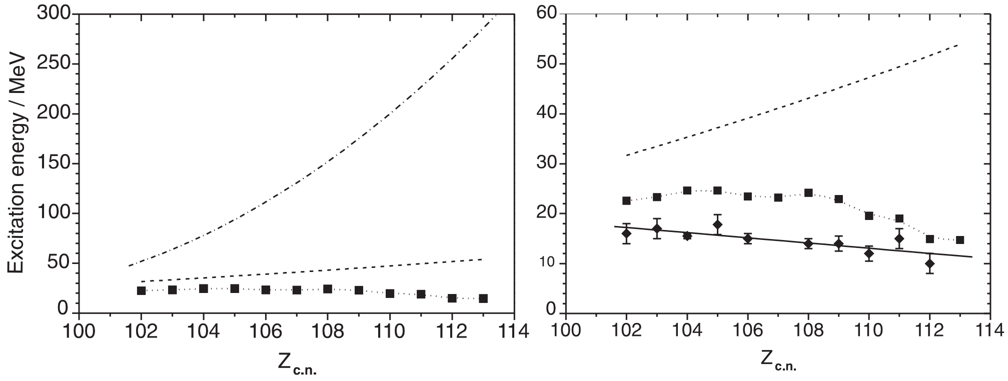

Fig. 1. – The excitation energies of heavy compound nuclei calculated at the Bass barrier: dot-dashed line: Swiatecki model; dashed line: Fröbrich model; squares: Möller *et al.* mass tables (left panel) and diamonds: experimental data (right panel).

successfully synthesized and identified. The high sensitivity in the experiments was provided by a stable high current beam from the heavy-ion accelerator UNILAC, and by a highly efficient separation of the reaction products by the SHIP velocity filter and a sensitive detector system. Altogether more than 15 new isotopes with $Z \geq 104$ were synthesized during the past 3 years.

The new results confirmed the tendency in decreasing the production cross-section for heavier elements, but they are in strong contradiction with all existing "extra push"- like models. Figure 1 (right) shows also the experimental data on the excitation energy of the elements with $Z \geq 102$ produced in the 1n cold fusion reactions. The data are taken for the elements $Z = 102, 103$ from [10], $Z = 104, 108, 110, 111$ from [8], $Z = 105$ from [11], $Z = 106$ from [12], $Z = 108, 109$ from [13] and $Z = 112$ from [9]. One can clearly see that the fusion of the reaction partners occurs below the Bass barrier, a slow trend towards lower excitation energies is clearly indicated and a need in the additional "extra push" or "surplus" energy has not been observed.

The excitation functions have been measured for elements with $102 \leq Z \leq 110$ and partly for elements 111 and 112. These data showed that the FWHM of the 1n excitation functions was typically < 5 MeV. Thus the needed accuracy of theoretical predictions for the projectile bombarding energy should be better than 1%, which seems to be problematic in the recent time.

Sub-barrier fusion has been studied extensively by many groups, both theoretically and experimentally [14], [15]. Now it is well known that the experimental cross-section exceeds that of theoretical predictions within the one-dimension WKB approximation (*e.g.* [16]) by several orders of magnitude. To explain this discrepancy several models have been advanced.

The calculations of the production cross-sections of the heaviest elements were performed by Pustylnik on the basis of existing models with the use of the modified version of the ALICE computer code [17]. The reactions with relatively light ions like ^{16}O and ^{50}Ti were satisfactorily described. This could not be achieved for the heavier ions. In fig. 2 the experimental data on the cross-sections σ_{1n} [8] and σ_f [18] in the reaction ^{64}Ni+^{208}Pb are compared with those calculated in [17] and according to [16]. The measured cross-sections for the production of ^{271}110 are overestimated by 10^5 in this calculation. One can put a

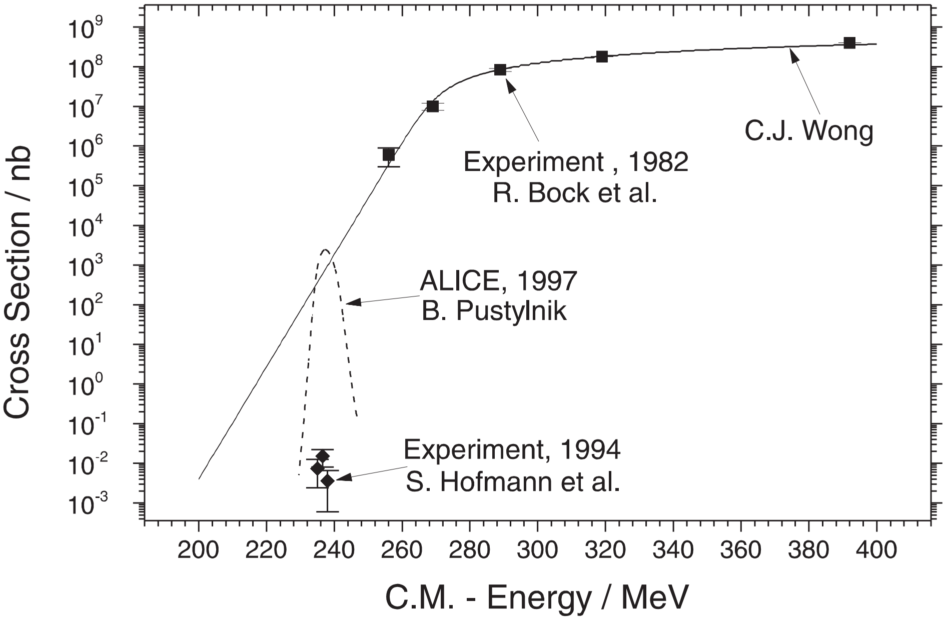

Fig. 2. – Experimental data of the cross-sections σ_{1n} (diamonds, [8]), σ_f (squares, [18]) in the reaction ^{64}Ni+^{208}Pb, and calculated in [17] (dashed line) and according to [16] (solid line).

question: why is the cross-section so low? Of course, this discrepancy should be explained, but here arises the opposite problem.

The data, shown as a function of the center-of-mass energy in fig. 2, correspond to the maxima of the excitation functions for producing the heaviest elements. They can be converted into the distances between the surfaces of the interacting nuclei according to the fusion model, *e.g.* with that of Bass [6] (see fig. 3). In all cold fusion reactions the reaction partners are slowed down to zero relative velocity before the partners touch each other and the intersurface distance is close to 3 fm. With the use of other parameters for the fusion model this distance is not varied significantly. A semiclassical WKB approximation results in a tunneling probability through the fusion barrier of less than 10^{-21}, which is much too low to contribute to the measured cross-section [19]. Now one can put another question: why is the production cross-section so high?

A possible explanation was proposed by Hofmann [20], the so-called "fusion initiated by transfer" (FIT). At the intersurface distances of 3 fm only nucleons at the surface of interacting nuclei are in contact and they may leave the orbit of one nucleus and move into a free orbit of the reaction partner. The transfer of pairs is more likely than that of single nucleons. After a transfer of protons the Coulomb repulsion decreases and the reaction partners are kept together for a time long enough to allow them to resolve their individual structures and to continue the fusion initiated by the transfer.

The transfer cross-sections experience a dramatic influence of the energetics involved in the reaction. Figure 4 shows the potential energy surface landscape $V(\Delta Z, \Delta N)$ for the ^{64}Ni+^{208}Pb reaction. ΔZ and ΔN denote the numbers of protons and neutrons transferred to the massive partner, *i.e.* target. $V(\Delta Z, \Delta N) = Q_{\mathrm{gg}} - \Delta V_{\mathrm{c}}$ with Q_{gg} being the Q-value for the ground state transition, and ΔV_{c} the difference between the Coulomb en-

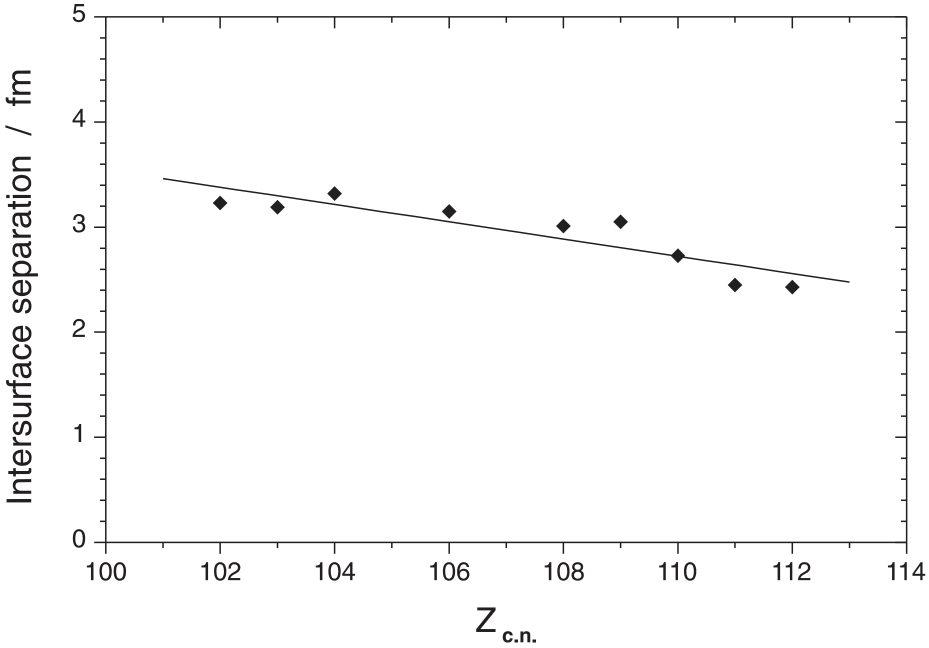

Fig. 3. – The distances between the surfaces of the interacting nuclei according to the fusion model [6].

ergies in the final and initial states $\Delta V_c = V_{cf} - V_{ci}$. For the calculation of Q_{gg} the "real" masses taken from the tables [7] were used.

The analysis of the potential energy surfaces of interacting nuclei adds a further argument to the FIT explanation. One can see that the transfer of several nucleons or clusters from the projectile to the target is energetically favourable. It would be possible to ex-

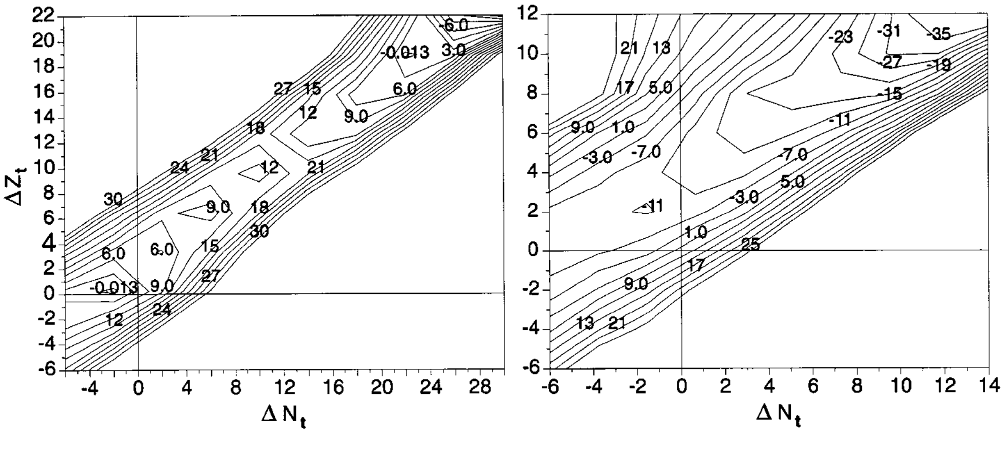

Fig. 4. – Potential energy surface landscapes for the ^{64}Ni+ ^{208}Pb (left) and ^{34}S+^{244}Pu (right) reactions.

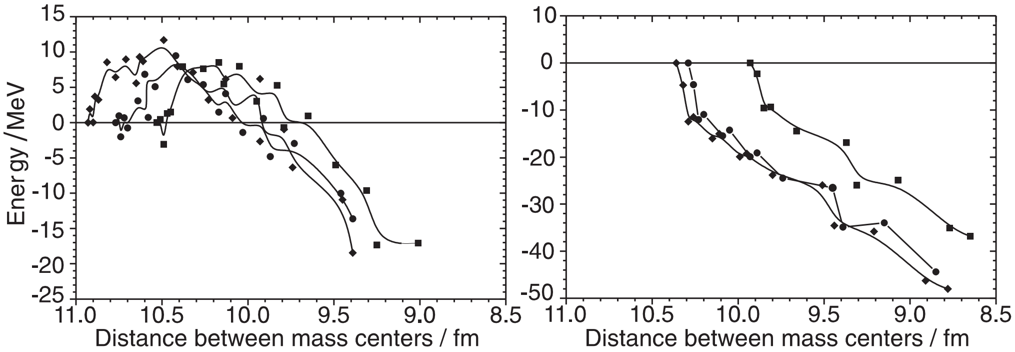

Fig. 5. – Fusion barriers for the ”cold” reactions (left panel): ^{50}Ti+^{208}Pb (squares), ^{58}Fe+^{208}Pb (circles), ^{64}Ni+^{208}Pb (diamonds), and ”hot” reactions (right panel): ^{26}Mg+^{238}U (squares), ^{34}S+^{238}U (circles), ^{34}S+^{244}Pu (diamonds).

cite molecular states which are dinuclear systems. The motivation of the concept of the dinuclear system (DNS) has already been presented in [21].

For fusion the system should develop towards the mass asymmetry. This is possible along the bottom of the potential valley, but on this way one can clearly see the barrier which hinders the mass transfer. To see this barrier better we can transform the landscape shown in fig. 4 into the one-dimensional dependence of the barrier height on the distance between the centers of interacting partners along the way at the bottom of the potential valley (see fig. 5). The barrier is really clearly seen and reaches 10 MeV. For a comparison similar pictures are shown on the right panels of figs. 4 and 5 for the ”hot” fusion reactions investigated by Lazarev’s group [22].

One can state that the mean difference between the ”cold” and the ”hot” fusion reactions is connected with the difference of their potential energy surfaces. *The ”cold” fusing systems are hindered by the mass transfer barrier, and the ”hot” systems do not have this barrier.*

How can a system overcome the barrier? It seems that a sequential transfer of nucleons is not the correct way. A transfer of a massive cluster can give a system the possibility to overcome the Businaro-Gallone point in one step. The dissociation of the projectile should be stimulated by a strong deformation. The numerical results are not yet present.

On the other side, the transfer of nucleons or clusters from the target to the projectile (ΔZ and ΔN negative) is also energetically possible. This process is not limited, and the system may develop towards the mass symmetry and reseparate. From the DNS concept this process is known as quasi-fission.

The possibilities to investigate the mechanism of the cold fusion reactions based on Pb targets are limited by extremely low cross-sections. The first step of the fusion process can be investigated by measuring the transfer products in the forward direction.

Other regions, where ”cold” fusion can be studied are the reactions between Kr+Xe, Kr+Sn, Sn+Sn and Xe+Xe. Preliminary results were already obtained in recent experiments at the SHIP and VASSILISSA separators.

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REFERENCES

[1] MÜNZENBERG G. *et al.*, *Z. Phys. A*, **309** (1982) 89.
[2] MÜNZENBERG G. *et al.*, *Z. Phys. A*, **317** (1984) 235.
[3] OGANESSIAN YU.TS. *et al.*, *Nucl. Phys. A*, **239** (1975) 353.
[4] SWIATECKI W. J., *Phys. Scr.*, **24** (1981) 113.
[5] FRÖBRICH P., *Phys. Rep.*, **116** (1984) 337.
[6] BASS R., *Nucl. Phys. A*, **231** (1974) 45.
[7] MÖLLER P. *et al.*, *At. Data Nucl. Data Table*, **59** (1995) 185.
[8] HOFMANN S. *et al.*, *Z. Phys. A*, **350** (1995) 277 and 281.
[9] HOFMANN S. *et al.*, *Z. Phys. A*, **354** (1996) 229.
[10] GÄGGELER H. *et al.*, *Nucl. Phys. A*, **502** (1989) 561.
[11] HESSBERGER F. P. *et al.*, *Z. Phys. A*, **322** (1985) 557.
[12] MÜNZENBERG G. *et al.*, *Z. Phys. A*, **322** (1985) 227.
[13] HOFMANN S. *et al.*, to be published in *Z. Phys A.*, **358** (1997).
[14] VANDENBOSH R., *Ann. Rev. Nucl. Sci.*, **42** (1992) 447.
[15] REISDORF W., *J. Phys. G*, **20** (1994) 1297.
[16] WONG C. Y., *Phys. Rev. Lett.*, **31** (1973) 766.
[17] PUSTYLNIK B. I., in *Dynamical Aspects of Nuclear Fission*, Dubna, E6 7-97-49 (1997) 121.
[18] BOCK R. *et al.*, *Nucl. Phys. A*, **388** (1982) 334.
[19] HOFMANN S. *et al.*, *GSI Scientific Report 1996*, GSI 97-1, 9.
[20] HOFMANN S., in *Low Energy Nuclear Dynamics*, St. Petersburg, 1995, p.305.
[21] VOLKOV V. V., *Izv. AN USSR, Ser. Fiz.*, **50** (1986) 1879, this issue, p. 1127.
[22] LAZAREV YU. *et al.*, *Phys. Rev. C*, **54** (1996) 620.