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PRODUCTION AND STABILITY OF NEW ELEMENTS

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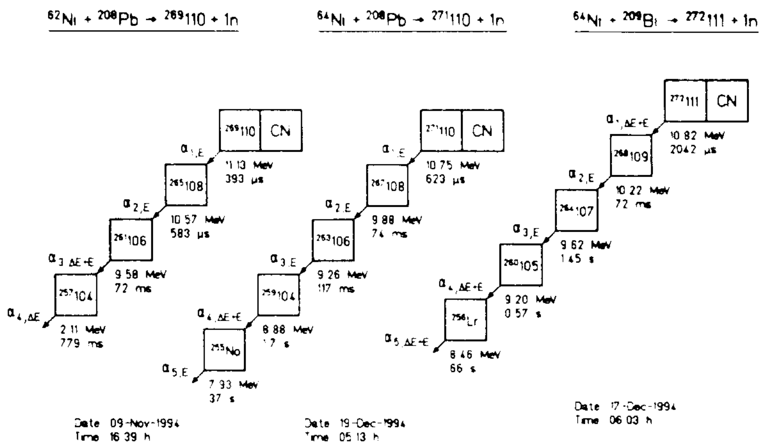

Fig. 3. Three representative decay chains of $^{269}110$, $^{271}110$ and $^{272}111$.

around $^{292}_{178}114$ forming an island of spherical superheavy nuclei (Fig. 4, top). The binding energies, beta-, alpha-, and fission half-lives were calculated. The known data could be reproduced with good accuracy. A rough sketch of the half-lives obtained is shown in Fig. 4, bottom. As a result, we can deduce that most nuclei that can be produced with stable projectiles and the available targets are predicted to be α emitters with half-lives between 1 μs and 1 s.

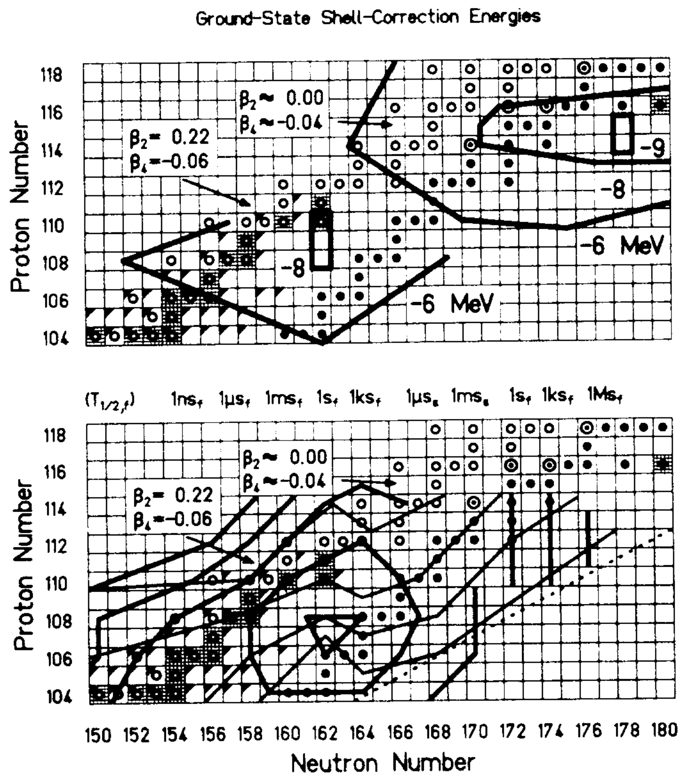

Fig. 4: Rough sketch of calculated microscopic shell correction energies (top) and half-lives (bottom) of even-even nuclei; bold lines: partial fission half-lives; fine lines: partial α half-lives; broken line: beta-stability line. The data are from [13-16]. The fission half-lives of odd and odd-odd nuclei may be longer as a result of additional hindrance factors. The arrows point to the region of strongly deformed nuclei centered around $^{272}110$ and to the region of spherical superheavies at around $^{292}114$; open circles: compound nuclei of reactions (Ti to Kr) + $^{208}Pb \rightarrow (Z = 104$ to $118)$; dots: compound nuclei of reactions (O to Ti) + $^{248}Cm \rightarrow (Z = 104$ to $118)$; full triangles: known nuclei; shaded: compound systems investigated with SHIP. The figure does not include estimates for production cross-sections.

Although the known decay data are reproduced well by theory, there are still uncertainties concerning the decay properties of superheavy nuclei. Fig. 5 shows as an example the predicted decay chain of $^{290}116$. The proposed reaction is discussed in Sect. 4. From the experimental point of view the neighboring odd-N decay chain may become more attractive, if fission half-lives become shorter than α half-lives for some of the even-even nuclei. A moderate fission hindrance factor of 10^3 was assumed.

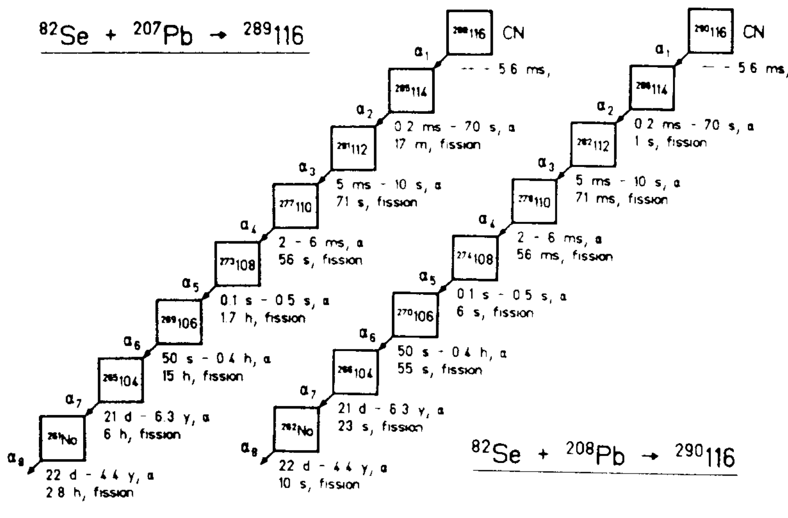

Fig. 5. Predicted decay chains of $^{289}116$ and $^{290}116$. The calculated α half-lives are from Ref. [14] (left numbers) and were calculated using the Q-values given by Ref. [15] (right numbers). The fission half-lives are from Ref. [14], multiplied by 10^3 for the odd-N nuclei. All nuclei shown are presently unknown.

4. Reaction Properties

4.1. Excitation Functions

The search for element 110 was complicated by the fact that no excitation functions for lighter elements down to $Z = 103$ were known accurately enough to fix a maximum of the cross-sections. In addition, predictions of extrapush theories influenced the choice of the beam energies for investigation of elements up to $Z = 109$. Therefore, we began the experiments with measurement of the excition functions for the elements 104 and 108. In both cases ^{208}Pb was used as a target and the projectiles ^{50}Ti and ^{58}Fe belong to the same chain of $T_z = 3$ nuclei, thus resulting in most similar reaction mechanisms, the best starting point for systematic investigations.

The measured excitation functions for the elements 104 and 108 are shown in Fig. 6. The data points were narrow enough to allow a safe determination of the positions for the cross-sections maxima. The beam energy for production of element 110 by the reaction $^{62}Ni + ^{208}Pb \rightarrow ^{269}110 + 1n$ was obtained by linear extrapolation.

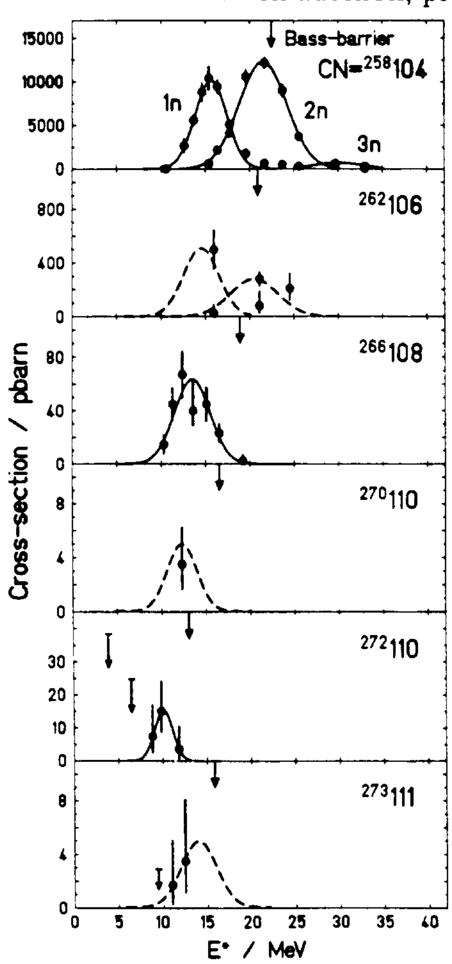

Fig. 6. Measured excitation functions for reactions with ^{208}Pb and ^{209}Bi targets and projectiles of ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{62}Ni and ^{64}Ni. The cross-sections are plotted as function of the dissipated energy E^*, calculated from the center-of-mass beam-energies in the middle of the targets and the Q-values using the mass tables of Ref. [17,18]. The data points for $Z = 106$ are from Ref. [19], all other data are from [7-9]. The lines are fits of gaussian curves through the data points, the dashed lines are interpolations and extrapolations, respectively. The arrows mark the interaction barriers of the reactions according to Bass [20].

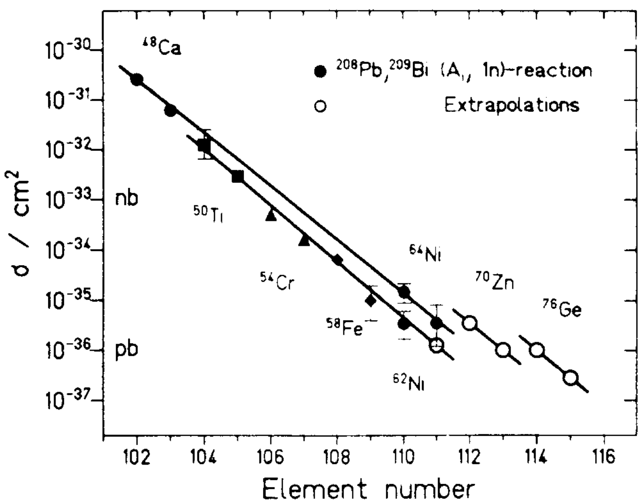

Fig. 7. Systematics of measured cross-section maxima and extrapolations.

This reaction was investigated at that energy only, and after observation of 4 decay chains the projectile ions were changed for ^{64}Ni. The reaction $^{64}\mathrm{Ni}+^{208}\mathrm{Pb} \rightarrow {}^{269}110+1n$ was investigated by 5 different beam energies. A total of 9 events were measured at the 3 higher energies, only upper limits were obtained at the lower energies. Finally, the target was changed for ^{209}Bi aiming at production of element $Z=111$. A total of 3 events was observed at 2 different energies, at a third lower energy a cross-section limit was obtained only. The systematics of the cross-section maxima is shown in Fig. 7.

4.2. Fusion Below the Barrier?

Fig. 6 shows a drastic reduction of the cross-section ratios $\sigma(2n)/\sigma(1n)$ from $Z=104$ to $Z=108$. The 1n cross-section decreases by ≈ 10 per 2 element numbers (Fig. 7), although the reaction Q-values allow decreasing dissipative energies and, hence, by fusion barriers increasingly unhindered 1n emission. In the region of the heaviest elements the fission probabilities increase rapidly by decreasing liquid-drop barriers and hence increasing sensitivity against centrifugal forces. The latter reduces fusion of high Z systems to central collisions, the former to low dissipative energies. The repulsive Coulomb forces between two heavy reaction partners become so strong that already at moderate additional angular momenta a compound system cannot be formed, the reaction partners just reseparate.

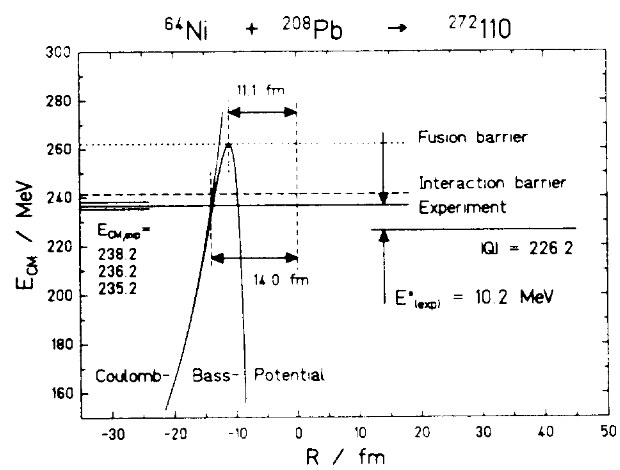

Fig. 8. Energy relations determining the barrier for the reaction $^{64}\mathrm{Ni}+^{208}\mathrm{Pb} \rightarrow {}^{272}110$.

Fig. 6 shows that in all investigated reactions the largest cross-sections were measured "below the barrier". The energy relations determining the barrier are drawn in Fig. 8 in case of the reaction $^{64}\mathrm{Ni}+^{208}\mathrm{Pb}$ and a barrier according to Bass [20].

All three measured cross-sections were observed at energies well below the Bass barrier. A tunneling process through this barrier cannot explain the measured cross-sections. A semiclassical WKB approximation results in a tunneling probability of 2×10^{-21} which is much too low to contribute to the measured cross-section. The conclusion is that additional effects must allow for fusion.

4.3. Fusion Initiated by Transfer (FIT)

The following considerations base 1. On the experimental result of fusion at low projectile energies, which means fusion at a distance of the reaction partners, and 2. On the investigation of cold multi-nucleon transfer by von Oertzen [21]. Compared to more sophisticated investigations of fusion [22], we can make some simplifications in our case in order to explain the observations:

1. The reactions are limited to spherical target nuclei and nearly spherical projectiles.
2. The reactions are head-on collisions with angular momenta close to zero and, therefore, high rotational symmetry.
3. The reactions proceed at extremely low dissipative energies as a result of nearly compensating Q-value and center-of-mass energy.

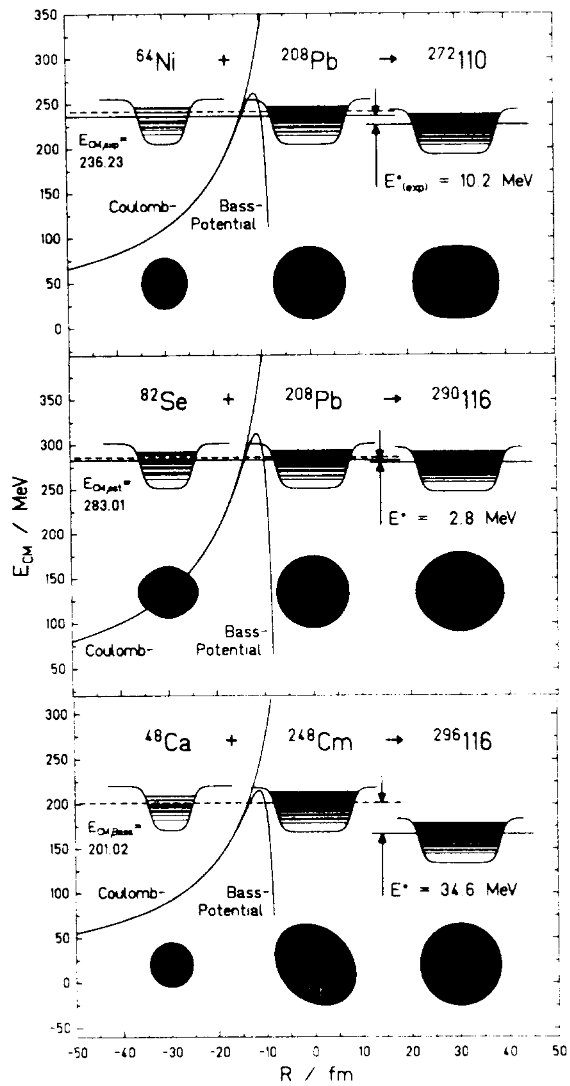

Fig. 9. Energy versus distance diagramm for reactions with spherical ^{208}Pb targets and deformed ^{248}Cm target resulting in the deformed fusion product ^{272}110 and nearly spherical nuclei of element 116. In case of ^{64}Ni beam the center-of-mass energies are experimental values, in case of ^{82}Se estimated, and in case of ^{48}Ca an average Bass-barrier value is given.

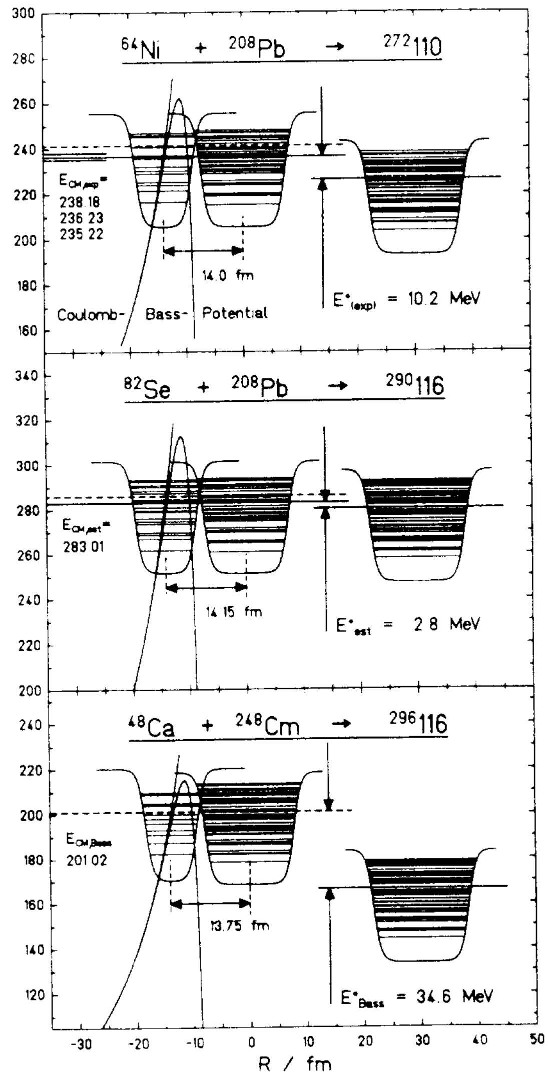

Fig. 10. Same as Fig. 9, but at a distance of the reaction partners, where maximum cross-sections were measured in case of the reaction ^{64}Ni + ^{208}Pb.

In the upper parts of Figs. 9 and 10 the reaction $^{64}Ni + ^{208}Pb$ is shown in an energy versus distance diagramm. The reaction partners are represented by their nuclear-potential wells (Woods-Saxon) including the orbital energies of the nucleons. The potential wells are shifted, so that the centers-of-gravity of the occupied levels coincide with the binding energies of the nuclei.

Fig. 9 shows the reaction partners at a distance of 30 fm, Fig. 10 at the distance where the reaction partners came to rest according Coulomb repulsion, at the initially given kinetic energy of 236.23 MeV. At that energy the cross-section maximum was measured. The distance determined is 14.0 fm.

As shown in Fig. 10, only the occupied levels at the Fermi surface are just in contact. Nevertheless, the system does not reseparate!

We remember that the kinetic energy of orbiting nucleons is low at the surface. Therefore, at the touching point of two nuclei in a central collision the probability is highest that nucleons or pairs of nucleons leave the orbit of one nucleus and move into a free orbit of the reaction partner. The process is shown schematically in Fig. 11.

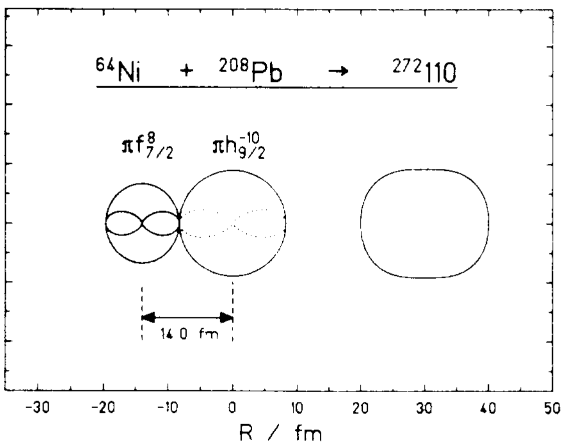

Fig. 11. Proton orbitals at the Fermi level for the reaction $^{64}Ni + ^{208}Pb$ at a distance of the centers of the nuclei that resulted in maximum cross-section.

This transfer process is especially attractive in case of lead as target. In ^{208}Pb the $h_{11/2}$ proton subshell and the $h_{9/2}$ and $i_{13/2}$ neutron subshells are filled. The free orbits are for the protons $h_{9/2}$ and $i_{13/2}$ The proton transfer profits first from the attractive proton-proton and after filling of the $h_{9/2}$ subshell from the attractive proton-neutron interaction. Similarly, neutrons transfered into free $i_{11/2}$ orbits are attracted by the neutrons in the already filled $i_{13/2}$ subshell.

Because of pairing energies and high orbital angular momenta involved, the transfer of pairs is more likely than that of single nucleons. The described process is a frictionless pair transfer happening at the contact point in a central collision at longitudinal momenta close to zero in irradiations of ^{208}Pb targets.

Already after transfer of 2 protons from ^{64}Ni to ^{208}Pb the Coulomb barrier is decreased by 14 MeV allowing to keep the reaction partners in close contact and to continue fusion initiated by transfer.

The center parts of Figs. 9 and 10 show an extrapolation to the system $^{82}Se + ^{208}Pb$ resulting in the superheavy nucleus $^{290}116$. The entrance channel remains essentially unchanged, but the fusion product is now nearly spherical. The Q-value changed, so that the fusion product will probably be produced in the ground-state or at extremely low excitation energies. It seems that these are most favorable conditions for production of superheavy nuclei, although a value of the cross-section is difficult to predict.

The bottom parts of Fig. 9 and 10 show the completely different situation in the bombardment of ^{248}Cm by ^{48}Ca, the favorite reaction in the past. The target nucleus is deformed, and at barrier energies only a fraction at certain orientation will lead to fusion. The occupations of levels at the Fermi surfaces are so that probably nucleons will transfer from the target to the projectile and thus increase the Coulomb repulsion. The Q-value allows for minimum excitation energies of ≈ 35 MeV only. A number of 3 or 4 neutrons need to be evaporated, a process that is accompanied with high probability by fission. Nevertheless, the recent results in Dubna have shown that element 110 could be produced by 5n evaporation using ^{244}Pu targets [12].

It seems that low energy nuclear dynamics in the field of superheavy element production covers a broad range of phenomena from well ordered microscopically determined systems to processes governed by statistical disorder.

The experiments at SHIP were carried out together with V. Ninov, F.P. Heßberger,
P. Armbruster, H. Folger, G. Münzenberg, H.J. Schött (GSI, Darmstadt),
A.G. Popeko, A.V. Yeremin, A.N. Andreyev (JINR, Dubna),
S. Saro, R. Janik (Comenius University, Bratislava),
M. Leino (University of Jyväskylä).

Essential for the experimental results obtained was a stable high current beam prepared by the colleagues from the ion-source group and accelerated with high precision up to the energy values needed by the UNILAC staff. Equally essential was a reliable data collection and analysis system installed by the colleagues from the department of experimental electronics and data acquisition. The enriched ion source material ^{58}Fe was provided by FLNR-JINR, Dubna.

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