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DISCOVERIES WITH COLD HEAVY-ION FUSION AND SHELL STABILISED NUCLEI AROUND HASSIUM

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Cold fusion, using reactions with the doubly magic nucleus ^{208}Pb and its neighbor ^{209}Bi, have lead to the discovery of the shell stabilized nuclei around ^{270}Hs paving the way to the artificial synthesis of superheavy nuclei. In this paper we present a brief history of the discoveries and their importance to the production and investigation of superheavy elements.

Key words: superheavy elements, fusion reactions, fission barriers, shell effects.

1. INTRODUCTION

How many elements can we find in nature and how far can we extend the table of chemical elements? With the development of microscopic theories the question arose whether it is possible to extend the number of elements by shell stabilization beyond the limit of macroscopic stability [1].

The first transfermium elements, beyond those created in nuclear reactors, were produced with actinide targets bred in high flux reactors, preferably ^{248}Cm, ^{249}Bk, and ^{249}Cf with beams of carbon, nitrogen, or oxygen isotopes. The reason was two-fold: the early cyclotrons could easily accelerate light beams and gaseous chemical elements could be utilised for ion sources in use at that time. Also, W. J. Swiatecki had developed a model which stated that heavy targets close to the mass of the final nucleus when combined with light projectiles fuse much more easily than massive systems [2] which cannot undergo fusion at the Coulomb barrier but need an extra energy above the barrier - the "extra push" [3]. However, the disadvantage of this type of reaction is the "hot" production of the compound system at comparatively high excitation energies typically around 40 MeV. The survival probability of such a highly excited nucleus decreases rapidly for the heaviest species because of the increasing fission loss in the de-excitation process on the way to the ground state.

2. THE DISCOVERY OF COLD FUSION IN MASSIVE NUCLEAR SYSTEMS

With the availability of more powerful heavy-ion accelerators the creation of isotopes of the very heavy elements became possible. Taking advantage of this new development, Yu. Ts. Oganessian proposed the use of the doubly magic ^{208}Pb as a target with appropriate projectile beams (such as the most neutron rich isotopes of titanium or chromium) to create colder compound systems in order to enhance the survival probability of these highly fissile elements at the top of the chart of nuclides [4]. The strong binding of the doubly magic ^{208}Pb makes possible the production of elements with Z=104 and beyond at excitation energies of only 20 MeV to 30 MeV to enhance the survival probability of these most heavy and fragile nuclei. This idea was revolutionary in view of the models proposed at the time and used as a guideline for heavy-element production in Berkeley. The concept was also supported on theoretical grounds by A. Sandulescu, who adopted a new point of view and used the fragmentation theory to select appropriate targets and projectiles for the production of superheavy elements [5].

In irradiations of ^{208}Pb and ^{209}Bi targets with beams of ^{50}Ti and ^{54}Cr, Oganessian and collaborators claimed the observation of elements 104 to 107 formed in the 2n and 3n channels [6, 7]. These assignments were based on the measurement of fission tracks and the results were debated, as spontaneous fission is not a reliable method of identification, especially for unknown species. Relying on the extra-push concept the Berkeley group was convinced that the fission activities reported from Oganessian *et al*. originate from transfer reactions and cannot be attributed to heavy elements [8].

The first proof the concept of cold fusion was presented through the observation of ^{257}Rf in irradiations of ^{208}Pb with ^{50}Ti, formed in the evaporation of one neutron from the compound nucleus ^{258}Rf [9]. The identification was made by $\alpha-\alpha$ correlation chains to known nuclides and established beyond any doubt. Fig. 1 displays the observed α-decay sequence of an individual atom of ^{257}Rf in comparison to properties taken from the literature [10].

The measured excitation functions [9] displayed in Fig. 2 show the 1n, 2n, and 3n channels. This success marked the first step into the trans-actinide region using cold fusion. It opened up new avenues for the creation of hitherto unknown elements such as rutherfordium (Z=104) and beyond, by the cold fusion of massive nuclear systems. This experiment provided indisputable proof of Yu. Ts. Oganessian's idea and confirmed the importance of nuclear clusters for SHE production as set out in the fragmentation theory of A. Sandulescu.

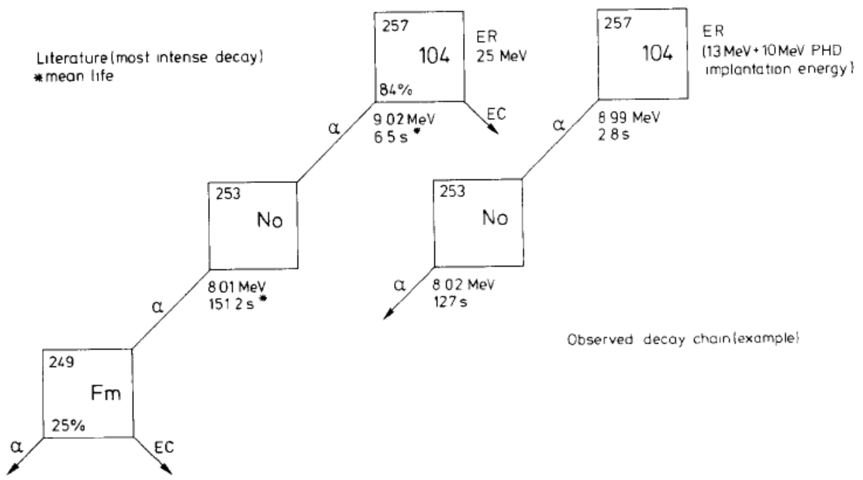

Fig. 1 – Example of a single-atom decay chain [9] (right) compared to literature data [10] (left).

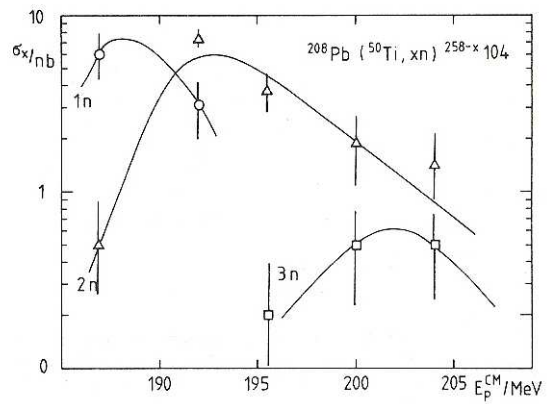

Fig. 2 – Excitation function for the fusion reaction ^{50}Ti + on ^{208}Pb, the first observation of cold fusion in transuranium element production [9].

The early SHE model calculations predicted a "sea of instability" separating the super heavy elements from the transuranium region. Fig. 3 displays the experimental and calculated partial fission half-lives [11] for the even-even isotopes of the transuranium elements up to element 110. Already at element 104 the half-lives drop below 1 ms, as fission competes with α decay. At element 108, half-lives drop below 1 μs which is the separation time of SHIP.

A consequence of the first series of experiments to create new elements at SHIP concentrated on odd-odd nuclei in an attempt to profit from the hindrance of the odd nucleon. The series was started with the production of elements 107 and 109. As expected, α-decay was observed. The production of the even-Z element

106 and the new element 108 created a sensation which was further compounded by the observation of α-decay from the doubly even isotope ^{264}108 [12] contrary to predictions at the time. Perhaps the crowning glory was when the odd-mass isotope ^{265}108 was produced in an irradiation of ^{208}Pb with ^{58}Fe and α-decay was observed [13]. It was clear that the discovery of enhanced stability against fission for element 108, hassium, would pave the way to the synthesis of still heavier elements.

Fig. 4 displays the experimental shell effects for the N-Z=48 isotopes [14]. They have been obtained from the experimental Q_α values (from which the nuclear mass can be extracted) and the macroscopic part of the Möller-Nix mass formula [15]. The dots correspond to even-even nuclei where we expect to have ground state transitions, the circles refer to odd-odd nuclei. The dashed lined is the calculated microscopic correction in the Möller-Nix formula. The lower part shows the experimental fission barriers for the same even-even nuclei. They have been calculated from the shell correction energies and an empirical liquid-drop fission barrier [16].

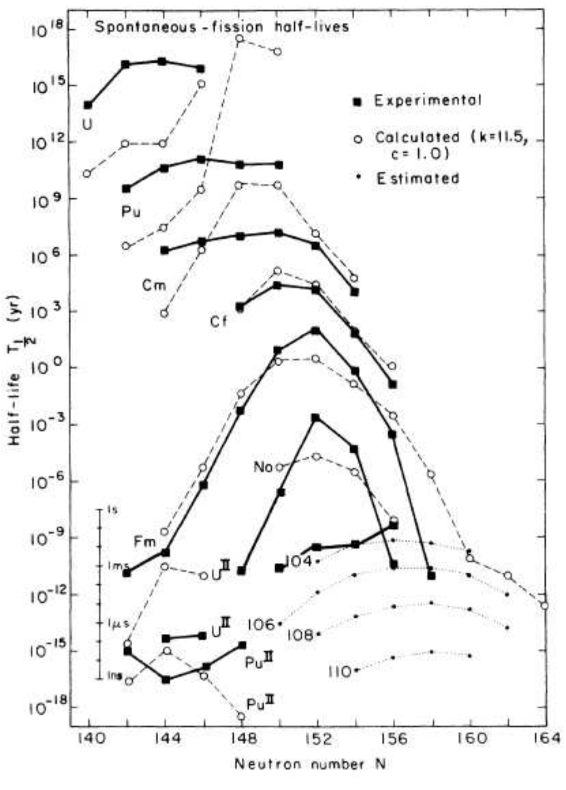

Fig. 3 – Experimental (dots), calculated (circles), and estimated (small dots) partial spontaneous fission half-lives for the transuranium elements up to element 110 as predicted 1976 [11].

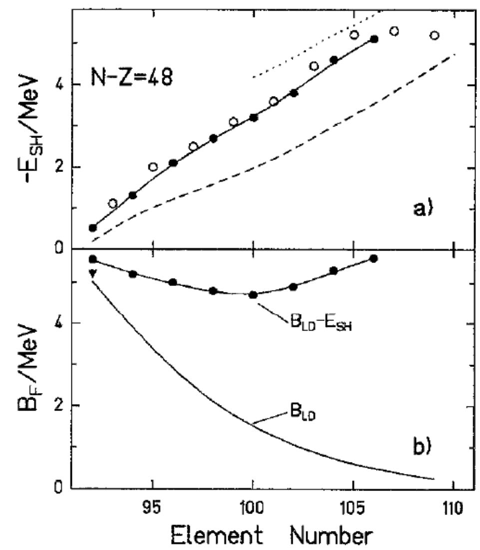

Fig. 4 – Upper panel: Experimental shell correction energies (circles and dots connected with solid line) compared to current predictions, lower panel: experimental fission barriers (dots connected with solid line). The liquid drop barrier is indicated a solid line [14].

The shell correction energies for element 104, rutherfordium, and above are as high as 4 MeV and increase up to 5 MeV for element 108, hassium. The fission barriers are in excess of 5 MeV for the region spanning uranium to hassium. The half-lives decrease by many orders of magnitude from uranium to hassium due to the decreasing thickness of the fission barrier.

Figure 4 clearly demonstrates that the trans-actinide elements, starting with 104 and above, exist due to shell stabilization. The macroscopic fission barrier has already dropped below 1 MeV at Z=104 and below 0.5 MeV at Z=106, close to the zero-point energy. These results motivated new theoretical studies of the transition region between the transuranium nuclei and the superheavies, such as the microscopic–macroscopic calculations by Möller and Nix [17]. They show a region of large shell correction energies up to 7 MeV, centred at ^{270}Hs, Z=108 and N=162, with a hexadecapole deformation. These results are schematically depicted as a composite background over which the nuclear chart showing the known nuclides is overlaid (Fig. 6). The longest half lives near the centre of the island are of the order of tens of seconds. Most interestingly, nuclides at the borderline of the blue coloured shell region exhibit fission, whereas the known nuclides at the centre undergo α-decay. Therefore many observed α-decay chains, *e.g.* from ^{266}109, are likely to terminate by spontaneous fission which is the expected signature while moving away from the “island of stability”.

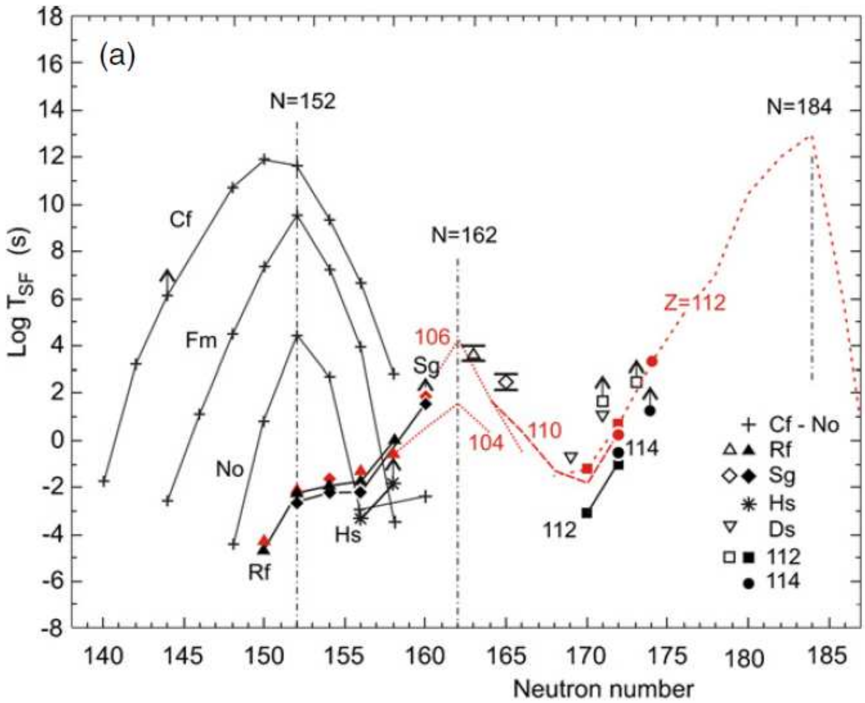

Fig. 5 – Partial half-lives for spontaneous fission $T_{(SF)}$ (s) *versus* the neutron number for the isotopes of elements Z = 98 to Z = 114, solid symbols and crosses: even – even nuclei, open symbols even – odd nuclei [18].

The actinides have long fission half-lives due to their thick liquid drop dominated barriers. Fig. 5 shows their fission half-life systematics [18] against the (deformed) N=152 shell gap indicated by the vertical dotted line. The shell stabilised region centred at N=162 (deformed) bridges the gap between the trans-uranium region and the (spherical) super heavy nuclei at N=184.

Recently, the chemical elements up to Z=118 have been discovered [18] as shown in the nuclear chart, Fig. 6. The magic proton number Z=114 has already been crossed but the spherical superheavies have not been found yet, possibly as the “magic” neutron number at N=184 is still far away. So the quest for the spherical SHE is still on [19, 20]. The idea that superheavy nuclei exist, only by shell stabilization in a region of vanishing liquid drop stabilization has been upheld with the discovery of the deformed shell nuclei around ^{270}Hs. The way had been paved by the cold fusion of massive nuclear clusters confirming the theoretical model of A. Sandulescu.

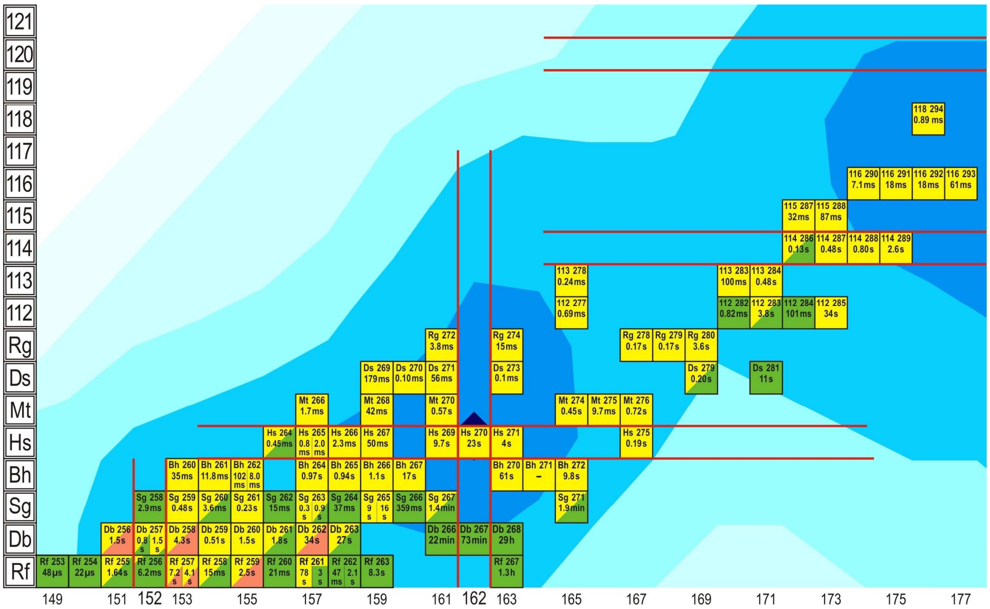

Fig. 6 – Chart of the transactinide region superimposed on the calculated shell correction energies [20].

3. PROSPECTS AND OUTLOOK

Presently, although 118 chemical elements are known, a more detailed knowledge of the properties of trans-actinide elements is scarce. Nuclear structure, atomic-, and chemical properties are in need of further exploration. The spherical superheavies have not yet been found. It is not even clear where they may be located. Microscopic–macroscopic models predict Z=114 and N=184 as magic numbers, while self-consistent calculations predict Z=120 or even Z=126 [21] with weaker shell closures around N~174 [22]. Most theories agree that N=184 will be a region of extra stability.

The general problem for all theoretical models is to predict a shell gap for the superheavy nuclei with large shells carrying large angular momenta. The very pronounced shell gap as observed in ^{208}Pb can hardly be expected for such heavy nuclear systems.

New experimental developments will have to include intensity upgrades of the accelerators to allow more detailed investigations of SHE. New reactions such as transfer or deep inelastic reactions need to be investigated at low cross sections to search for neutron-rich heavy nuclei. Nuclear clusters may help here to create the spherical SHE.

These developments require the planning and design of a new generation of in-flight separators with increased background suppression and an added option for mass resolution. These questions are already being addressed through a Giessen-

GSI-Manipal collaboration aimed at providing a conceptual design for the next generation separator. It is believed that such a separator will greatly aid the synthesis of very heavy and superheavy nuclei produced not just by complete fusion but also by the inelastic collision of massive nuclei.

REFERENCES

1. U. Mosel, W. Greiner, Z. Phys. 222, 261-282 (1969).
2. W. J. Swiatecki, S. Bjornholm, Physics Reports, 4, 325–342 (1972).
3. W. J. Swiatecki, Nucl. Phys. A376, 275-291 (1982).
4. Yu. Ts. Oganessian, Lecture Notes in Physics 33, 221-252 (1974).
5. A. Sandulescu, R. K. Gupta, W. Scheid, W. Greiner, Phys. Lett. 60B, 225-228 (1976).
6. Yu. Ts.Oganessian, Nucl. Phys. A239, 157-171 (1975).
7. Yu. Ts. Oganessian *et al.*, Nucl. Phys. A273, 505- 522 (1976).
8. V. E. Viola Jr., A. C. Mignerey, H. Breuer, K. L. Wolf, B. G. Glagola, W. W. Wilcke, W. U. Schröder, J. R. Huizenga, D. Hilscher, J. R. Birkelund, Phys. Rev. C22, 122–127 (1980).
9. G. Münzenberg, P Armbruster, W. Faust, K. Güttner, F.-P. Heßberger, S. Hofmann, W. Reisdorf, C. C. Sahm, K.-H. Schmidt, H.-J. Schött, B. Thuma, D. Vermeulen, Isotope identification in the transfermium region by $\alpha-\alpha$ correlation after in-flight separation, *Actinides in Perspective*, Ed. N. E. Edelstein, Pergamon, Oxford, 223-243 (1981).
10. A. Ghiorso, M. Nurmia, J. Harris, K. Eskola, P. Eskola, Phys. Rev. Lett. 24, 1317-1320 (1969).
11. J. Randrup, S. E. Larsson, P. Möller, S. G. Nilsson, K. Pomorski, A. Sobiczewski, Phys. Rev. C13 , 229 -239 (1976).
12. G. Münzenberg, P. Armbruster, H. Folger, F.-P. Heßberger, S. Hofmann, J. Keller, K. Poppensieker, W. Reisdorf, K.-H. Schmidt, H.-J. Schött, M. E. Leino, R. Hingmann, Z. Phys. A317, 235-236 (1984).
13. G. Münzenberg, P. Armbruster, G. Berthes, H. Folger, F.P. Heßberger, S. Hofmann, K. Poppensieker, W. Reisdorf, B. Quint, K.-H. Schmidt, H.-J. Schött, K. Sümmerer, I Zychor, M. E. Leino, Z. Phys. A 324, 489-490 (1986).
14. G. Münzenberg, S. Hofmann, H. Folger, F.P. Heßberger, J. Keller, K. Poppensieker, W. Reisdorf, B. Quint, K.-H. Schmidt, H.-J. Schött, P. Armbruster, Z. Phys. A 322, 227-235 (1985).
15. P. Möller, J. P. Nix, At. Data Nucl. Data Tables 26, 165-196 (1981).
16. M. Dahlinger, D. Vermeulen, K.-H. Schmidt, Nucl. Phys. A376, 94-130 (1982).
17. P. Möller, J. R. Nix, At. Data Nucl. Data Tables 39, 213-223 (1988).
18. Yu. Ts. Oganessian, J. Phys. G34, R165–R 242 (2007).
19. S. Hofmann, G. Münzenberg, Rev. Mod. Phys. **72**, 733–756 (2000).
20. G. Münzenberg, M. Gupta, Production and Identification of Transactinide Elements, *Handbook of Nuclear Chemistry 2*, Eds. A.Vertes, S. Nagy, Z. Klencsar, 877- 923 (2011).
21. M. Bender, K. Rutz, P.-G. Reinhard, J. A. Maruhn, W. Greiner, Phys. Rev. C60, 034304 1-20 (1999).
22. Y. K. Gambhir, A. Bhagwat, M. Gupta, Ann. Phys. (New York), 320-429 (2005).