

## The importance of closed shell structures in the synthesis of super heavy elements

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**Abstract.** The importance of shell closures and gaps in the single-particle energies for protons and neutrons on the stability of elements beyond  $Z = 100$  will be described. Following the development of microscopic models with shell corrections, microscopic-macroscopic models predicted large gaps in the single-particle energy levels for protons and neutrons at  $Z = 102$ ,  $108$  and  $N = 152$ ,  $162$  for the same deformed shapes. Shell gaps for spherical shapes for  $N = 184$  and  $Z = 114$ ,  $120$  or  $126$  were also predicted to form an “Island of Stability” with very long half lives for fission and alpha decay. Cold fusion reactions involving beams of Ca to Zn and targets of stable  $^{208}\text{Pb}$  and  $^{209}\text{Bi}$  were pioneered at GSI and used to synthesize new elements for  $Z = 107$  to  $112$  and in Japan a new isotope of  $113$ . Hot fusion reactions between radioactive actinide targets and neutron-rich  $^{48}\text{Ca}$  beams were pioneered in JINR leading to the synthesis of new elements with  $Z = 113$  to  $118$ . Data on two neutron separation energies, spontaneous fission half lives and total half lives of super heavy elements showing the importance of reinforcement of the  $Z = 102$ ,  $N = 152$  and  $Z = 108$ ,  $N = 162$  single particle level gaps at the same deformation and  $Z = 114$ - $126$ ,  $N = 184$  shell gaps in the synthesis of super heavy elements  $107$  to  $118$  are presented along with the latest results on their synthesis.

By around 1965, eight new elements beyond U ( $Z = 92$ ) up to  $Z = 100$  had been discovered. Could one go further? Macroscopic models, like liquid drop models, at that time, predicted that nuclei beyond  $Z \approx 100$  could not be synthesized because beyond this  $Z$  the barrier against fission would go to zero and then nuclei would fission on a time scale  $T_{\text{SF}} \approx 10^{-19}$  s. Then came the introduction of microscopic models with shell corrections [1]. Macroscopic-microscopic models predicted large gaps in the single-particle energy levels for protons and neutrons for deformed shapes first for  $Z = 100$ ,  $N = 152$  [2] and then for  $Z = 102$ ,  $N = 152$  and  $Z = 108$ ,  $N = 162$  [3]. The reinforcement of the  $Z = 102$ ,  $N = 152$  and  $Z = 108$ ,  $N = 162$  level gaps at the same deformations provide the added stability to allow nuclei around these regions to have observable half lives (see Fig. 1). Calculations also predicted for  $N = 184$  and  $Z = 114$ ,  $120$  or  $126$  there were shell gaps for spherical shapes (for example, refs. 4-6). While all the calculations have predicted  $N = 184$  is a spherical closed shell for neutrons,  $Z = 114$ ,  $120$



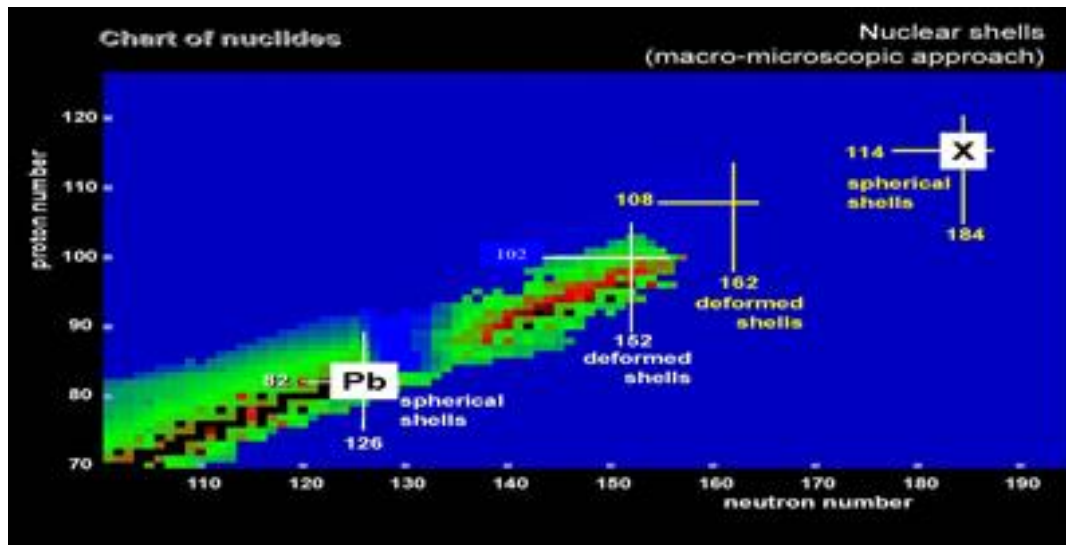


Figure 1. Chart of the nuclides showing the spherical gaps at  $Z = 82$ ,  $N = 126$  and predicted  $Z = 114$ ,  $N = 184$  and shell gaps for deformed shapes at  $Z = 102$ ,  $N = 152$  and  $Z = 108$ ,  $N = 162$

and 126 have been predicted in different approaches to be the next spherical closed shell for protons (for example, ref. 7-10). Earlier in macroscopic-microscopic calculations an "Island of Stability" was predicted around these spherical shell gaps where nuclei could have very long half lives for fission and alpha decay. In Fig. 2 are shown the single particle levels calculated in a microscopic-macroscopic approach for both neutrons (a) and protons (b) as a

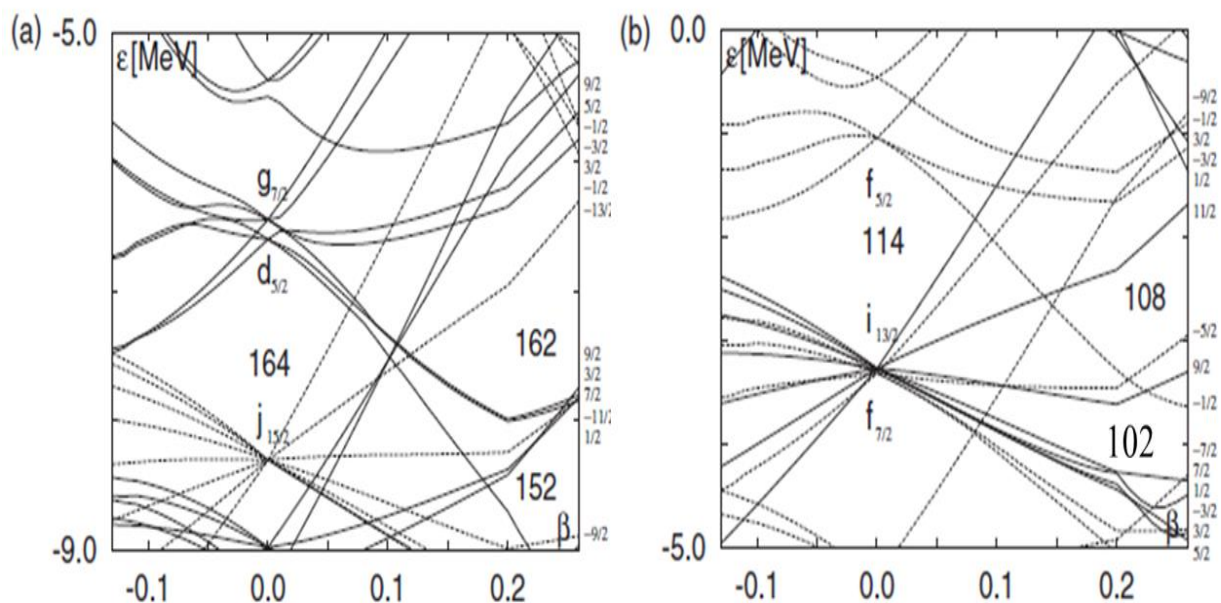


Fig. 2. Neutron (a) and proton (b) single particle energies with shell gaps seen at  $Z = 102$ ,  $108$  and  $N = 152$ ,  $162$  at  $\beta \sim 0.23$ .

function of deformation  $\beta$ . Note the occurrence of shell gaps for  $Z = 102$ ,  $N = 152$  and  $Z = 108$ ,  $N = 162$  all at the same deformation  $\beta \sim 0.23$ . The occurrence of these shell gaps at the same deformation reinforce each other to give added stability for these  $Z, N$  combinations. The importance of these gaps and their reinforcement will be seen in the experimental data presented later.

These theoretical predictions led to two approaches to synthesize new elements [11, 12, 13]. Cold fusion reactions involving beams of Ca to Zn and targets of stable  $^{208}\text{Pb}$  and  $^{209}\text{Bi}$  where the excitation energy was so low only one neutron was evaporated were pioneered at GSI in Germany. The velocity separator SHIP was used at GSI in these studies [11, 12]. These cold fusion reactions were used to synthesize new elements for  $Z = 107$  to 112 [11, 12] and in Japan a new isotope of element 113 [14]. Hot fusion reactions between radioactive actinide targets and neutron-rich  $^{48}\text{Ca}$  beams where 3 to 5 neutrons were evaporated were pioneered in Russia [11, 13]. The Dubna gas-filled recoil separator DGFRS was used in the Dubna work [11, 13]. These reactions led to the synthesis of new elements with  $Z = 113$  to 118. The reactions and new elements synthesized in these two approaches and the elements into which they decay are given in Fig. 3. Elements 114 and 116 have recently received names, *Florovium* and *Livermorium*, respectively.

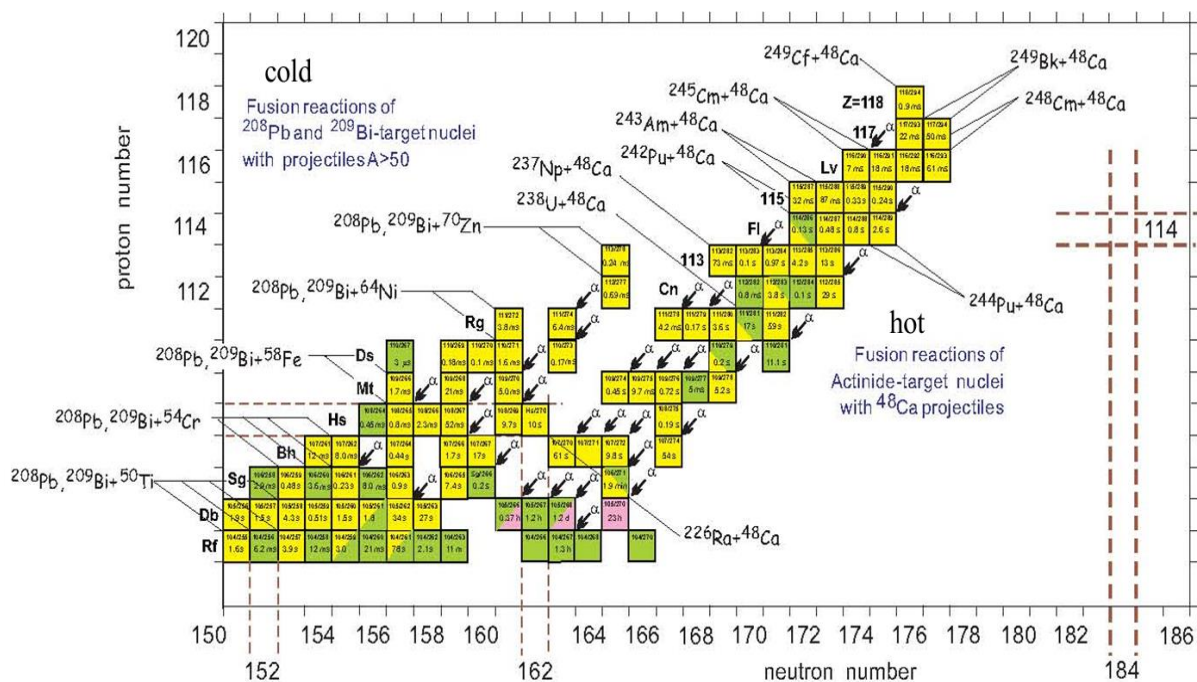


Fig. 3. Most known nuclei (as of 2013) and the reactions required for their production. For each known isotope, the element name, mass number, and half-life are shown. The relatively neutron-deficient isotopes of the elements up to  $Z = 113$  were created in cold fusion reactions. The more neutron-rich isotopes of elements 112-118 were produced in hot fusion reactions. Spherical closed shells for  $Z = 114$  and  $N = 184$  are shown. The bold dashed lines indicate nuclei with increased stability due to large gaps between the single particle energy levels at  $Z = 108$  and  $N = 152$  and  $162$ .

In recent experiments, definitive evidence for the synthesis of the new elements 113, 115 and 117 have been published [15, 16, 17, 18]. The Dubna, Oak Ridge, Vanderbilt, Livermore, Reactor Institute Collaboration carried out two sets of experiments of the  $^{243}\text{Am} + ^{48}\text{Ca}$  reaction from November 2010 – February 2012 at five beam energies to observe 28 new events of  $^{288}\text{115}$ , and five of a new isotope  $^{289}\text{115}$ , to firmly establish the earlier report of the synthesis of elements 115 and 113. The  $^{289}\text{115}$  is especially important because this isotope is likewise observed in the  $^{249}\text{Bk} + ^{48}\text{Ca}$  reaction to synthesizing the isotope  $^{293}\text{117}$  which alpha decays to  $^{289}\text{115}$ . The agreement of these two reactions provides cross-bombardment evidence for the discoveries of 117, 115 and 113. Subsequently, a group using the new TASCA separator at GSI also observed 22 decay chains of  $^{288}\text{115}$  in the  $^{243}\text{Am} + ^{48}\text{Ca}$  reaction [17] with the same decay properties as the 31 chains seen in Dubna to provide independent laboratory confirmation of the new elements of 113 and 115. Studies of the  $^{249}\text{Bk} + ^{48}\text{Ca}$  reactions were repeated in Dubna to yield 11 new events of  $^{293}\text{117}$  and 3 of  $^{294}\text{117}$  and repeated at TASCA to yield two new similar  $^{294}\text{117}$  decay chains [18] to provide independent confirmation of element 117.

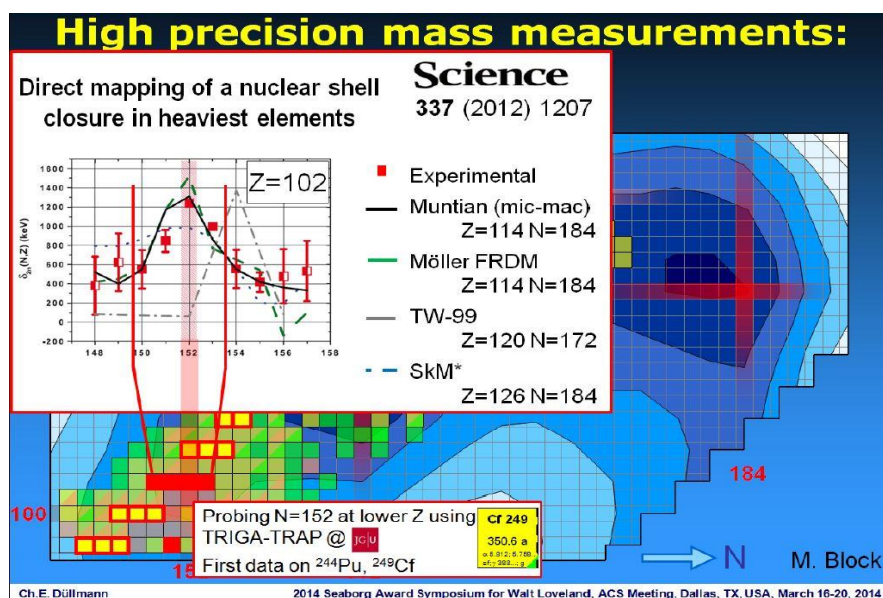


Fig. 4. The two neutron separation energies as a function of  $N$  for  $Z = 102$ . The strong increase at  $N = 152$  demonstrates the importance of this shell closure as it is reinforced by the  $Z$  shell closure

Fig. 4 shows evidence for the double shell gaps at  $Z = 102$  and  $N = 152$  where the two neutron separation energy strongly peaks at  $N = 152$  for  $Z = 102$ . In Figure 5 is shown the partial half lives for spontaneous fission vs.  $N$ . Note the strong peaks, longer half lives, for all  $Z$  for  $N = 152$ , 162 and approaching  $N = 184$ . The  $\alpha$ -decay half lives likewise show a strong increase as  $N$  increases toward  $N = 184$  (see Fig. 6). The rapidly increasing half lives for  $Z = 111, 113, 115$  and  $117$  as a function of  $N$  support the predictions of a long-lived “Island of Stability” around  $N = 184$ .

We see the synthesis of new elements beyond  $Z = 100$  are strongly dependent on both the neutron and proton shell structures, in particular, the reinforcing shell gaps for deformed shapes for  $Z = 102, N = 152$  and  $Z = 108, N = 162$  and the strong spherical gap at  $N = 184$



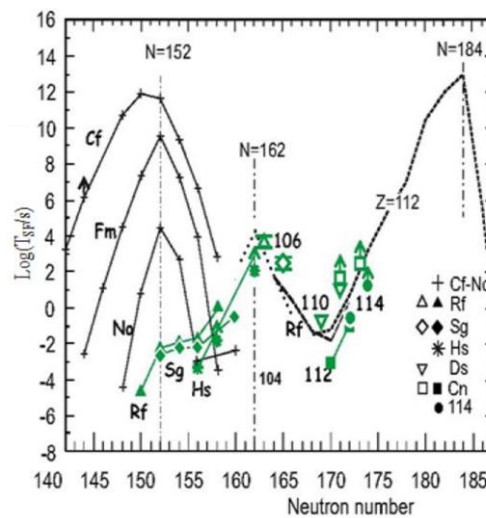


Figure 5. Spontaneous fission half-lives versus  $N$ . The solid symbols and crosses denote even-even nuclei; open symbols denote even-odd nuclei. Solid lines are drawn through the experimental points of even-even nuclei. The dashed lines represent theoretical calculations. Abbreviation: SF, spontaneous fission.

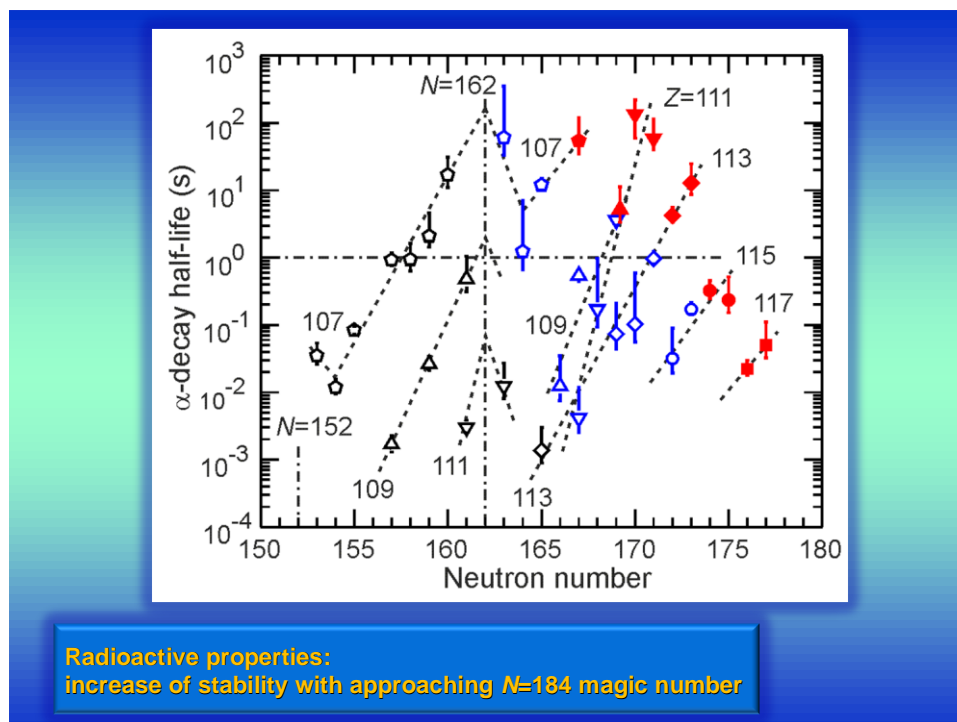


Figure 6. Alpha decay half lives as a function of  $N$ .

where the next spherical shell closure for  $Z$  is yet to be determined. There is little evidence it is for  $Z = 114$ . Recent theoretical studies indicate it will be for  $Z \geq 120$  [9]. Efforts at

TASCA to synthesize element 119 in the  $^{249}\text{Bk} + ^{50}\text{Ti}$  reactions yielded only an upper limit of 70 Femto barn for the production cross-section. The FLNR laboratory is in the process of building a SHE facility that should produce up to 1000 SHE in less than a year. This new facility can provide the opportunity to synthesize new elements 119 and 120 despite their very low production cross-sections.

“The discoveries of the new elements from 107 to 112 in cold fusion and from 113 to 118 in hot fusion are now well established. Cross-bombarded verification, measurements of excitation functions and reproducible results at different laboratories were all important in establishing these discoveries.

From the properties of the heaviest nuclei and their decay products with  $Z = 104\text{--}118$  and  $N = 153\text{--}177$  covering a mass range  $A = 257\text{--}294$  (given in Fig. 3) one sees that for nuclei having  $Z$  40% larger than that of Pb, an impressive extension in nuclear survivability is observed. Although SHE are at the limits of Coulomb stability, shell stabilization lowers the ground-state energy, creates a fission barrier, and thereby enables SHE to exist. The basic theoretical concept of the existence of closed shells in the region of the hypothetical super heavy nuclei and their decisive role in determining the limits of nuclear mass has received clear experimental verification” [11].

### Acknowledgement

J.H.H.’s work at Vanderbilt University was supported by the US Department of Energy through grant DE-FG-05-88ER40407. S.H.’s was supported by the Helmholtz Association through a Helmholtz Professorship. We acknowledge the support of the Russian Foundation for Basic Research through grants 11-02-12050 and 11-02-12066.

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