Chapter 10

SuperHeavy Elements

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Abstract: The long quest to detect SuperHeavy Elements (SHEs) that might exist in nature or to artificially synthesize them at accelerators or in multiple-neutron capture reactions is briefly reviewed. Recent reports of the production and detection of the SHEs 114, 116, and 118 are summarized and discussed. Implications of these discoveries and the prospects for the existence and discovery of additional SHE species are considered.

Keywords: SHEs, searches in nature, transactinides, elements 114,116,118, multiple-neutron capture reactions, nuclear reactions

10.1 EARLY PREDICTIONS OF SUPERHEAVY ELEMENTS

The possibility of relatively stable elements well beyond uranium, the heaviest element found in large quantities in nature, was considered in the early 1950s. This interest was sparked by the totally unexpected discovery of the new elements 99 (einsteinium) and 100 (fermium) in debris from the first U. S. thermonuclear device "Mike", tested on Eniwetok Atoll in the South Pacific on November 1, 1952 by the Los Alamos Scientific Laboratory. Prior to that discovery, only the elements through californium (atomic number 98) were known. Scientists postulated that the enormous, nearly instantaneous high neutron flux generated in the 15-megaton detonation of Mike resulted in the successive capture of at least 17 neutrons in the uranium-238 (^{238}U) present in the device. In this way, the heavier uranium isotopes through ^{255}U were produced and many of these isotopes decayed rapidly by successive emission of negatively charged β-particles to produce isotopes of known elements with atomic numbers of 93 through 98. The uranium isotopes of masses 253 and 255 decayed all the way to the new elements having proton numbers of 99 and 100 and mass numbers of 253 and 255 as shown in the schematic diagram in Figure 1.

Figure 1. Schematic diagram of production of heavy uranium isotopes by successive neutron captures in uranium-238 followed by their subsequent β-decay to spontaneously fissioning or α-decaying nuclides. Mass chains detected in debris from the Mike thermonuclear test are shown.

Publication (Ghiorso *et al*. 1955) of these 1952-53 discoveries of elements 99 and 100 by Berkeley, Argonne and Los Alamos scientists was delayed until after the data were declassified in 1955. During that same year John A. Wheeler published (Wheeler 1955) a paper on nuclear fission and nuclear stability in which he extrapolated the rates of spontaneous fission (SF) and other processes limiting nuclear stability to the region of very large masses. In a talk presented at the 1955 International Conference on the Peaceful Uses of Atomic Energy (Wheeler 1956) he showed a diagram of the estimated limits of nuclear stability within which half-lives would be greater than a ten-thousandth of a second. Although he cautioned that his extrapolations might be appreciably in error, he still concluded that it was reasonable to look for nuclei with masses perhaps twice as heavy as $^{256}100$, the heaviest nucleus known at the time, i.e., masses of 500 or more! He further suggested that massive neutron irradiation of existing heavy nuclides might be an appropriate method for building such superheavy nuclei. The possible existence of superheavy elements was also discussed by Gertrude Scharff-Goldhaber (Scharff-Goldhaber 1957). She speculated that there might be another region of relative stability around $^{310}126$ because it might be expected to have two especially stable, spherical closed nuclear shells (similar to closed electron shells). These spherical shells, or "magic" numbers as they are often called, were thought to be at proton number 126 and neutron number 184, thus making $^{310}126$ a "doubly magic" nucleus. Such ideas spurred the quest to produce still heavier elements in subsequent thermonuclear tests.

Indeed, the rather long-lived isotope ^{257}Fm (half-life = 100 d) was detected in later nuclear tests, indicating capture of at least 19 neutrons in uranium. But, attempts to produce and detect still heavier elements in underground nuclear tests conducted at the Nevada Test Site all failed, thus dashing hopes that heavier long-lived elements could be produced via this multiple neutron-capture process which it had been postulated might "mimic" production of heavy elements in astrophysical processes. These unsuccessful attempts were reviewed by R. W. Hoff (Hoff 1978) at a symposium held at Berkeley in 1978 to commemorate the 25th anniversary of the discovery of elements 99 and 100. He postulated that the neutron fluxes were high enough to have produced masses heavier than 257, but the measured SF half-lives of 0.4 ms for ^{258}Fm and 1.5 s for ^{259}Fm were so short that formation of masses heavier than 257 by additional neutron capture was effectively blocked. It was suggested that perhaps the very neutron-rich, long-lived ($T_{1/2}$~9700 years) nuclide, ^{250}Cm, formed in rather large quantities in these tests, might be recovered afterward. It could then be used as target material to produce SuperHeavy Elements (hereafter in this chapter to be called **SHEs**) by bombardments at accelerators with projectiles as heavy as ^{238}U.

Myers and Swiatecki (Myers and Swiatecki 1966) in 1966 and Meldner in 1967 (Meldner 1967) predicted that an "Island of SuperHeavy Elements" well beyond uranium might exist around elements with atomic numbers 114 or 126. This raised the possibility that very long-lived SHEs might still exist on earth after having been formed during the last nucleosynthesis in our solar system some 5 billion years ago. Later theoretical studies based on new theories of nuclear structure (Strutinsky 1966, Nilsson *et al.* 1969a, Fiset and Nix 1972, Randrup *et al.* 1974) confirmed that an island of nuclear stability stabilized by spherical nuclear shells should be centered around 110 to 114 protons and 184 neutrons. These calculations led to the conclusion that these spherical closed nuclear shells or "magic numbers" should be nearly as strong as those at 82 protons and 126 neutrons found in doubly magic, stable (non-radioactive) lead-208, the most abundant isotope of naturally occurring lead. Some calculations even indicated that element 110 with 184 neutrons (^{294}110) should be the longest-lived with a half-life in the range of hundreds of thousands to a billion years as shown in the contour plots (Fiset and Nix 1972, Randrup *et al*. 1974) in Figure 2.

Figure 2. Contour plots of predicted half-lives of SHEs as a function of proton and neutron number according to: a) Fizet and Nix 1972 and b) Randrup *et al*.1974.

These elements near the predicted islands of nuclear stability around the spherical closed shells at proton numbers 110 to 114 (or even 126) and 184 neutrons are typically referred to as SHEs. Although arguments have been made (Armbruster and Münzenberg 1989) that the heavy elements that would not exist except for stabilization by nuclear shells, whether or not they are spherical, should be designated as SHEs, the term has usually been reserved for those elements in the region of the predicted spherical doubly magic nuclei.

A 1968 periodic table with the "superactinide" series proposed by Glenn T. Seaborg (Seaborg 1968) is shown in Figure 3. Seaborg stated that in placing what he called the "Superactinides" at the bottom of the periodic table under the lanthanides and actinides, he had tried for simplicity's sake to conform as nearly as possible to the current form of the periodic table. This 32-member "superactinide" series would begin with element 122 and end with element 153 after filling of the $5g^{18}$ and $6f^{14}$ electronic shells, perhaps in mixed electronic configurations. However, Seaborg cautioned that complications from intruding *7d* and *8p* electrons might also occur and cause deviations from this picture and from the predominantly trivalent character expected for this superactinide series. The predicted SHE with atomic number 126 would be a member of this series. A few examples of some of the early searches for SHEs in nature and at accelerators will be described in the next sections of this Chapter and are discussed in much more detail by Hoffman, Ghiorso, and Seaborg in the Transuranium People: The Inside Story (Hoffman *et al*. 2000).

Figure 3. Representation of Glenn T. Seaborg's "conventional" form of the periodic table showing predicted location of new elements, including Superactinides, in parentheses.

10.2 EARLY SEARCHES FOR SHES

10.2.1 In nature

Among the earliest searches for SHEs in nature were those conducted at Berkeley between 1968 and 1972 by S. G. Thompson's group (Nilsson *et al*. 1969b, Cheifitz *et al*. 1972). Searches were begun in natural ores for element 110 as eka-platinum and elements 111 through 114 as eka-gold, -mercury, -thallium, and -lead. Initially, they looked specifically for eka-platinum, element 110**,** using low background counting techniques and sensitive analytical methods. Among the most sensitive measurements are those based on evidence of SF decay. This process is very rare among the known naturally occurring radionuclides, and even if SHEs decay by other modes, they were expected to end in SF. The results of the searches were negative, corresponding to a concentration of $<10^{-11}$ g/g. Later, they used their very high efficiency, large liquid scintillator system in an attempt to measure the high multiplicity of neutrons predicted (Nix 1969) to be emitted during the SF of spherical SHE isotopes in the region of element 114. In order to reduce effects from cosmic-ray background, they placed their detector some 250-m deep in a cross passage inside the Bay Area Rapid Transit (BART) system tunnel then under construction between Berkeley and Orinda, California. More than 40 large samples of ores, natural minerals such as galena and gold nuggets, manganese nodules from the ocean floor, moon rocks, and placer platinum were surveyed**,** but they found no evidence for increased neutron emission. Assuming a half-life of a billion years, they set a limit of $<10^{-14}$ moles of SHEs per mole of sample.

In 1969, G. N. Flerov and coworkers (Flerov and Perelygin 1969) in Dubna, Russia reported detecting fission tracks in lead glass which they attributed to the possible decay of SHEs. Based on additional observations of fission events in lead ore samples, they concluded they had found SF events with an apparent half-life of 4×10^{20} years that they attributed to SHEs. However, other researchers (Price *et al*. 1970) were not able to observe any fission tracks in old lead- and gold-rich minerals and set lower limits that were in contradiction with the Flerov results.

G. Hermann (Herrmann 1974) published a review of early searches for SHEs in nature and concluded that no positive results had yet been obtained in either terrestrial or extraterrestrial samples, although many extremely sensitive methods had been developed and used in the search.

In 1976, R. V. Gentry and others (Gentry *et al*. 1976, Fox *et al.* 1976) reported evidence for element 126 and possibly elements 116, 124, and 127 in several "Giant Halos" found in mica samples. Gentry suggested that these giant halos had to be caused by 12- to 14-MeV α-particles, much higher than the known members of radioactive decay series, and might have been produced by SHEs. Measurements of miniscule samples containing a single giant halo were bombarded with low energy protons and the induced X-rays were measured. These so-called "PIXIE" measurements indicated L X-rays at the appropriate energies for the SHEs 126 and possibly 116, 124, and 127 as well. These results created great excitement and elation in the community and, at first,

it appeared that at last there was some firm physical evidence for SHEs. Unfortunately, the "X-rays" turned out to be nuclear gamma-rays induced in cerium-praseodymium isotopes present in the inclusions, and yet another discovery disappeared.

10.2.2. At accelerators

First attempts to produce SHEs "artificially" were also conducted at Berkeley in 1968 by S. Thompson and Al Ghiorso and co-workers (Thompson 1968, Bowman 1968). They used reactions of heavy ion projectiles with heavy actinide targets, e.g., $^{40}Ar + {}^{248}Cm \longrightarrow {}^{288}114$ followed by neutron emission. No SHEs were detected and only limits could be set on the production cross sections and half-lives.

A. Marinov *et al.* (Marinov *et al.* 1971a) published an article in *Nature* in January, 1971, claiming production of element 112, eka-mercury, after they observed SF events in a mercury fraction chemically separated from the products of a long irradiation of tungsten with 24-GeV protons. The production mechanism was presumed to be secondary reactions with suitable targets of the heavy recoil products from the interactions of the high-energy protons. Later experiments showed (Marinov *et al.* 1971b) that some 70% of the observed SF activity was due to contamination from ^{252}Cf, and subsequent attempts by members of the group to repeat the initial results were unsuccessful. Subsequent more sensitive experiments (Batty *et al.* 1973, Bimbot *et al.* 1971) also proved to be negative.

In 1972, Flerov and Oganessian (Flerov and Oganessian 1972) reported detecting SF activity with a half-life of about 150 days in sulfide fractions containing osmium and bismuth separated from the products of long bombardments of ^{238}U with a variety of ions as heavy as ^{136}Xe. However, the average number of neutrons per fission was typical of actinides rather than SHEs so, again, another report seemed unlikely. Attempts were initiated to try to produce SHEs in uranium + uranium collisions at the UNILAC in Darmstadt, Germany and in reactions of ^{48}Ca projectiles with ^{248}Cm at the SuperHILAC at Berkeley, but no positive results were obtained.

10.3. SUMMARY OF RESULTS TO 1978

The quest for SHEs continued in spite of the negative results, and in 1978 a large International Symposium on Superheavy Elements (Lohdi 1978) was held to assess the results and to consider future experiments. Most of the researchers working in the field and many other interested scientists attended. Some 15 countries and 50 different institutions were represented. The results of both searches in nature and attempts to synthesize SHEs were summarized. The quest had been extended by Anders and co-workers (Anders *et al*. 1975) to investigations of anomalous stable xenon ratios arising from fission of SHEs in meteorites, but the results were model dependent and controversial. The detection of neutrons from SF found in separated samples of hot

springs water from the Cheleken Peninsula by Flerov and his group (Flerov 1977) was non-specific as pointed out by D. C. Hoffman (Hoffman 1978, Hoffman *et al*. 1980) and remained inconclusive. Investigations of the reaction of ^{48}Ca with ^{248}Cm at Berkeley (Hulet *et al*. 1977, Otto *et al*. 1978, Illige *et al*. 1978) continued to prove fruitless, and resulted only in pushing the limit on the production cross section still lower to 0.1 nb. At the UNILAC at Darmstadt, Herrmann and colleagues (Herrmann 1982) utilized their unique uranium beams to bombard uranium targets, but also to no avail, although he predicted that the planned increases in fluence levels would permit reaching cross sections as low as 0.01 nb. In the closing summary of the Superheavy Elements Symposium, G. A. Cowan (Cowan 1978), suggested using uranium beams to bombard ^{248}Cm, or even ^{250}Cm, recovered from underground nuclear tests. The conclusion was that there was still no positive evidence for the discovery of SHEs either in nature or in the products of accelerator bombardments. With the reduction of most of the half-life predictions from 10^9 down to 10^4 years or even only a year depending on estimates of SF half-lives, most plans for future attempts to find SHEs were focused on production at accelerators.

10.4. SEARCHES FOR SHES SINCE 1978

Subsequent to 1978, a large collaboration (Armbruster *et al*. 1985) of nuclear scientists, both chemists and physicists, from groups in the USA, Germany, and Switzerland conducted an exhaustive "final" investigation of the reaction of ^{248}Cm with ^{48}Ca projectiles in 1982-83 first at the SuperHILAC at Berkeley, USA and then at the UNILAC in Darmstadt, Germany. The earlier attempts at Berkeley (Hulet *et al*. 1977, Otto *et al*. 1978, Illige *et al*. 1978) and Dubna (Oganessian *et al*. 1978) using bombarding energies corresponding to excitation energies of the compound system of 33 to 53 MeV had all been negative. Therefore, the new experiments were conducted with projectile energies between 16 and 40 MeV, close to the reaction barrier, in an attempt to keep the excitation energy as low as possible in order to minimize losses due to prompt fission. The results are shown in Figure 4. The recoil fragment separators, Small Angle Separator System (SASSY) at the SuperHILAC, Lawrence Berkeley Laboratory (LBL) and Separator for Heavy Ion Reaction Products (SHIP) at the Universal Linear Accelerator (UNILAC) at the Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany, were used to search for nuclides with half-lives as short as microseconds. In addition, both on-line and off-line radiochemical separation techniques were utilized to search for species as short as a few seconds and as long as years. But, again, no evidence was found for SHEs with production cross sections larger than 0.1nb to 0.01 nb over a half-life range of 1 microsecond to 10 years.

Figure 4. Upper limits (95% confidence level) for production cross sections of SHEs in the reactions of ^{48}Cm projectiles with ^{248}Cm targets (Armbruster *et al*. 1985). Curve 1) Results from SASSY; 2) Results from SHIP; 3) Results from the On-Line Gas Chromatography Apparatus (OLGA) for separation of volatile "Pb-like" species; 4) Results from the on-line cryogenic system for detecting volatile "Rn-like" species; 5) Results of search for "Pt-like" species using the on-line Automatic Rapid Chemistry Apparatus (ARCA); Results from off-line radiochemical separations: 6) Elements 112 through 116, volatile at temperatures up to 1000^{o}C ("Pb-like"); 7) Elements 112 or 114, volatile at room temperature ("Rn-like"); 8) Elements 108-116, ("Pt-like"), expected to form strong anionic bromide complexes in aqueous solution.

Searches for naturally occurring SHEs in Atlantis II hot brine reported by Flerov and coworkers (Flerov *et al*. 1979), by Halperin and co-workers (Halperin *et al*. 1981), and by Feige and coworkers (B. Feige *et al*. 1987) also all proved to be negative. By the end of 1987, no credible evidence for SHEs, either in nature or artificially produced, remained and the quest was essentially abandoned.

10.5. DISCOVERY OF ELEMENTS 107 THROUGH 112

Meanwhile, between 1981 and 1984, three new elements, bohrium (107), hassium (108), and meitnerium (109), were discovered. A timeline of the discovery of the transuranium elements is shown in Figure 5. They were produced (Münzenberg *et al*. 1981, Münzenberg *et al*. 1982a, 1982b) at the UNILAC using so-called "cold fusion" production reactions suggested by Oganessian *et al*. (Oganessian *et al.* 1975). Targets of doubly magic stable ^{208}Pb or nearby stable ^{209}Bi were bombarded with the

appropriate heavy-ion projectiles (e.g., enriched stable ^{54}Cr and ^{58}Fe ions). These "shell-stabilized" targets react with the stable projectiles to give a compound nucleus that is the sum of their proton and neutron numbers. The resulting compound nuclei are produced with much lower excitation energies than those resulting from "hot fusion" reactions in which unstable heavy actinide targets are used. These "cold" compound nuclei are much more likely to de-excite by emitting only a single neutron and thus have larger production cross sections because they are less likely to be destroyed by fission. The isotopes ^{262}107, ^{265}108, ^{266}109 of these elements were separated and identified using the in-flight Separator for Heavy-Ion reaction Products (SHIP), built at GSI under the direction of Peter Armbruster. The names and symbols hassium (Hs) for 107, bohrium (Bh) for 108, and meitnerium (Mt) for 109 were officially adopted for these elements along with rutherfordium (Rf) for element 104, dubnium (Db), formerly called hahnium (Ha) for element 105, and seaborgium (Sg) for 106 by the International Union of Pure and Applied Chemistry in August 1997 (CNIC 1997).

Figure 5. Timeline of discovery of transuranium elements.

Four different isotopes of element 110 have been reported by three different groups of scientists (Ghiorso *et al*. 1995a, 1995b, Hofmann *et al*. 1995, Lazarev *et al.* 1996) as evidence for discovery of this element. More details on these discoveries are given by D. C. Hoffman (Hoffman 1998). Ghiorso and co-workers reported evidence for a single atom of ^{267}110 produced in the ^{209}Bi(^{59}Co,n) reaction. After many improvements in the SHIP, S. Hofmann and coworkers (Hofmann *et al*. 1995a, 1995b, Hofmann *et al*. 1995c) reported evidence for ^{269}110 and ^{271}110 as well as for ^{272}111 and ^{277}112. These were produced in cold fusion reactions of lead and bismuth targets with ^{62,64}Ni and ^{70}Zn

projectiles. In 1996, Yu. A. Lazarev *et al.* (Lazarev *et al*. 1996) reported evidence for decay of a single event of the neutron-rich isotope ^{273}110 produced in the hot fusion reaction ^{244}Pu(^{34}S,5n). Recently, Hofmann *et al*. (Hofmann *et al.* 2002) reanalyzed their data and performed additional experiments to obtain more data for the isotopes of elements 110 through 112 to support their originally reported discoveries. As of 2002, names have not yet been approved for these elements. As discussed in Section 10.1, it has been proposed (Armbruster and Münzenberg 1989) that even though these isotopes of elements 107 through 112 are probably not spherical they should nevertheless qualify as superheavies since without stabilization from nuclear shells they would not exist. However, they have not been generally recognized as "true" SHEs.

One of the most significant things about the elements 107 through 112 is that they decay predominantly by α-emission rather than SF, contrary to earlier predictions. These discoveries helped to give scientists renewed hope that it would be possible to reach the predicted island of SHE stability around element 114. The newly discovered isotopes also helped to substantiate the theoretical model and calculations of A. Sobiczewski and his group (Sobiczewski 1997, Smolańczuk *et al*. 1995) at the Soltan Institute for Nuclear Studies in Warsaw that predicted a doubly magic deformed region of extra stability around proton number 108 and neutron number 162 in addition to the island of spherical stability around Z=114 and N=184.

10.6. REPORTS OF DISCOVERIES OF SHES (1999-2002)

After the discovery of element 112 in 1996, researchers at GSI attempted to produce element 113 but were unsuccessful. Extrapolation from their previous experiments with lead and bismuth targets led them to believe that the cross sections for producing the elements beyond 112 had dropped so low that they needed to further upgrade and increase the efficiency of their SHIP system before continuing the search.

Under the leadership of Yu. Ts. Oganessian, researchers from the Joint Institutes of Nuclear Research (JINR), Dubna, Russia and the Lawrence Livermore National Laboratory (LLNL) heavy element group used the Dubna gas-filled recoil separator to investigate production of heavier elements via the "hot fusion" technique. In bombardments of rotating ^{244}Pu targets with ^{48}Ca projectiles accelerated in the Dubna U-400 heavy ion cyclotron they found evidence for a single decay chain which they attributed to element 114 in data obtained from some 40 days of running time during November and December, 1998. This would correspond to a cross section of about 1 picobarn or less. Based on the bombarding energy of 236 MeV, which corresponded to the calculated maximum for the 3-n evaporation reaction, and the characteristics of the observed α-decay chain, they attributed the event to ^{289}114 formed via the ^{244}Pu(^{48}Ca,3n) reaction. They observed (Oganessian *et al.* 1999c) a long α-decay chain ending with SF of ^{277}108. The measured time intervals between the successive decays indicated the relatively long half-lives of about 20 s, 11 min, 1 min, and 11 min for ^{289}114, ^{285}112, ^{281}110, and ^{277}108, respectively. The half-lives they reported for ^{285}112

and ^{281}110 are about 100 times longer than the heaviest previously known isotopes of these elements that have 8 fewer neutrons. Evidence for ^{288}114 via the 4n out reaction was also observed. In similar experiments conducted in 1999, two additional chains attributed to ^{288}114 were detected, but the production of ^{289}114 could not be confirmed (Lougheed *et al.* 2000). The proposed decay chains for ^{288,289}114 are shown in Figure 6.

In mid-April 1999, a multinational collaboration also led by Oganessian, reported evidence for two events of ^{287}114 from the ^{242}Pu(^{48}Ca,3n) reaction using the Dubna electrostatic recoil vacuum separator VASSILLISSA. These results were published (Oganessian *et al.* 1999b) in July 1999.

Figure 6. Reported decay chains for ^{288,289}114 (Oganessian *et al.* 1999c, Lougheed *et al*. 2000). Measured time intervals between successive decays are given.

Figure 7. Reported [57] decay chain for ^{287}114 (Oganessian *et al*. 1999b). Measured time intervals between successive decays are given.

As shown schematically in Figure 7, in one event, a 10.29-MeV α-particle was followed 1.3 s later by SF, while in the other event an escape peak with an α-energy of only 2.31 MeV followed by SF was detected. The SF half-life can be estimated to be about 4.5 min from these two events which the authors cite as evidence that it is the same SF activity of about 1.4 min which they produced previously in the $^{238}U + ^{48}Ca$ reaction (Oganessian *et al.* 1999a) and attributed to $^{283}112$. Unfortunately, positive identification based on SF activity is extremely difficult and additional evidence for production of this isotope is needed. In 2000, the Dubna/LLNL collaboration reported evidence for the production of $^{292}116$ in the $^{248}Cm(^{48}Ca,4n)$ reaction (Oganessian *et al.* 2000, 2001). The published decay chain is shown in Figure 8.

Figure 8. Published decay chain for $^{292}116$ (Oganessian *et al*. 2000). Measured time intervals are given.

Bombardment of ^{208}Pb with 449-MeV ^{86}Kr projectiles to produce $^{293}118$ by a 1n out reaction was predicted by Smolańczuk (Smolańczuk 1999a, 1999b) to have a large production cross section and decay via a unique chain of six high energy α-emitters with rather short half-lives as shown in Table 1. In 1999, the reaction was investigated by researchers at LBNL using the recently completed Berkeley Gas-filled Separator (BGS) at the 88-Inch Cyclotron. Because of the odd neutron in these nuclides, the half-lives might be as much as a factor of ten longer than these predictions. Due to the very low excitation energy of only 13.3 MeV calculated for the compound nucleus, emission

of two neutrons is energetically forbidden, and single neutron emission is much more probable than alpha or proton emission from the compound nucleus. Ninov *et al.* (Ninov *et al.* 1999) reported finding three such decay chains with a cross section of a few picobarns in initial experiments conducted in April and May 1999, but upon re-examination of the original data these results could not be verified. Later experiments conducted in 2001 (Gregorich *et al.* 2002) showed no evidence for these decay chains and an upper limit of about 1 picobarn for production of this decay chain in the reaction of ^{208}Pb with 449-MeV ^{86}Kr projectiles was set.

TABLE 10.6.1. Smolańczuk predictions for ^{293}118 decay chain

$^{A}Z_{N}$	Q_α (MeV)	Half-lives
$^{293}118_{175}$	12.23	31 – 310 μs
$^{289}116_{173}$	11.37	0.96 – 9.6 ms
$^{285}114_{171}$	11.18	0.80 – 8.0 ms
$^{281}112_{169}$	11.00	0.61 – 6.1 ms
$^{277}110_{167}$	10.77	0.62 – 6.2 ms
$^{273}Hs_{165}$	9.69	0.12 – 1.2 s
$^{269}Sg_{163}$	8.35	8.0 – 80 min
$^{265}Rf_{161}$		T_{SF} ~ 41 min

10.7. FUTURE

There is now evidence for elements for three isotopes of element 114, $^{287\text{-}289}$114, and one of element 116, ^{292}116. Calculations (Smolańczuk 1997) indicate that these isotopes are nearly spherical with deformation energies ranging from only about 0.1 MeV for ^{292}116 to 0.2-0.3 MeV for the 114 isotopes, compared to zero deformation energy for the spherical doubly magic ^{298}114 and 7.8 MeV (Sobiczewski *et al.* 2001*)* for the doubly deformed magic nucleus, ^{270}108. Thus they qualify as spherical SHEs even though they do not have the full complement of 184 neutrons. Although confirmation of these recently reported new elements and isotopes is needed, they are shown in Figure 9 together with the previously known isotopes of Sg through element 112. The new isotopes near the doubly magic deformed region, ^{266}Bh and ^{267}Bh, produced (Wilk *et al.* 2000) at Berkeley in early 1999, are also included.

A 2002 periodic table showing the newly reported elements 114 and 116 is given in Figure 10. Of course, these reports of SHEs must be confirmed by other groups before they can be officially placed in the periodic table.

Figure 9. Isotopes of Sg (106) through element 116 reported as of mid-2002.

Figure 10. Periodic table of 2002. Elements yet to be confirmed are shown in parentheses.

Recent theoretical predictions (Smolańczuk 1997, 2001, Chasman and Ahmad 1997) indicate that isotopes with half-lives of microseconds or longer will exist all along the way to the predicted islands of stability shown earlier in Figure 2. A contour plot with all the isotopes reported in this "transition" region since then is shown in Figure 11. The predictions of half-lives for nuclei in the region of the island of stability

have decreased dramatically since the 1970s. For example Smolańczuk predicts that the spherical doubly magic superheavy nucleus ^{298}114 will decay predominantly by α-emission with a half-life of only about 12 min, but that ^{292}110 may α-decay with a half-life of about 50 years. Whether additional SHEs can be produced depends very much upon whether the cross sections for the "cold" fusion reactions in which only a single neutron is emitted and the "hot" fusion reactions with 3 or 4 neutrons emitted are large enough to permit detection. Cold fusion reactions such as ^{208}Pb or ^{209}Bi with ^{87}Rb or ^{86}Kr projectiles could produce ^{294}119 (Smolańczuk 1999b,1999c) whose half-life is estimated to be only microseconds. However, it is predicted to decay to the new longer-lived odd-Z elements 117, 115, and 113 via succession α-emission, ending with the known isotope 3.6-h ^{262}Lr. Production of ^{295}120 (~2 microsec) via the ^{208}Pb(^{88}Sr,1n) reaction and detection of its high-energy α-decay chain have been proposed (Smolańczuk 2001). Hot fusion reactions between ^{48}Ca projectiles and ^{249}Bk and ^{249}Cf targets to produce elements ^{293,294}117 and 118, respectively, are currently being investigated by the Dubna/LLNL group.

Figure 11. Plot of heavy element topology from 1978 showing some landing points for proposed reactions. New heavy element isotopes reported as of mid-2002 are indicated with symbols denoting the following half-life ranges: **+ = 0.1 ms to 0.1 s; o = 0.1 s to 5 min; ● = > 5 min.**

Some other recent calculations (Krupps *et al.* 2000) predict that the strongest spherical shell effects might be at Z=124 or 126 and N=184 while still others propose the maximum effect might be at Z=120 and N=172. Doughnut-like, toroidal shapes with lower density or a hole in the middle to alleviate the effects of Coulomb repulsion have even been postulated. How many more elements can exist is still unclear and it is

even more unclear how many of these we can actually produce. Reactions that can produce a higher ratio of neutrons to protons will certainly be most advantageous and need to be investigated. Myers and Swiatecki have suggested (Myers and Swiatecki 2000) that so-called "unshielded" reactions in which the Coulomb barrier is below the bombarding energy may result in enhanced production yields for some of the higher Z elements. Their hypothesis that the cross section for ^{277}112 produced in the symmetric reaction ^{142}Ce(^{136}CXe,n) might be much larger than that for the 112 discovery reaction ^{208}Pb(^{70}Zn,n)^{277}112 should be tested experimentally. If so, the unshielded reaction ^{170}Er(^{136}Xe,n) to make ^{305}122 which has 183 neutrons might be a method for getting closer to the spherical neutron shell. The nuclide is expected to decay by successive α-emission to the isotope ^{289}114, reported by the Dubna/LLNL group.

Although it now appears that many more relatively long-lived SHE species can exist, new production reactions, imaginative techniques for optimizing overall yields, and methods for "stockpiling" long-lived products for off-line studies must be devised if this exciting region is to be fully explored.