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Superheavy Elements: A Crossroads

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For the past 12 years many nuclear scientists from around the world have devoted a considerable fraction of their time and resources to an attempt to synthesize superheavy elements (SHE's)—elements with atomic (proton) numbers $Z \geq 110$. To date, the results of this quest have been negative. The time now appears ripe for a careful examination of the synthetic routes that have been explored and the prospects for future success along untested paths.

Summary. The failure to synthesize superheavy elements by using complete fusion reactions is most likely understandable in terms of the low survival probabilities of the superheavy precursors formed in these reactions or (in some cases) the failure to achieve complete fusion. Further attempts to synthesize these elements by using complete fusion or deep inelastic transfer reactions, or both, are discussed in light of these results.

In 1972 Thompson and Tsang (*1*) outlined the reasons for believing that a massive extension of the periodic table of the elements was possible through the production of SHE's. In this article we will comment briefly on current views of these expectations and summarize the results of attempts to synthesize SHE's by scientists in the United States, Europe, and the Soviet Union. This will be followed by an examination of some of the reasons why these attempts have failed. Finally, we will briefly discuss exciting new prospects for success in this quest that have been stimulated by recent experiments at the Gesellschaft für Schwerionenforschung (GSI) at Darmstadt, West Germany. We will close this survey by commenting on the past and expected future impact of this effort on nuclear chemistry and physics. Highly technical details will not be discussed, nor will the fascinating question of whether such elements or their decay products have been found in nature; for those wishing such information a number of excellent review articles and conference proceedings are available (*2, 3*).

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Background

For many years nuclear scientists believed that the periodic table had been extended nearly to its limit, defined as the point where the number of protons in the nucleus, and consequently the repulsion between them, becomes so large that the cohesive nuclear forces cannot hold the nucleus together and the nucleus therefore undergoes very rapid spontaneous fission decay. This idea was based on the observation of shorter and shorter spontaneous fission half-lives as the atomic number of the nucleus increased.

In the period from 1966 to 1972, a number of calculations (*2*) based on modern theories of nuclear structure showed that in the region of proton number $Z = 114$ and neutron number $N = 184$ the ground states of nuclei were stabilized against fission. This stabilization was due to the complete filling of major proton and neutron shells in this region and is analogous to the stabilization of chemical elements, such as the noble gases by the filling of their electronic shells. Some of these detailed calculations even suggested that the half-lives of some of these superheavy nuclei might be on the order of the age of the universe, and this stimulated a great effort to observe these "missing elements" in nature. The superheavy elements were predicted to form an island of relative stability extending both above and below $Z = 114$ and $N = 184$ and separated from the peninsula of known nuclei by a sea of instability (see Fig. 1).

Some more recent calculations (*4*), based on a careful consideration of the effect of mass asymmetry on the fission barrier and a reduced spin-orbit coupling strength, have indicated that the $Z = 114$ shell effect is not very large. These calculations do confirm the existence of a shell at $N = 184$, but also suggest less stability for species with $N < 184$; that is, the island of stability has a cliff with a sharp drop-off for $N < 184$, as shown in Fig. 2. If these considerations are correct, it would become considerably more difficult to synthesize and detect the SHE's.

During the period following the initial optimistic predictions, efforts began at Berkeley, Orsay, Dubna, and later Darmstadt to "jump the gap" between the peninsula of known nuclei and the predicted island of stability by fusing two heavy nuclei together in a nuclear reaction, thus synthesizing SHE's in the laboratory. These investigations, while failing to synthesize SHE's, appear to have provided insight into the relative stability of the SHE's and guidance for future research.

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Predicted Properties of the Superheavy Elements

Nuclear properties. Although theoretical calculations have indicated that nuclei around $Z = 114$ and $N = 184$ should be relatively stable, some estimates have attached more importance to the neutron shell at $N = 184$ and have indicated less importance for the $Z = 114$ shell (*4*). Some calculations (*5*) point to shell closure at $Z = 126$ and not at $Z = 114$, but the general consensus of such calculations (*2*) has supported the idea of shell closure at $Z = 114$. (As our considerations here will show, the synthesis of nuclei with Z as high as 126 seems to be beyond experimental reach.) These shells affect the synthesis of SHE's in two ways: (i) by determining whether any excited superheavy nucleus formed in a nuclear reaction will survive destruction by fission during its de-excitation process (by controlling the height of the fission barrier), and (ii) by determining whether any "cold" superheavy nucleus that survives its de-excitation will live long enough to be detected through its alpha or spontaneous fission decay. Contours showing the half-lives for decay by spontaneous fission and alpha-particle emission as calculated by Randrup *et al.* (*4*) (that is, the more recent "pessimistic" estimate) are shown in Fig. 2.

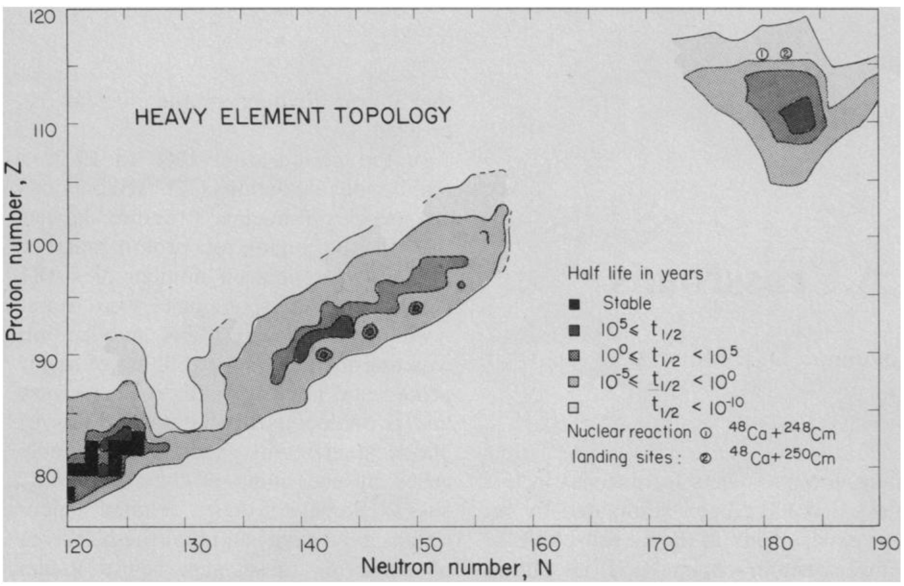

Fig. 1. Representation of the stability of nuclei [based on known and predicted (*6*) total decay half-lives], showing a peninsula of known elements and an island of predicted relative stability (nuclei near $Z = 114$ and $N = 184$) in a sea of instability. The positions of the initial composite species found in the $^{48}Ca + ^{248,250}Cm$ reactions are also shown to emphasize the large number of neutrons that must be added to reach the island of stability.

Table 1. Attempts to synthesize superheavy elements by using complete fusion reactions.

Reaction studied	Compound nucleus: A_z	Mean excitation energy (MeV)	Predicted survival probability	Observed upper-limit cross section for SHE production for indicated half-life (cm^2)	Reference
		Class 1: Compound nuclei with low survival probabilities			
$^{232}Th + ^{48}Ca$	$^{280}110$	44.5	10^{-21}	4×10^{-35} (>3 msec)	(*32*)
$^{231}Pa + ^{48}Ca$	$^{279}111$	34	10^{-17}	5×10^{-35} (76 minutes)	(*32*)
$^{233}U + ^{48}Ca$	$^{281}112$	33	0*	7×10^{-35} (20 hours)	(*32*)
$^{248}Cm + ^{40}Ar$	$^{288}114$	45	0*	10^{-30} (10^{-8} to 10^{-1} second)	(*33*)
$^{242}Pu + ^{48}Ca$	$^{290}114$	43.5	0*	10^{-35} (6 hours to 1 year)	(*17*)
$^{243}Am + ^{48}Cm$	$^{291}115$	41	0*	2×10^{-35} (6 hours to 1 year)	(*17*)
		Class 2: Small probability of forming compound nuclei			
$^{208}Pb + ^{84}Kr$	$^{292}118$	25.5	~0 (10^{-9})†	10^{-30} (>6×10^{-7} second)	(*34*)
$^{238}U + ^{68}Zn$	$^{306}122$	47	1.0	10^{-30} (10^{-9} second to 1 year)	(*35*)
$^{232}Th + ^{76}Ge$	$^{308}122$	32	1.0	10^{-34} (5 msec to 1 year)	(*36*)
$^{242}Pu + ^{68}Zn$	$^{310}124$	45	0.9	10^{-30} (10^{-9} second to 1 year)	(*35*)
$^{238}U + ^{76}Ge$	$^{314}124$	68	3×10^{-2}	10^{-33} (5 msec to 1 year)	(*36*)
$^{243}Am + ^{68}Zn$	$^{311}125$	39	0.9	2×10^{-32} (10^{-9} second to 1 day)	(*35*)
$^{246}Cm + ^{68}Zn$	$^{314}126$	34	0.3	10^{-30} (10^{-9} second to 1 year)	(*35*)
$^{232}Th + ^{84}Kr$	$^{316}126$	51	<10^{-14}	5×10^{-30} (>6×10^{-7} second)	(*34*)
		Class 3: Compound nuclei with possible survival			
$^{246}Cm + ^{48}Ca$	$^{294}116$	40	<5×10^{-16} (10^{-11})†	2×10^{-35} (6 hours to 1 year)	(*17*)
$^{248}Cm + ^{48}Ca$	$^{296}116$	44	<4×10^{-11} (10^{-5})†‡	5×10^{-35} (6 hours to 1 year)	(*13, 17, 18*)

* Nuclei whose survival rate is exactly zero represent cases in which some member of the neutron emission chain has a nonexistent fission barrier. †The cumulative survival rate for these nuclei up to the last step in the de-excitation process is given in parentheses. In the last step of the de-excitation process, the excitation energy is at or below the neutron binding energy and well above the fission barrier. The result of this circumstance is a fission catastrophe in which nearly all the nuclei fission. ‡See text for discussion.

As one can see from examining Fig. 2, several nuclides in the island are predicted to have total decay half-lives substantially greater than 10^{-7} year (~3 seconds). But note the precipitous decrease in spontaneous fission half-life (implying a decrease in the effective fission barrier height) as the neutron number decreases from $N = 184$ at a constant proton number. This trend in the fission barriers gives one a feel for the importance of forming superheavy nuclei with the lowest excitation energy and the largest value of N possible.

The greater instability of elements with $Z \sim 114$ toward alpha-particle decay (compared to decay by spontaneous fission) leads to the prediction that nuclei near $Z = 110$ and $N = 184$ should have the longest overall half-lives. According to the predictions summarized in Fig. 2, the total decay half-life of $^{294}110$ is $\sim 10^5$ years. The older, more optimistic prognostications (*6*) estimated the total decay half-life of this nucleus to be $\sim 10^9$ years.

In summarizing the uncertainty in these calculations, Bemis and Nix (*2*) asserted that the accuracy of these half-life predictions is $\sim 10^{\pm 10}$ for spontaneous fission half-lives and $\sim 10^{\pm 3}$ for alpha-decay and beta-decay half-lives. Because of the very long half-lives predicted for the most stable residents of the island of stability, a large error in the calculated half-lives could occur and still leave the possibility of forming detectable superheavy nuclei. However, this uncertainty also indicates that we may have to use techniques capable of detecting very short-lived nuclei in searching for SHE's. On the optimistic side, we should note that all the predicted nuclear properties refer to nuclei with even values of Z and N, but it is well known that nuclei with odd values of Z or N, or both, have higher fission barriers and longer spontaneous fission and alpha-decay half-lives.

Once formed, a superheavy element must give a unique signal in its decay in order to be easily distinguished from the many other products of the synthesis reactions. The high atomic number of the SHE might lead (*7*) to increased fission fragment kinetic energies (235 million electron volts for Z = 114 compared to 172 MeV for Z = 92), higher alpha-particle energies (7 MeV for Z = 114 compared to 4 MeV for Z = 92), and a very large number of neutrons emitted per fission event (10 for Z = 114 compared to 2.4 for ^{235}U). An international group of scientists have proposed criteria for the discovery of chemical elements (*8*) in which they insist that any claim to detection of a SHE must involve some proof concerning the atomic number of the new element. The aforementioned decay properties are general indicators of the formation of an element in the SHE category; detailed claims for the discovery of a particular SHE would have to be predicated on clear-cut establishment of the atomic number by such means as chemical separation or observation of characteristic x-rays.

Chemical properties. Among the most interesting aspects of the SHE's are their predicted chemical properties (*9*). The electronic properties of the elements are fairly well understood as the result of relativistic Hartree-Fock and Hartree-Fock-Slater calculations. The prediction of a chemical property such as the heat of vaporization on the basis of these electron configurations usually involves the judicious use of Mendeléev-like extrapolation of a smooth trend in the variation of the property among the members of a particular group in the periodic table (Fig. 3 shows the predicted position of the SHE's in the periodic table). Not surprisingly, most calculations predict chemical properties for the SHE's that are similar to those of their homologues; for instance, element 114 is characterized by a +2 oxidation state like its homologue lead. Pitzer (*10*) has pointed out, however, that because of relativistic effects the elements 112 (eka-mercury) and 114 (eka-lead) may, in fact, be very noble—that is, volatile gases or liquids.

Thus one must be cautious in predicting SHE chemical properties because of the importance of relativistic effects in determining their electron configurations. For example, the six $7p$ electrons are predicted to be split into two groups, four $7p_{3/2}$ and two $7p_{1/2}$ electrons, with the splitting between their energies being

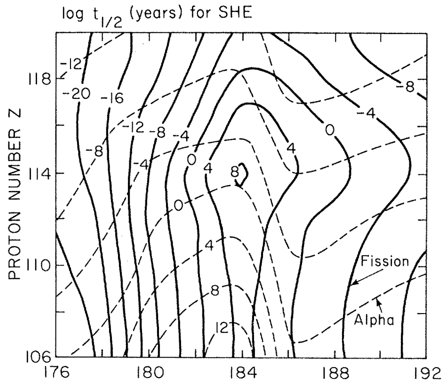

Fig. 2. Combined diagram of the predicted half-lives ($t_{1/2}$) of the superheavy nuclei with respect to spontaneous fission (solid lines) and alpha decay (dashed lines). [From Randrup *et al.* (*4*)]

such that the filled $7p_{1/2}{}^2$ orbital will act as a closed shell and additional $7p_{3/2}$ electrons will act as electrons outside a closed shell. As an example of this effect, element 115 (eka-bismuth) is predicted to have its valence electrons in the configuration $7p_{1/2}{}^2\,7p_{3/2}$ with a stable +1 oxidation state, in contrast to the stable +3 oxidation state of its homologue bismuth. Thus chemists are excited about this possibility of studying "relativity in a test tube."

Chemical separation methods for identifying the atomic numbers of any superheavy nuclei produced in laboratory syntheses, assuming that their half-lives might be sufficiently long (>1 second), have been devised on the basis of these predicted chemical properties. Separations based on the ion exchange behavior of the bromide complexes of the elements (*11*), the tendency of the elements to coprecipitate with cupric sulfide (*12*), and their volatility and ease of reduction (*13*) have been applied in attempts to synthesize and chemically identify SHE's.

Reported Attempts to Synthesize Superheavy Elements

Table 1 is a summary of recent attempts to synthesize SHE's in nuclear reactions, utilizing the complete fusion of two heavy ions. The energetics of the reactions, fission barrier heights, and neutron binding energies were taken from appropriate recent calculations (*14*). Since the sought-after SHE is initially produced as an excited compound nucleus, its survival requires the loss of its excitation energy by the emission of neutrons in competition with the much more probable fission process (which will destroy the superheavy nucleus if it occurs). A simple estimate of the survival rate of the superheavy nuclei formed in these reactions was made by using expressions for level densities of a Fermi gas, including consideration of the effect of angular momentum on SHE survival (*15*). [When two heavy nuclei collide, large amounts of rotational angular momentum (30 to 100 $\hbar$, where $\hbar$ is Planck's constant divided by 2π) are introduced into the system. The centrifugal forces that arise increase the probability of nuclear fission.]

In examining the data in Table 1, one should remember that the probability of producing a detectable superheavy nucleus is equal to the product of two factors: (i) the probability of initially getting the reacting heavy ions to fuse, or form a composite superheavy system, and (ii) the probability of the excited superheavy system formed in the nuclear reaction surviving its de-excitation process. The results summarized in Table 1 are grouped in three general classes.

Class 1. An attempt was made to fuse a heavy nucleus with a light ion to form a composite system with Z near 114. The survival rate—factor (ii) above—was so low as to preclude production and observation of superheavy nuclei.

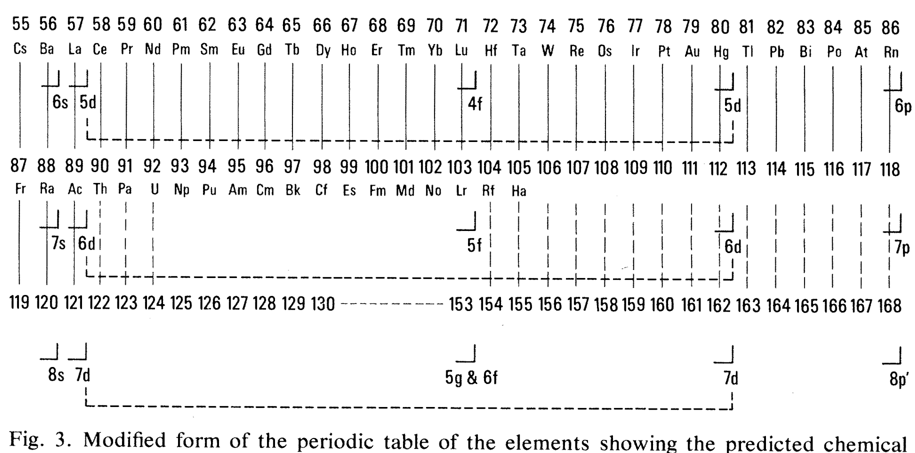

Fig. 3. Modified form of the periodic table of the elements showing the predicted chemical properties of the superheavy elements.

Class 2. An attempt was made to fuse a heavy target nucleus with a heavy ion projectile to form a composite system that "overshoots" the center of the island of stability and then, after de-excitation, decays by alpha and beta decay toward the center of the island of stability. Because of the large number of neutrons in the composite system (190 neutrons in the $^{76}Ge + ^{238}U$ reaction) in these reactions, the overall predicted survival rates of these species are very good. Despite extensive searches over a wide range of bombarding energies, projectile-target combinations, and product half-lives by scientists in the Soviet Union, there were no successful SHE syntheses and rather low upper limits were set on SHE production. There are very strong indications (*16*) that the initial fusion probability—factor (i) above—rapidly approaches zero as the Z of the heavy ion exceeds ~26. Thus no SHE's appear to be formed by these overshoot reactions. (In fact, if SHE's exist, the experimental upper limits on SHE production may serve as upper limits on the extent of complete fusion in these systems.)

Class 3. This is the intriguing case of the $^{48}Ca + ^{248}Cm$ system, in which both the fusion probability and the survival probability up to the poorly known last step in the de-excitation process are such that they might allow detectable quantities of superheavy nuclei to be formed. Unfortunately, a "fission catastrophe" in the last step of the de-excitation process leads to a prediction of a low overall survival rate.

Because of the promising character of the $^{248}Cm + ^{48}Ca$ reaction for synthesizing superheavy nuclei and the apparent failure of this reaction to do so, it behooves us to examine this system in greater detail to see why production of SHE's was not observed.

Why Were Superheavy Elements Not Seen in the $^{48}Ca + ^{248}Cm$ Reaction?

The reaction of $^{48}Ca + ^{248}Cm$ to produce SHE's has been extensively studied by groups at Lawrence Berkeley Laboratory, Lawrence Livermore Laboratory, and the Joint Institute for Nuclear Research, Dubna (*13, 17, 18*). The reacting heavy ion and the target nucleus were brought together at the minimum energy (about 20 MeV above the interaction barrier) thought to be necessary to cause complete fusion and, it was hoped, produce a composite system with some 40+ MeV of excitation energy. In the course of many carefully planned and ex-

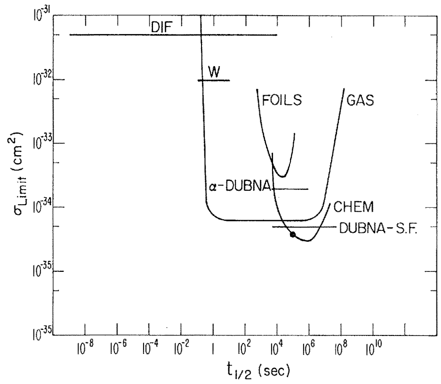

Fig. 4. Observed upper limits on the production cross section for superheavy elements produced in the $^{48}Ca + ^{248}Cm$ reaction. Labeling of curves is explained in the text. References: *CHEM*, *DIF*, *W*, and *FOILS* (*18*), *α-DUBNA* and *DUBNA-S.F.* (*17*), and *GAS* (examination of volatile products) (*13*).

ecuted experiments, upper limits for the production of SHE's (expressed as cross sections) were measured; these are summarized in Fig. 4. Superheavy products of these reactions were searched for by a variety of techniques, including (i) spontaneous fission decay in flight of the recoil superheavy nuclei (labeled *DIF* in Fig. 4), (ii) gas jet collection of the recoils followed by alpha-particle and spontaneous fission counting (*W*), (iii) direct counting of the stopped recoils for spontaneous fission activity (*FOILS*), and (iv) chemical separations of product nuclei based on their projected chemical properties followed by spontaneous fission and alpha-particle counting (*CHEM*, *α-DUBNA*, *DUBNA-S.F.*, and *GAS*).

What would we have expected the formation cross section for superheavy nuclei to be in this reaction? An estimate of the cross section for the fusion of ^{48}Ca and ^{248}Cm might be $\sigma_F \geq 10^{-27}$ square centimeters based on the observation (*19*) of the production of the complete fusion product $^{254}_{102}No$ with a cross section of 3×10^{-30} cm² from the similar $^{48}Ca + ^{208}Pb$ fusion reaction. Using the method of Table 1 to estimate survival probabilities, one calculates a survival probability of $\sim 10^{-5}$ for ^{254}No nuclei, implying a complete fusion cross section of $\sim 300 \times 10^{-27}$ cm². From this number and the systematics of complete fusion cross sections, we extrapolate a value of $\sigma_{CF} \geq 10^{-27}$ cm² for the $^{48}Ca + ^{248}Cm$ reaction. In addition, we note that in the reaction of ^{40}Ar and ^{48}Ca with ^{238}U, products were observed (*20, 21*) (with a production cross section $\geq 60 \times 10^{-27}$ cm²) that appear to have resulted from the fusion of the ^{48}Ca or ^{40}Ar and the ^{238}U nucleus followed by fission. (These products have excitation functions and angular distributions characteristic of the fusion-fission process.) Since the only definitive signature of the complete fusion process in the $^{48}Ca + ^{248}Cm$ reaction is the detection of SHE's, it is possible that the reacting ions did not actually fuse—a possibility suggested by some calculations (*22*)—but in view of the evidence cited above, we will proceed under the assumption that some fusion (cross section $\geq 10^{-27}$ cm²) did take place in the $^{48}Ca + ^{248}Cm$ reaction.

A schematic representation of the de-excitation of any $^{296}116$ compound nuclei formed in the $^{48}Ca + ^{248}Cm$ reaction is shown in Table 2, where we used two different estimates of the reaction energetics and fission barrier heights to calculate the survival rates of the superheavy nuclei. The estimates used are those of Fiset and Nix (*6*) and those of Randrup *et al.* (*4*); the former are similar to most theoretical calculations done in the period from 1966 to 1972, and the latter represent the more recent approach. The "experimental" upper limit on the SHE survival rate in this reaction can be calculated as the ratio of the SHE production cross section upper limit to the complete fusion cross section; that is, $5 \times 10^{-35}/10^{-27} = 5 \times 10^{-8}$. Clearly, the calculations based on the older, more optimistic barriers and energetics grossly overestimate the survival probabilities in this reaction, giving values approaching unity. The calculations based on the more recent, pessimistic barriers and energetics are consistent with the data. The calculations based on the barriers and energetics of Fiset and Nix can be brought into agreement with the observed upper limits to the cross sections for SHE production by using values for the fission barrier heights that are 4 to 5 MeV lower than those originally predicted. The overall cross section for the production of detectable superheavy nuclei would be $10^{-27} \times 10^{-11} \lesssim 10^{-38}$ cm², using the barriers of Randrup *et al.* One can appreciate the minuscule magnitude of these cross sections by realizing that under the most favorable experimental conditions available today, a production cross section of 10^{-35} cm² would correspond to the production of one to three SHE atoms per day of irradiation.

Thus the failure to observe SHE's in this reaction seems to indicate that the fission barriers of these elements are considerably lower than those reported earlier (*2, 6*). This observation has certain qualitative consequences. If one accepts the calculations of Randrup *et al.* (*4*) as correctly describing the properties of the superheavy nuclei (which is consistent with the experimental data for the $^{48}Ca + {}^{248}Cm$ reaction), then, as noted previously, one concludes that the longest total half-life of a superheavy nucleus is $\sim 10^5$ years—which precludes their observation in terrestrial matter or any object whose age significantly exceeds 10^5 years, such as cosmic radiation. (This, of course, does not preclude observation of fossil remnants of extinct SHE's, such as decay products or fission tracks.) At the same time, one must be careful to note that the experimental results only test the cumulative survival probabilities, not the topology of the superheavy island. Thus we do not know whether the island of stability has a structure like the Matterhorn, steeply falling into the sea of instability as N decreases from 184, as suggested by the calculations of Randrup *et al.*, or whether it is a lesser peak with a broad base extending to significantly lower values of N, thus resembling the legendary home of Satan in the San Francisco Bay area, Mount Diablo, as would be suggested by the Fiset and Nix topology appropriately lowered to fit experimental data.

Table 2. De-excitation of superheavy element precursors from the $^{48}Ca + {}^{248}Cm$ reaction.

Nucleus	Excitation energy (MeV)	Based on Randrup *et al.* (*4*)		Based on Fiset and Nix (*6*)	
		Fission barrier height (MeV)	Fraction surviving fission (%)	Fission barrier height (MeV)	Fraction surviving fission (%)
$^{296}116 \xrightarrow{\text{fission (f)}}$	44	5.7	18	11.0	98
$\downarrow$ neutron emission (n)					
$^{295}116 \xrightarrow{f}$	34	5.9	23	10.5	99
$\downarrow$ n					
$^{294}116 \xrightarrow{f}$	26	4.1	1.4	10.0	99
$\downarrow$ n					
$^{293}116 \xrightarrow{f}$	16	3.5	1.4	9.6	100
$\downarrow$ n					
$^{292}116 \xrightarrow{f}$	8	2.9	5×10^{-4}	9.3	100
γ,n					
Predicted cumulative survival probability			$<4 \times 10^{-11}$		0.96

Some Future Possibilities

Have we learned anything that might aid us in future attempts to produce SHE's in complete fusion reactions?

From an examination of the estimates (in Table 2) of survival probabilities based on the barriers of Randrup *et al.* (*4*), one concludes that in the $^{48}Ca + {}^{248}Cm$ reaction the survival of superheavy nuclei is quite good until the last step or steps in the de-excitation chain, at which time a fission catastrophe is estimated to occur in which one "rolls off the island of stability." The yield of SHE's produced in this reaction would obviously be improved if the compound nucleus $^{296}116$ could be produced at an excitation energy less than 44 MeV. For example, if the initial excitation energy of the $^{296}116$ species were 37 MeV instead of the 44 MeV used in the experiments, the overall SHE survival probability would increase by 10^2 to 10^3, giving a SHE production cross section of 10^{-36} to 10^{-35} cm^2 or less.

Sierk (*22*) and others, however, have argued on the basis of hydrodynamic calculations that complete fusion of ^{48}Ca and ^{248}Cm will not occur unless the projectile energy is such that the $^{296}116$ species is produced with an excitation energy of 55 to 70 MeV. According to our calculations, such an excitation energy would cause all the SHE precursors to fission, leaving no SHE survivors. Thus we appear to be caught on the horns of a dilemma. If the bombarding energy is low, the reacting nuclei do not fuse; if the bombarding energy is high enough for fusion, the product nuclei do not survive.

However, an investigation (*21*) of a similar reaction, $^{40}Ar + {}^{238}U$, has shown that the fusion reaction begins to occur when the energy of the projectile is 8 to 12 MeV above the Coulomb barrier, in agreement with other theoretical considerations (*23*). The bombardments of ^{248}Cm with ^{48}Ca were performed at an average ^{48}Ca laboratory energy (in the target) of 255 MeV, which is 22 MeV higher than the simple Coulomb barrier for this reaction. Thus it appears possible to lower the ^{48}Ca energy to the region 241 to $245 \leq E_{Ca} \leq 248$ MeV (increasing the SHE survival probability) and still allow some complete fusion to occur.

Another possible way to improve the survival probability for superheavy nuclei formed in complete fusion reactions is to begin with a more neutron-rich target such as ^{250}Cm. Using the same estimation procedures employed in constructing Table 1 and similar values of the excitation energy, we predict that the survival probability of the superheavy species in the $^{48}Ca + {}^{250}Cm$ reaction will increase by a factor of $\sim 10^4$ compared to that in the $^{48}Ca + {}^{248}Cm$ reaction. If the complete fusion cross section for the $^{48}Ca + {}^{250}Cm$ reaction is $\sim 10^{-27}$ cm^2, then we would predict a superheavy production cross section of $\sim 10^{-34}$ cm^2 or less—a conceivably detectable level.

In any case, the results of the $^{48}Ca + {}^{248}Cm$ experiments serve as a valuable benchmark for any other attempts to produce superheavy nuclei. They tell us that present methods were not adequate to detect the superheavy survivors from a process yielding superheavy precursors with a cross section of 10^{-27} cm^2 and an excitation energy of $\sim$40 MeV.

Deep Inelastic Pathways to Superheavy Elements: Hope for the Future?

A new mechanism for the interaction of heavy ions was discovered (*24*) some 6 years ago and has been investigated extensively (*25*). Termed deep inelastic scattering, it is inelastic scattering in which there is massive transfer of energy and nucleons between the projectile and the target. It soon became apparent this reaction might offer another pathway to the SHE's.

A preliminary report of the production of SHE's by the deep inelastic mechanism in the $^{136}Xe + {}^{238}U$ reaction has appeared (*12*), but attempts to duplicate the results have not been successful (*26, 27*). However, recent experiments at the GSI in Darmstadt (*28*) have encouraged those who believe that it may be possible to make SHE's by this new reaction pathway. The atomic number distribution of the products resulting from the reaction of 1785-MeV ^{238}U ions with a thick ^{238}U target is shown in Fig. 5. There is a broad distribution of high-mass products with atomic numbers near that of uranium. These products are the survivors of the deep inelastic scattering process. A detailed examination of the data in Fig. 5 reveals the production (with a cross section of 10^{-33} cm^2) of ^{255}Fm from ^{238}U (a net transfer of eight protons and nine neutrons to the target with survival of this product). There are preliminary indications (*29*) that more nucleons are transferred per MeV of excitation energy in the U + U reaction than in deep in-

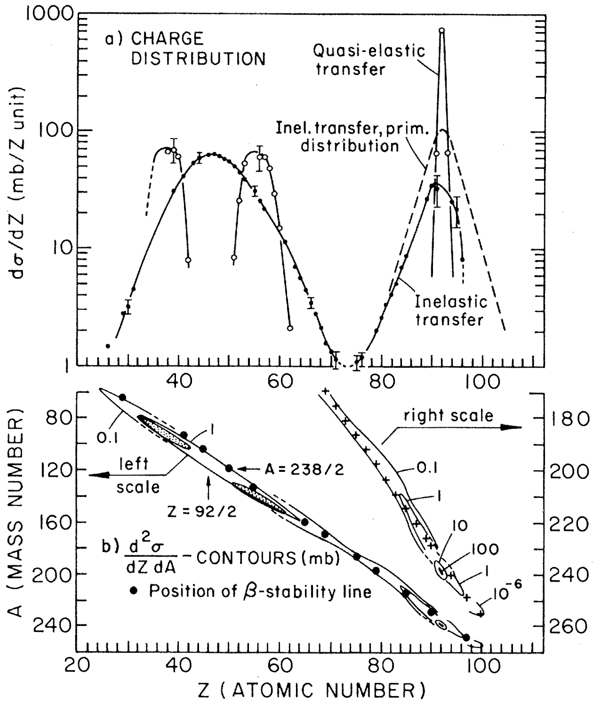

Fig. 5. Product distributions in the ^{238}U + ^{238}U reaction [from Schädel *et al.* (*28*)]. (a) Distribution in atomic number of the products. (b) Contour plot of the yields of products with particular values of Z and A; contours are labeled in millibarns (1 millibarn = 10^{-27} cm^2).

elastic scattering reactions involving heavy targets and lighter projectiles, indicating the production of colder products in the U + U system. Thus, on paper at least, one might think of reactions involving heavy target nuclei in which massive nucleon transfers could lead to the production and survival of superheavy nuclei.

The proper question to be asked is whether one can put a quantitative base under such extrapolations. For the ^{238}U + ^{238}U reaction, studied by Schädel *et al.* (*28*), the yield of products with $Z = 70$ from the starting point of $Z = 92$ corresponds to a production cross section of 10^{-28} cm^2. Assuming that the number of $Z = 70$ products did not change during the de-excitation process, the symmetrical character of the U + U system dictates that the yield of primary products with $Z = 114$ corresponds to a cross section of 10^{-28} cm^2, in rough agreement with the predictions of Ayik *et al.* (*30*). The excitation energy of the $Z = 114$ species is not well known. If one believes that in the ^{48}Ca + ^{248}Cm reaction complete fusion occurred to an extent such that $\sigma_{CF} \cong 10^{-27}$ cm^2, then the U + U deep inelastic reaction offers no improvement over this system unless the excitation energy of the $Z = 114$ species is ≤ 40 MeV or these species are very neutron-rich.

A further problem is the experimental observation that in deep inelastic scattering reactions involving heavy targets (such as the reactions of Xe + Ta, Ca + Cm, and U + U), the heaviest survivors of the deep inelastic transfer process correspond to a net transfer of roughly equal numbers of neutrons and protons, giving rise to neutron-deficient products. This can be seen as a consequence of the transfer of increasing excitation energy with increasing numbers of nucleons (the excitation energy causes the emission of more neutrons). This is clearly not desirable for SHE synthesis, where one needs to make as neutron-rich a species as possible (see Fig. 2). For example, to go from ^{238}U to $^{298}114$ requires an increase of ~ 1.7 neutrons for every proton added, implying an initial transfer of more than 1.7 neutrons per proton. Using the reaction ^{160}Gd + ^{136}Xe as a test for the increase of 18 protons and 34 neutrons (to produce ^{212}Pb), Otto *et al.* (*27*) set an upper limit for the cross section for this reaction of 10^{-33} cm^2. However, Schädel *et al.* (*28*) pointed to evidence that in the deep inelastic process, the maximum primary product yield is for N/Z ratios near the valley of β^- stability, which leads to predictions of more neutron-rich SHE precursors.

In any case, if one starts with a very heavy target nucleus, then the probability of transferring the proper number of nucleons at a low enough excitation energy to form a surviving SHE should increase dramatically. There are possible modifications of the ^{238}U + ^{238}U experiment that could significantly improve the survival rates of the SHE's. For example, bombardment of a ^{248}Cm target with a heavier projectile such as ^{244}Pu should allow the primary yield of the SHE precursors to increase (because of the need to transfer fewer nucleons than in the ^{238}U + ^{238}U reaction) and the excitation energy of the superheavy precursors to decrease, which would increase the survival rate of the secondary products. The decrease in excitation energy of the SHE precursors is a consequence of the fact that the excitation energy of deep inelastic products divides as the mass; thus a heavier projectile will carry away more excitation energy, leaving less in the superheavy precursor. Also, as hinted at in the considerations of the U + U reaction (*28, 31*), the special stability of the "magic" superheavy nucleus could lead to minimum excitation of this deep inelastic transfer product. Using the calculational framework suggested by Ayik *et al.* (*30*), the yields of superheavy products from the ^{248}Cm + ^{244}Pu reaction should be at least ten times greater than the yields from the ^{238}U + ^{238}U reaction. The use of even heavier targets, such as ^{254}Es, has the advantage that a smaller number of nucleons needs to be added to synthesize SHE's, but this advantage may be offset by the small quantity of available target material. For example, the formalism of Ayik *et al.* would predict a 40-fold increase in SHE yield from the ^{254}Es + ^{244}Pu reaction compared to the ^{238}U + ^{238}U reaction, but this increase is completely negated by the 400-fold decrease in achievable target thickness.

Since the exact details of the SHE production process within the deep inelastic transfer mechanism depend so critically on the poorly characterized tails of the distributions of product mass, charge, and excitation energy, it is very difficult to make meaningful quantitative estimates of the SHE production probabilities, and the estimates cited above should be viewed with caution. Once it has been determined that there is a possibility of producing detectable numbers of SHE nuclei, which appears to be the case for various postulated heavy target–heavy projectile deep-inelastic transfer processes, then the attempt to synthesize and identify these elusive elements by this reaction path should be continued.

Outlook for the Future

The effort to synthesize SHE's is at a crossroads. We have been deeply disappointed by the failure of apparently promising approaches. Yet there are still enough possibilities to sustain future effort. What does the future hold for the quest to synthesize SHE's? Ideally, all of the following might be part of our future.

1) A general improvement of the methods used to detect SHE's. With no further changes in much of the detector apparatus, an increase of 10 to 100 in detection sensitivity could be obtained by irradiating target nuclei with higher-intensity particle beams for longer times. More research is needed into the problems of running these high-intensity, high-energy beams of heavy ions through thin foils of heavy elements. Such research may be crucial to future experiments with exotic beams and targets, especially when one realizes that because of these "targetry" problems, current experiments only utilize a small fraction of the total ion beams available from modern accelerators.

Better means are also needed for detecting superheavy activities with short (<1 second) half-lives. More emphasis needs to be placed on purely physical method detectors, such as magnetic spectrometers and velocity separators, which can identify the atomic number of the product without chemical separation.

2) A further extension of the complete fusion approach to SHE synthesis, using the $^{48}Ca + ^{250}Cm$ reaction and the reaction of ^{48}Ca with ^{248}Cm at a lower bombarding energy. The addition of two more neutrons to the target (^{250}Cm in place of ^{248}Cm) will, by the estimation procedures used in Table 1, increase the survival probability of the superheavy species by a factor of $\sim 10^4$. The availability of ^{250}Cm is very limited, unfortunately, and quantities sufficient for an experiment could probably become available only after recovery from the debris of an old nuclear weapons test. As discussed earlier, further studies of the $^{48}Ca + ^{248}Cm$ reaction at lower bombarding energies could also lead to an increase in SHE production of 10^2 to 10^3.

3) The ultimate extension of the deep inelastic transfer approach to SHE synthesis, using an exotic target (such as ^{248}Cm or possibly ^{254}Es) and an exotic projectile (^{244}Pu). For the favorable case of the $^{248}Cm + ^{244}Pu$ reaction, the production cross section for SHE's might increase dramatically, allowing detection of any SHE formed.

The reader may ask why one should bother with such unusual and expensive projects. Why not just give up and turn from this crossroads to an easier task? Many of the original reasons for embarking on this attempt are still valid and compel us to further effort. There is the opportunity to uniquely test so much of modern nuclear science in this dramatic extension to a new and unknown region, and the possibility of opening up a vista of many new chemical elements whose behavior and properties might be governed by rules (relativistic ones) not used in describing today's experiments. Also, the new experiments, like the old ones, should have a significant "fallout" in other areas of nuclear science and chemistry. For even if we fail to make SHE's, the chances seem good that we will greatly enhance our knowledge of the nuclear structure and chemistry of the actinides and transactinides by the production of new isotopes of existing elements or of new non-superheavy chemical elements by such efforts.

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14. For nuclei with $Z \leq 120$, the droplet model masses [W. D. Myers, *The Droplet Model of Atomic Nuclei* (Plenum, New York, 1978)] were corrected by using the shell corrections in (*4*) to give reaction energetics and neutron binding energies. For $Z > 120$, the energetics and barriers were taken from (*6*).
15. The formalism used is outlined by R. Vandenbosch and J. R. Huizenga [*Nuclear Fission* (Academic Press, New York, 1973), pp. 233–250]. Details of its applications are given by W. Loveland [*Oregon State Univ. Rep. RLO-2227-TA35* (1978)]. Each emitted neutron was assumed to remove an excitation energy equal to the sum of the neutron binding energy and twice the nuclear temperature ($B_n + 2T$). Values of the mean square projection of the nuclear angular momentum on the nuclear symmetry axis, K_0^2, were taken from typical values for transuranium nuclei (p. 202 in Vandenbosch and Huizenga); the fission level density parameter a_f was set equal to $1.1\ a_n = 1.1(A/8)$, where a_n is the neutron level density parameter and A is the nuclide mass number.
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