Predictions for superheavy nuclei

The quest for ever-heavier nuclei turns to heavy-ion accelerators that could produce hundreds of excited short-lived species —and possibly a few, in their ground states, that live for years.

James Rayford Nix

A frantic search for nuclei considerably heavier than any known up to now has been going on for the past five years. The search for these "superheavy" nuclei has included attempts to produce them artificially, as products of various reactions at accelerators throughout the world, as well as attempts to find them in nature. Man's quest in nature has led him from a 14th-century Russian Orthodox church to the ocean floor off the Fiji Islands, from California platinum and gold mines to meteorites and moon rocks. None of these attempts have yet resulted in any conclusive evidence for the existence of superheavy nuclei. But with the Berkeley SuperHILAC now joining accelerators in the USSR and France that are potentially capable of producing them, the coming years will witness a renewed search for these nuclei, whose existence was predicted seven years ago.

Why are such nuclei expected to be so stable against their various modes of decay? What are the best methods for trying to produce them? And if we are able to produce them, what will be their chemical and physical properties? These are the topics I shall discuss here.

James Rayford Nix is a member of the Theoretical Division at the Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico.

Qualitative considerations

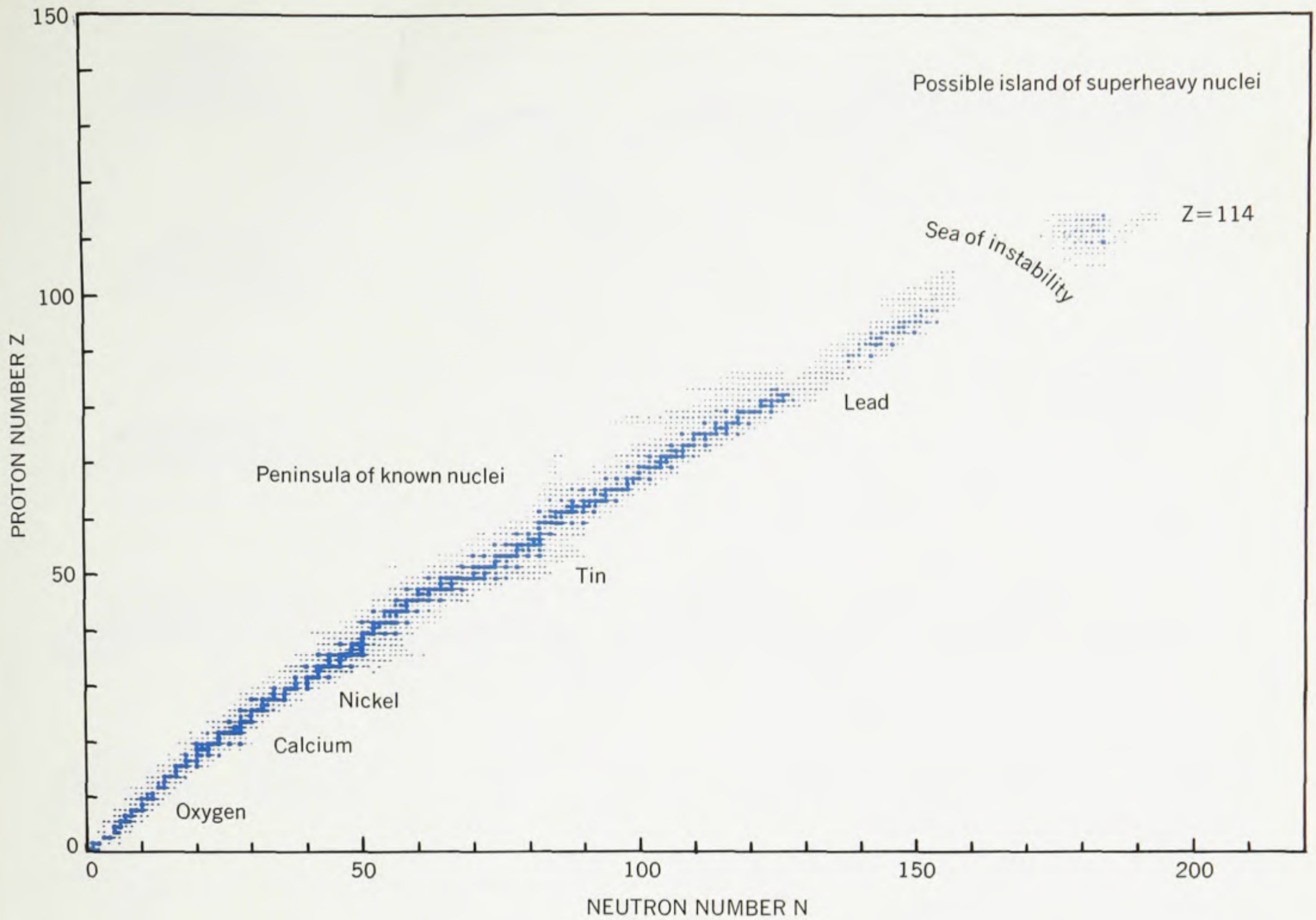
One finds in nature some 300 nuclei, representing isotopes of elements containing from one to at most 94 protons. These naturally occurring nuclei are seen in figure 1, along with some 1200 additional nuclei that have been made artificially in the past 50 years; the heaviest nucleus produced to date has 105 protons and a mass number of 262.

This "peninsula" of known nuclei terminates because of nuclear fission. As we move along the peninsula toward heavier nuclei, the disruptive Coulomb forces grow faster than the cohesive nuclear forces, and spontaneous fission becomes a rapid mode of decay. In addition, the large Coulomb forces cause heavy nuclei to decay rapidly by the emission of alpha particles.

If spontaneous fission and alpha decay become so likely for heavy nuclei, how can we hope to find an island of still heavier nuclei past the end of the peninsula? The answer lies in the extra stability that arises from the closing of a proton or neutron shell. As we increase the particle number of nuclei along the peninsula, successive protons and neutrons go into definite single-particle orbits. When a given shell of protons or neutrons is completely filled, that nucleus has relatively lower energy, that is, extra binding and hence increased stability. Elements corresponding to the closing of proton shells are indicated in the figure.

The magnitude of this extra binding can be seen in figure 2. The points represent the difference between the measured ground-state masses of nuclei and the smooth contribution to the masses from the liquid-drop model, or in other words, the experimental effect of single particles on the ground-state energy.[1] The single-particle effect is plotted against proton number Z and against neutron number N. We see empirically that the closing of a single major shell leads to some 5 MeV additional binding energy, and the closing of both a proton and a neutron shell, such as at Pb^{208} ($Z = 82, N = 126$), to over 10-MeV extra energy. It turns out that to a fairly good approximation the height of the potential barrier against fission is increased just by the amount of this additional binding.

The next shell closures beyond lead are predicted to occur at 114 protons and 184 neutrons, corresponding to a mass number of 298. In the absence of single-particle effects, the fission barrier of such a superheavy nucleus would be vanishingly small. But this closing of



Location of sought-for superheavy nuclei relative to observed nuclei. Each nucleus is positioned according to the number of protons and the number of neutrons it contains. The known nuclei are seen to form a "peninsula," and the superheavy nuclei that we may be able to produce lie on an "island" well beyond the tip of the peninsula. Heaviest points represent naturally occurring nuclei, middle-size points represent nuclei with halflives greater than one year, and lightest points represent nuclei with halflives less than one year. Figure 1

two shells leads to a fission barrier some 10 MeV high. Now, this is a substantial barrier: For comparison, the barriers of conventional nuclei such as uranium are only about 5 MeV high! Thus superheavy nuclei with nearly closed proton and neutron shells should be relatively stable against spontaneous fission, even though nuclei between the end of the peninsula and the island are not.

The extra binding also increases nuclear stability against the emission of alpha particles but only for the closed-shell and lighter nuclei. The alpha-emission probability is actually increased for heavier nuclei decaying toward a closed shell; this increased probability is responsible for the absence of naturally occurring nuclei just heavier than lead. We therefore expect nuclei in the center and in the lower left-hand part of the island to be relatively stable against alpha decay, but nuclei in the upper part of the island should decay rapidly by alpha emission.

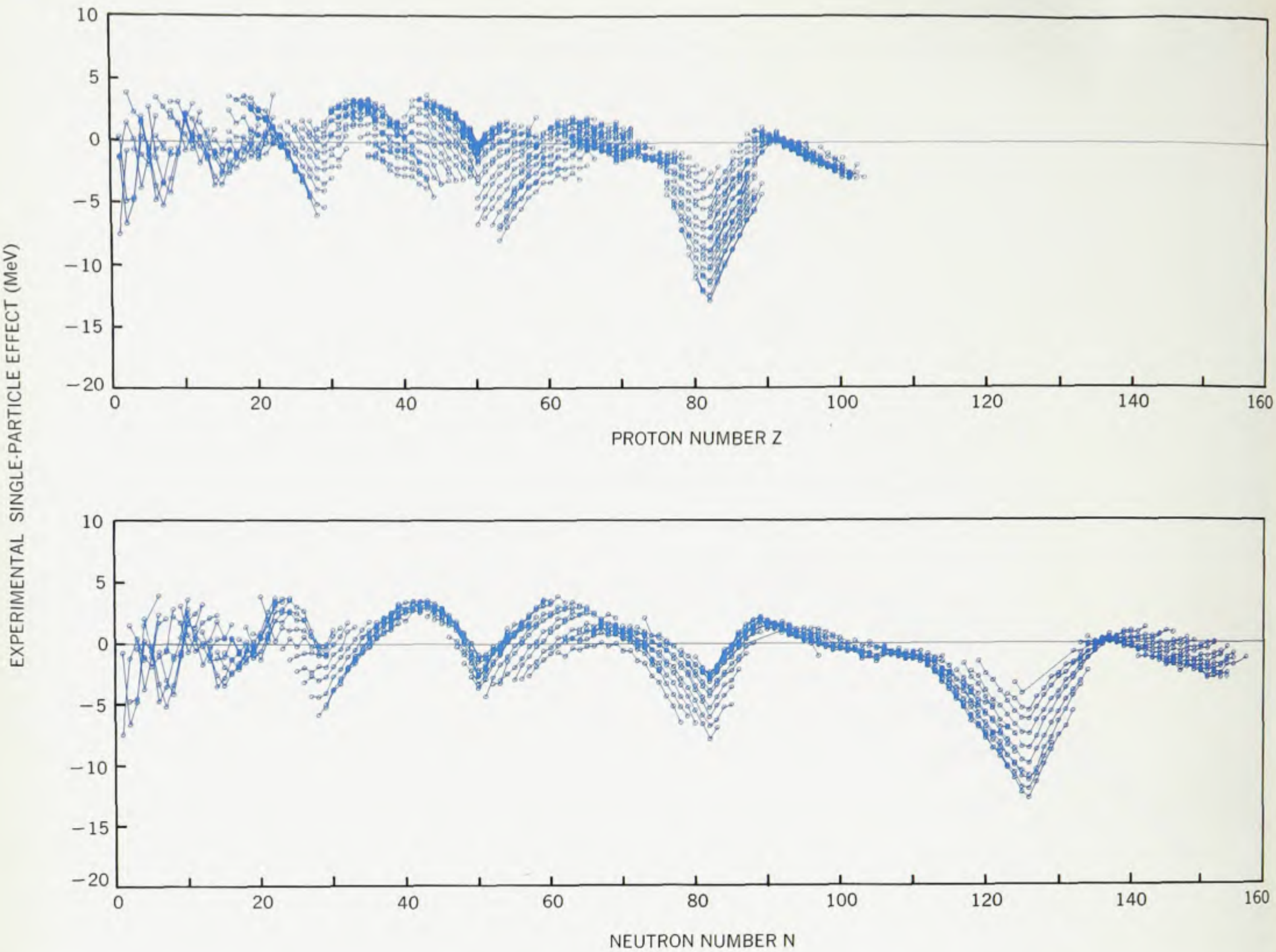
Finally, from the trend of the peninsula you would expect the line of stability against beta decay to pass almost precisely through the center of the island. This means that at least some of these nuclei should also be stable against beta decay (including electron capture).

We have seen simple, qualitative arguments for expecting nuclei in the region of ${}_{114}X^{298}$ to be relatively stable with respect to spontaneous fission, alpha decay and beta decay, the three relevant modes of decay. How has the search for these supposedly stable superheavy nuclei proceeded?

Historical comments

Although the possibility of superheavy nuclei had been considered much earlier, the modern widespread interest in them began seven years ago in Berkeley as a result of two independent developments.[2] The first of these was the estimate by William Myers and Wladyslaw Swiatecki that the fission barrier of a superheavy nucleus should be several MeV high, and the second was the suggestion by Heiner Meldner that the next closed proton shell after 82 is 114. It had always been thought before, in analogy with the case for neutrons, that 126 would be the next closed proton shell. The Coulomb force, which becomes increasingly important for heavier nuclei, is responsible for this difference. Additional evidence that 114 is the next closed proton shell was provided soon by several other calculations.

Shortly after these two initial developments, Vilen Strutinsky developed an improved method for calculating the



Increased stability of nuclei near closed shells. The measured ground-state masses of nuclei relative to a smooth liquid-drop mass formula show characteristic fluctuations that arise from single-particle effects. Note especially the increased binding energy of nuclei that contain approximately 82 protons or 126 neutrons; a similar increase is expected to appear again at 114 protons and 184 neutrons. Figure 2

potential energy of a nucleus as a function of its shape,[3] and he and his coworkers used the method to calculate the fission barriers of several superheavy nuclei.[4] Then, Sven Gösta Nilsson and his coworkers applied Strutinsky's method to a generalized harmonic-oscillator single-particle potential to make the first systematic survey of the expected stability of superheavy nuclei.[5] More recently, several other groups have also begun to consider this problem. I cannot here review everyone's contributions but instead will describe those results that best illustrate the physical principles involved and our *current* expectations concerning superheavy nuclei. (Exhaustive references to both the early and more recent work on superheavy nuclei can be found in reference 6.)

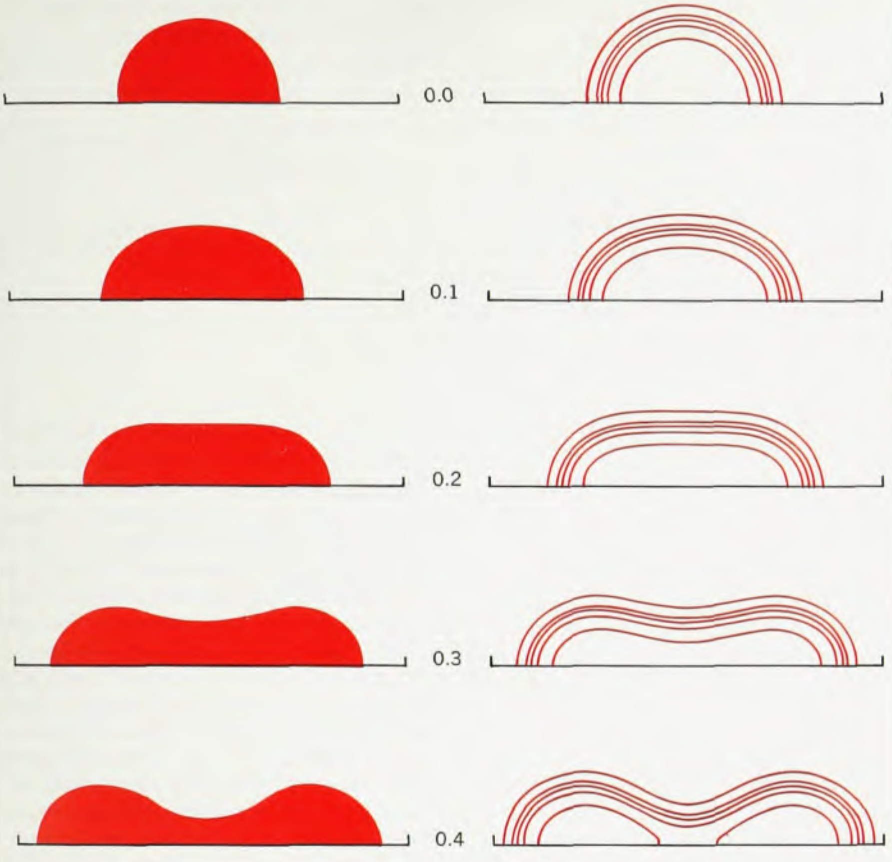
Nuclear stability

As we have seen, one of the possible modes of decay of a superheavy nucleus is spontaneous fission. During fission the shape of the nucleus changes in a way that is illustrated on the left-hand side of figure 3. To determine the stability of the nucleus against fission, we must calculate its potential energy as a function of deformations such as these.

How should we go about doing these calculations? Should we not start with a fundamental nucleon–nucleon interaction derived from scattering data and solve the appropriate many-body equations in some approximation, for example the Hartree–Fock approximation? These procedures are very basic in principle, but in practice they have difficulties even describing such essential properties as the total binding energy and radii of *spherical* nuclei. In addition, such first-principles calculations have not yet been carried out for the large deformations that are encountered in fission.

Fortunately, an alternative method has been developed that overcomes these difficulties. This method is a two-part approach, with the smooth trends of the potential energy taken from a macroscopic model and the local fluctuations from a microscopic model. The basic idea is that a macroscopic approach such as the liquid-drop model describes quantitatively the smooth trends of the nuclear potential energy but not the local fluctuations, whereas a microscopic approach such as the single-particle model describes the local fluctuations but not the smooth trends. So, why not synthesize the two? The combined macroscopic–microscopic method should then, we hope, reproduce both the smooth trends and the local fluctuations. The steps involved in calculating the potential energy by this method are:

- ▶ Specify nuclear shape
- ▶ Calculate macroscopic (liquid-drop) energy
- ▶ Generate single-particle potential felt by nucleons
- ▶ Solve Schrödinger equation for single-particle energies
- ▶ Calculate the appropriate micro-



Nuclear shapes in fission and the corresponding spin-independent nuclear single-particle potentials, for deformation varying from zero (spherical) through 0.4. The equipotential curves are shown for 10 (outermost), 30, 50, 70 and 90 percent of the well depth. The total potential felt by a nucleon also contains a spin-orbit term and, for protons, a Coulomb term.
Figure 3

scopic (shell and pairing) corrections.
▶ Add results of second and fifth steps to obtain total potential energy

This macroscopic–microscopic method has already helped solve longstanding puzzles in fission, such as the division of heavy nuclei into fragments of *unequal* size, as well as more recent problems, such as spontaneously fissioning isomers. The same method can also be used to discuss in a unified way such related areas as heavy-ion reactions and nuclear ground-state masses and deformations. There are still difficulties in justifying the method from basic principles. But at present it is the only practical way to calculate fission barriers, and the method has now been used by some half-dozen groups throughout the world.

An example of these calculations is shown in figure 4, which summarizes the fission barriers for superheavy nuclei that Mark Bolsterli, Edmund Fiset, John Norton and I have calculated recently at Los Alamos.[7] The liquid-drop contributions to the barriers are, we see, very small. Stability against fission arises primarily from the negative single-particle correction for the spherical shape.

The barrier for the doubly closed-shell nucleus $_{114}X^{298}$ is 13 MeV high. As neutrons are added beyond 184, the barrier height decreases drastically. Subtracting neutrons also lowers the barrier but not as much as if the same number were added. When a small number of protons are added beyond 114, the barrier height actually increases slightly. When protons are subtracted, the barrier is again lowered.

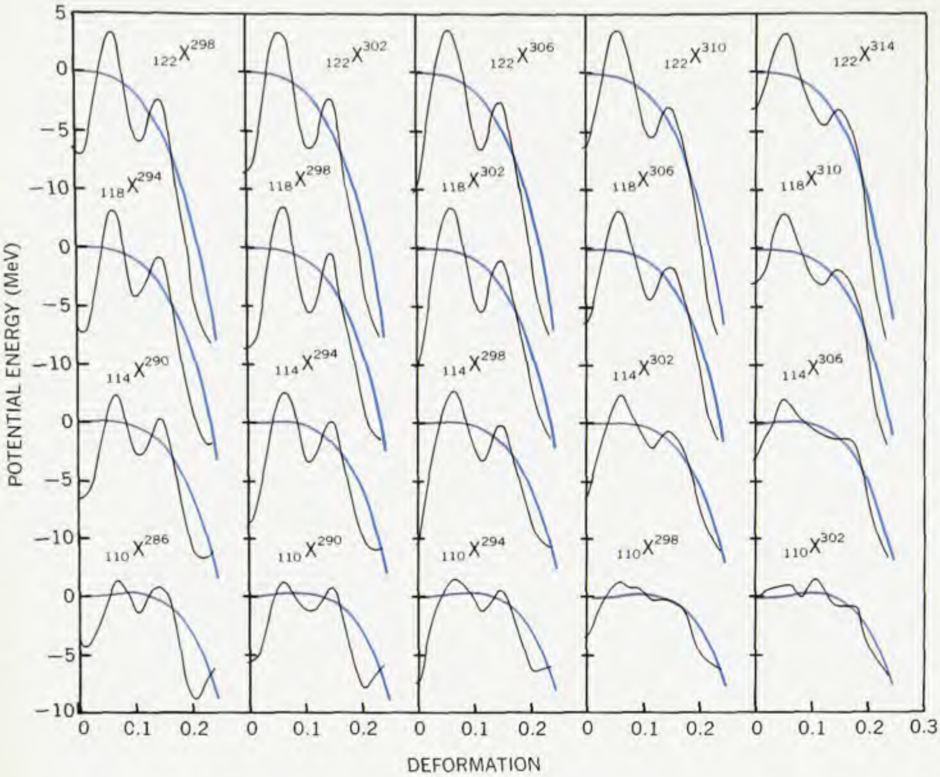
Spontaneous fission is a tunneling process through potential barriers such as these. However, the stability of a nucleus with respect to spontaneous fission is determined not only by its potential barrier, but also by the inertia, or effective mass, associated with the deformation. The inertia can be determined semiempirically by adjusting its value to reproduce known spontaneous-fission halflives of actinide nuclei, or alternatively it can be calculated by means of the microscopic "cranking" or "pushing" formalism. In this latter method the nucleus is forced externally into a given type of collective motion, and the inertia is then deduced from the increase in energy arising from this motion.

Once both the potential barrier and the inertia are known, the spontaneous-fission halflife is determined by use of the WKB (quasiclassical) approximation for penetrability through the barrier. The halflives calculated for these barriers and a semiempirical estimate for the inertia are given in figure 5.[8] These results are for even nuclei, that is, nuclei that contain even numbers of protons and neutrons.

As we move away from the doubly closed-shell nucleus with 114 protons and 184 neutrons, the calculated spontaneous-fission halflives decrease from 10^{15} years for nuclei along the inner contour to 10^{-5} years (about 5 min) for nuclei along the outer contour. With respect to spontaneous fission, the island of superheavy nuclei is a mountain ridge running north and south, with the descent down to the sea of instability most gentle in the northwest direction.

The peak at $_{114}X^{298}$ in the spontaneous-fission halflives is connected topologically to the peninsula of known nuclei by a saddle point of height 10^{13} years at 108 protons and 184 neutrons. Thus, along the 184-neutron shell the spontaneous-fission halflives *increase* as the proton number decreases below 108, whereas to either side of 184 neutrons they drop off precipitously. These neutron-rich nuclei are of course beta unstable.

Figure 5 also shows the calculated halflives with respect to alpha decay



Calculated fission barriers for superheavy nuclei. The colored curves give the liquid-drop contributions, and the black curves give the total potential energies.
Figure 4

and beta decay for even nuclei.[8] These halflives are determined, by fairly standard approximations, from the energy released in the decays; this energy is found from the calculated ground-state masses of the nuclei involved. As we increase the proton number, the calculated alpha-decay halflives decrease from 10^{15} years for nuclei along the bottom contour to 10^{-15} years (about 30 nanosec) for nuclei along the top contour. The discontinuities arise from the effects of closed neutron and proton shells and the transitions from spherical to deformed nuclei. As we move away from the beta-stable nuclei, which are indicated by the points, calculated beta-decay halflives decrease from one year for nuclei along the inner contours to 10^{-7} years (about 3 sec) for nuclei along the outer contours.

The *total* halflives are determined by considering all three decay modes. For even nuclei the halflives decrease from 10^5 years for nuclei along the inner contour to 10^{-15} years for nuclei along the top contour. For nuclei with odd numbers of protons or neutrons, the spontaneous-fission and alpha-decay halflives increase relative to the values for even nuclei, but the beta-decay halflives decrease. After odd-particle effects are taken into account, the even nucleus $_{110}X^{294}$ has the longest calculated total halflife, which is 10^9 years. (The superheavy nuclei included in figure 1 have total halflives longer than 10^{-5} years.)

Methods of production

By this point, we should all be hopeful that some superheavy nuclei are going to be relatively stable if they can be formed in their ground states. But before I describe the two general methods by which this may conceivably be done, we should remind ourselves that there may be defects in any theory. For example, in a recent synthesis of an isotope of fermium,[9] the experimentally determined halflife was only about 10^{-8} times that predicted, and it is not yet clear where the error in this case lies.

The two methods for producing superheavy nuclei are multiple capture of neutrons and a reaction involving two fairly heavy nuclei. The former method, which is like trying to swim over to the island, would produce nuclei in the southeastern, or neutron-rich side of the island. There are two major variations, the so-called "r" process and nuclear explosions. In the r process (duration about ten seconds), a given nucleus successively increases its mass by capturing one or more neutrons and its proton number by emitting a beta particle, and so on. Many naturally occurring nuclei were made in supernovas by this process. In a nuclear explosion (duration less than or equal to about 10^{-6} sec), everything occurs so quickly that a nucleus does not have time to beta decay and then capture more neutrons; instead, the nucleus must initially capture sufficient neutrons that subsequent beta decays would take it to the region of superheavy nuclei.

Unfortunately, both these variations are fraught with the same basic limitation: Intermediate nuclei formed between the peninsula and the island end the process by undergoing fission. Although this conclusion is not definitely established, it appears unlikely that superheavy nuclei can be made by either the r process in nature or artificially by nuclear explosions.

This prospect, then, leaves heavy-ion reactions as the primary hope. The method, which is like trying to fly over to the island, produces nuclei in the northwestern, or neutron-deficient side of the island. Two fairly heavy nuclei are brought into contact by accelerating one of them in a heavy-ion accelerator such as the Berkeley SuperHILAC. These two nuclei could combine to form a superheavy nucleus, plus some additional particles that carry off surplus energy.

There are several ways to classify the different types of heavy-ion reactions for producing superheavy nuclei; I shall classify them here according to the reaction mechanism involved. The possibilities are compound-nucleus formation, direct transfer reactions and fission. In compound-nucleus formation, a target and projectile are brought together to form an excited compound nucleus. In most cases this nucleus will undergo fission, but there is also some probability that it will instead de-excite by the emission of neutrons. In a direct transfer reaction, the target and projectile do not completely fuse, but instead a light particle is released during the original interaction. This light particle can carry away some energy and angular momentum that would otherwise remain as undesirable excitation energy and rotational energy. In the fission mechanism, a heavy target and projectile, such as uranium plus uranium, fuse to form a massive excited nucleus. This nucleus then undergoes fission, the hope being that one of the fission fragments will be a superheavy nucleus.

As we see in Table 1, the most likely reaction mechanism for producing a superheavy nucleus is expected to change from compound-nucleus formation to a direct transfer reaction to fission as the total mass of the combined system increases, although there is considerable overlap in these mechanisms.

Table 1. Heavy-Ion Reaction Mechanisms for Producing Superheavy Nuclei

Mechanism	Examples	Neutron–proton ratio	Angular momentum	Internal excitation	Nuclear distortions
Compound-nucleus formation	${}_{90}Th^{232} + {}_{32}Ge^{76} \rightarrow {}_{122}X^{308*}$	Poor	Moderate	Moderate	Smaller
	${}_{60}Nd^{150} + {}_{60}Nd^{150} \rightarrow {}_{120}X^{300*}$	Poorest	Large	Lower	Moderate
Direct transfer reaction	${}_{94}Pu^{244} + {}_{40}Zr^{96} \rightarrow {}_{114}X^{300*} + {}_{20}Ca^{40*}$	Fair	Moderate	Low?	Small?
	${}_{78}Pt^{198} + {}_{78}Pt^{198} \rightarrow {}_{116}X^{300*} + {}_{20}Ca^{48*} + {}_{20}Ca^{48*}$	Good	Large	Low?	Small?
Fission	${}_{92}U^{238} + {}_{92}U^{238} \rightarrow {}_{184}X^{476*} \rightarrow {}_{114}X^{298*} + {}_{70}Yb^{178*}$	Good	Moderate	?	Large?

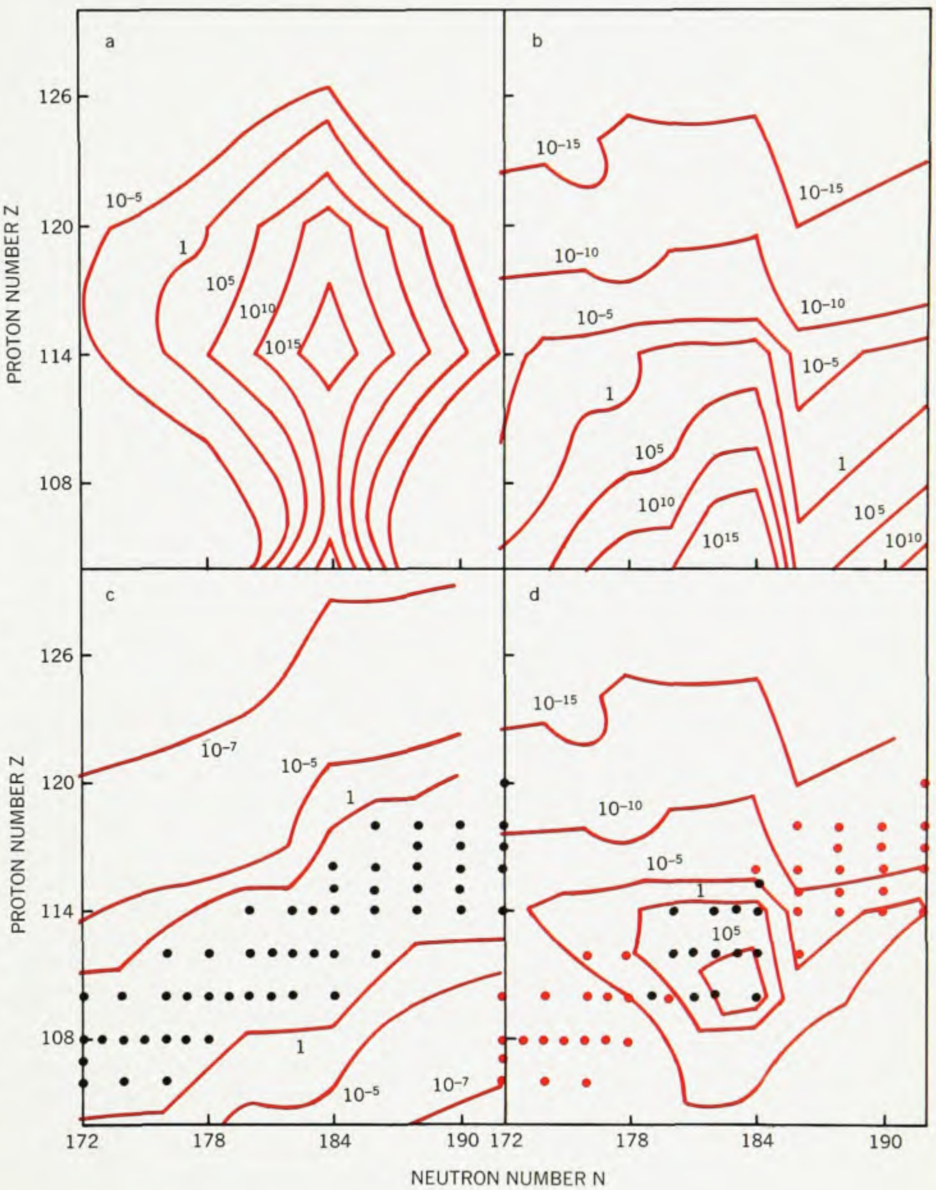
Inherent heavy-ion problems

Table 1 also lists the four major difficulties that plague attempts to produce superheavy nuclei by heavy-ion reactions. These difficulties concern forming a system with a sufficiently high neutron–proton ratio, with only a small amount of angular momentum, with only a small amount of excitation energy and in a nearly spherical shape. Unfortunately, none of the reaction mechanisms overcome all these difficulties: The mechanism that is best for one purpose is usually worst for another.

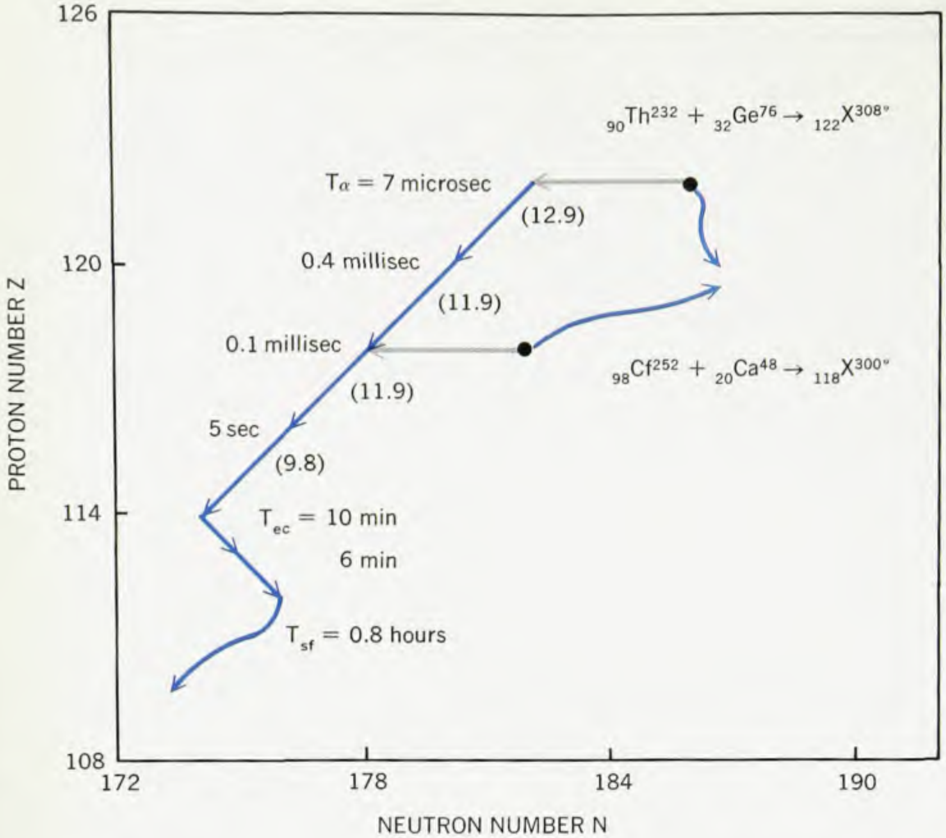
The first difficulty arises because beta-stable nuclei become increasingly neutron-rich with increasing mass number, so that it is difficult to obtain a sufficiently large number of neutrons in the final system. The second difficulty results from the unusually large angular momentum involved in heavy-ion reactions; this reduces the effective height of the fission barrier and consequently hinders or even prevents altogether the formation of a superheavy nucleus.

The third difficulty is the effect of the internal excitation energy on the fission probability. To form a superheavy nucleus, this energy must be dissipated through the emission of neutrons (or alpha particles) and gamma rays *before* the system undergoes fission. Unfortunately, the probability for this happening is very small even for moderate excitations, because the high fission barrier for a superheavy nucleus in its ground state is created by protons and neutrons occupying closed shells. At high excitation energies, many particles are elevated to higher states, which reduces the effects of the closed shells. This in turn reduces the barrier height (in a loose manner of speaking) and hence greatly increases the fission probability.

The fourth difficulty comes about because a relatively small distortion can initiate fission in a superheavy nucleus. The fission barrier of a superheavy nucleus is much thinner than the barrier for a conventional nucleus such as uranium: Uranium does not undergo fission until it is deformed past a very



Halflives calculated for even superheavy nuclei. The numbers shown are the halflives in years against spontaneous fission (a), alpha decay (b), electron capture and beta decay (c) and all decay processes (d). In the last part we have divided the beta-stable nuclei into two groups: those nuclei with total halflives that are longer than one year (black points) and those nuclei with total halflives that are shorter than one year (colored points). Figure 5



Two heavy-ion reactions of the compound-nucleus type. Calculations show that, in most cases, the excited nuclei that are formed fission rapidly (upper curves). There is a very small probability that they can de-excite by the emission of about four neutrons and some gamma rays (straight lines). In this case, a series of high-energy alpha particles (numbers in parentheses give alpha-decay energies, in MeV) will be emitted, until the closed proton shell at $Z = 114$ is reached. Then two successive electron captures followed by spontaneous fission of the final nucleus $_{112}X^{288}$ ends the series.
Figure 6

elongated saddle-point shape, but a superheavy nucleus will undergo fission once it is deformed past a saddle-point shape of very small eccentricity. Therefore, a superheavy nucleus must be formed in a nearly spherical shape if it is not to undergo fission immediately.

To do this in a heavy-ion reaction, we start with two spherical (or slightly deformed) nuclei at infinity and bring them together by accelerating one of them. At the moment of first touching, the two nuclei are still nearly spherical and are moving fairly slowly, because most of their original kinetic energy has been converted into Coulomb potential energy. After the nuclei have touched, there are strong forces perpendicular to the path that leads from the configuration of two tangent spheres to a single sphere. Therefore, to reach the single-sphere configuration, the two nuclei must be brought together with somewhat more energy than is needed to make them just touch. If the energy is too low, the dynamical path will bend back around toward immediate fission. If the energy is too high, the path will overshoot and then lead to fission. If the energy is just right, the system will, we hope, reach the single-sphere configuration and start oscillating about it. The presence of a finite nuclear viscosity converts the energy in these oscillations into internal excitation energy, which must be dissipated rapidly through the emission of neutrons before the nucleus fissions.

The first reaction mechanism that has been tried experimentally, and that will continue to be tried for some time, is compound-nucleus formation with a heavy target and light projectile.[10,11] In addition to its own relative attractiveness, as predicted by theory, this choice is technologically easiest because it requires accelerating lighter ions. Figure 6 illustrates the possible fate of two such reactions.[8] In both cases the excited compound nuclei will usually undergo fission, but there is also a very small probability they will de-excite by emitting about four neutrons and some gamma rays. When this occurs, the resulting nuclei in their ground states are predicted to decay primarily by the rapid emission of a series of high-energy alpha particles. However, once the closed proton shell at $Z = 114$ is reached, electron capture becomes the predominant decay mode. After two successive electron captures, the final nucleus $_{112}X^{288}$ terminates the series by undergoing spontaneous fission with a halflife of 0.8 hours.

Reactions in which the excitation energy is carried off by an alpha particle and two neutrons rather than by four neutrons are also possible. The decay paths for such reactions are similar to those shown in figure 6 but are displaced two neutrons to the right. The final nucleus $_{112}X^{290}$ in this decay chain has a spontaneous-fission halflife of 0.2 years. If the decay path involves nuclei with an odd number of neutrons or protons, then the enhanced probability for electron capture relative to spontaneous fission and alpha decay can lead to final nuclei that are even more long-lived. For example, reactions in which the excitation energy is carried off by three neutrons (with or without the prompt emission of an alpha particle) lead primarily to the final nucleus $_{110}X^{289}$, which decays by spontaneous fission with a halflife of 1.6 years.

The reactions that already have been tried experimentally[10,11] are somewhat less favorable than these. Although no conclusive evidence was found for the formation of superheavy nuclei in their ground states, measurements of the kinetic energies of the resulting fragments in some cases suggest that the targets and projectiles do indeed successfully complete the first step, namely fusing to form a single nucleus.[11] However, the nuclei that are produced are highly excited and deformed, and they probably undergo prompt fission into two fragments of comparable size, rather than de-exciting by neutron emission.

Predicting the properties

Suppose that we are ultimately successful in producing superheavy nuclei by one means or another. What chemical and physical properties should they have? Figure 7 is a periodic table that includes elements heavier than those already discovered. Elements are arranged in a periodic table according to the order in which the electrons—rather than the nucleons—fill their orbits. This order can be learned by doing self-consistent calculations for the electrons surrounding the nuclei, for example relativistic Hartree–Fock calculations.

Such calculations have been performed by several groups at Los Alamos and elsewhere, and the results indicate

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	57–71	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	89–103	Rf 104	Ha 105	106	107	108	109	110	111	112	113	114	115	116	117	118
119	120	121–															

Lanthanide series	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Actinide series	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103
121 series	121	122	123	124	125	126									

Periodic table shows predicted locations of new elements. Known elements are indicated by chemical symbols and undiscovered elements by numbers. Figure 7

that the order of filling electronic orbits is somewhat more complicated than had been supposed. For example, we had always thought that elements 103 through 120 would fill their orbits in the analogous way to those in the preceding row in the periodic table, but Joseph Mann's recent calculations suggest that there are exceptions at elements 103, 110 and 111. Also, beginning with element 121 the order of filling the shells is different from the order in the actinide elements.[12] These differences arise from relativistic effects associated with the higher charge of these elements. Therefore, whereas element 114 and lead, for example, should have analogous chemical properties, the chemical properties of some of the other superheavy elements and their lighter homologs should be somewhat less similar.

Electronic self-consistent field calculations can also be used for predicting other chemical and physical properties,[12,13] such as we see in Table 2. The electronic ground-state configuration of element 114 is, we have already noted, analogous to that of lead; the electrons are simply filling the next shell. But lead is primarily divalent and is sometimes tetravalent, whereas element 114 is expected to be purely divalent. The ionization potential for element 114 should be only slightly higher than that for lead, but the x-ray energies will be substantially higher. Element 114 should be somewhat more dense than lead. Finally, the melting and boiling points for element 114 are predicted to be substantially lower than those for lead, but these predictions arise from a complicated extrapolation and consequently are more uncertain than the other results.[13]

The properties I shall consider last are associated with the *fission* of a superheavy nucleus.[14] Because of the increased Coulomb energy that arises from the higher charge of superheavy nuclei, substantially more energy is released when a superheavy nucleus divides than when a conventional nucleus divides. For example, as we see in Table 3, the energy release per *binary* fission is expected to increase by over 50% from plutonium to element 114. (Actually, more energy is released for nuclei heavier than rare-earth nuclei if the division is into three fragments rather than into two. This of course does not mean that superheavy nuclei will divide predominantly into three fragments, but the frequency of ternary divisions should be higher for superheavy nuclei than for conventional nuclei.) The larger fraction of this energy is the translational kinetic energy of the centers of mass of the fission fragments themselves. The remaining portion is excitation energy of the fragments; this energy is dissipated primarily through the emission of neutrons. The excitation energy is roughly three times as large for superheavy nuclei as for Pu^{240}. In addition, less energy is needed to emit a neutron from a fragment that results from the fission of a superheavy nucleus, because these fragments are more neutron-rich than those from Pu^{240}. The two effects combined mean that almost four times as many neutrons should be released in the fission of a superheavy nucleus as in the fission of Pu^{240}! For example, on the average 2.8 neutrons are released when Pu^{240} undergoes fission, but we expect

Table 2. Comparison of Predicted Chemical and Physical Properties of $_{114}X^{298}$ with Observed Values for Pb^{208}

Property	Pb^{208}	$_{114}X^{298}$
Electronic ground-state configuration	Xe core + $4f^{14}5d^{10}6s^26p^2$	Rn core + $5f^{14}6d^{10}7s^27p^2$
Oxidation state	+2 (+4)	+2
Ionization potential (eV)	7.4	8.8
K_{α_1} x-ray energy (keV)	75	174
Density (grams/cm³)	11	14
Melting point (deg C)	327	67
Boiling point (deg C)	1620	147

Table 3. Comparison of Predicted Fission Properties of Superheavy Nuclei with Observed Values for Pu^{240}

Fissioning nucleus	Energy release per fission (MeV)	Translational kinetic energy (MeV)	Excitation energy (MeV)	Number of neutrons per fission
$_{114}X^{298}$	317	235	82	10.5
$_{110}X^{294}$	290	216	74	10.6
Pu^{240}	205	178	27	2.8

some 10.5 neutrons to be released in the fission of $_{114}X^{298}$. This predicted increase is providing the basis for several experimental searches for superheavy nuclei in nature.

The coming years will witness the formation of hundreds of excited superheavy nuclei that live for a few nuclear periods. But can any of these nuclei escape a rapid death by fission and successfully de-excite to become long-lived ground-state nuclei? This is the question we are waiting for the experimentalists to answer.

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References

1. W. D. Myers, W. J. Swiatecki, Arkiv Fysik **36,** 343 (1967).
2. W. D. Myers, W. J. Swiatecki, Nucl. Phys. **81,** 1 (1966).
3. V. M. Strutinsky, Yad. Fiz. **3,** 614 (1966); Sov. J. Nucl. Phys. **3,** 449 (1966); D. D. Clark, PHYSICS TODAY **24,** no. 12, December 1971, page 23.
4. V. M. Strutinsky, Nucl. Phys. **A95,** 420 (1967); **A122,** 1 (1968); Yu. A. Muzychka, V. V. Pashkevich, V. M. Strutinsky, Yad. Fiz. **8,** 716 (1968); Sov. J. Nucl. Phys. **8,** 417 (1969).
5. S. G. Nilsson, J. R. Nix, A. Sobiczewski, Z. Szymański, S. Wycech, C. Gustafsson, P. Möller, Nucl. Phys. **A115,** 545 (1968); S. G. Nilsson, C. F. Tsang, A. Sobiczewski, Z. Szymański, S. Wycech, C. Gustafsson, I. L. Lamm, P. Möller, B. Nilsson, Nucl. Phys. **A131,** 1 (1969).
6. J. R. Nix, *Proceedings* of the International Conference on the Properties of Nuclei Far From the Region of Beta-Stability, Leysin, 1970, Report CERN 70-30, Geneva, 1970, vol. 2, page 605; T. Johansson, S. G. Nilsson, Z. Szymański, Ann. Phys. (Paris) **5,** 377 (1970).
7. M. Bolsterli, E. O. Fiset, J. R. Nix, J. L. Norton, Phys. Rev. Lett. **27,** 681 (1971); Phys. Rev. **C5,** 1050 (1972).
8. E. O. Fiset, J. R. Nix, Los Alamos Preprint LA-DC-13345 (1972).
9. E. K. Hulet, J. F. Wild, R. W. Lougheed, J. E. Evans, B. J. Qualheim, M. Nurmia, A. Ghiorso, Phys. Rev. Lett. **26,** 523 (1971).
10. H. R. Bowman, R. C. Gatti, R. C. Jared, L. G. Moretto, W. J. Swiatecki, S. G. Thompson, Lawrence Radiation Laboratory Nuclear Chemistry Division Annual Report, 1967, Report UCRL-17989, Berkeley, 1968, page 147; G. N. Flerov, *Proceedings* of the International Conference on Heavy Ion Physics, Dubna, 1971, Report JINR-D7-5769, Dubna, 1971, page 43.
11. T. Sikkeland, Phys. Lett. **27B,** 277 (1968); M. Lefort, R. Bimbot, H. Gauvin, Y. Le Beyec, J. Pèter, B. Tamain, X. Tarrago, Orsay Preprint (1971).
12. J. B. Mann, J. T. Waber, J. Chem. Phys. **53,** 2397 (1970); B. Fricke, W. Greiner, J. T. Waber, Theoret. Chim. Acta (Berlin) **21,** 235 (1971).
13. O. L. Keller Jr, J. L. Burnett, T. A. Carlson, C. W. Nestor Jr, J. Phys. Chem. **74,** 1127 (1970).
14. J. R. Nix, Phys. Lett. **30B,** 1 (1969). □