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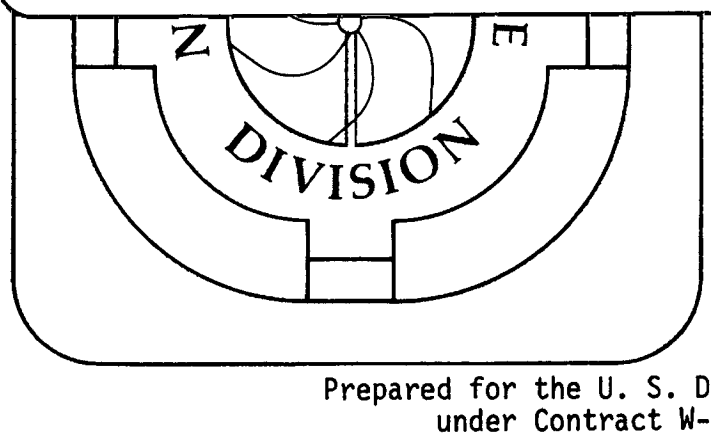

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THE PERIODIC TABLE
Tortuous path to man-made elements

Glenn T. Seaborg, University of California, Berkeley

This article is based on the Priestley Medal Address presented by Glenn T. Seaborg of the University of California, Berkeley, on April 2 during the ACS/CSJ Chemical Congress in Honolulu. Seaborg, winner of the Nobel Prize for Chemistry (with E. M. McMillan) in 1951 and president of ACS in 1976, received the medal, ACS's highest award, in recognition of his distinguished services to chemistry.

The periodic table of the chemical elements has been the key to the discovery of many elements since its formulation as a guiding principle almost exactly 110 years ago. Occasionally, when improperly used, it has misled investigators into temporary excursions along erroneous routes to new elements. However, even these tortuous paths eventually have led to the correct destination. I shall describe the part that the periodic table has played in the discovery of the man-made elements, especially the transuranium elements, and its possible future role.

The story begins, of course, on March 6, 1869, when Dmitri Ivanovich Mendeleev and his associate, Nikolai Menshutkin, presented a paper to the Russian Chemical Society in St. Petersburg (now Leningrad) which postulated that the elements showed a periodicity in their chemical properties when they were arranged in the order of their atomic weights. This in itself was not novel. Several chemists in other countries had observed some kind of orderliness in the elements then known, the most prominent being the German Johan W. Dobereiner and his triads (1829), the Frenchman A. E. Béguyer de Chancourtois and his "telluric screw" (1862), and the Englishman John A. R. Newlands and his "law of octaves" (1864).

It is not generally known that some American chemists of the 19th century also proposed various forms of periodic classifications, including Oliver W. Gibbs in 1845 and Josiah P. Cooke Jr. in 1854. The only real challenge to the generally accepted validity of Mendeleev's originality, however, has come from the work of Lothar Meyer in Germany, who in 1870 produced independently a generalization almost identical to that of Mendeleev.

The reason for the general acceptance of Mendeleev's pre-eminence is straightforward: Not only did he show that periodicity existed in the properties of the elements then known, but he had the courage and the vision to state that his method of classification constituted a fundamental law of nature, and that where there appeared to be deficiencies in his periodic table, they were due to gross errors in the measurement of atomic weights or simply to the fact that certain elements had not yet been discovered. Indeed, Mendeleev's claim to priority in the discovery of the periodic system was not completely accepted until his predictions of missing elements were proved by experimental evidence in later years.

The periodic table Mendeleev published in 1871, which incorporates improvements made in the original version of 1869, predicts the existence and properties of the elements with atomic weights of 44, 68, and 72. These correspond to scandium, gallium, and germanium, as we know them. These three elements were actually found in nature during the period from 1875 to 1886. Many other experimental proofs of Mendeleev's "law" were made in the years that followed.

As time progressed, adjustments had to be made to the periodic table to accommodate the rapidly expanding knowledge of the properties of the elements and their atomic and nuclear structures. Also, additional elements were discovered during the late 19th century and the first part of the 20th century which required some reconstruction of the Mendeleev periodic system. The most significant changes were the addition of another vertical row, or group, of elements now known as the noble gases, and the substitution of a series of elements—the rare earths, or lanthanides—in the place of a single element (placed between barium and hafnium).

By the end of the first decade of the 20th century the total number of elements had increased to 85, and soon thereafter the concept of atomic number, as the fundamental basis for the ordering of the elements in the periodic table, was established. During the next 25 years, three more elements were discovered, leaving below uranium (element 92, the heaviest element) those having atomic number 43, 61, 85, and 87 as the missing elements. Even these properly empty places in the periodic table were filled under names such as masurium for element 43, illinium for element 61, alabamine for element 85, and virginium for element 87. These "discoveries," however, were erroneous. The state of the understanding of the atomic nucleus was such in the 1930's that it could be shown that the missing elements were all radioactive, with such short half-lives that their existence in appreciable concentration on earth was not possible.

The periodic table, as it looked before World War II when scientists first tried to produce elements beyond uranium, includes elements 43, technetium (Tc); 61, promethium (Pm); 85, astatine (At); and 87, francium (Fr), although they were actually given their names later, and some were first synthesized or discovered at a later date.

Thoughts on the position in the periodic table of the heaviest elements varied considerably before the final recognition that another series of elements, resulting from the addition of electrons to an inner shell (5*f*), should

[31]	Группа I	Группа II	Группа III	Группа IV	Группа V	Группа VI	Группа VII	Группа VIII. Переход к группе I
	H = 1							
Типические элементы	Li = 7	Be = 9,4	B = 11	C = 12	N = 14	O = 16	F = 19	
Первый период, Ряд 1-й	Na = 23	Mg = 24	Al = 27,3	Si = 28	P = 31	S = 32	Cl = 35,5	
Первый период, — 2-й	K = 39	Ca = 40	— = 44	Ti = 50?	V = 51	Cr = 52	Mn = 55	Fe = 56, Co = 59, Ni = 59, Cu = 63
Второй период, — 3-й	(Cu = 63)	Zn = 65	— = 68	— = 72	As = 75	Se = 78	Br = 80	
Второй период, — 4-й	Rb = 85	Sr = 87	(?Yt = 88?)	Zr = 90	Nb = 94	Mo = 96	— = 100	Ru = 104, Rh = 104, Pd = 104, Ag = 108
Третий период, — 5-й	(Ag = 108)	Cd = 112	In = 113	Sn = 118	Sb = 122	Te = 128?	J = 127	
Третий период, — 6-й	Cs = 133	Ba = 137	— = 137	Ce = 138?	—	—	—	— —
Четвертый период, — 7-й	—	—	—	—	—	—	—	
Четвертый период, — 8-й	—	—	—	—	Ta = 182	W = 184	—	Os = 199?, Ir = 198? Pt = 197?, Au = 197
Пятый период, — 9-й	(Au = 197)	Hg = 200	Tl = 204	Pb = 207	Bi = 208	—	—	
Пятый период, — 10-й	—	—	—	Th = 232	—	Ur = 240	—	
Высшая солинан окись	R^2O	R^2O^2 или RO	R^2O^3	R^2O^4 или RO^2	R^2O^5	R^2O^6 или RO^3	R^2O^7	R^2O^8 или RO^4
Высшее водородное соединение			(RH^5?)	RH^4	RH^3	RH^2	RH	—

Mendeleev's periodic table of 1871 predicted three then-unknown elements

occur somewhere in the heavy-element region. This new family of elements would be similar to the 14-member rare-earth or lanthanide (chemically similar to lanthanum) series of elements which results from the addition of inner 4*f* electrons.

Even until World War II, however, the three heaviest known elements—thorium, protactinium, and uranium—were believed to be related to hafnium, tantalum, and tungsten, respectively. The next element—number 93—was thus expected to have chemical properties resembling those of rhenium. Similarly, elements 94 to 100 were expected to fit neatly into the periodic table.

The first attempts to produce elements beyond uranium were made by Enrico Fermi, Emilio G. Segré, and coworkers, who bombarded uranium with neutrons in Italy in 1934. They actually found a number of interesting radioactive products. The radioactive products of the neutron bombardment of uranium were the object of chemical investigations during the following years by Otto Hahn, Lise Meitner, and Fritz S. Strassmann, in Germany, and by numerous other scientists. On the basis of incomplete tracer studies, some of these activities seemed to have chemical properties such as would be expected for "transuranium" elements with an atomic number such as 94 or 96—properties similar to those of elements such as osmium and platinum listed directly above elements 94 and 96 in the periodic table of that time.

Subsequent work—especially the discovery of nuclear fission by Hahn and Strassmann and their coworkers late in 1938—showed that this interpretation was not correct. This subsequent work revealed that these products of uranium bombardments with neutrons actually were radioactive isotopes of lighter elements and thus were fission product elements such as barium, lanthanum, iodine, tellurium, or molybdenum.

The synthesis and identification (i.e., discovery) of an element with atomic number higher than 92, neptunium, at the University of California, Berkeley, came in 1940 as a result of the work of Edwin M. McMillan and Philip H. Abelson. This was followed shortly by the discovery of plutonium by McMillan, Joseph W. Kennedy, Arthur C. Wahl, and me in late 1940, also at the University of California, Berkeley. The tracer chemical experiments with neptunium (atomic number 93) and plutonium (atomic number 94) showed that their chemical properties were much like those of uranium and not at all like those of rhenium and osmium! The pre-World War II periodic table had misled Fermi and Hahn and their coworkers, but the ultimate result was the monumental discovery of nuclear fission.

For a few years following this, uranium, neptunium, and plutonium were considered to be sort of "cousins" in the periodic table, but the family relationship was not clear. It was thought that elements 95 and 96 should be much like them in their chemical properties. Thus it was thought that these and the following elements formed a "uranide" (chemically similar to uranium) group.

The periodic table of 1944 therefore implied that the chemical properties of elements 95 and 96 should be very much like those of neptunium and plutonium. These assumptions proved to be wrong, and the experiments directed toward the discovery of elements 95 and 96 on this basis failed. Again, the undiscovered elements 95 and 96 apparently refused to fit the pattern indicated by the periodic table of 1944.

Then, in 1944, I conceived the idea that perhaps all the known elements heavier than actinium were misplaced on the periodic table. The theory advanced was that these elements heavier than actinium might constitute a second series similar to the series of "rare-earth" or "lanthanide" elements. The lanthanides are chemically very similar to

How the periodic table has evolved during past 40 years

1 H																2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	(43)	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71 La-Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	(85)	86 Rn
(87)	88 Ra	89 Ac	90 Th	91 Pa	92 U	(93)	(94)	(95)	(96)	(97)	(98)	(99)	(100)				

57 La	58 Ce	59 Pr	60 Nd	(61)	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

Pre-World War II periodic table predicted erroneous positions for transuranic elements

By 1944, two new transuranium elements had been placed in an "uranide" group

55 Cs	56 Ba	57-71 La-Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt
87 Fr	88 Ra	89 Ac	90 Th	91 Pa	92-106 U-(106)				

92 U	93 Np	94 Pu	(95)	(96)	(106)

Note: In the accompanying periodic tables, atomic numbers of undiscovered elements are in parentheses.

An actinide series of heavy elements revised the periodic table in 1945

1 H 1.008															1 H 1.008	2 He 4.003
3 Li 6.940	4 Be 9.02											5 B 10.82	6 C 12.010	7 N 14.008	8 O 16.000	9 F 19.00	10 Ne 20.183
11 Na 22.997	12 Mg 24.32	13 Al 26.97										13 Al 26.97	14 Si 28.06	15 P 30.98	16 S 32.06	17 Cl 35.457	18 A 39.944
19 K 39.096	20 Ca 40.08	21 Sc 45.10	22 Ti 47.90	23 V 50.95	24 Cr 52.01	25 Mn 54.93	26 Fe 55.85	27 Co 58.94	28 Ni 58.69	29 Cu 63.57	30 Zn 65.38	31 Ga 69.72	32 Ge 72.60	33 As 74.91	34 Se 78.96	35 Br 79.916	36 Kr 83.7
37 Rb 85.48	38 Sr 87.63	39 Y 88.92	40 Zr 91.22	41 Cb 92.91	42 Mo 95.95	43	44 Ru 101.7	45 Rh 102.91	46 Pd 106.7	47 Ag 107.880	48 Cd 112.41	49 In 114.76	50 Sn 118.70	51 Sb 121.76	52 Te 127.61	53 I 126.92	54 Xe 131.3
55 Cs 132.91	56 Ba 137.36	57 La 138.92 / 58-71 See La series	72 Hf 178.6	73 Ta 180.88	74 W 183.92	75 Re 186.31	76 Os 190.2	77 Ir 193.1	78 Pt 195.23	79 Au 197.2	80 Hg 200.61	81 Tl 204.39	82 Pb 207.21	83 Bi 209.00	84 Po	85	86 Rn 222
87	88 Ra	89 Ac / See Ac series	90 Th	91 Pa	92 U	93 Np	94 Pu	95	96							

LANTHANIDE SERIES	57 La 138.92	58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61	62 Sm 150.43	63 Eu 152.0	64 Gd 156.9	65 Tb 159.2	66 Dy 162.46	67 Ho 163.5	68 Er 167.2	69 Tm 169.4	70 Yb 173.04	71 Lu 174.99
ACTINIDE SERIES	89 Ac	90 Th 232.12	91 Pa 231	92 U 238.07	93 Np 237	94 Pu	95	96							

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

LANTHANIDES	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
ACTINIDES	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Modern periodic table fits in all elements through number 118

Futuristic periodic table finds places for elements extending to number 168

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Ha	106	(107)	(108)	(109)	(110)	(111)	(112)	(113)	(114)	(115)	(116)	(117)	(118)
(119)	(120)	(121)	(154)	(155)	(156)	(157)	(158)	(159)	(160)	(161)	(162)	(163)	(164)	(165)	(166)	(167)	(168)

LANTHANIDES	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
ACTINIDES	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

SUPER-ACTINIDES	(122)	(123)	(124)	(125)	(126)		(153)

Quiz Kids Sheila Conlan (center) and Robert Burke (right) appeared with Glenn Seaborg when he informally announced discovery of elements 95 and 96 on radio show in 1945

each other and usually are listed in a separate row below the main part of the periodic table. This would mean that all these heavier elements really belong with actinium—directly after radium in the periodic table—just as the known "lanthanides" fit in with lanthanum between barium and hafnium.

The revised periodic table, then, listed the heaviest elements as a second "rare-earth" series. These heaviest elements (including undiscovered elements), with the name "actinide" elements, were paired off with those in the already-known lanthanide rare-earth series in a table (*1*) published in C&EN, Dec. 10, 1945.

The new concept meant that elements 95 and 96 should have some properties in common with actinium and some in common with their rare-earth "sisters," europium and gadolinium, especially with respect to the difficulty of oxidation above the III state. When experiments were designed according to this new concept, elements 95 and 96 were soon discovered at the wartime Metallurgical Laboratory at the University of Chicago—that is, they were synthesized and chemically identified.

Quite by chance, the discovery of elements 95 and 96 was revealed informally on a nationally broadcast radio program, the Quiz Kids, in which I appeared as guest on Nov. 11, 1945. The discovery information had already been declassified (removed from the "Secret" category) for presentation at an American Chemical Society meeting to be held at Northwestern University the following Friday. Participating on the program with me were Quiz Kids Sheila and Patrick Conlan, Robert Burke, Harvey Fishman, and Richard Williams. When Richard asked me if any new elements had been discovered in the course of research on transuranium elements during the war, I revealed the discovery of elements 95 and 96. Apparently, many kids in America told their teachers about it the next day and, judging from some of the letters I received from such youngsters, they were not entirely successful in convincing their teachers.

Not only did this new understanding lead to the elements americium and curium (95 and 96), but to the synthesis and identification of berkelium and californium (97 and 98) in 1949 and 1950, einsteinium and fermium (99 and 100) in 1952 and 1953, mendelevium (101) in 1955, and nobelium (102) in 1958. It also signaled the end of the actinide series at lawrencium (103) when this element was discovered in 1961.

Since all the elements beyond actinium through lawrencium, element 103, belong to the actinide group, the elements thorium, protactinium, and uranium have been removed from the positions they occupied in the periodic table before World War II and placed in this transition family. Elements 104, 105, and 106 have taken over the positions previously held by thorium, protactinium, and uranium.

Rutherfordium (104), hahnium (105), and element 106 (as yet not named) were synthesized and identified during the next 13 years by Albert Ghiorso and coworkers at Berkeley. (It now seems clear that competing claims to the discovery of these elements by G. N. Flerov and coworkers at the Dubna Laboratory in the Soviet Union cannot be substantiated.) And we can confidently place all of the undiscovered elements through number 118 in their expected places in the periodic table.

The elements beyond the actinides in the periodic table can be termed the "transactinides." These begin with the element with atomic number 104 and extend, in principle, indefinitely. Although only three such elements—numbers 104, 105, and 106—are definitely known at this time, there are some prospects for the discovery of a number of additional elements. Such elements may be synthesized and identified in the region just beyond number 106 or may be synthesized in the region of much larger atomic numbers. They would be synthesized by the bombardment of heavy nuclides with heavy ions. The early transactinide elements find their place back in the main body of the modern periodic table.

Study of the chemical properties of element 104 has confirmed that it is indeed homologous to hafnium, as demanded by its position in the periodic table (*2*). No definitive chemical studies have been made for element 105 and no chemical studies have been made for element 106. Such studies are very difficult because the longest-lived isotope of 104 ($^{261}104$) has a half-life of only about one minute, of 105 ($^{262}105$) a half-life of about 40 seconds, and of 106 ($^{263}106$) a half-life of about one second.

On the basis of the simplest projections, it is expected that the half-lives of the elements beyond element 106 will become shorter and shorter as the atomic number is increased, and this is true even for the isotopes with the longest half-life for each element. Thus, if this rate of decrease could be extrapolated to ever-increasing atomic numbers, we would expect half-lives of the order of 10^{-10} second for the longest-lived isotope of element 110, and 10^{-20} second for element 115, and so forth, with decay by spontaneous fission becoming of dominating importance beginning with element 106. To make the situation even worse, predictions indicate that the yields from the nuclear production reactions will fall off drastically with atomic number as we proceed beyond element 106. The observed yields for the production of element 106 are down to the level of one atom per hour.

These considerations would present somewhat dismal future prospects for heavier transuranium elements, but other factors have entered the picture in recent years. These led to an increased optimism concerning the prospects for the synthesis and identification, or even the discovery in nature, of elements well beyond the observed upper limit of the periodic table—elements that have come to be referred to as "superheavy" elements. An excellent review article on the superheavy elements was written by S. G. Thompson and C. F. Tsang (*3*) in 1972.

Complicated theoretical calculations, based on filled

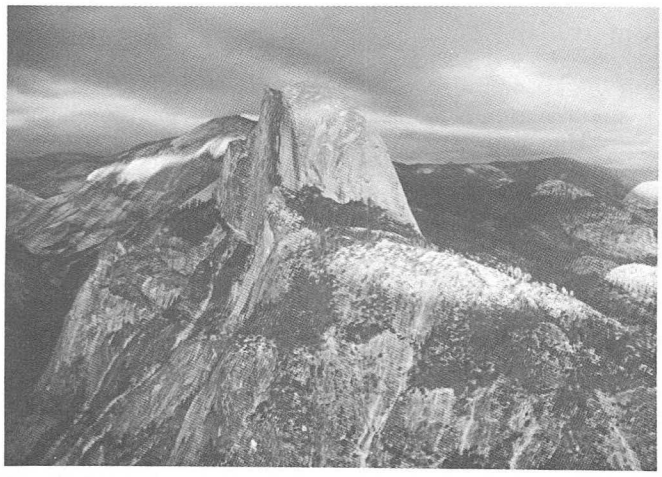


Photo by David Seaborg

The "island of stability" for superheavy elements may have sharply dropping slopes, like Half Dome in Yosemite . . .

Photo by Glenn Seaborg

. . . rather than the more gentle slopes of Mt. Diablo, which is located in the San Francisco Bay area

shell (magic number) and other nuclear stability considerations, led to these extrapolations to the far transuranium region. These suggested the existence of closed nucleon shells at Z = 114 and N = 184 that exhibit great resistance to decay by spontaneous fission, the main cause of instability for the heaviest elements. Earlier considerations had suggested a closed shell at Z = 126, by analogy to the known shell at N = 126, and some calculations suggest a closed shell at N = 228. Although Z = 164 and N = 318 may represent additional hypothetical points of stability, they correspond to a much more extensive extrapolation and any predictions are therefore much more uncertain.

Enhancing the prospects for the actual synthesis and identification of superheavy nuclei was the fact that the calculations showed the doubly magic nucleus $^{298}114$ not to be the single long-lived specimen but to be merely the center of a rather large "island of stability" in a "sea of spontaneous fission."

More recent calculations suggest that the shell effect of Z = 114 is not very large. Although these calculations confirm the existence of a closed shell at N = 184 they suggest a lesser stability for the region with N < 184. Thus the island of stability would have a sharp dropoff for N < 184—a structure like Half Dome in Yosemite, steeply falling into the sea of instability, and not like the more gentle slopes of my favorite Mt. Diablo in the San Francisco Bay area.

If these later considerations are correct, it will become much more difficult to synthesize and detect the superheavy elements, and their observation in terrestrial matter or any object whose age significantly exceeds 10^5 years will be precluded. A recent review article (*4*) describes the present situation with respect to superheavy elements taking into account these more recent considerations.

Turning to consideration of electronic structure, upon which chemical properties must be based, modern high-speed computers have made possible the calculation of such structures (*5*). The calculations show that elements 104 through 112 are formed by filling the 6*d* electron subshell, which makes them, as expected, homologous in chemical properties with the elements hafnium (72) through mercury (80). Elements 113 through 118 result from the filling of the 7*p* subshell and are expected to be similar to the elements thallium (81) through radon (86). Thus these calculations are consistent with the modern periodic table.

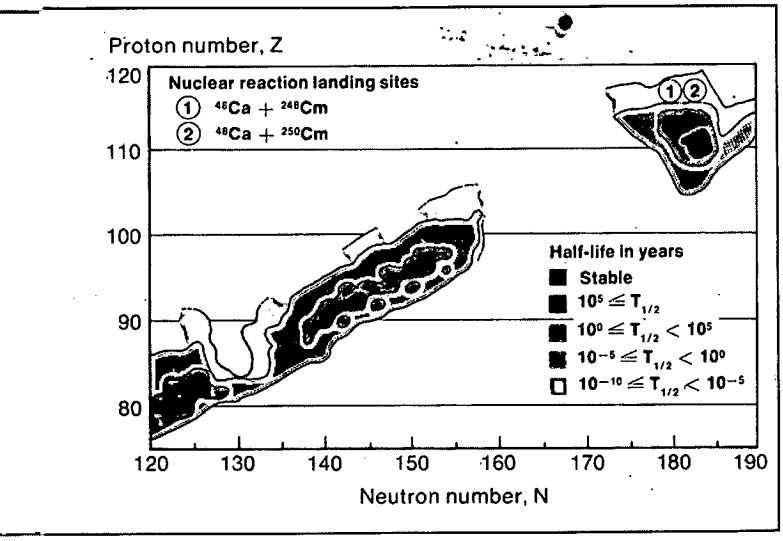
The calculations indicate the 8*s* subshell should fill at elements 119 and 120, thus making these an alkali and alkaline earth metal, respectively. Next the calculations point to the filling, after the addition of a 7*d* electron at element 121, of the inner 5*g* and 6*f* subshells, 32 places in all, which I have termed the "superactinide" elements and which terminate at element 153. This is followed by the filling of the 7*d* subshell (elements 154 through 162) and 8*p* subshell (elements 163 through 168).

Actually, more careful calculations have indicated that the picture is not this simple. The calculations indicate that other electrons (8*p* and 7*d*) in addition to those identified in the above discussion enter the picture as early as element 121 (or even element 104), thus further complicating the picture. These and other perturbations, caused by spin-orbit splitting, lead to predictions of chemical properties that are not consistent, element by element, with those suggested by the modern and futuristic periodic tables. Here again we are in danger of making wrong predictions about the chemical properties of undiscovered elements by using the periodic table incorrectly (*5*).

For example, the six 7*p* electrons, because of relativistic effects, are predicted to be split into two subshells, four $7p_{3/2}$ and two $7p_{1/2}$ electrons, with a separation of energies such that the filled $7p_{1/2}$ orbital will act as a closed shell and additional $7p_{3/2}$ electrons will act as electrons outside a closed shell. Thus element 115 (eka-bismuth) is predicted to have its valence electrons in the configuration $7p_{1/2}^2\ 7p_{3/2}$ with a consequent stable I oxidation state in contrast to the stable III oxidation state of its homolog bismuth. Another predicted result of relativistic effects is that element 112 (eka-mercury) and element 114 (eka-lead) may be very noble, that is, liquids or volatile gases. These considerations raise the exciting possibility of studying "relativity in a test tube." They become especially significant beyond the superactinide series, a region far beyond the region of expected nuclear stability, which is the only region where it might be possible to synthesize or find superheavy elements.

Simple considerations indicate that, as a first approximation, elements in the island of stability can be predicted to have chemical properties as follows. Element 114 should be a homolog of lead, that is, should be eka-lead, element 112 should be eka-mercury, element 110 should be eka-platinum, and so on. If there is an island of stability at element 126, this superactinide element and its neighbors should have chemical properties like those of the actinide and lanthanide elements.

Attempts to synthesize and identify superheavy elements, through bombardments of a wide range of heavy nuclides with a wide range of heavy ions, have so far been



Topological map of the heavy elements shows a peninsula of stability for known elements and an island of predicted stability near Z = 114 and N = 184 in a surrounding sea of instability or spontaneous fission. The fusion reactions $^{48}Ca + ^{248}Cm$ and $^{48}Ca + ^{250}Cm$ are two possible ways to form nuclei that would approach the island of stability

unsuccessful (*4*). Also, every attempt to find evidence, direct or indirect, of the superheavy elements in nature associated with the island of stability centered on element 114 has led to negative results or has not been conclusive enough to give a clear-cut answer.

Numerous attempts (*4*) have been made to synthesize and detect the superheavy elements through the fusion of heavy ions (atomic number Z_1) with heavy target nuclei (atomic number Z_2) to produce compound superheavy nuclei (atomic number $Z_1 + Z_2$). Relatively strong nuclear shells, with their accompanying high potential barriers for nuclear fission, are required for two reasons: to enable any excited superheavy nucleus formed in a nuclear fusion reaction to survive destruction by fission during its de-excitation process, and to enable any "cold" superheavy nucleus that survived its de-excitation to live long enough to be detected through its alpha particle or spontaneous fission decay.

To maximize the probability for the compound nuclei to escape destruction by fission during their de-excitation, they should be produced with the lowest possible excitation energy. In other words, they should be synthesized with a bombarding energy for the projectile heavy ion which just barely exceeds the Coulomb barrier. Unfortunately, more energy than this is apparently required for the two participating nuclei to fuse to form a compound system.

Thus we appear to be caught on the horns of a dilemma. If the bombarding energy is low, the reacting nuclei don't fuse; if the bombarding energy is high enough to produce fusion, the product nuclei don't survive. To further exacerbate the situation, projectile nuclei with Z greater than about 25 do not seem to fuse with very heavy target nuclei to form a compound system at any bombarding energy.

The reaction $^{48}Ca + ^{248}Cm$ to form the compound nucleus $^{296}116$ has been studied extensively because of several favorable factors: The projectile ^{48}Ca is light enough presumably to allow some fusion to take place, its double shell closure (high binding energy) reduces the excitation energy of the product, and its relative neutron excess allows an approach toward the closed shell at N = 184 (which needs to be attained for best results, but unfortunately is not quite reached even in this case). Unfortunately, even these experiments have all led to negative results so far. A possibility for improving the survival probability of superheavy nuclei formed in this fusion reaction is to use a more neutron-rich target, such as ^{250}Cm, which would allow a closer approach to the desired N = 184. Unfortunately, the availability of ^{250}Cm is very limited and quantities sufficient to undertake an experiment could only become available through expensive recovery from the debris of an old or a future underground nuclear weapons test.

Another possibility (*4*) for the synthesis and identification of superheavy elements, not yet so extensively studied, is by the use of the "deep inelastic transfer" reaction, in which there is a massive energy and nucleon transfer between projectile and target. Success of this approach apparently depends on the use of the heaviest available projectile and target. Experiments at the Gesellschaft für Schwerionenforschung Laboratory in Darmstadt, West Germany, where uranium ions are already available as projectiles, have been performed with the reaction $^{238}U + ^{238}U$. Products as heavy as ^{255}Fm, corresponding to a net transfer of eight protons and nine neutrons, have been observed there. Although this leaves a long way to go to reach the island of stability, there is hope that the expected barriers for fission will enhance the yields in this region. Pursuit of this route using reactions such as ^{248}Cm (target) + ^{244}Pu (projectile), or even ^{249}Cf or ^{254}Es (target available in only very small quantity) + ^{244}Pu might lead to positive results.

Additional attempts might be along the lines of using higher-intensity heavy ion beams, improved methods of detection, and more emphasis on detecting short half-lives (one second down to 10^{-9} second or less).

It will be frustrating if we are left with the strong feeling that the island of stability must be there but we are unable to devise means of reaching it. Chemists would like the challenge of once again testing the role of the periodic table in predicting the chemical properties of new chemical elements. They hope to travel once again the tortuous path to man-made elements. □

References

1. Seaborg, G. T., "Chemical and Radioactive Properties of the Heavy Elements," *Chem. Eng. News*, **23,** 2190 (1945).
2. Silva, R., Harris, J., Nurmia, M., Eskola, K., Ghiorso, A., "Chemical Separation of Rutherfordium," *Inorg. Nucl. Chem. Lett.*, **6 (12),** 871 (1970).
3. Thompson, S. G., Tsang, C. F., "Superheavy Elements," *Science*, **178,** 1047 (1972).
4. Seaborg, G. T., Loveland, W., Morrissey, D. J., "Superheavy Elements—A Crossroads," *Science*, **203,** 711 (1979).
5. Keller, O. L., Jr., Seaborg, G. T., "Chemistry of the Transactinide Elements," *Ann. Rev. Nucl. Sci.*, 139 (1977).

Suggestions for additional reading

Van Spronsen, J. W., "The Periodic System of Chemical Elements: A History of the First Hundred Years," Elsevier Publishing Co., Amsterdam, London, New York, 1969.

Seaborg, G. T., "The Transuranium Elements," Yale University Press, 1958.

Seaborg, G. T., "Transuranium Elements: Products of Modern Alchemy," Dowden, Hutchinson & Ross Inc., Stroudsburg, Pa., 1978. (Compilation of reprints of original papers.)

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