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ORIGIN OF THE ACTINIDE CONCEPT

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Origin of the Actinide Concept

by Glenn T. Seaborg

1. BACKGROUND

A typical periodic table of the time just prior to World War II, with predicted positions for elements beyond uranium, is shown in Figure 1. The heaviest natural elements, thorium, protactinium, and uranium, of atomic numbers 90, 91, and 92, respectively, were placed in corresponding positions just below the sixth period "transition" elements--hafnium, tantalum, and tungsten--in which the 5d electron shell is being filled. Hafnium, tantalum, and tungsten are similar in their chemical properties to the corresponding transition elements in the fifth period--zirconium, columbium, and molybdenum--in which the 4d shell is being filled.

It had long been known that the chemical properties of thorium, protactinium, and uranium resemble those of the 4d and 5d elements. For this reason most of the textbooks and standard works on chemistry and physics in which the electronic structure was discussed accepted the view that it was the 6d shell that was being filled. Thus the structures of the elements above radon (element 86) through uranium were written to show the addition of the next two electrons in the 7s shell for element 87 (francium) and element 88 (radium) and addition in the 6d shell for actinium, thorium, protactinium, and uranium. Latimer and Hildebrand (1940); Richtmeyer and Kennard (1942); Taylor and Glasstone (1942).

Many of the early papers that appeared after N. Bohr's (1913) classical work on the quantized nuclear atom discuss the electronic structure of the heaviest elements. It was recognized by many that the next hypothetical rare gas should have the atomic number 118 in a place 32 elements beyond radon (Z = 86), thus implying transition groups similar to those between xenon (Z = 54) and radon (Z = 86). Rydberg (1913) as early as 1913 implied that this was to be expected. There was general agreement that some type of transition group should begin in the neighborhood of uranium, although there were differences of opinion as to where it begins and as to which electron shell is involved. A number of the earliest publications suggested that this transition series involves the filling of the 5f shell, thus possibly giving rise to a "rare-earth" group in a manner analogous to that resulting from the filling of the 4f shell. The filling of the 4f shell results in the well known group of fourteen rare-earth elements of atomic numbers 58 to 71, inclusive; these elements follow lanthanum. It is of interest here to note a few of the early and also the later suggestions in order to review the general previous status of this question. Most of these early investigators thought that the filling of the 5f shell should begin at some point beyond uranium, that is, beyond the elements that were known to them.

In early papers Bohr (1923) suggested that the addition of the 5f electrons might begin in this region, and in a Bohr-Thomsen type of periodic table he pictured the first entry at the element with atomic number 94. Goldschmidt (1924) thought the transuranium elements up to atomic number 96 should be homologs of the platinum group, and Hahn (1929) thought this view was worthy of serious consideration. Suguira and Urey (1926), using the old quantum theory, published the results of

their calculations, which indicated that the first entry of an electron into the 5f shell should occur at element 95, whereas Wu and Goudsmit (1933), on the basis of a more refined calculation, showed that their solution of the Schrodinger equation indicated such entry at uranium or element 93. McLennan, McLay, and Smith (1926) suggested, as an alternative to the filling of the 6d shell, the possibility that the 5f shell begins to be occupied in thorium. In a review article Dushman (1926) stated that it is doubtful that the added electrons enter the 6d level (thus implying an analogy with cerium, etc.). Swinne (1926) pointed out that the available evidence on thorium and uranium was consistent with the first entry of 5f electrons at protactinium or uranium, but he also thought that it might occur beyond uranium. Saha and Saha (1934) suggested as an alternate possibility to the filling of the 6d shell, the entry of the first 5f electron at thorium. Karapetoff (1930) suggested that the element with atomic number 93 might be the first in which the 5f shell begins to be filled, and Von Grosse (1935; 1928; 1930) suggested as a possible alternative to filling of the 6d shell, the entry of the first electron in the 5f shell at uranium. Quill (1938), largely for the purpose of illustration, presented periodic table arrangements in which the first 5f electron appears in element number 95 in one case and in element number 99 in another. Perrin (1935), Rudy (1927), and Carranza (1935), on general considerations, proposed as a possibility the theory that the first 5f electron appears in thorium, and Villar (1942; 1940) suggested that some of the chemical evidence supports this viewpoint. Somewhat earlier, on the basis of his crystallographic work, Goldschmidt (1937) had changed his original point of view and had come to the view that the first 5f electron enters at protactinium, although he pointed out the

possibility that this might occur earlier, in thorium, or later, in uranium, or in the (at the time unknown) transuranium elements. By analogy with the name "lanthanide" series, which he and others (1925) had already proposed for the rare-earth elements because these fourteen elements following lanthanum have lanthanum as their prototype, he proposed the name "thoride" series for the fourteen elements following thorium. At the same time he was the first to suggest that terms such as "actinide," "protactinide," and "uranide" might describe the group if it should eventually be found to begin earlier or later than this.

It can be seen that although many interesting and perspicacious proposals had been made up to this time, the electronic structure and place in the periodic table of these elements could not be regarded as established.

The discovery of the transuranium elements and the study of their properties, especially the chemical properties, furnished a tremendous amount of additional evidence of just the type needed to clarify this problem. It is in the transuranium elements that the really definitive chemical properties, from the standpoint of placing the heaviest elements in the periodic table, first appear. The first conclusive evidence that the 5f shell undergoes filling in this heavy region came from the tracer chemical observations of McMillan and Abelson (1940) on element 93, neptunium. Upon their discovery of neptunium, the first transuranium element, McMillan and Abelson were able to show definitely that it resembles uranium in its chemical properties and bears no resemblance to rhenium, which is the element immediately above it in the periodic table of that time. This excellent experimental evidence was interpreted by them to indicate that this new "rare-earth" group of similar

elements starts at the next element beyond uranium. The later calculations of Mayer (1941) indicated that the energy and spatial extension of the 5f eigenfunctions drop sharply at about element 91 and therefore that the filling of the 5f shell might begin at the first element beyond protactinium or uranium. Daudel (1943), in commenting on Mayer's paper, made some remarks concerning the special nature of the f electrons at the beginning of the rare-earth and the heavy-transition groups. Starke (1943) and Bedreag (1943) also interpreted the tracer experiments with element 93 as indicating that the first 5f electron comes at element 93, but Strassmann and Hahn (1942) thought, on the basis of their tracer experiments with this element, that it was difficult to make any deduction. As a result of our first tracer experiments with element 94, together with our consideration of the tracer investigations with element 93, Wahl and I (1942; 1948; 1949) made the suggestion that this transition group might begin earlier and that thorium or actinium might be the zero element in the series. On the basis of his complete crystallographic evidence, including especially observations on the transuranium elements, Zachariasen (1940a, 1944b) agreed with Goldschmidt that a thoride series is involved. Some spatial classifications of the elements appeared in which the heaviest elements, starting with thorium as the homolog of cerium, are listed as the chemical homologs of the rare-earth elements, but the reason in these cases appears to be mainly connected with the symmetry of and the ease of making such an arrangement. Djounkovsky and Kavos (1944); Talpain (1945).

2. SUGGESTION OF ACTINIDE CONCEPT

I considered all of the evidence, especially the chemical properties of the elements with the atomic numbers 93 and 94, and made the suggestion that a rare-earth-like series begins with actinium in the same sense that the rare-earth or "lanthanide" series begins with lanthanum. On this basis it might be termed the "actinide" series and the first 5f electron might--although would not necessarily--appear in thorium. The salient point is that the characteristic oxidation state would be the III state.

This suggestion was advanced in a secret report (1944) I prepared in July 1944 at the wartime Metallurgical Laboratory of the University of Chicago, which is quoted in its entirety as follows:

> "Plutonium is the eighth element in the seventh period of the periodic table. The correlation of its chemical properties with its atomic structure can best be accomplished by considering it together with a number of the other elements in the seventh period (elements 89 to 94) in a discussion involving the chemical and physical properties of these elements.
>
> It seems very probable that some kind of a transition group should begin in the neighborhood of these elements. The elements 90 to 94 lie in corresponding positions just below the sixth-period transition elements hafnium to osmium (atomic numbers 72 to 76), in which the 5d shell is being filled. The transition elements hafnium to osmium are very similar in their chemical properties to the corresponding 4d transition elements of the fifth period (zirconium to ruthenium,

atomic numbers 40 to 44). Although the first members ($_{90}$Th, $_{91}$Pa) of the group 90 to 94 show a great deal of resemblance in chemical properties to the first members ($_{72}$Hf, $_{73}$Ta) in the 5d transition series and to the first members ($_{40}$Zr, $_{41}$Cb) in the 4d transition series, the later members ($_{93}$Np, $_{94}$Pu) show practically no resemblance to $_{75}$Re and $_{76}$Os or to element 43 and $_{44}$Ru. Neptunium and plutonium are much more electropositive in character than the noble elements rhenium, element 43, osmium, and ruthenium. There is no evidence for a volatile plutonium tetroxide in contrast with the volatile osmium and ruthenium tetroxides, and there is no evidence for an oxidation number of VIII in plutonium. Thus it seems certain that the transition in the elements 89 to 94 does not involve the simple filling in of the 6d shell.

On the other hand, the chemical properties of neptunium and plutonium are very similar to those of uranium and thorium and are such as to suggest that the 5f shell is being filled and that we are dealing with another rare-earth series similar to the well known lanthanide series, $_{58}$Ce-$_{71}$Lu, in which the 4f shell becomes filled. Many people had suggested, on the basis of considerations of electronic structure, that a rare-earth-like series should begin in this region. There has been a large degree of uncertainty in these predictions with regard to the starting point of this series. The two principal choices have been between a thoride and a uranide series. From the standpoint of the chemical properties of $_{90}$Th, $_{91}$Pa, and $_{92}$U considered

alone, the evidence for such a series was not strong. However, with the discovery of neptunium and plutonium and the observation of the marked similarity of these elements to uranium and thorium in chemical properties, the chemical evidence for a rare-earth-like series has become very strong.

The persistence of the IV oxidation state through the elements thorium, uranium, neptunium, and plutonium is certainly good evidence that electrons are going into the 5f shell. The observation by Zachariasen of the isomorphism of the compounds ThO_2, UO_2, NpO_2, and PuO_2 and his observation of the regular decrease in radius of the metallic ion in these oxides in the anticipated manner are also very good evidence that the electrons are going into the 5f shell. A number of other crystallographic observations by Zachariasen lend support to this view. There are other points of evidence, for example (1) magnetic susceptibility measurements on uranium and plutonium, (2) the sharpness of the optical absorption in aqueous solutions of uranium and plutonium, and (3) evidence for organic complexes of U^{+4} and Pu^{+4} in which these elements have a coordination number of 8 (indicating that the 6d, 7s, and 7p orbitals are available), which facts also give strong support to this conclusion. It seems very probable from these lines of evidence that uranium and plutonium (and neptunium) have electrons in the 5f shell; however, it is not possible to deduce whether or not uranium is the first element in the series for which this is the case. It would be consistent with this evidence for thorium

and protactinium to have no electrons in the 5f shell and for uranium to have two electrons in this shell.

An attractive hypothesis is that this rare-earth-like series begins with actinium in the same sense that the lanthanide series begins with lanthanum. On this basis it may be termed the "actinide series," and the first 5f electron may appear in thorium. Thus, the ground state of thorium may have the structure $5f^1 6d 7s^2$ beyond the radon core. With an actinide series, uranium may have the electron configuration $5f^3 6d 7s^2$, neptunium the configuration $5f^4 6d 7s^2$, and plutonium the configuration $5f^5 6d 7s^2$. It is very interesting to note that Kiess, Humphreys, and Laun (1944) give a preliminary description of the analysis of the spectrum of neutral uranium atoms and come to the conclusion that the electron configuration of the lowest state of uranium is $5f^3 6d 7s^2$ (with the term symbol $^5L_6$), which supports the above view.

It may be that, as in the lanthanide series, electrons do not tend to occupy the 6d orbital; rather, an additional electron goes into a 5f orbital and gives, for example, the configuration $5f^2 7s^2$ for thorium and the configuration $5f^4 7s^2$ for uranium. There is evidence that thorium emits a complex spectrum corresponding to a rare earth with an electron structure like that of $_{58}Ce$, whose ground state is known to have the configuration $4f^2 6s^2$, and that uranium has a spectrum similar to that of the rare-earth element $_{60}Nd$, whose ground state is known to have the configuration $4f^4 6s^2$.

It may be, of course, that there are no 5f electrons in thorium and protactinium and that the entry into a rare-earth-like series begins at uranium, with three electrons in the 5f shell. It would still seem logical to refer to this as an actinide series.

In an actinide series it may seem rather peculiar at first sight that the persistent oxidation number of IV should be in this region. The IV oxidation state seems to be most prevalent and generally most stable among these elements. However, as referred to above, in the lanthanide series there are usually only two electrons present in the 5d and 6s shells, whereas the persistent oxidation state is certainly III. This generally involves the removal of a 4f electron. There are also a number of cases in the lanthanide series where the oxidation number IV is found. In the "actinide" series, although the oxidation number IV is perhaps prevalent, the oxidation number III seems also to be found in most of the members of the series. Zachariasen has recently reported crystallographic evidence for tripositive thorium compounds (ThF_3 and ThOF), although magnetochemical experiments by Selwood have failed to confirm this report.

There is one way in which the actinide series definitely differs from the lanthanide series. This is in the existence of oxidation states higher than IV [protactinium (V), uranium (VI), neptunium (VI), plutonium (VI)] in this series. It must be concluded that the 5f electrons are not so tightly bound as the 4f electrons. This is certainly reasonable. However, the

evidence so far is in favor of a maximum oxidation number of VI in this series, so that the removal of three electrons, or four if there are no electrons in the 6d orbitals, from the 5f orbitals is the maximum that occurs in ordinary chemical reactions.

It is interesting to speculate a little about the chemical properties of the series members which we have not yet had an opportunity to study. The element $_{91}Pa$ is obviously interesting to study from a chemical and crystallographic point of view in order to throw further light on the situation. It seems very likely that this element will have oxidation states of IV and III in addition to the V state, and probably at least the IV state will have a reasonable amount of stability. It seems almost certain, also, that neptunium will have an oxidation state of III, intermediate in stability between U^{+3} and Pu^{+3}. If the picture of the actinide series is correct, the configuration $5f^7 6d^1 7s^2$ may be reached with element 96 (similar to the configuration of $_{64}Gd$); this configuration should be especially stable. The prediction may be made that with element 96 it will be very difficult, if not impossible, to reach any oxidation states above III or IV. In the case of element 95 the configuration of $5f^7 7s^2$, similar to $_{63}Eu$, may be possible, and it may be expected that the oxidation state II will exist. Oxidation states higher than IV may also be difficult or impossible to reach in the case of element 95. There already seems to be some evidence for a trend toward greater stability for the lower oxidation states in the members of the series that have been studied so far. Thus, in going

from uranium to plutonium, there seems to be a trend toward greater stability of the III oxidation state and greater difficulty in reaching the VI state. If the series is truly a thoride or a uranide series, the most stable lower oxidation states will occur at elements beyond 95 and 96; however, even in this event some tendency may be expected in this direction at elements 95 and 96. It would obviously be of great interest and value in elucidating the nature of this series to study the chemical properties of elements such as 95 and 96."

The recognition that the elements with the atomic numbers 95 and 96 should have relatively stable lower (i.e., III) oxidation states made it possible, during the ensuing months, to chemically identify (i.e., discover) these elements at the wartime Metallurgical Laboratory following their production by nuclear synthesis reactions. I made the announcement of this discovery at a symposium at Northwestern University on Friday, November 16, 1945 (following my premature disclosure of this discovery to a national radio audience when I appeared as a guest on the "Quiz Kids" program the preceding Sunday). This talk was published by me in Chemical and Engineering News the following month (1945). This was my first open publication of a description of the actinide concept. Following is a quote from the article:

"The elements 90 to 94 lie in corresponding positions just below the sixth period transition elements Hf to Os (atomic numbers 72 to 76) in which the 5d electron shell is being filled. The transition elements Hf to Os are similar in their chemical properties to the corresponding 4d transition elements in the fifth period (Zr to Ru, atomic numbers 40 to

44). Although the first members ($_{90}$Th, $_{91}$Pa) of the group 90 to 94 show a great resemblance in chemical properties to the first members ($_{72}$Hf, $_{73}$Ta) in the 5d transition series and to the first members ($_{40}$Zr, $_{41}$Cb) in the 4d transition series, the later members ($_{93}$Np, $_{94}$Pu) show practically no resemblance to $_{75}$Re and $_{76}$Os and to element 43 and $_{44}$Ru. This suggests that it is the 5f electron shell which is being filled, although it is not possible to deduce from this chemical evidence alone whether uranium is the first element in the series for which this is the case. While it is beyond the scope of this discussion to give all the supporting evidence, we would like to advance the attractive hypothesis that this rare-earth-like series begins with actinium in the same sense that the "lanthanide" series begins with lanthanum. On this basis it might be termed the "actinide" series and the first 5f electron might appear in thorium. Thus the characteristic oxidation state--i.e., the oxidation state exhibited by those members containing seven 5f and fourteen 5f electrons--for this transition series is III.

The oxidation state of IV demonstrated by thorium is then analogous to the IV oxidation state of cerium. From the behavior of uranium, neptunium, and plutonium it must be deduced that as many as three of the assumed 5f electrons are readily given up, so that the failure of thorium to demonstrate an oxidation state of III is accounted for. On the basis of this hypothesis, elements 95 and 96 should exhibit very stable III states; in fact, element 96 should exhibit the III

state almost exclusively because, with its seven 5f electrons, it should have an electron structure analogous to that of gadolinium, with its seven 4f electrons.

The experiments of G. T. Seaborg, R. A. James, L. O. Morgan, and A. Ghiorso in the Metallurgical Laboratory have recently led to the identification of isotopes of elements 95 and 96, making it possible to study the chemical properties of these isotopes by the tracer technique. These investigators have studied the products produced as a result of the bombardment of U^{238} and Pu^{239} with very high energy (40 Mev) helium ions in the Berkeley cyclotron. This work was made possible by the vital participation and cooperation of J. G. Hamilton and his group at the University of California, who have recently rebuilt the 60-inch cyclotron to produce the high energy particles needed and who performed the bombardments.

Of course in the case of some of the elements in the series it may be something of an academic matter to assign electrons to the 5f or 6d shells, as the energy necessary for the shift from one shell to the other may be within the range of chemical binding energies. The electron configuration may differ from compound to compound of an element or even with the physical state of a given compound. This shifting of electron configuration would probably be most pronounced with the middle members of the first half of the series--that is, uranium, neptunium, and plutonium. Since the energy difference between the 5f and 6d shells is rather small and

since the resonance effects should be rather large, the latter may predominate in determining which energy level lies lowest.

It is probably worth while to make a brief summary at this point with the following statements. As of today, the periodic system consists of 96 known, identified elements--that is, there is now positively known at least one isotope, stable or radioactive, for each of the elements from atomic number 1 to atomic number 96, inclusive. The evidence points to an atomic structure for the heaviest elements--that is, those elements with atomic number greater than 88--corresponding to a transition series in which the 5f shell of electrons is being filled. This series differs in chemical properties from the rare earth series (the 14 elements of atomic number 58 to 71, inclusive, following lanthanum) in which the 4f shell of electrons is being filled, in that the first members of this heavy series are much more readily oxidized to oxidation states greater than III. As the atomic numbers of the elements in this series increase, the lower oxidation states, and particularly the III state, increase in stability. The first 5f electron probably appears in thorium and the stable configuration consisting of seven 5f electrons probably comes with element 96."

Included in that article was the version of the periodic table shown in Figure 2.

The clearance process (i.e., removal of secrecy classification) did not allow me to state explicitly in the article that elements 95 and 96

exhibited very stable lower (i.e., III) oxidation states. This was stated explicitly in a later article (1946). I announced names for these elements--americium (Am) for element 95 and curium (Cm) for element 96, by analogy with the naming of the homologous lanthanide elements, europium and gadolinium--on April 10, 1946 at a meeting of the American Chemical Society in Atlantic City the following spring..

3. FURTHER DEVELOPMENT OF ACTINIDE CONCEPT

About three years later (1949) I published the following account of the status of the actinide concept:

"CORRELATIONS AND DEDUCTIONS

3.1 Electronic Configurations. Table 5 gives what appears to be the configuration or the best prediction for the configuration, beyond the radon structure, of the ground state of the neutral gaseous atom for each of the elements actinium to curium, inclusive. The trend in the chemical properties with its implication that the 5f becomes progressively of lower energy, compared to the 6d level, as the atomic number increases, has been used as an aid in making the predictions.

The configurations beyond xenon, of the corresponding neutral rare-earth elements are given (Yost et al., 1947; Meggers, 1947; Klinkenberg, 1947) for comparison. The ground states given for cerium and praseodymium are those predicted (Yost et al., 1947; Klinkenberg, 1947) on the basis of the recently determined ground states of the singly ionized atoms

(Meggers, 1942) and that of element 61 is obtained by interpolation; consequently, these are subject to some doubt. The ground states given for neodymium (Schuurmans, 1946), samarium, europium, and gadolinium are those spectroscopically determined (Meggers, 1942) for the neutral atoms and should be considered as well established.

Table 5-------Suggested Electron Configurations (beyond Radon and Xenon) for Gaseous Atoms of Actinide and Lanthanide Elements

Atomic No.	Element	Configuration	Atomic No.	Element	Configuration
89	Ac	$6d7s^2$	57	La	$5d6s^2$
90	Th	$6d^27s^2$ (or $5f6d7s^2$)	58	Ce	$4f^26s^2$
91	Pa	$5f^26d7s^2$ (or $5f6d^27s^2$)	59	Pr	$4f^36s^2$
92	U	$5f^36d7s^2$	60	Nd	$4f^46s^2$
93	Np	$5f^57s^2$ (or $5f^46d7s^2$)	61	Pm	$4f^56s^2$
94	Pu	$5f^67s^2$ (or $5f^56d7s^2$)	62	Sm	$4f^66s^2$
95	Am	$5f^77s^2$	63	Eu	$4f^76s^2$
96	Cm	$5f^76d7s^2$	64	Gd	$4f^75d6s^2$

It should be emphasized that it would be entirely consistent from the point of view that we are dealing here with a series of actinide elements if it should

eventually be found that there are no 5f electrons present in thorium (or protactinium). It is quite possible, on the basis of present evidence, that protactinium, or even uranium, may be the first to have 5f electrons. It seems very likely, however, that electrons will be placed in the 5f shell earlier in the series than uranium and that protactinium will have at least one such electron. An essential point is that curium definitely seems to have seven 5f electrons, and element 103 probably would have fourteen 5f electrons.

In the case of some of the elements in the series it may be difficult to assign electrons to the 5f or 6d shells, because the energy necessary for the shift from one shell to the other may be within the range of chemical binding energies. Many of the experimental facts already described, such as the ease of oxidation to higher states and the more complicated situation for the magnetic susceptibilities as compared to the rare-earth elements, point to lower binding and less electrostatic shielding by outer electrons of 5f than of 4f electrons. This was to be expected, and the magnitude of these effects seems reasonable. The electronic configuration may differ from compound to compound or even with the physical state of a given compound. Moreover, one certainly can not be sure that the configuration of the gaseous atom, for

example, will correspond to that of the compounds or of the hydrated ions in solution. In the case of the lanthanides, in fact, the configuration of the gaseous atom has in general only two electrons (beyond the xenon structure) outside the 4f shell, although the predominant oxidation state is certainly the III state. Since the energy difference between such far-outlying levels as the 5f and 6d shells is rather small, and since resonance effects should be rather large, these may predominate in determining that a composite energy level lies lowest. Thus some of these elements may possibly constitute what might more properly be called a 5f-6d range in this series rather than being considered as part of a totally 5f transition group.

The evidence that has accumulated so far seems, nevertheless, to point to lower energies for the 5f levels, as compared to the 6d levels, for the compounds of the element, as early as uranium in this series. It is in the case of the elements thorium and protactinium that the relative energy positions of these levels are as yet most uncertain. As in the other transition series, the relative energy level of the shell that is undergoing the filling process becomes lower as the successive electrons are added, and by the time americium and curium, and presumably the subsequent members of the series, are reached,

the 5f shell seems clearly to be of lower energy than the 6d shell. Also, it is not yet possible to place the electrons in neptunium and plutonium with confidence, and hence in Table 5 alternative structures for gaseous neptunium and plutonium are suggested. It seems quite possible, for those elements in which the energies are so nearly equal, that the 5f as well as the 6d and outer orbits may be involved in the chemical binding in some compounds and complex ions, an interesting possibility for a new type of bonding.

Figure 3 is an extremely rough and qualitative pictorial representation of the binding energy of the most easily removable 5f and 6d electron (of those present) for each of the heaviest elements. A rough representation such as this can be justified only if it helps somewhat in the understanding of the situation. It is hoped that such is the case.

3.2 Possible Deductions without Data on Transuranium Elements. Although it is the information on the transuranium elements that has been decisive in enabling us to come to the present view concerning the electronic structure of, or, more properly speaking, the best position in the periodic table for, the heaviest elements, it is interesting to conjecture, in retrospect, whether it would have been possible to arrive at a similar conclusion without this information. Actually, there has been much

information about actinium, thorium, protactinium, and uranium, especially about the latter, which pointed in this direction. . . there is the similarity among the metals of these elements with respect to electropositive character. In addition the melting point of uranium metal seems to relate it more closely to the immediately preceding elements than to tungsten and molybdenum. . .

Uranium differs considerably from tungsten and molybdenum in the chemistry of the lower oxidation states. Uranium(III) has great similarity to the tripositive rare-earth elements and actinium, and uranium(IV) resembles thorium and cerium(IV). Thus uranium(III) and uranium(IV) are not acidic in character; they do not tend, like tungsten and molybdenum, to form such exceedingly strong complex ions in solution; they have fluorides that are insoluble and isomorphous with the fluorides of the rare-earth elements; and they have other halides with crystal structures that are in general isomorphous with the corresponding rare-earth halides. On the other hand tungsten(III) and tungsten(IV) exist in aqueous solution predominantly as strong complex ions; for example, tungsten(III) has a strong chloride complex ion, and tungsten(IV) forms strong fluoride and cyanide complex ions. In this connection Thompson (1947) has pointed out that tungsten(IV) forms the

very stable complex ion $W(CN)_8^{-4}$ with the stable configuration of eighteen outer electrons, but uranium(IV) possesses no significant tendency to form an analogous complex cyanide ion, as would probably be expected if uranium possessed the same outer electronic structure as tungsten.

Although molybdenum dioxide and tungsten dioxide have isomorphous crystal structures, tungsten dioxide and uranium dioxide do not, but uranium dioxide, thorium dioxide, and cerium dioxide do have isomorphous structures. It is interesting to note that although uranium is not associated with tungsten in minerals, uranium and thorium minerals practically always have the rare-earth elements associated with them, and the rare-earth minerals practically always contain uranium or thorium.

Arguments on the basis of the scanty evidence from the chemical properties of thorium and uranium alone have been given by others, including Villar (1940) and, more recently, Stedman (1947), for a 5f-type transition series in the heaviest elements, beginning with thorium.

3.3 Position in Periodic Table and Nomenclature. Soon after the establishment of the concept of atomic number, the rare-earth elements could be properly fitted into the classification of the elements, and the

periodic table took its present form. There is general agreement as to the various groups and subgroups, with differences only in regard to the best geometrical arrangements for presenting the information. Thus even the undiscovered elements with atomic numbers within the confines of this classification had their places fixed, and, when they were discovered, no reasons were found to change their positions. However, this is not the situation with respect to the transuranium elements, whose positions could only be fixed after experimental determination of their properties. Their positions, in turn, apparently influence the positions of elements that had been given places previously.

Since this seems to present a new problem, it is necessary to consider carefully the facts that have given rise to the present classification in order to try to find the traditional criteria for placement in the periodic table to apply to the elements now under consideration. The chemical properties, especially in aqueous solution, have been important criteria. Thus, the rare-earth elements assumed a position by virtue of their predominant trivalency in aqueous solution, a property that is not deducible from the electronic structure of their atomic ground states. However, the spectroscopic data have determined the general regions of the transition series, where the 3d, 4d, 5d,

and 4f shells undergo filling, and seem to have influenced the practice of uninterrupted placing of the transition elements in subgroups. (That is, all ten 3d transition elements from $_{21}Sc$ to $_{30}Zn$ are usually in uninterrupted subgroups, and the same holds true for the 4d, 5d, and 4f transition series.)

With such criteria the best method of presenting the actinide elements in the periodic table seems to be that shown in Fig. 4. Here are shown the fourteen elements of atomic numbers 90 to 103, inclusive, with actinium, element 89, as the prototype. These fourteen elements are listed as a series below, and in a manner similar to, the common listing of the fourteen rare-earth elements of atomic numbers 58 to 71, inclusive, for which lanthanum, element 57, is the prototype. It is not suggested that this particular form of the periodic table has any more merit than any of a number of others that place these elements in positions homologous to the rare-earth elements, because it is obvious that they can be analogously placed in a number of other types of tables or charts. The elements 90 to 96, inclusive, or the first few of them, could in addition be listed separately below the 5d elements in recognition of the resemblance of the first few of these to 5d elements. This appears to be undesirable, however, because the last members of this group bear no such resemblance, and it is

probably impossible to draw a line as to just where the resemblance ends.

Since my suggestion (1945; 1946) that the information on the transuranium elements appeared to have reached such a state as to make it possible to place the heaviest elements in definite positions in the periodic table (as an actinide transition series), a number of publications (Zimen, 1948; Harvey, 1948; Meggers, 1947; Spence, 1949; Maddock, 1948; Purkayastka, 1948; Hardwick, 1947) commenting on this proposal have appeared. These in general agree with the suggestion, although in some cases the reasons therefor differ and in others there is an understandable expression of desire to see more of the evidence in detail. A number of different periodic tables in which these elements have been placed as actinides homologous to the lanthanides have been published recently (Wheeler, 1947; Summons, 1947; Villar, 1947; Oppegaard, 1948; Akhumov, 1947).

As mentioned above, a very important point is the presence of seven 5f electrons in stable tripositive curium (element 96), making this element very actinium-like. A series of thoride elements, for example, would imply stable IV oxidation states in elements 95 and 96 and the presence of seven 5f electrons and the IV state almost exclusively in element 97. A series of this type seems to be ruled

out by the now-known instability of americium in solution in the IV state and by the apparent nonexistence in aqueous solution of any oxidation state other than III in curium. Moreover, the III state of uranium would be surprising on this basis, because this element would be the second member of a thoride, or "IV oxidation state," series. The fact that nearly a year was spent in an unsuccessful effort to separate tracer amounts of americium and curium from the rare earths, immediately following the discovery of these two elements, illustrates how unnatural it would be to regard them as members of a thoride, or IV oxidation state, group.

The group probably could have been described just as well by some other term, such as "curide series," rather than "actinide," which is derived by analogy with the term "lanthanide." Another possibility would be to use a term such as "type 5f rare earths" or another name analogous to rare earths. A possibility here might be "synthetic earths" in view of the synthetic source of all except the first three members. [The best source of actinium is synthetic; actinium comes from pile neutrons by the reactions $Ra^{226}(n,\gamma)Ra^{227} \xrightarrow{\beta^-} Ac^{227}$.] Irrespective of the name that usage will finally assign to this group of elements, however, it seems that the outstanding characteristics of the group, namely, the

ekagadolinium character of curium (and the presumed ekalutecium character of element 103), together with the regularly increasing trend toward actinium-like character in going from thorium to curium, are best represented by listing these elements in corresponding positions under the rare-earth elements if it is desirable to give each element only one place in the periodic table.

3.4 Predicted Properties of Transcurium Elements. There has been a great deal of speculation concerning the upper limit of atomic number for the existence of elements, consideration being given to the fact that such a limit might arise from either atomic or nuclear (radioactivity or spontaneous fission) instability. If the former is not the limiting factor, it appears likely, on the basis of extrapolation from the nuclear properties of the heaviest elements, that the first few elements above element 96 will have isotopes of sufficiently long life to make possible their investigation at least on the tracer scale, if the problem of their production in detectable amount should be solved.

It is interesting to speculate about the chemical properties of these undiscovered elements beyond curium. The seven elements immediately following, that is, elements 97 to 103, inclusive, should constitute the second half of this rare-earth-like

transition group. It appears likely that the electrons added in proceeding up this series will be placed in a 5f shell of definitely lower energy than the 6d shell. Element 97 will probably have a IV as well as a III oxidation state, and in view of the lower binding energy of the 5f as compared to the 4f electrons it might be easier to oxidize element 97 (ekaterbium) to this IV state than is the case for terbium since the hydration and lattice energies do not appear to reverse the simple prediction for oxidation potentials from ionization potentials in these elements. Correspondingly, it should be easier to oxidize element 98 (ekadysprosium) to the IV and V oxidation states than is the case for dysprosium, for which oxidation above the III state is practically impossible. Toward the end of the series, elements 102 and 101 should be capable of being reduced to the II oxidation state, which would be analogous to the reduction of ytterbium and thulium, and element 103 should be similar to lutecium with respect to the complete stability of the III state.

Element 104 should continue with the filling of the 6d shell and be a true ekahafnium. After the filling of the 6d shell in the following elements there would be addition to the 7p shell, with the attainment of the rare-gas structure at hypothetical element 118

(on the logical assumption that the 5g shell does not start to fill before this point).

4. SUMMARY

All available evidence leads to the view that the 5f-electron shell is being filled in the heaviest elements, giving rise to a transition series. This transition series begins formally with actinium in the same sense that the rare-earth or "lanthanide" series begins with lanthanum. Such an "actinide" series is suggested on the basis of the following evidence: (1) chemical properties, (2) absorption spectra in aqueous solution and crystals, (3) crystallographic structure data, (4) magnetic susceptibility data, and (5) spectroscopic data. This series differs from the rare-earth series in having more oxidation states above the III state, and it differs in other ways that are connected with the lower binding of 5f compared to 4f electrons. The salient point is that the characteristic oxidation state is the III state, and the group is placed in the periodic table on this basis. (The characteristic oxidation state is exhibited by the member containing seven 5f electrons and presumably also by the member containing fourteen 5f electrons, curium and element 103.) The data also make it possible to give a suggested table of electronic configurations of the ground state of the gaseous

atom for each of the elements from actinium to curium, inclusive."

4. COMPLETION OF ACTINIDE SERIES

The following seven elements, completing the actinide series as predicted at element 103, were synthesized and identified (i.e., discovered) during the following twelve years (i.e., by the year 1961). Their chemical properties conformed very well with those predicted on the basis of the actinide concept. Elements 104 and 105, the first elements beyond the actinide series, were later also shown to have the predicted chemical properties. I summarized the situation in my book, Man-Made Transuranium Elements (1963), as follows:

> "Table 6 presents the electronic configuration, or the best prediction for the electronic configuration, of the gaseous atoms of the actinide elements. Similar information for the lanthanide elements is given for purposes of comparison. The configurations enclosed in parentheses are predicted ones.

Table 6
Electronic Configurations for Gaseous Atoms of Actinide and Lanthanide Elements

Atomic Number	Element	Electronic Configuration[a]	Atomic Number	Element	Electronic Configuration[b]
89	actinium	$6d7s^2$	57	lanthanium	$5d6s^2$
90	thorium	$6d^27s^2$	58	cerium	$4f5d6s^2$
91	protactinium	$5f^26d7s^2$	59	praseodymium	$4f^36s^2$
92	uranium	$5f^36d7s^2$	60	neodymium	$4f^46s^2$
93	neptunium	$5f^46d7s^2$	61	promethium	$4f^56s^2$
94	plutonium	$5f^67s^2$	62	samarium	$4f^66s^2$
95	americium	$5f^77s^2$	63	europium	$4f^76s^2$
96	curium	$5f^76d7s^2$	64	gadolinium	$4f^75d6s^2$
97	berkelium	($5f^86d7s^2$ or $5f^97s^2$)	65	terbium	$4f^96s^2$
98	californium	($5f^107s^2$)	66	dysprosium	$4f^106s^2$
99	einsteinium	($5f^117s^2$)	67	holmium	$4f^116s^2$
100	fermium	($5f^127s^2$)	68	erbium	$4f^126s^2$
101	mendelevium	($5f^137s^2$)	69	thulium	$4f^136s^2$
102	----------	($5f^147s^2$)	70	ytterbium	$4f^146s^2$
103	lawrencium	($5f^147s^2$)	71	lutetium	$4f^145d6s^2$

Predicted configurations are in parentheses.

[a] In addition to the electronic structure of radon (element number 86), whose electronic configuration is: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 4d^{10}\ 4f^{14}\ 5s^2\ 5p^6\ 5d^{10}\ 6s^2\ 6p^6$

[b] In addition to the electronic structure of xenon (element number 54), whose electronic configuration is: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 4d^{10}\ 5s^2\ 5p^6$

As shown in Table 6, fourteen 4f electrons are added in the lanthanide series, beginning with cerium (atomic number 58) and ending with lutetium (atomic number 71); and in the actinide elements fourteen 5f electrons are added, beginning formally (though not actually) with thorium (atomic number 90) and ending with lawrencium (atomic number 103). In the cases of actinium, thorium, uranium, and americium, the configurations were determined from an analysis of spectroscopic data obtained by the measurement of the emission lines from neutral and charged gaseous atoms. The knowledge of the electronic structures for protactinium, neptunium, plutonium, and curium, results from atomic-beam experiments.

It is important to realize that the electronic structures listed in Table 6 are those of the neutral (un-ionized) gaseous atoms, whereas it is the electronic structure of the ions and compounds that we are chiefly concerned with in chemistry. The relationship of the electronic structure of the gaseous atom of an element to that of its compounds can be rather complicated. For example, in the case of the actinide and lanthanide elements, one would not necessarily predict the predominance of the III oxidation state from the electronic structures of the gaseous atoms; there are usually only two so-called "valence electrons," the 7s or 6s electrons, which might indicate a preference for the II oxidation state.

Apparently, specific factors in the crystal structure of, and the aquation (hydration) energies of, the compounds and ions are important in determining the stability of the III oxidation state. Thus, the characteristic tripositive oxidation state of the lanthanide elements is not related directly to the number of "valence electrons" outside the 4f subshell, but is the somewhat accidental result of a nearly constant small difference between large energy terms (ionization potentials on the one hand, and hydration and crystal energies on the other) which persists over an interval of fourteen atomic numbers. Therefore, if we could somehow have a very extended Periodic Table of Elements containing numerous "f" transition series, we might expect that the 5f, rather than the 4f, elements would be regarded as more nearly representative of such f series.

Nevertheless, the electronic structures given in Table 6 will have some relevance to the electronic structures of the ions and compounds of these elements. Fortunately, it is possible to determine the electronic structure of the ions and compounds by a number of methods, such as the measurement of such properties as paramagnetic resonance, paramagnetic susceptibility, light absorption, etc. These measurements, together with consideration of the chemical and other properties of these elements, have provided a great deal of information about the electronic configurations of the aqueous actinide ions and of the

actinide compounds. It is interesting to note that these data do show that, in general, all of the electrons--in addition to the radon core--in the actinide compounds and in aqueous actinide ions are indeed in 5f orbitals. There are very few exceptions (such as U_2S_3) and subnormal compounds (such as Th_2S_3) where 6d electrons are present.

Except for the early actinide elements, the III oxidation state is the characteristic oxidation state for each series of elements. . . ease of oxidation of the early members of the actinide series is due to the looser binding of the 5f electrons early in the series and the nearness in energy of several electronic levels in this region (7s, 6d, and 5f).

The electronic configurations $5f^7$ or $4f^7$, representing the half-filled f shells of curium and gadolinium, have special stability. Thus, tripositive curium and gadolinium, are especially stable. A consequence of this is that the next element in each case readily loses an extra electron through oxidation, so as to obtain the f^7 structure, with the result that terbium and especially berkelium can be readily oxidized from the III to the IV oxidation state. Another manifestation of this is that europium (and to a lesser extent samarium)--just before gadolinium--tends to favor the $4f^7$ structure with a more stable than usual II oxidation state. Similarly, the stable f^{14} electronic configuration leads to a more stable than usual II oxidation state in ytterbium (and to a lesser extent in thulium) just

before lutetium (whose tripositive ion has the $4f^{14}$ structure). This leads to the prediction that element 102, the next to the last actinide element, will have an observable II oxidation state.

After the completion of the 5f shell at lawrencium (element 103), the last actinide element, it is predicted that electrons will be added to the 6d shell in the succeeding transactinide elements. It might be added, mainly for the sake of completeness, that the filling of the 6d shell should be followed by the addition of electrons to the 7p shell, with the attainment of the rare-gas structure at hypothetical element 118. The filling of the 5g shell, corresponding to a wholly new kind of inner transition series of eighteen elements, is predicted to begin at about this region of atomic numbers. It is unfortunate that nuclear instability precludes the possibility of synthesizing and studying such very interesting elements. The predicted electronic structures of some transactinide elements are given in Table 7."

Table 7

PREDICTED ELECTRONIC STRUCTURES OF SOME TRANSACTINIDE ELEMENTS

Element	Electronic Sturcture[a]	Element	Electronic Structure[a]
104	$5f^{14}6d^{2}7s^{2}$	112	$5f^{14}6d^{10}7s^{2}$
105	$5f^{14}6d^{3}7s^{2}$	113	$5f^{14}6d^{10}7s^{2}7p^{1}$
106	$5f^{14}6d^{4}7s^{2}$	118	$5f^{14}6d^{10}7s^{2}7p^{6}$
107	$5f^{14}6d^{5}7s^{2}$	120	$5f^{14}6d^{10}7s^{2}7p^{8}s^{2}$
108	$5f^{14}6d^{6}7s^{2}$	125	$5f^{14}5g^{5}6d^{10}7s^{2}p^{6}8s^{2}$

[a]In addition to the electronic structure of radon (element number 86).

5. SUPERACTINIDE ELEMENTS

In Table 7 note is taken of the existence of the next "rare earth" series containing 5g electrons. The predicted nature of this inner transition series, corresponding to the filling of the 5g and 6f electron shells, and which I characterized as a "superactinide" group, is described in an article I published in 1968:

"3.4.4 Predicted Electronic Configuration and Chemical Properties of Superactinide Elements.

Although it is uncertain as to the exact point where the 5g or 6f subshells begin to be filled (because the energy levels of the two subshells may be very close together), it seems likely that in a formal sense this would begin at element 122. It is interesting to speculate on the electronic structure and chemical properties of such a "superactinide" group of elements in which the 18 places in the 5g electron shell and the 14 places in the 6f electron shell might be filled in a comingling fashion, leading to a mixed transition series

of 32 elements terminating at Z=153. I believe that the best way of fitting them into the Periodic Table of the Elements--although this is admittedly an approximation and a matter of finding the best compromise--is as a third rare-earth type of transition series below the lanthanide and actinide series. Thus in this oversimplification of a complicated situation the elements beyond element 121 would be considered as homologs of the elements beyond lanthanum (atomic number 57) and actinium (atomic number 89) on an element-by-element basis. . . If the analogy is valid, the (III) oxidation state of the "superactinide" group should be typical. However, there are reasons to expect deviations. At the beginning of the series, as is the case for the actinides and for similar reasons, we might expect higher oxidation states to be readily reached. Somewhat later in the series we might expect to find a prominent (II) oxidation state, analogous to the effect observed in the heavier actinides."

6. STATUS OF ACTINIDE ELEMENTS

As the result of increasing sophistication of the experiments a large range of oxidation states of the actinide elements is known, which are summarized in Table 8 (Katz et al., 1986). These are well understood on the basis of the actinide concept, fitting in well with the expected stability of the III oxidation state of the middle element (element 96 with the half-filled $5f^7$ structure) and the last element (element 103 with the filled $5f^{14}$ structure).

TABLE 8 The Oxidation States of the Actinide Elements[a]

Atomic Number:	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Element:	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Oxidation States															
													1?		
							(2)	(2)		(2)	(2)	2	2	2	
	3	(3)	(3)	3	3	3	3	3	3	3	3	3	3	3	3
		4	4	4	4	4	4	4	4	4	(4)	4?			
			5	5	5	5	5	5?		5?					
				6	6	6	6	6?							
					7	(7)	7?								

[a] The most common oxidation states are underlined, unstable oxidation states are shown in parentheses. Question marks indicate species that have been claimed but not substantiated.

The actinides show an unusually broad range of oxidation states, ranging from +2 to +7 in solution, as summarized by Loveland and me (1990). The most common oxidation state is +3 for the transplutonium actinide elements, similar to the lanthanides, with +2 oxidation states being observed for the heaviest species. A stable +4 state is observed for the elements thorium through plutonium and berkelium. The +5 state is well established for protactinium through americium and the +6 state for uranium through americium. Following the normal trend for polyvalent cations, lower oxidation states are stabilized by acid conditions while the higher oxidation states are more stable in basic solutions. Complexing, can, of course, change this general trend.

In compounds of the +2, +3, +4 oxidation states, the elements are present as simple M^{+2}, M^{+3} or M^{4+} cations but for higher oxidation states, the most common forms in compounds and in solution are the oxygenated actinyl ions MO_2^{+} and MO_2^{2+}. Disproportionation reactions are an important part of the chemistry of the actinide elements, especially for the +4 and +5 oxidation states.

A few comments on the various oxidation states found in solution follow:

M(I) The existence of Md^{+} has been reported by Mikheev et al. (1973) but studies by other groups have failed to confirm these observations (Hulet et al., 1980).

M(II) Both No^{2+} and Md^{2+} form readily in solution. No^{2+} is the most stable oxidation state of nobelium, a result of the stability of the completely filled $5f^{14}$ shell. Pulse radiolysis of acid solutions has been used to make unstable Am^{2+}, Cm^{2+}, Bk^{+2}, Cf^{2+}, and Es^{2+}. Fm^{2+} is more stable than these ions but less stable than Fm^{3+}.

M(III) The +3 oxidation state is the most stable oxidation state for americium through mendelevium and for lawrencium. It is easy to produce Pu^{3+} and Np^{3+} but U^{3+} is such a strong reducing agent that it is difficult to keep in solution.

M(IV) The most stable oxidation state of thorium is +4. Pa^{4+}, U^{4+}, and Np^{4+} are stable but are oxidized by O_2. Pu^{4+} is stable in acid solutions with low plutonium concentration. Americium, curium, and californium can be oxidized to the +4 state with strong oxidizing agents like persulfate, pulse radiolysis or other strong oxidation and complexation techniques. Bk^{4+} is relatively stable as a result of the half-filled shell, $5f^{7}$.

M(V) The actinides protactinium through americium form MO_2^{+} ions in solution. PuO_2^{+} may be the dominant species in

solution in low concentrations in natural waters that are relatively free of organic materials.

M(VI) UO_2^{2+} is the most stable oxidation state of uranium. Neptunium, plutonium and americium form MO_2^{2+} ions in solution with the stability ordering being U > Pu > Np > Am.

M(VII) M(VII) species, in oxygenated form such as MO_5^{3-} have been reported for neptunium, plutonium, and americium but are unstable.

7. TRANSACTINIDE ELEMENTS

The transactinide elements with atomic numbers 104-109, inclusive, have been synthesized and identified (i.e., discovered) (Loveland and I, 1990). The known elements beyond 103 (rutherfordium, hahnium, 106, 107, 108, and 109) should be members of a new fourth d-electron transition series extending from rutherfordium to element 112, in which the 6d electronic shell is being filled. The chemical properties of the members of this group should generally resemble those of their homologs hafnium to mercury in the third d-electron transition series. The chemical properties of these elements, as predicted by Keller and me (1977), are shown in Table 9. The predicted chemical properties are generally the result of a judicious extrapolation of periodic table trends for each group together with consideration of relativistic effects predicted for these elements. Of especial interest are the properties of 112, eka-mercury. Pitzer (1979) has suggested that relativistic effects

will make 112 more noble than mercury and that 112 will be a volatile liquid or a gas.

TABLE 9 Predicted Chemical Properties of Elements 104-112

	Rf	Ha	106	107	108	109	110	111	112
Stable oxidation states	III, IV	IV, V	IV, VI	III-VII	II-VIII	I-VI	I-VI	III, (-1)	I, II
First ionization energy (eV)	5.1	6.6	7.6	6.9	7.8	8.7	9.6	10.5	11.4
Standard electrode potential (V)	4→0 -1.8	5→0 -0.8	4→0 -0.6	5→0 +0.1	4→0 +0.4	3→0 +0.8	2→0 +1.7	3→0 +1.9	2→0 +2.1
Ionic radius (Å)	(+4) 0.71	(+5) 0.68	(+4) 0.86	(+5) 0.83	(+4) 0.80	(+3) 0.83	(+2) 0.80	(+3) 0.76	(+2) 0.75
Atomic radius (Å)	1.50	1.39	1.32	1.28	1.26				
Density (g cm^{-3})	23	29	35	37	41				
Heat of sublimation (kJ mol^{-1})	694	795	858	753	628	594	481	335	29
Boiling point (K)	5800								
Melting point (K)	2400								

Of the transactinide elements, only the chemistry of rutherfordium and hahnium has been studied. These elements all have short half-lives and study of their chemical properties must occur at the accelerators where they are produced. Since typical production rates are such that the elements are produced one-atom-at-a-time, the experiments to deduce the chemistry of these elements must be carried out many times with the results of the individual experiments being added together to produce a statistically significant result. The experiments must be very reproducible and involve sensitive

detection techniques such as high-resolution α-particle spectroscopy and fission tracking counting.

The chemistry of rutherfordium has been shown to be similar to the chemistry of hafnium rather than the chemistry of the heavier actinides, a clear demonstration of the expected end of the actinide series at lawrencium. This demonstration involved both aqueous and gas phase chemistry. In the gas phase experiments by Zvara et al. (1972) the 3-sec isotope ^{259}Rf, produced in the ^{242}Pu (^{22}Ne, 5n) reaction was used. Zvara and co-workers were able to use thermochromatography to show a difference in volatility of the $RfCl_4$ which condensed at ~220° C as compared to the chlorides of the heavier actinides which have much higher condensation temperatures.

In aqueous solution experiments, the 1-min isotope ^{261}Rf produced in the ^{248}Cm (^{18}O, 5n) reaction, was used by Silva et al. (1970). Atoms of rutherfordium recoiling from the target were caught in an NH_4Cl layer sublimed onto platinum discs, dissolved with ammonium α-hydroxyisobutyrate solution and added to a heated Dowex-50 cation exchange resin column. The neutral and anionic complexes of hafnium, zirconium, and rutherfordium were not adsorbed on the cation exchange column while actinides were strongly absorbed. Thus the hafnium, zirconium (tracers) and the rutherfordium atoms eluted within a few column volumes while the actinides eluted after several hundred column volumes. The time from end of bombardment to start of sample counting was less then one half-life of ^{261}Rf and after several hundred experiments Silva and co-workers

were able to detect the decay of 17 atoms of ^{261}Rf in the eluant.

This work was extended by Hulet et. al. (1980) to the chloride complexes of rutherfordium. Computer automation was used to help perform the chemical operations rapidly and reproducibly. An HCl solution containing ^{261}Rf was passed through an extraction chromatography column loaded with trioctylmethylammonium chloride which strongly extracts anionic chloride complexes. Such complexes are formed by the Group IVB elements such as rutherfordium while the actinides, and members of Groups IA and IIA, form weaker complexes and are not extracted. Thus the actinide recoil products elute first and zirconium, hafnium, and rutherfordium were shown to elute in a second fraction as expected for Group IVB elements.

Hahnium (Ha) is expected to have the valence electron configuration $7s^26d^3$ and thus to be a homolog of Ta (with the valence electron configuration $6s^25d^3$). Zvara et al. (1976) have carried out a set of thermochromatography experiments similar to those done with rutherfordium. The isotope used for the study was the 1.8-sec ^{261}Ha produced in the $^{243}Am(^{22}Ne, 4n)$ reaction, with detection by obsevation of its decay by spontaneous fission. The results of the experiments show the volatility of the chlorides and bromides of hahnium to be less than that of niobium (a $4d^3$ element which has the same deposition temperature in the chromatographic apparatus as tantalum) but relatively similar to that of hafnium. If this result is verified by additional gas phase or aqueous solution

work, it could indicate an unexpected departure in the chemical behavior of hahnium from that expected for eka-tantalum. However, capricious adsorption behavior can lead to uncertainties in the interpretation of the results of such experiments.

Gregorich et al. (1988) have investigated some aqueous solution chemistry of hahnium, using the 35-sec ^{262}Ha, produced in the ^{249}Bk (^{18}O, 5n) reaction. With nearly a thousand batch experiments hahnium was found to hydrolyze in strong HNO_3 solution and adhere to glass surfaces. Such hydrolysis is characteristic of Group VB elements and different from group IVB elements as verified in experiments with tantalum and niobium tracers under the same conditions. In other experiments, by Kratz, et al (1989) hahnium did not form extractable anionic fluoride complexes in HNO_3/HF solutions under conditions in which tantalum was extracted nearly quantitatively. This observation may be explained by an extrapolation of the properties of Group VB elements, in that the tendency to hydrolyze or to form fluoride-complexes may be stronger for hahnium than for tantalum, leading to a failure to observe extraction. In the pioneering work of Gregorich et al. (1988), the total study involved the identification of 47 atoms of ^{262}Ha on the basis of observation of decay by spontaneous fission and alpha-particle emission, including the time correlation of alpha-particle decays from ^{262}Ha and its 4-sec daughter ^{258}Lr.

7. MODERN PERIODIC TABLE

A periodic table that places the actinide elements and the transactinide elements in positions that best represent our present understanding is shown in Figure 5. A more futuristic periodic table that includes the unattainable "superactinide" group of elements with 5g and 6f electrons is shown in Figure 6.

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REFERENCES

Akhumov, A. I., 1947, J. Gen. Chem. U.S.S.R. 17, 1241.

Bedreag, C. G., 1943, Naturwissenschaften 31, 490.

Bohr, N., 1913, Phil. Mag. 26, 476.

Bohr, N., 1923, Nature 112, 30.

Carranza, M., 1935, Bol. Soc. Quím. Peru (I) 6, 41.

Daudel, R., 1943, C. R. Acad. Sci., Paris 217, 396.

Djounkovsky, G. E. and S. Kavos, 1944, J. Phys. Radium (8) 5, 53.

Dushman, S., 1926, Chem. Rev. 5, 137.

Goldschmidt, V. M., 1924, Norske Videnskaps-Acad. Skrifter, Geochemiske Verteilungsgesetze der Elemente 2, 23.

Goldschmidt, V. M., 1937, Travaux du Congres Jubilaire Mendeleev II, 387.

Goldschmidt, V. M., T. Barth, and G. Lunde, 1925, Norske Videnskaps-Acad. Skrifter 1, Geochemische Verteilungsgesetze der Elemente V, 10.

Gregorich, K. E., R. A. Henderson, D. M. Lee, M. J. Nurmia, R. M. Chasteler, H. L. Hall, D. A. Bennett, C. M. Gannett, R. B. Chadwick, J. D. Leyba, D. C. Hoffman and G. Herrmann, 1988, Radiochim. Acta 43, 223.

Hahn, O., 1929, Angew. Chem. 42, 924.

Hardwick, T. J., 1947, Proceedings of Conference in Nuclear Chemistry, Part 1 (McMaster University, Canada), p. 44.

Harvey, B. G., 1948, Nucleonics 2, 30.

Hulet, E. K., R. W. Lougheed, J. F. Wild, J. H. Landrum, J. M. Nitschke, and A. Ghiorso, 1980, J. Inorg. Nucl. Chem. 42, 79.

Karapetoff, V., 1930, J. Franklin Inst. 210, 609.

Katz, J. J., G. T. Seaborg, and L. Morss, 1986, Chemistry of the Actinide Elements, 2nd Ed. (Chapman and Hall, London), p. 1139.

Keller, O. L., Jr., and G. T. Seaborg, 1977, Annu. Rev. Nucl. Sci. 27, 139.

Kiess, C.C., C. J. Humphreys, and D. D. Laun, Report A-1747, U.S. Natl. Bur. Standards (Feb. 7, 1944).

Klinkenberg, P. F. A., 1947, Physica 13, 1.

Kratz, J. V., H. P. Zimmerman, U. W. Scherer, M. Schädel, W. Brüchle, K. E. Gregorich, C. M. Gannett, H. L. Hall, R. A. Henderson, D. M. Lee, J. D. Leyba, M. J. Nurmia, D. C. Hoffman, H. Gäggeler, D. Jost, U. Baltensperger, Ya Nai-Qi, A. Türler, and Ch. Lienert, 1989, Radiochim. Acta 48, 121.

Latimer, W. M. and J. H. Hildebrand, 1940, Reference Book of Inorganic Chemistry (The MacMillan Company, New York), p. 519.

Maddock, A. G., 1948, Research 1, 690.

Mayer, M. Goeppert, 1941, Phys. Rev. 60, 184.

McLennan, J. C., A. B. McLay, and H. G. Smith, 1926, Proc. Roy. Soc. London A112, 76.

McMillan, E. M. and P. H. Abelson, 1940, Phys. Rev. 57, 1185.

Meggers, W. F., 1942, Rev. Mod. Physics 14, 96.

Mikheev, N. B., V. I. Spitsyn, A. N. Kamenskaya, I. A. Rumer, B. A. Grozdez, N. A. Rosenkevich, and L. N. Auerman, 1973, Dokl. Acad. Nauk 208, 1146.

Oppegaard, A. G., 1948, J. Chem. Soc., 318-321.

Perrin, J., 1935, Grains de Matiére et de Lumiére, vol. II (Hermann & Cie, Paris), p. 30.

Pitzer, K. S., 1979, Acc. Chem. Res. 12, 271.

Purkayastka, B. C., 1948, Nucleonics 3, 2.

Quill, L. L., 1938, Chem. Rev. 23, 87.

Richtmeyer, F. K. and E. H. Kennard, 1942, Introduction to Modern Physics (McGraw-Hill Book Company, Inc., New York), p. 707.

Rudy, R., 1927, Gen. Sci. 38, 671.

Rydberg, J. R., 1913, Lunds Univ. Årsskr. 2, 9.

Saha, M. N. and N. K. Saha, 1934, Treatise on Modern Physics (The Indian Press, Ltd., Allahabad and Calcutta), pp. 583 and 588.

Schuurmans, P., 1946, Physica 11, 419.

Seaborg, G. T., Metallurgical Project Report CK-1968 (A-2845) (July 17, 1944) p. 55; Metallurgical Laboratory Memorandum, MUC-GTS-858 (July 17, 1944).

Seaborg, G. T., 1945, Chem. Eng. News 23, 2190.

Seaborg, G. T., 1946, Science 104, 379.

Seaborg, G. T., 1949, Electronic Structure of the Heaviest Elements, Paper 21.1 in The Transuranium Elements-Research Papers, National Nuclear Energy Series IV, v. 14B, Part II, Editors, G. T. Seaborg, J. J. Katz, and W. M. Manning, (McGraw Hill, New York), pp. 1492-1524.

Seaborg, G. T., 1963, Man-Made Transuranium Elements (Prentice Hall, Englewood Cliffs, N.J.), pp. 80-82.

Seaborg, G. T., 1968, Elements Beyond 100, Present Status and Future Prospects, Annu. Rev. Nucl. Sci. 18, 53.

Seaborg, G. T. and W. D. Loveland, 1990, The Elements Beyond Uranium (John Wiley and Sons, New York), pp. 84-86, 113-116.

Seaborg, G. T. and A. C. Wahl, Report A-135, report to "Uranium Committee," Washington, D.C., March 19, 1942.

Seaborg, G. T. and A. C. Wahl, 1948, J. Am. Chem. Soc. 70, 1128.

Seaborg, G. T and A. C. Wahl, 1949, The Chemical Properties of Elements 94 and 93, Paper 1.6 in The Transuranium Elements: Research Papers, National Nuclear Energy Series IV, v.14B, Part II, Editors, G.T. Seaborg, J. J. Katz, and W. M. Manning, (McGraw Hill, New York), pp. 25-38.

Silva, R., J. Harris, M. Nurmia, K. Eskola, and A. Ghiorso, 1970, Inorg. Nucl. Chem. Lett. 6, 871.

Spence, R., 1949, Research 2, 115.

Starke, K., 1943, Z. Anorg. Allg. Chem. 251, 251.

Stedman, D. F., 1947, Can. J. Research 25B, 199.

Strassmann, F. and O. Hahn, 1942, Naturwissenschaften 30, 256.

Suguira, Y. and H. C. Urey, 1926, Kgl. Danske Videnskab. Selskab, Math.Fys. Medd. 7, 3.

Summons, B. M., 1947, J. Chem. Educ. 24, 588.

Swinne, Z., 1926, Tech. Physik 7, 205.

Talpain, L., 1945, J. Phys. Radium (8) 6, 176.

Taylor, H. S. and S. Glasstone, 1942, Treatise on Physical Chemistry, vol. 1 (D. Van Nostrand Company, Inc., New York), p. 298.

Thompson, S. G., private communication, October, 1947.

Villar, G. E., 1940, Anas Acad. Brasil. Cienc. 12, 51.

Villar, G. E., 1942, J. Chem. Educ.19, 329.

Villar, G. E., 1947, Bol. Soc. Quím. Peru 13, 73.

Von Grosse, A., 1928, Chem. Ber. 61, 233.

Von Grosse, A., 1930, J. Am. Chem. Soc. 52, 1742.

Von Grosse, A., 1935, J. Am. Chem. Soc. 57, 440.

Wheeler, T. S., 1947, Chem. Ind. (London), 639-642.

Wu, T. Y. and S. Goudsmit, 1933, Phys. Rev. 43, 496.

Wu, T. Y., 1933, Phys. Rev. 44, 727.

Yost, D. M., H. Russell, Jr., and C. S. Garner, 1947, The Rare-earth Elements and Their Compounds (John Wiley & Sons, Inc., New York), pp. 3-4.

Zachariasen, W. H., 1944a, Metallurgical Project Report CK-1518 (March 1944) p. 3.

Zachariasen, W. H., 1944b, Metallurgical Project Report CN-1807 (June 1944).

Zimen, K. E., 1948, Festskrift Tillagnad J. Arvid. Hedvall, 635.

Zvara, I., V. Z. Belov, V. P. Domanov, Yu. S. Korotkin, L. P. Chelnokov, M. R. Shalavskii, V. A. Shchegolev, and M. Hussonis, 1972, Radiokhimiya, p. 119.

Zvara, I., V. Z. Belov, V. P. Domanov, Yu. S. Korotkin, L. P. Chelnokov, M. R. Shalavskii, V. A. Shchegolev, and M. Hussonis, 1972, Sov. Radiochem. 14, 115.

Zvara, I., V. Z. Belov, V. P. Domanov, and M. R. Shalzevskii, 1976, Sov. Radiochem. 18, 328.

Figures

Figure 1. Periodic table before World War II (atomic numbers of undiscovered elements are shown in parentheses). (XBL 769-10601)

Figure 2. Periodic table showing heavy elements as members of an actinide series. Arrangement by the author in 1945. (XBL 769-10603)

Figure 3. Qualitative representation of electronic binding energies in the heaviest elements. (XBL 918-1759)

Figure 4 Periodic table showing heavy elements as members of an actinide series in 1949. (XBL 918-1760)

Figure 5. Modern periodic table of the elements (atomic numbers of undiscovered elements are shown in parentheses). (XBL 751-2037A)

Figure 6. Futuristic periodic table (atomic numbers of undiscovered elements are shown in parentheses). (XBL 751-2036).

PERIODIC TABLE - BEFORE WORLD WAR II

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

XBL 769-10601

Figure 1

PERIODIC TABLE SHOWING HEAVY ELEMENTS AS MEMBERS OF AN ACTINIDE SERIES

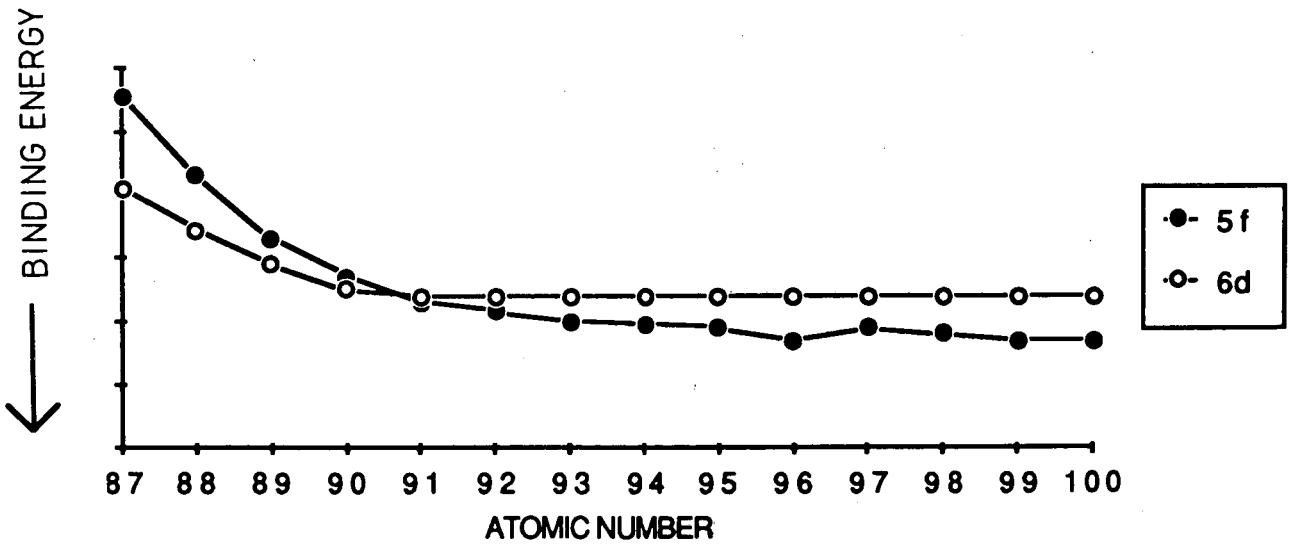
Arrangement by Glenn T. Seaborg, 1945

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							

XBL 769-10603

Figure 2



XBL 918-1759

Figure 3

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	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 Tc	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 At	86 Rn
87 Fr	88 Ra	89 Ac	See Ac Series														

LANTHANIDE SERIES	57 La 138.92	58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61 Pm	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 Am	96 Cm							

XBL 918-1760

Figure 4

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

XBL751-2037A

Figure 5

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)

XBL751-2036

Figure 6

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