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SUMMARY OF THE PROPERTIES OF THE LANTHANIDE AND ACTINIDE ELEMENTS

by Glenn T. Seaborg and David E. Hobart

Abstract

The chemical properties, ion exchange behavior, oxidation states, ion types and stabilities, ionic radii, electronic structures, and crystal structures of the 14 lanthanides (plus lanthanum) and the 14 actinides (plus actinium) are discussed on a comparative basis. The analogous positions of these two groups of elements in the periodic table are described. Also included are tables outlining the above properties and identifying the discoverers of these 30 elements. A discussion of the practical application of many of the lanthanides and actinides is also included.

Outline

Key words

- lanthanide elements
- f-electrons
- actinide elements
- periodic table

Other Possibilities

- ion exchange behavior
- ion types
- ionic radii
- absorption and luminescence spectra
- oxidation states
- crystal structure
- solid compounds
- practical applications

SUMMARY OF THE PROPERTIES OF THE LANTHANIDE AND ACTINIDE ELEMENTS

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Introduction

A century ago when Becquerel first discovered the phenomenon of radioactivity, Mendeleev's Periodic Table of the Elements was largely incomplete. Many of the main group elements were known, but another fifty years would pass before advanced methods were developed to separate sucessfully the lanthanides into individual elements and before synthetic preparation of the transuranium actinides would begin. Since then, 11 new actinide and 8 new transactinide elements have been discovered! (see **Figure 1**.)

The elements lanthanum (atomic number 57) and actinium (atomic number 89) occupy analogous positions in the Periodic Table as prototypes for the lanthanide and actinide series which constitute 25% of the known chemical elements (**Figure 1**). In the lanthanide series, the fourteen *4f* electrons are added one-by-one beginning with cerium (atomic number 58) and ending with lutetium (atomic number 71). The fourteen *5f* electrons are added to the actinide elements beginning formally with thorium (atomic number 90) and ending with lawrencium (atomic number 103). The shielding of *5f* electrons by outer electrons is less effective than that of the *4f* electrons and, as a consequence, the actinides exhibit a richer chemistry than do the lanthanides. This is particularly true for the lighter actinides where a wide variety of oxidation states are exhibited. Shielding becomes more effective in the heavier end of the actinide series and these elements exhibit more lanthanide-like behavior. The names, symbols, atomic numbers, and discoverers for each of the lanthanide and actinide elements are given in **Tables 1** and 2, respectively.

The atomic weights for each of the lanthanide elements (with the exception of radioactive promethium) are listed in **Table 1**. There is frequently a need for values to be assigned for the atomic weights of the actinide elements. Any precise experimental work would require a value for the isotope or isotopic mixture being used, but where there is a purely formal demand for atomic weights, mass numbers that are chosen on the basis of half-life and availability have customarily been used.

A list of these is provided in **Table 2**. All of the lanthanide elements with the exception of promethium exist as naturally occurring, stable isotopes in fixed proportions for each element. The most available isotope of promethium is a fission product of uranium decay and has the mass number 147 (half-life 2.6 years). Four of the actinide elements (actinium, thorium, protactinium, and uranium) are naturally occurring. The transuranium elements, however, were all prepared synthetically. Each of the actinide elements has a number of isotopes, all radioactive and some that can be obtained in isotopically pure form. More than 200 in number and mostly synthetic in origin, they are produced by neutron or charged-particle induced transmutations [1, 2]. The known isotopes of the lanthanides and actinides are given in **Tables 3** and **4**, respectively [3]. Thorium and uranium have long been known, and uses dependent on their physical or chemical, not on their nuclear, properties were developed prior to the discovery of nuclear fission. The discoveries of actinium and protactinium were among the results of the early studies of naturally occurring radioactive substances. The first transuranium element, synthetic neptunium, was discovered during an investigation of nuclear fission, and this event rapidly led to the discovery of the next succeeding element, plutonium. The realization that plutonium as ^{239}Pu undergoes fission with slow neutrons, and thus could be utilized in a nuclear weapon, supplied the impetus for its thorough investigation. This research provided the background of knowledge and techniques for the production and identification of nine more actinide elements (and eight transactinide elements).

Position in the periodic table and electronic structure

Prior to 1944, the elements thorium, protactinium, and uranium were commonly placed in the Periodic Table immediately below the elements hafnium, tantalum, and tungsten. In 1944, on the basis of earlier chemical studies of neptunium and plutonium, the similarity between the actinide and the lanthanide elements was recognized [4]. Intensive study of the heavier actinides revealed a series of elements similar to the lanthanide series, beginning with actinium **(Fig. 1)**. Corresponding pairs of elements show resemblances in (a) spectroscopic and magnetic behavior that arise because of the similarity of electronic configurations for the ions of the homologous elements in the same state of oxidation and (b) crystallographic properties owing to the near matching of ionic radii for ions of the same charge. The two series are not, however, entirely comparable. One difference, for example, lies in the oxidation states. The tripositive state characteristic of lanthanide elements does not appear in aqueous solutions of thorium and protactinium and does not become the most stable oxidation state in aqueous solution until americium is reached. The elements uranium through americium have several oxidation states, unlike the lanthanides These differences can be interpreted as resulting from the proximity of the *7s*, *6d*, and *5f* electronic energy levels.

Table 5 presents the actual or predicted electronic configurations (beyond the xenon and radon cores, respectively) of the lanthanide and actinide elements [1]. As indicated previously, fourteen *4f* electrons are added in the lanthanide series, beginning with cerium and ending with lutetium; in the actinide elements, fourteen *5f* electrons are added, beginning, formally, with thorium and ending with lawrencium. In the cases of the lanthanide elements, actinium, thorium, uranium, americium, berkelium, californium, and einsteinium, the configurations were determined from an analysis of spectroscopic data obtained in connection with the measurement of the emission lines from neutral and charged gaseous atoms. The knowledge of the electronic structures for protactinium, neptunium, plutonium, curium, and fermium results from atomic beam experiments.

Measurements of paramagnetic susceptibility, paramagnetic resonance, light absorption and reflectance, luminescence, x-ray absorption and nuclear magnetic resonance spectroscopies, and crystal structure determinations, in addition to a consideration of chemical and other properties, have provided a great deal of information about the electronic configurations of the aqueous actinide ions and compounds. In general, all of the electrons beyond the radon core in the actinide compounds and in aqueous actinide ions are in the *5f* shell. There are exceptions such as U_2S_3 and subnormal compounds such as Th_2S_3, where *6d* electrons are present.

Properties

Ion exchange behavior. There are many similarities in the chemical properties of the lanthanide and actinide elements, especially in the same oxidation states. A striking example of this resemblance is furnished by their ion-exchange chromatographic behavior. **Figure 2** shows the comparative elution data for tripositive lanthanide and actinide ions obtained by the use of the ion-exchange resin Dowex-50 (a copolymer of styrene and divinylbenzene with sulfonic acid groups) and the eluting agent ammonium α-hydroxyisobutyrate [1]. In this system, which is used for illustration because of its historical importance, the elutions occur in the inverse order of atomic number. The elution sequence depends on a balance between the adherence to the stationary resin and the stability of the complex ion formed with the mobile eluting agent and may be correlated with the variation of ionic radius with atomic number.

Actinide ions in the III, IV, and VI oxidation states can be adsorbed by cation-exchange resins and, in general, can be desorbed by elution with chloride, nitrate, citrate, lactate, α-hydroxyisobutyrate, ethylenediaminetetraacetate, and other complexants. Ion-exchange separations can also be made by the use of a polymer with exchangeable anions; in this case, the lanthanide or actinide elements must be initially present as complex anions. The anion-exchange resins Dowex-1 (a copolymer of styrene and divinylbenzene with quaternary ammonium groups) and Amberlite IRA-400 (a quaternary ammonium polystyrene) have been used successfully. The order of elution is often the reverse of that from cation-exchange resins.

Metals. The lanthanide and actinide metals (oxidation state 0) are highly electropositive. They can be prepared by electrolytic reduction in molten salts or by solid state reaction of a lanthanide or actinide salt with an even more electropositive metal such as calcium or barium. A wide range of alloys and intermetallic compounds has been observed [1, 6].

Oxidation states. The oxidation states of the lanthanides [7-9] and actinides [1] are listed in **Tables 6** and 7, respectively. The situation is rather simple for the lanthanide elements. Besides the III state throughout the series, only the II state for samarium, europium, and ytterbium and the IV state for cerium, praseodymium, and terbium exist in aqueous solution. The situation is more complicated for the actinide elements. The IV state of curium is limited to CmO_2 and CmF_4 solids and an ion stable only in highly complexing aqueous solutions The IV state of californium is limited only to solid CfO_2, CfF_4, and double salts such as $7NaF{\cdot}6CfF_4$. In the second half of the actinide series, the II state first appears in the form of solid compounds at californium and becomes successively more stable in proceeding to nobelium. The II state is observed in aqueous solution for fermium, mendelevium, and nobelium. The existence of americium(II) (observed only in solid compounds) and berkelium(IV) demonstrate the stability of the half-filled 5*f* configuration ($5f^7$). The fact that the II state is the most stable oxidation state for nobelium shows the stability associated with the filled 5*f* configuration ($5f^{14}$). Similarly, the existence of terbium(IV) (observed only in solid state and in strongly complexing solutions) and europium(II) show the stability of the half-filled 4*f* configuration ($4f^7$). Ytterbium(II) existence demonstrates the stability of the full 4*f* configuration ($4f^{14}$). The greater tendency toward stability of the II state in the actinides, as compared to the lanthanides, is a result of the increasing binding of the 5*f* (and 6*d*) electrons upon approaching the end of the actinide series. Claims of the posible existence of plutonium(VIII) and mendeleveim(I), based on the expected stability of the empty ($5f^0$) and filled ($5f^{14}$) configurations, respectively, have not been confirmed. It should be noted, however, that the existence and/or stability of an oxidation state is not only a result of its electronic configuration but includes other contributing factors such as ionization, hydration, and lattice energies, etc.

The lanthanides and actinides exhibit uniformity in the nature of their ionic forms throughout both series of elements. The lanthanide and actinide ions and their colors are listed in **Tables** 8 and 9, respectively. Open spaces in these tables indicate that the corresponding oxidation states are not known to exist in solution. The lanthanide ions in aqueous solution are all simple hydrated M^{2+}, M^{3+}, and M^{4+} cations. The situation is more complicated for the actinide ions. In addition to the simple hydrated cations noted above, the actinides exhibit higher valent oxycations, MO_2^+, MO_2^{2+}, and MO_5^{3-}. It should be noted that protactinium(V) is an unusual case in that it tends to hydrolyze, polymerize, and readily precipitate even in highly acidic aqueous solutions and thus, it is unlikely that true ionic forms of Pa(V) are present in solution. The wide variety of colors exhibited by the lanthanide and actinide ions is characteristic of transition series of elements.

Although corresponding ionic types for both series are similar in chemical behavior, the oxidation-reduction relationships and, thus, the relative stabilities differ from element to element. The actinide oxycations MO_2^+ and MO_2^{2+} are stable with respect to their binding of "actinyl oxygen" atoms and remain unchanged through a great variety of chemical reactions. They behave as single entities with properties intermediate to those of singly or doubly charged ions and ions of similar size but of higher charge. The VII oxidation states found for neptunium and plutonium are probably in the form of ions of the type MO_5^{3-} in alkaline aqueous solution. In acid solution both of these VII ions instantaneously oxidize water.

Table 10 presents a summary of the oxidation-reduction characteristics of lanthanide ions [7-9] and **Table 11** shows a summary for the actinide ions [1]. Again, the situation for the actinide ions is more complex than that for the lanthanides. The disproportionation reactions of UO_2^+, Pu^{4+}, PuO_2^+, and AmO_2^+ are very complicated and have been studied extensively. The situation is complex and somewhat unique for plutonium in that four oxidation states, (III, IV, V, and VI) can exist together in aqueous solution in equilibrium with each other at appreciable concentrations. (Americium is the only other element known to exist simultaneously in these same four oxidation states and it does so only in concentrated aqueous carbonate solutions [1]). Metallic plutonium is quite unique in that it possesses six allotropic modifications.

Solid compounds. The smaller range of accessible oxidation states limits the extent of possible lanthanide compounds formed in comparison to the number of possible compounds of the actinides, which exhibit a wider variety of oxidation states. The lanthanides form a variety of compounds mostly in the trivalent oxidation state including oxides, nitrates, halides, carbonates, oxalates, sulfates, molybdates, etc. [7-10]. Thousands of compounds of the actinide elements have been prepared. These include hundreds of binary compounds ranging from the hydrides, AcH_2 and ThH_2, to the hexahalides, PuF_6 and UCl_6 and numerous ternary compounds ranging from borohydrides, $PuBH_4$, to carbonate double salts, $NaAmO_2CO_3$ [1, 10]. Hundreds of actinide organometallic compounds are also known [11, 12].

Crystal structure and ionic radii. Crystal structure data have provided the basis for the ionic radii (coordination number = CN = 6), which are summarized in **Table 12** [1]. As can be seen for both M^{3+} and M^{4+} ions, there are pronounced lanthanide and actinide "contractions" resulting from an increasing positive charge on the nuclei in proceeding from lanthanum to lutetium and from actinium to lawrencium, respectively. A natural consequence of this increase in nuclear charge along the two series for a given oxidation state is an increasing tendency for outer electrons to feel less shielding from the nuclear charge. This causes the observed contractions, which result in increasingly smaller ionic radii for heavier members of the two series of elements. The contraction phenomenon explains, for example, why the lanthanides and actinides elute in reverse order of their atomic numbers in their cation exchange behavior. Smaller ions with higher charge-to-volume ratios than their lighter relatives, form stronger complexes with eluting agents and hence are removed from stationary resins before their lighter relatives (see **Figure 2**).

As a consequence of the ionic character of their compounds and of the similarity of the ionic radii for a given oxidation state, analogous compounds are generally isostructural. In some cases, e.g. $LaPO_4$ through $LuPO_4$ and UBr_3, $NpBr_3$, $PuBr_3$, and $AmBr_3$, there are changes in structural type with increasing atomic number consistent with the contraction in ionic radius.

The stability of the MO_2 (fluorite type) structure is especially noteworthy, as demonstrated by the existence of compounds such as PaO_2, AmO_2, CmO_2, and CfO_2, despite the instability of the IV oxidation state of these elements in solution. The effects of the lanthanide and actinide contractions and the isostructural nature of their compounds constitute some of the best evidence for the transition element character of these two series of elements.

Absorption, reflectance, and luminescence spectra. The electronic spectra of the lanthanides and actinides arise from three types of electronic transitions: (a) *f-f* , (b) *f-d* , and (c) ligand-to-metal charge-transfer. The absorption spectra of lanthanide and actinide ions in aqueous solution and in crystalline form exhibit very narrow *f-f* bands in the near-ultraviolet, visible, and near-infrared regions of the electromagnetic spectrum that give rise to the observed colors of the ions. Ample evidence indicates that these bands arise from electronic transitions within the 4*f* and 5*f* shells in which the $4f^n$ and $5f^n$ configurations are preserved in the upper and lower states for a particular ion. These *f-f* transitions are forbidden in principal by quantum mechanical selection rules but do occur because the symmetry of the metal ion is decreased by crystal field effects. The crystal field effect is stronger for the actinides than for the lanthanides and, consequently, the intensity of actinide *f-f* bands is generally an order of magnitude greater than that of the lanthanides. The *f-f* absorption spectra of lanthanide and actinide ions provide distinctive "fingerprints" of the element and oxidation state and this has been extensively exploited for qualitative and quantitative chemical analysis. **Figure 3** shows a diffuse reflectance spectrum showing typical actinide *f-f* transitions for a solid neptunium(V) double salt, $Na_3NpO_2(CO_3)_2 \cdot nH_2O$. The *f-d* transitions and charge-transfer bands which are allowed for lanthanide and actinide ions give rise to broader, more intense absorbance bands and are the reason for the deep colors characteristic of higher oxidation state complexes with strongly polarizing ligands.

Luminescence (fluorescence and phosphorescence) has long been considered a complimentary technique to absorption spectroscopy. Analytical determination of lanthanide and actinide ions via luminescence in solution and solid state has enjoyed a revitalization with the advent of powerful tunable lasers and multichannel optical detectors. Luminescence has been reported for the trivalent lanthanides and for the transplutonium trivalent actinides (Am - Es) in solution. Interestingly, solutions of Cm^{3+} have been observed to luminesce without the use of an external excitation source! "Self-luminescence" resulted from excitation by the energy released from radioactive decay of curium-244. Solid state self-luminescence was also observed from curium diluted with SrF_2, BaF_2 and $SrCl_2$ salts. Luminescence has also been observed in the trichlorides of uranium, neptunium, americium, and curium, diluted with lanthanum chloride [1].

Nuclear magnetic resonance and X-ray absorption spectra. Nuclear magnetic resonance measurements exploit detection of spin active atoms in lanthanide and actinide complexes (e.g., ^{1}H, ^{13}C, ^{17}O) to elucidate their structures and speciation in solution or solid state. Such measurements have been used to study ligand exchange reaction mechanisms, activation energies, and kinetics, hydration numbers, solution speciation, etc. X-ray absorption spectral methods measure the attenuation of X-rays absorbed by the metal atoms as well as fine structure caused by interference of outgoing photoelectron waves and backscattering from neighboring atoms. The net result is the determination of distances from the metal (lanthanide/actinide) atoms to near neighbor atoms which allows for elucidation of the structure and oxidation state of the element. Synchrotron-based X-ray absorption spectroscopy is one of the few structure sensitive probes that can provide direct molecular level information, including oxidation state speciation, local structure, identity and distance of nearest neighbors, etc. of lanthanide and actinide complexes in solution, solid state, and at solid-solution interfaces.

Practical applications

The lanthanide elements have numerous practical uses, growing in number, including steel making, abrasives, petroleum cracking catalysis, TV screen phosphores, lasers, high temperature superconductors, high strength permanent magnets, chemical probes, etc. [13]. The first members of the series are used in carbon-arc lighting, especially in the motion picture industry. They are used as components of misch metal, which is used in the manufacture of pyrophoric alloys for cigarette lighters, etc. Lanthanide salts are used to color glasses and enamels. Promethium (^{247}Pm) can be used as the energy source for a nuclear-powered battery. Small amounts of lanthanides, such as gadolinium, can improve the workability and stability of iron, chromium, and related alloys. Several lanthanide compounds are used as laser materials. Several lanthanide nuclides (e.g., dysprosium) have large thermal neutron absorption cross sections that make them useful for nuclear control applications. Recent discoveries have shown that compounds containing lanthanide elements can have application as relatively high temperature superconductors.

The practical use of two actinide nuclides, ^{235}U and ^{239}Pu, as nuclear fuel is well known [2]. When a neutron of any energy strikes the nucleus of one of these nuclides, each of which is capable of undergoing fission with thermal (essentially zero energy) neutrons, the fission reaction can occur in a self-sustaining manner. As is well known, these nuclides can serve as the explosive ingredients for nuclear weapons. A controlled self-perpetuating chain reaction using such nuclear fuels can be maintained in a manner such that the heat energy can be extracted or converted by conventional means to electrical energy. In a typical nuclear power reactor operating in the United States using enriched ^{235}U as the fuel (approx. 3% ^{235}U and 97% ^{238}U), about 60% of the energy comes from ^{235}U and about 40% from ^{239}Pu derived from the non-fissionable fertile ^{238}U. About 20% of the electricity generated in the United States and almost 20% worldwide comes from nuclear power plants. The complete utilization of nonfissionable ^{238}U (through conversion to fissionable ^{239}Pu) should eventually be accomplished by breeder reactor technology.

In addition, three other actinide nuclides (^{238}Pu, ^{241}Am, and ^{252}Cf) have other practical applications [1]. One gram of ^{238}Pu produces approximately 0.56 Watt of thermal power, primarily from alpha-particle decay, and this property has been used in space exploration to provide energy for small thermoelectric power units. The most noteworthy example of this latter type of application is a radioisotopic thermoelectric generator left on the Moon. It produced 73 Watts of electrical power to operate the scientific experiments of the Apollo lunar exploration and was fueled with 2.6 kg of plutonium dioxide, $^{238}PuO_2$. Similar generators powered the instrumentation for other Apollo missions, the Viking Mars lander, and the Pioneer and Voyager probes to Jupiter, Saturn, Uranus, Neptune, and beyond. Americium-241 has a predominant gamma-ray energy of 60 keV and a long half-life of 433 years for decay by the emission of alpha particles, which makes it particularly useful for a wide range of industrial gaging applications, the diagnosis of thyroid disorders, and for smoke detectors. When mixed with beryllium, it generates neutrons at the rate of 1.0×10^7 neutrons/per second/per gram of ^{241}Am. The mixture is designated "^{241}Am-Be" and a large number of such sources are in worldwide daily use in oil-well logging operations to find how much oil a well is producing in a given time span. Californium-252 is an intense neutron source: 1 gram emits 2.4×10^{12} neutrons per second. This isotope is being tested for applications in neutron activation analysis, startup sources for nuclear reactors, neutron radiography, portable sources for field use in mineral prospecting and oil-well logging, and in airport neutron-activation detectors for nitrogenous materials (i.e., explosives). Both ^{238}Pu and ^{252}Cf have been used for medical applications: the former as a power source for use in heart pacemakers and heart pumps and the latter as a neutron source for the effective irradiation of certain tumors for which gamma-ray treatment is relatively ineffective.

Concluding remarks

The lanthanides and actinides constitute a quarter of all of the known chemical elements. One lanthanide and eleven actinides have synthetic origins. These two series of transition elements are continuing to occupy positions of increasing importance in the areas of fundamental science and practical applications. From glazes to lasers to high temperature superconductors, the lanthanides have numerous practical applications. From power sources to smoke alarms to biomedical applications, the actinides have many practical applications. Uranium and plutonium, for example, have assumed roles of extraordinary importance. When nuclear waste disposal problems are solved, these nuclear fuels have the potential of providing unlimited renewable energy sources for many centuries to come. Fundamental studies of the lanthanide and actinide series of elements will continue to provide insight into the basic nature of matter and its arrangement in the Periodic Table. Of special fundamental interest will be the "one-atom-at-a-time" investigations of the heaviest actinide and transactinide elements.

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LIST OF TABLES

Table 1. The lanthanide elements

ATOMIC NUMBER	ELEMENT	SYMBOL	ATOMIC WEIGHT	DISCOVERER (S)	YEAR OF DISCOVERY
57	Lanthanum	La	138.9055(2)	C. G. Mosander	1839
58	Cerium	Ce	140.115(4)	M. H. Klaproth; J. J. Berzelius and W. Hisinger	1803
59	Praseodymium	Pr	140.90765(3)	C. von Welsbach	1885
60	Neodymium	Nd	144.24(3)	C. von Welsbach	1885
61	Promethium	Pm	147	J. A. Marinsky, L. E. Glendenin, and C. D. Coryell	1945
62	Samarium	Sm	150.36(3)	L. de Boisbaudran	1879
63	Europium	Eu	151.965(9)	E. A. Demarcay	1901
64	Gadolinium	Gd	157.25(3)	L. de Boisbaudran	1886
65	Terbium	Tb	158.92534(3)	C. G. Mosander	1843
66	Dysprosium	Dy	162.50(3)	L. de Boisbaudran	1886
67	Holmium	Ho	164.93032(3)	M. Delafontaine and L. Soret; P. T. Cleve	1878
68	Erbium	Er	167.26(3)	C. G. Mosander	1842
69	Thulium	Tm	168.93421(3)	P. T. Cleve	1879
70	Ytterbium	Yb	173.04(3)	G. Urbain; C. von Welsbach	1907
71	Lutetium	Lu	174.967(1)	G. Urbain; C. von Welsbach; C. James	1907

Table 2. The actinide elements

ATOMIC NUMBER	ELEMENT	SYMBOL	ATOMIC WEIGHT	DISCOVERER(S)	YEAR OF DISCOVERY
89	Actinium	Ac	227	A. Debierne	1899
90	Thorium	Th	232	J. J. Berzelius	1828
91	Protactinium	Pa	231	O. Hahn and L. Meinter; F. Soddy and J. A. Cranston	1917 1917
92	Uranium	U	238	M. H. Klaproth	1789
93	Neptunium	Np	237	E. M. McMillan and P. H. Abelson	1940
94	Plutonium	Pu	242	G. T. Seaborg, E. M. McMillan, J. W. Kennedy, and A. C. Wahl	1940-1941
95	Americium	Am	243	G. T. Seaborg, R. A. James, L. O. Morgan, and A. Ghiorso	1944-1945
96	Curium	Cm	248	G. T. Seaborg, R. A. James, and A. Ghiorso	1944
97	Berkelium	Bk	249	S. G. Thompson, A. Ghiorso, and G. T. Seaborg	1949
98	Californium	Cf	249	S. G. Thompson, K. Street, Jr., A. Ghiorso, and G. T. Seaborg	1950
99	Einsteinium	Es	254	A. Ghiorso, S. G. Thompson, G. H. Higgins, G. T. Seaborg, M. H. Studier, P. R. Fields, S. M. Fried, H. Diamond, J. F. Mech, G. L. Pyle, J. R. Huizenga, A. Hirsch, W. M. Manning, C. I. Browne, H. L. Smith, and R. W. Spence	1952
100	Fermium	Fm	257	A. Ghiorso, S. G. Thompson, G. H. Higgins, G. T. Seaborg, M. H. Studier, P. R. Fields, S. M. Fried, H. Diamond, J. F. Mech, G. L. Pyle, J. R. Huizenga, A. Hirsch, W. M. Manning, C. I. Browne, H. L. Smith, and R. W. Spence	1953
101	Mendelevium	Md	258	A. Ghiorso, B. G. Harvey, G. R. Choppin. S. G. Thompson, and G. T. Seaborg	1955
102	Nobelium	No	259	A. Ghiorso, T. Sikkeland, J. R. Walton, and G. T. Seaborg; E. D. Donets, V. A. Schegolov and V. A. Ermakov	1958 1964
103	Lawrencium	Lr	260	A. Ghiorso, T. Sikkeland, A. E. Larsh, and R. M. Latimer; E. D. Donets, V. A. Schegolov and V. A. Ermakov	1961 1965

Table 3. Isotopes of the lanthanide elements

ATOMIC NUMBER	ELEMENT	NUMBER OF ISOTOPES	ISOTOPES	NATURAL ABUNDANCE OF ISOTOPES (PERCENT)
57	Lanthanum	31	120-150	138(0.09), 139(99.91)
58	Cerium	30	123-152	136(0.19), 138(0.25), 140(88.43), 142(11.13)
59	Praseodymium	30	121, 124, 126, 128-154	141(100)
60	Neodymium	30	127-156	142(27.13), 143(12.18), 144(23.8), 145(8.30), 146(17.19), 148(5.76), 150(5.64)
61	Promethium	28	130, 132-158	not applicable, transient
62	Samarium	28	131, 133-160	144(3.1), 147(15.0), 148(11.3), 149(13.8), 150(7.4), 152(26.7), 154(22.7)
63	Europium	29	134-162	151(47.8), 153(52.2)
64	Gadolinium	28	137-164	152(0.20),154(2.18), 155(14.80), 156(20.47), 157(15.65), 158(24.84), 160(21.66)
65	Terbium	26	140-165	159(100)
66	Dysprosium	29	141-169	156(0.06), 158(0.10), 160(2.34),161(18.9), 162(25.5),163(24.9), 164(28.2)
67	Holmium	29	144-172	165(100)
68	Erbium	29	145, 147-174	162(0.14), 164(1.61), 166(33.6), 167(22.95), 168(26.8), 170(14.9)
69	Thulium	32	146-177	169(100)
70	Ytterbium	30	151-180	168(0.13), 170(3.05), 171(14.3), 172(21.9), 173(16.12), 174(31.8),176(12.7)
71	Lutetium	35	150-184	175(97.41), 176(2.59)

Table 4. Isotopes of the actinide elements

ATOMIC NUMBER	ELEMENT	NUMBER OF ISOTOPES	ISOTOPES	NATURAL ABUNDANCE OF ISOTOPES (PERCENT)
89	Actinium	26	209-234	not applicable, transient
90	Thorium	25	212-236	232(100)
91	Protactinium	24	215-238	not applicable, transient
92	Uranium	19	222, 225-240, 242	234(0.0055), 235(0.720), 238 (99.2745)
93	Neptunium	20	225-244	not applicable
94	Plutonium	17	230, 232-247	not applicable
95	Americium	14	232, 234, 236-247	not applicable
96	Curium	14	238-251	not applicable
97	Berkelium	13	236, 238, 240, 242-251	not applicable
98	Californium	18	239-256	not applicable
99	Einsteinium	17	241-257	not applicable
100	Fermium	18	242-259	not applicable
101	Mendelevium	14	247-260	not applicable
102	Nobelium	12	250-260, 262	not applicable
103	Lawrencium	11	252-262	not applicable

Table 5. Electronic configurations of f-block atoms and ions

LANTHANIDE SERIES					ACTINIDE SERIES					
SYMBOL	GASEOUS ATOM	M^{2+}(g)	M^{3+}(g)	M^{4+}(g)	SYMBOL	GASEOUS ATOM	M^{+}(g)	M^{2+}(g)	M^{3+}(g)	M^{4+}(g)
La	$5d^1 6s^2$		[Xe]		Ac	$6d^1 7s^2$	$7s^2$	$7s^1$	[Rn]	
Ce	$4f^1 5d^1 6s^2$	$4f^2$	$4f^1$		Th	$6d^2 7s^2$	$6d^1 7s^2$	$5f^1 6d^1$	$5f^1$	
Pr	$4f^3 6s^2$	$4f^3$	$4f^2$	$4f^1$	Pa	$5f^2 6d^1 7s^2$	$5f^2 7s^2$	$5f^2 6d^1$	$5f^2$	$5f^1$
Nd	$4f^4 6s^2$	$4f^4$	$4f^3$	$4f^2$	U	$5f^3 6d^1 7s^2$	$5f^3 7s^2$	$5f^3 6d^1$?	$5f^3$	$5f^2$
Pm	$4f^5 6s^2$		$4f^4$		Np	$5f^4 6d^1 7s^2$	$5f^5 7s^1$	$5f^5$?	$5f^4$	$5f^3$
Sm	$4f^6 6s^2$	$4f^6$	$4f^5$		Pu	$5f^6 7s^2$	$5f^6 7s^1$	$5f^6$	$5f^5$	$5f^4$
Eu	$4f^7 6s^2$	$4f^7$	$4f^6$		Am	$5f^7 7s^2$	$5f^7 7s^1$	$5f^7$	$5f^6$	$5f^5$
Gd	$4f^7 5d^1 6s^2$	$4f^7 5d^1$	$4f^7$		Cm	$5f^7 6d^1 7s^2$	$5f^7 7s^2$	$5f^8$	$5f^7$	$5f^6$
Tb	$4f^9 6s^2$	$4f^9$	$4f^8$	$4f^7$	Bk	$5f^9 7s^2$	$5f^9 7s^1$	$5f^9$	$5f^8$	$5f^7$
Dy	$4f^{10} 6s^2$	$4f^{10}$	$4f^9$	$4f^8$	Cf	$5f^{10} 7s^2$	$5f^{10} 7s^1$	$5f^{10}$	$5f^9$	$5f^8$
Ho	$4f^{11} 6s^2$	$4f^{11}$	$4f^{10}$		Es	$5f^{11} 7s^2$	$5f^{11} 7s^1$	$5f^{11}$	$5f^{10}$	$(5f^9)$
Er	$4f^{12} 6s^2$	$4f^{12}$	$4f^{11}$		Fm	$5f^{12} 7s^2$	$(5f^{12} 7s^1)$	$(5f^{12})$	$(5f^{11})$	$(5f^{10})$
Tm	$4f^{13} 6s^2$	$4f^{13}$	$4f^{12}$		Md	$(5f^{13} 7s^2)$	$(5f^{13} 7s^1)$	$(5f^{13})$	$(5f^{12})$	$(5f^{11})$
Yb	$4f^{14} 6s^2$	$4f^{14}$	$4f^{13}$		No	$(5f^{14} 7s^2)$	$(5f^{14} 7s^1)$	$(5f^{14})$	$(5f^{13})$	$(5f^{12})$
Lu	$4f^{14} 5d^1 6s^2$		$4f^{14}$		Lr	$(5f^{14} 6d^1 7s^2)$ or $(f^{14} 7s^2 7p^1)$	$(5f^{14} 7s^2)$	$(5f^{14} 7s^1)$	$(5f^{14})$	$(5f^{13})$

Predicted configurations in parentheses.

Table 6. The oxidation states of the lanthanide elements

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
		(2)	(2)		2	2			(2)	(2)		(2)	2	
$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$
	4	4	(4)					4	(4)					

Parentheses indicates solid state only or not well characterized.
Underline indicates the most stable state.

Table 7. The oxidation states of the actinide elements

Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103
						(2)			(2)	(2)	2	2	$\underline{2}$	
$\underline{3}$	(3)	(3)	3	3	3	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	3	$\underline{3}$
	$\underline{4}$	4	4	4	$\underline{4}$	4	4	4	(4)					
		$\underline{5}$	5	$\underline{5}$	5	5								
			$\underline{6}$	6	6	6								
				7	7	(7)								

Parentheses indicates solid state only or not well characterized.
Underline indicates the most stable state.

Table 8. Ion types and colors for lanthanide ions

ATOMIC NUMBER	ELEMENT	SYMBOL	M^{+2}	M^{+3}	M^{+4}
57	Lanthanum	La		colorless	
58	Cerium	Ce		colorless	yellow
59	Praseodymium	Pr		light green	golden yellow*
60	Neodymium	Nd		lilac	
61	Promethium	Pm		pink to yellow	
62	Samarium	Sm	blood red	light yellow	
63	Europium	Eu	yellow-green	colorless	
64	Gadolinium	Gd		colorless	
65	Terbium	Tb		colorless	red brown*
66	Dysprosium	Dy		colorless	
67	Holmium	Ho		salmon	
68	Erbium	Er		pink	
69	Thulium	Tm		colorless	
70	Ytterbium	Yb	yellow	colorless	
71	Lutetium	Lu		colorless	

* In concentrated aqueous carbonate media.

Table 9. Ion types and colors for actinide ions

ATOMIC NUMBER	ELEMENT	SYMBOL	M^{3+}	M^{4+}	MO_2^+	MO_2^{2+}	MO_5^{3-}
89	Actinium	Ac	colorless				
90	Thorium	Th		colorless			
91	Protactinium	Pa		colorless	colorless		
92	Uranium	U	red	green	colorless	yellow	
93	Neptunium	Np	blue to purple	yellow-green	emerald green	burgundy	dark green
94	Plutonium	Pu	blue to violet	tan to orange-brown	rose	yellow to pink-orange	dark green
95	Americium	Am	pink or yellow	red-brown*	yellow	rum colored	
96	Curium	Cm	pale green	color unknown			
97	Berkelium	Bk	green	yellow			
98	Californium	Cf	green				

* In concentrated aqueous carbonate media.

Table 10. Stability of lanthanide ions in aqueous solution

Ion	Stability
Sm^{2+}	very readily oxidized
Eu^{2+}	readily oxidized
Yb^{2+}	readily oxidized
La^{3+}	stable
Ce^{3+}	stable
Pr^{3+}	stable
Pm^{3+}	stable
Sm^{3+}	stable
Eu^{3+}	stable
Gd^{3+}	stable
Tb^{3+}	stable
Dy^{3+}	stable
Ho^{3+}	stable
Eu^{3+}	stable
Tm^{3+}	stable
Yb^{3+}	stable
Lu^{3+}	stable
Ce^{4+}	stable to water but readily reduced
Pr^{4+}	stable in strongly complexing solutions
Tb^{4+}	stable in strongly complexing solutions

Table 11. Stability of actinide ions in aqueous solution

Ion	Stability
Md^{2+}	stable to water, but readily oxidized
No^{2+}	stable
Ac^{3+}	stable
U^{3+}	aqueous solutions evolve hydrogen on standing
Np^{3+}	stable to water, but readily oxidized by air to Np^{4+}
Pu^{3+}	stable to water and air, but easily oxidized to Pu^{4+}; oxidizes slightly under the action of its own alpha radiation (in form of ^{239}Pu)
Am^{3+}	stable; difficult to oxidize
Cm^{3+}	stable
Bk^{3+}	stable; can be oxidized to Bk^{4+}
Cf^{3+}	stable
Es^{3+}	stable
Fm^{3+}	stable
Md^{3+}	stable, but rather easily reduced to Md^{2+}
No^{3+}	easily reduced to No^{2+}
Lr^{3+}	stable
Th^{4+}	stable
Pa^{4+}	stable to water, but readily oxidized
Pa^{5+}	stable; hydrolyzes readily
U^{4+}	stable to water, but slowly oxidized by air to UO_2^{2+}
Np^{4+}	stable to water, but slowly oxidized by air to NpO_2^+
Pu^{4+}	stable in concentrated acid, e.g. 6 M HNO_3, but disproportionates to Pu^{3+} and PuO_2^{2+} at lower acidities or forms colloidal hydrolysis products
Am^{4+}	known in solution only as the flouride or carbonate complex
Cm^{4+}	known in solution only as the flouride complex
Bk^{4+}	marginally stable; easily reduced to Bk^{3+}
UO_2^+	disproportionates to U^{4+} and UO_2^{2+}, most stable at pH 2-4
NpO_2^+	stable; disproportionates only at high acidities
PuO_2^+	always tends to disproportionate to Pu^{4+} and PuO_2^{2+} (ultimate products); most stable at very low acidities and at very low concentration
AmO_2^+	disproportionates in strong acid to Am^{3+} and AmO_2^{2+} reduces fairly rapidly under the action of its own alpha radiation at low acidities (in form of ^{241}Am)
UO_2^{2+}	stable; difficult to reduce
NpO_2^{2+}	stable; easy to reduce
PuO_2^{2+}	stable; easy to reduce; reduces slowly under the action of its own alpha radiation (in form of ^{239}Pu)
AmO_2^{2+}	easy to reduce; reduces fairly rapidly under the action of its own alpha radiation (in form of ^{241}Am)
NpO_5^{3-}	observed only in alkaline solution
PuO_5^{3-}	observed only in alkaline solution; oxidizes water

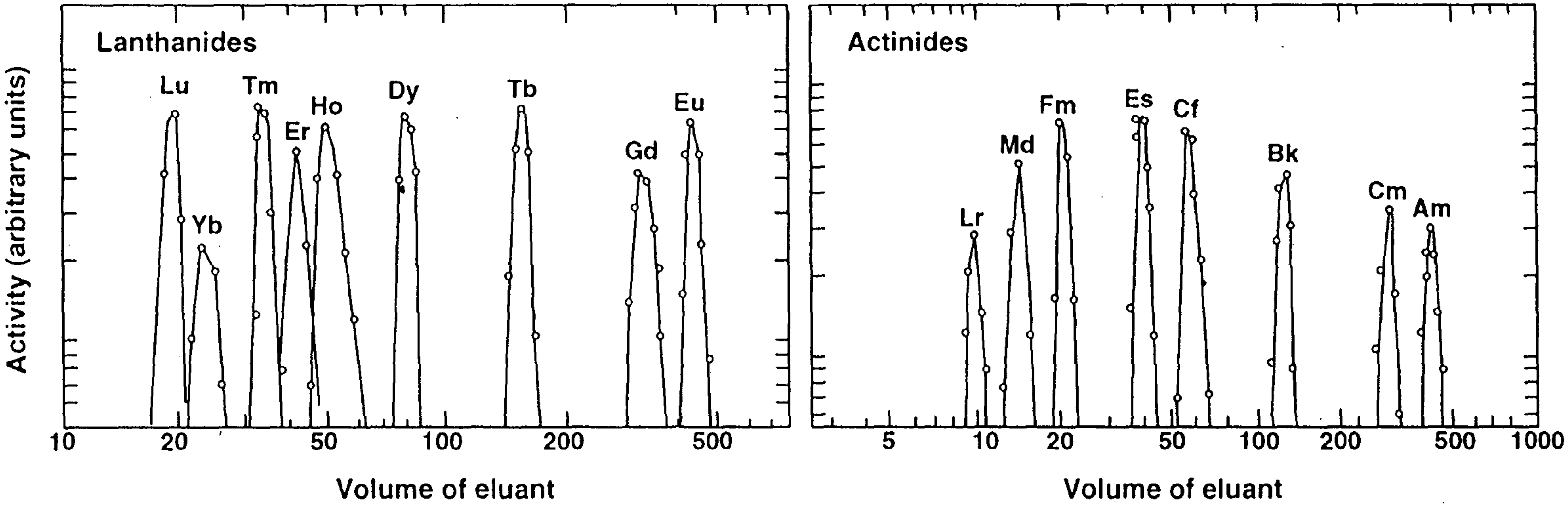
Table 12. Ionic radii of lanthanide and actinide elements

	Lanthanide series (CN=6)						Actinide series (CN=6)					
Number of 4f/5f electrons	M^{2+} ion	radius (nm)	M^{3+} ion	radius (nm)	M^{4+} ion	radius (nm)	M^{2+} ion	radius (nm)	M^{3+} ion	radius (nm)	M^{4+} ion	radius (nm)
0			La	0.1032	Ce	0.087			Ac	0.112	Th	0.0932
1			Ce	0.101	Pr	0.085			Th	0.108	Pa	0.0906
2			Pr	0.099					Pa	0.105	U	0.0889
3			Nd	0.0983					U	0.1028	Np	0.0874
4	Nd	0.121	Pm	0.097					Np	0.1011	Pu	0.0859
5			Sm	0.0958					Pu	0.0995	Am	0.0848
6	Sm	0.119	Eu	0.0947					Am	0.098	Cm	0.0841
7	Eu	0.117	Gd	0.0938	Tb	0.076	Am	0.119	Cm	0.097	Bk	0.0833
8			Tb	0.0923					Bk	0.0955	Cf	0.0821
9			Dy	0.0912					Cf	0.0945		
10	Dy	0.107	Ho	0.0901			Cf	0.112	Es	0.0934		
11			Er	0.089					Fm	0.0922		
12			Tm	0.088					Md	0.0912		
13	Tm	0.103	Yb	0.0868					No	0.0902		
14	Yb	0.102	Lu	0.0861			No	0.105	Lr	0.0896		

LIST OF FIGURES

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 Sg	107 Ns	108 Hs	109 Mt	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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Volume of eluant
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Md
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Cm
Am
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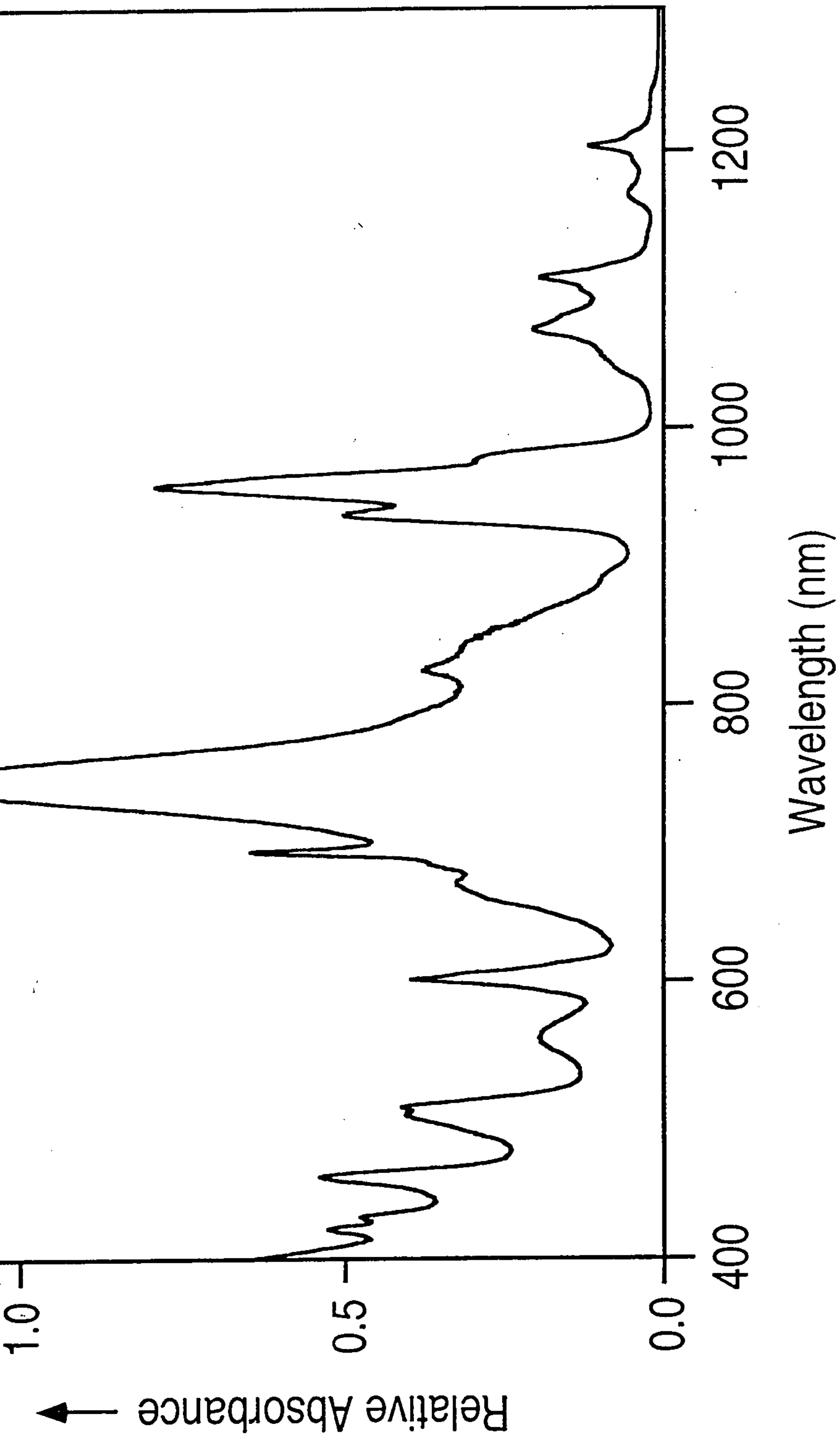
Volume of eluant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Wavelength (nm)

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