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[For invited presentation at the *Symposium Celebrating the 100<sup>th</sup> Anniversary of the Birth of Glenn T. Seaborg and Charles Coryell*, American Chemical Society Fall National Meeting, Philadelphia, PA, August 19-23, 2012]

LA-UR-12- 20007

## **Glenn Seaborg's Contributions to Heavy Element Science and the Periodic Table**

David E. Hobart  
Los Alamos National Laboratory  
Los Alamos, New Mexico USA

In celebrating the centennial anniversary of the birth of Glenn T. Seaborg it is fitting that we recount and pay tribute to his legacy. Many know of the scientific accomplishments of this man who became a legend and anyone who has attended his lectures can attest to how informative, educational, and entertaining he was. He had a beguiling and whimsical sense of humor and used this to drive home his points and share his passion and quest for discovery. The periodic table is a fundamental cornerstone of science and remains a central unifying principal. Seaborg was the architect of the actinide series of elements and their proper placement in the periodic table and co-discoverer of ten transuranium elements – one of which bears his name, element 106, *seaborgium*. The work and achievements of this Nobel laureate have touched the lives of many and his legacy will continue for generations to come.



# Glenn Seaborg's Contributions to Heavy Element Science and the Periodic Table

**David E. Hobart**

**Guest Scientist - Retired**

**Los Alamos National Laboratory**

**Los Alamos, NM 87545 USA**

***American Chemical Society Fall National Meeting***  
**Philadelphia, PA, August 19-23, 2012**



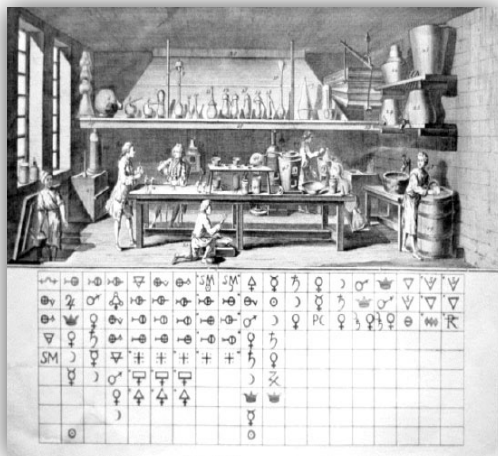
# The Greek Periodic Table ~ 400 BC

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The Greek Periodic Table was accepted for centuries

# Discovery of New Elements



Gold, silver, copper, tin, lead,  
Mercury known from antiquity.



Henning Brand discovers  
phosphorous



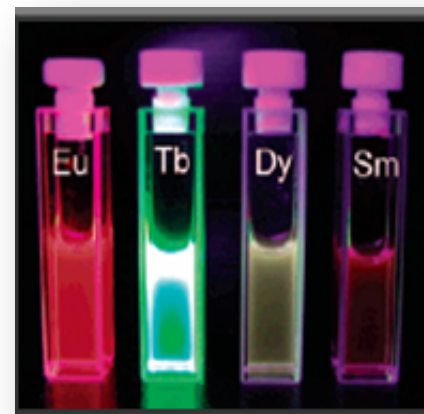
Martin Klaproth  
Ti, Zr, U, Te, Sr, Ce, Cr



Jöns Berzelius  
Si, Se, Ce, Li, V, Th



Sir Humphrey Davy  
Alkali earths, C, Cl, Br



lanthanides discovered by  
many scientists

# Discovery of Thorium and Uranium

---



*Uraninite or Pitchblende*

In 1789 Klaproth discovered ***uranium*** shortly after the discovery of the planet *Uranus*.



**Martin Klaproth**  
1743 -1817



**Jöns Jacob Berzelius**  
1779 -1848

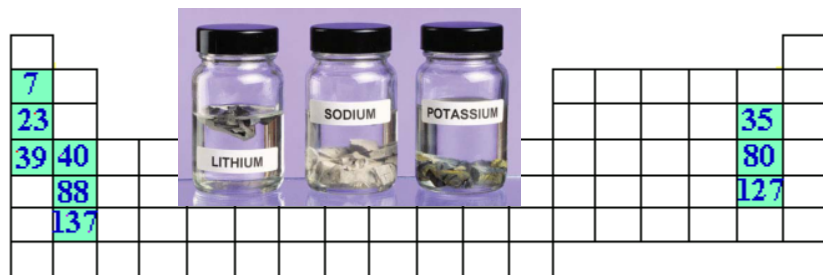
In 1828 Berzelius discovered ***thorium*** and named it after *Thor* the Norse god of thunder



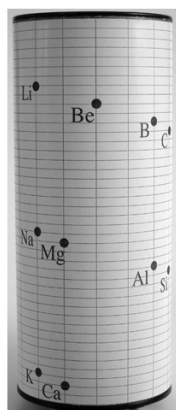
***Thorianite (ThO<sub>2</sub>)***

# New Elements - Emerging Patterns

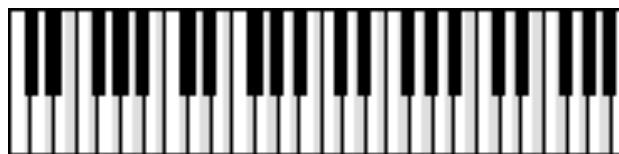
## Dobereiner's Law of Triads (1817)



## Alexandre-Emile Béguyer de Chancourtois' Cylinder (1862)



## Newland's Law of Octaves (1863)



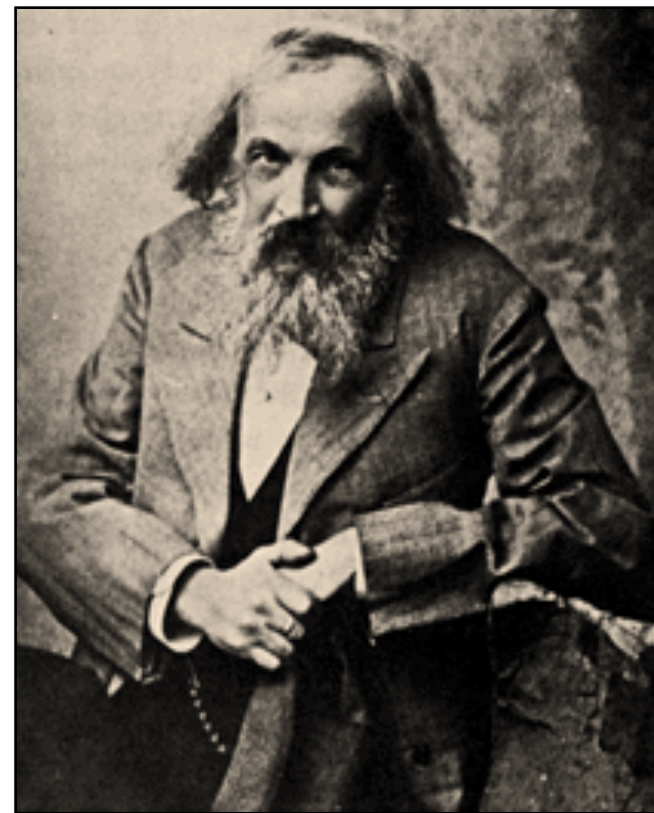
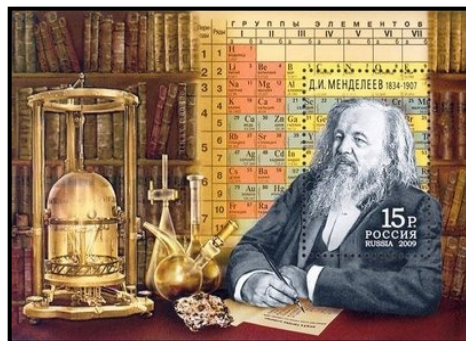
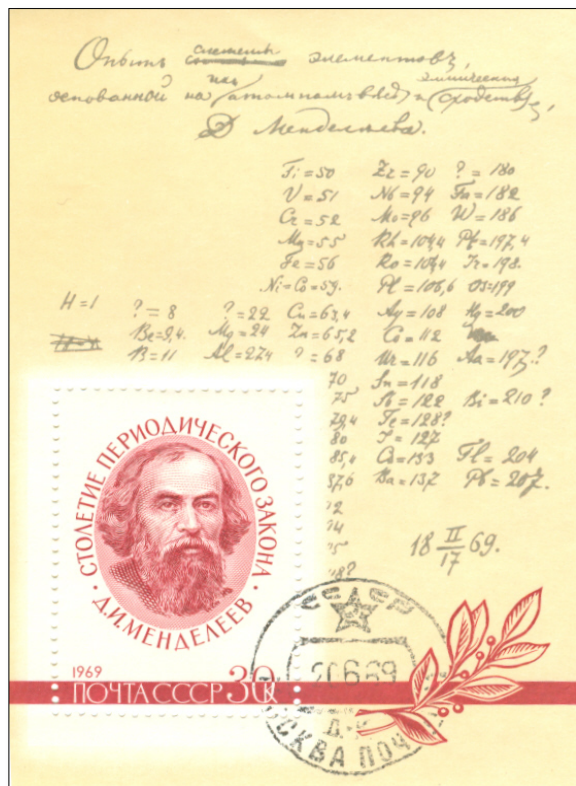
### Newlands' Arranged Elements in Octaves:

H	F	Cl	Co/Ni	Br	Pd	I	Pt/Ir
Li	Na	K	Cu	Rb	Ag	Cs	Tl
G	Mg	Ca	Zn	Sr	Cd	Ba/V	Pb
Bo	Al	Cr	Y	Ce/La	U	Ta	Th
C	Si	Ti	In	Zn	Sn	W	Hg
N	P	Mn	As	Di/Mo	Sb	Nb	Bi
O	S	Fe	Se	Ro/Ru	Te	Au	Os





# Mendeleev's Periodic Table 1869

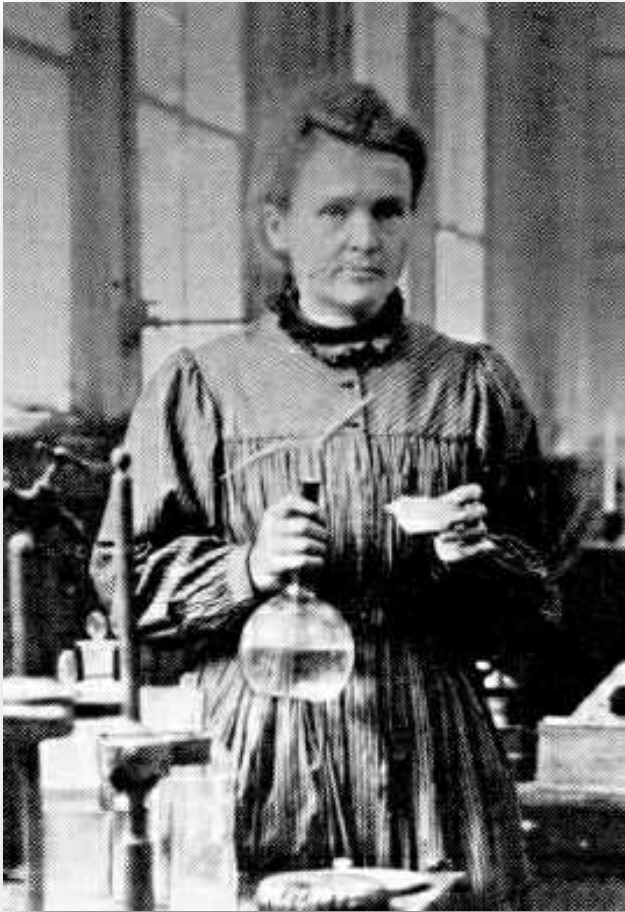


Russian chemist D. I. Mendeleev developed the *Periodic Table* and recognized that it was not a convenient tabulation but a natural phenomenon

**Dmitri Ivanovich Mendeleev**  
1834-1906

# Discovery of Polonium and Radium

---



**Marie Curie (1867-1934)**



**Pierre Curie (1859-1906)**

In 1898 Madam Curie and her husband Pierre isolated the new elements polonium and radium from the uranium ore pitchblende - filling holes and adding new elements to Mendeleev's table.

# The Periodic Table 1938

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Th	Pa	U												
		<i>Lanthanides</i>															
		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		



# Modern Alchemy by Transmutation



Leo Szilard (1898-1964)



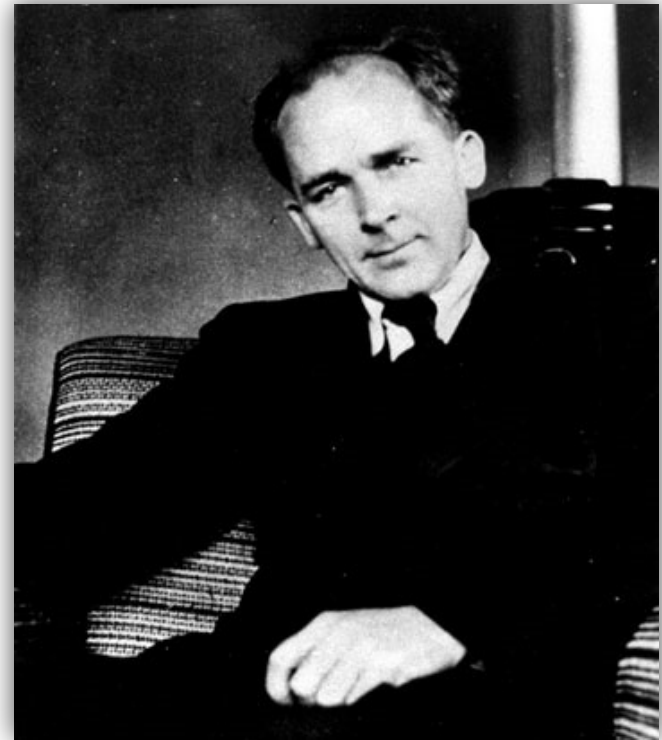
Enrico Fermi (1901-1954)

- In 1934 Enrico Fermi and Leo Szilard proposed using neutron bombardment to cause a “chain reaction.”
- They also attempted synthesizing new elements by neutron bombardment of uranium with mysterious and inconclusive results.

# Discovery of Fission

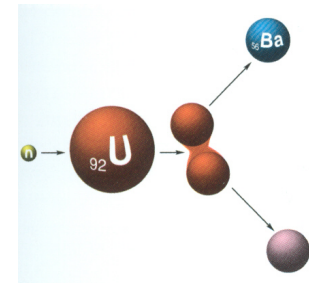


Otto Hahn (1879-1968) Lise Meitner (1878-1968)



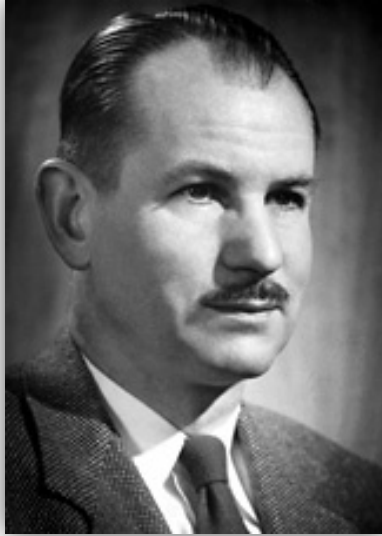
Fritz Strassman (1902-1980)

In the 1930's Hahn, Meitner, and Strassmann bombarded uranium atoms with neutrons and eventually concluded that they had “fissioned” or split the uranium atom into radioactive daughter elements!



# Discovery of Neptunium

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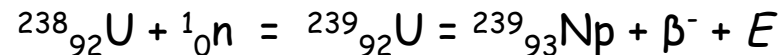


**Edwin McMillan**  
(1907-1991)



**Philip Abelson**  
(1913-2004)

With excitement about fission reaching the University of California, Berkeley, McMillan and Abelson bombarded uranium with moderated (slow) neutrons, resulting in “fusion” of the reactants:



Announced in 1940, the new man-made element was named neptunium (Np) after Neptune, the next planet beyond Uranus.

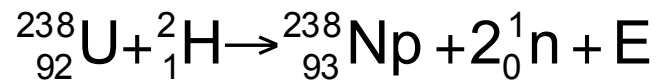
# The Discovery of Plutonium

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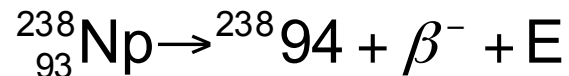
McMillan called away to work on a new wartime device -*RADAR*.

Berkeley professor Glenn Seaborg and graduate student Art Wahl discussed fission experiments and the discovery of neptunium at a candy store in Berkeley.

In 1940-1941 they bombarded uranium with deuterons to make neptunium and followed its beta decay...



$$t_{1/2} {}_{93}^{238}\text{Np} = 2.1 \text{ days}$$



$$t_{1/2} {}_{94}^{238} = 87.7 \text{ years}$$



# The Discovery of Plutonium

---

Seaborg named the new element plutonium after the next planet, Pluto and assigned it the symbol Pu

Announcement of the discovery was withheld because of security when the unusual nuclear behavior of one isotope of this element was determined



20 mg of plutonium hydroxide - 1942





# The Unusual Properties of Plutonium

---



Seaborg and coworkers found that Plutonium-239 (with a half life of 24,100 years) had a fission cross-section 50% greater than that of  $^{235}\text{U}$  the best fissioning element known

In an effort to beat Nazi Germany in developing a nuclear weapon, Seaborg was called to lead the *Plutonium Production Lab* at the *University of Chicago*



The “*Met Lab*” produced the plutonium for the *Trinity Test* conducted in New Mexico by *Los Alamos Laboratory* Director, Robert Oppenheimer and *Army General*, Leslie Groves

## Lanthanides

# Discovery of Americium and Curium

---



In 1944/1945, Seaborg and coworkers synthesized two new elements:

- *Element 95, americium* was named after it's continent of discovery
- *Element 96, curium* honors Madame Curie

Seaborg inadvertently announced these discoveries on the "Quiz Kids" radio program!

The chemistry of americium and curium was very perplexing and these elements were not behaving as was expected from predictions of the periodic table!



# Seaborg' s Actinide Hypothesis

---

Seaborg found that americium and curium did not behave chemically like *eka*-osmium and *eka*-iridium, respectively

With their *rare-earth-like* behavior, Glenn Seaborg proposed a radical rearrangement of the Periodic Table, a design unchanged since 1869, and proposed a new “actinide” series.

Seaborg was told by his major professor, G. N. Lewis, that if he published this theory, he would *ruin his reputation*!

Seaborg said he didn' t have a reputation and published anyway! Seaborg' s hypothesis was right on target!

# Seaborg's Periodic Table 1946



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
Lanthanides			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
Actinides			Th	Pa	U	Np	Pu	Am	Cm								

# Actinide Oxidation States

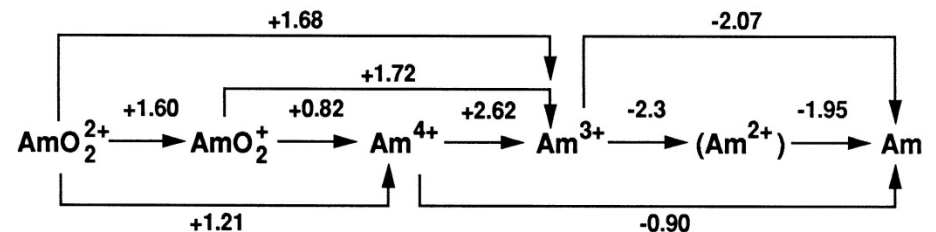
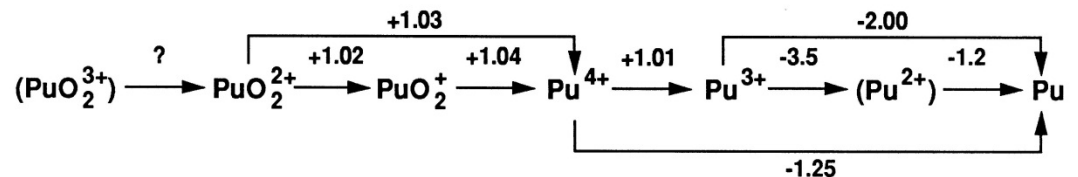
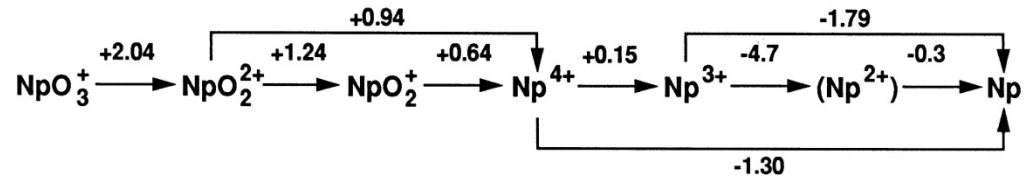
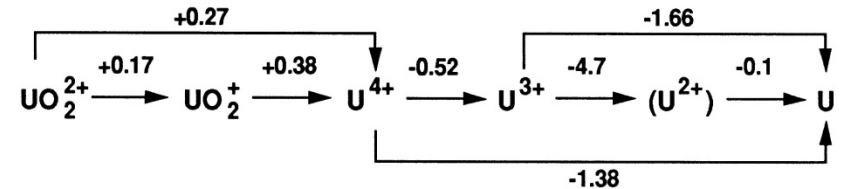
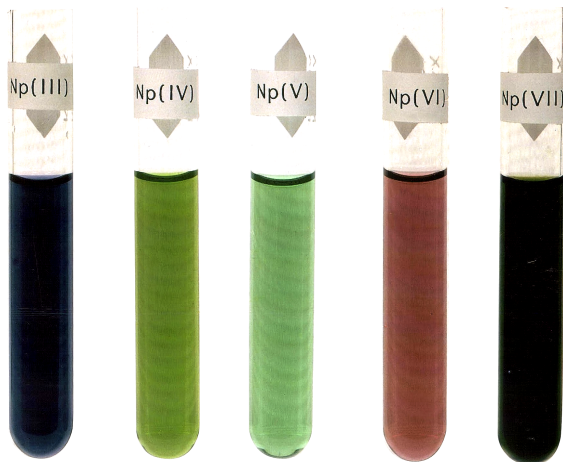
Z	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Symbol	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

The diagram illustrates the common oxidation states of actinides, showing a branching structure of Roman numerals (III, IV, V, VI, VII, VIII, II) below the periodic table. The states are as follows:

- Ac (89):** III
- Th (90):** IV
- Pa (91):** IV, V, VI
- U (92):** IV, V, VI
- Np (93):** III, IV, V, VI, VII
- Pu (94):** III, IV, V, VI, VII, VIII
- Am (95):** III, IV, V
- Cm (96):** III, IV
- Bk (97):** III, IV
- Cf (98):** III, IV
- Es (99):** III
- Fm (100):** III
- Md (101):** III
- No (102):** II, III
- Lr (103):** III

# Actinide Oxidation-Reduction Potentials



# Development of Quantum Mechanics



**Niels Bohr**  
(1885-1962)



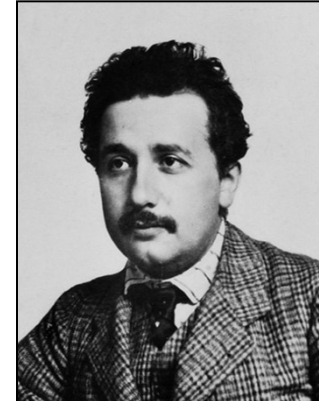
**Werner Heisenberg**  
(1901-1976)



**Erwin Schrödinger**  
(1887-1961)



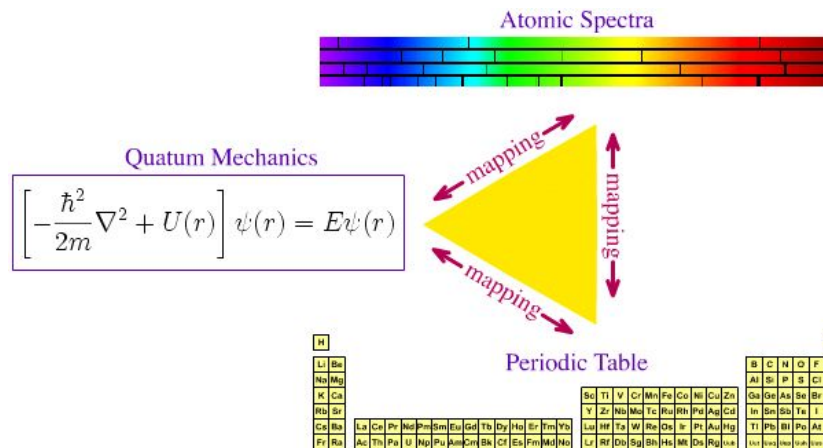
**Wolfgang Pauli**  
(1900-1958)



**Albert Einstein**  
(1879-1955)



**Max Born**  
(1882-1970)



**Paul Dirac**  
(1902-1984)

The uncertainty principle combined with the Bohr atom and the duality of wave and particle properties resulted in the quantum mechanical description of the atom through the collaborative effort of some of the most brilliant minds of the 20<sup>th</sup> Century

# Quantum Explanation of Periodicity

Quantum numbers  $n$ ,  $l$ ,  $m$ ,  $s$

$s$

$l = 0 \rightarrow$  **sharp**

$l = 1 \rightarrow$  **principal**

$l = 2 \rightarrow$  **diffuse**

$l = 3 \rightarrow$  **fundamental**

$p$

$d$

$f$

H		$l = 1 \rightarrow$ <i>principal</i>																He	
Li	Be	$l = 2 \rightarrow$ <i>diffuse</i>																	
Na	Mg	$l = 3 \rightarrow$ <i>fundamental</i>																	
		<i>d</i>											<i>p</i>						
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe		
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn		
Fr	Ra	<i>f</i>																	
Lanthanides		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu				
Actinides		Th	Pa	U	Np	Pu	Am	Cm											



# Discovery of Berkelium and Californium

---



In 1949 Seaborg and coworkers at Berkeley synthesized elements 97 and 98 by nuclear bombardment

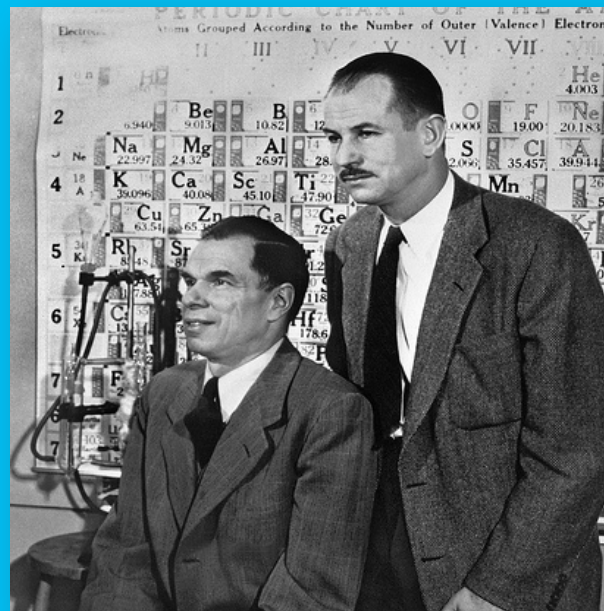
They named them after the city and state of their discovery, *berkelium*, and *californium* with symbols Bk and Cf

Street, Thompson, Seaborg, and Ghiorso

# 1951 Nobel Prize in Chemistry

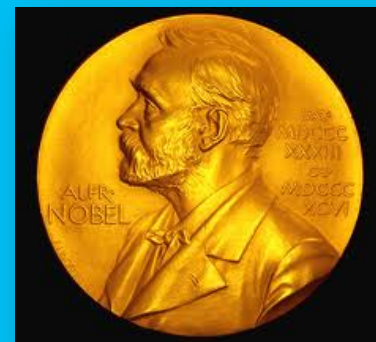


The King of Sweden giving the Nobel Prize to Glenn Seaborg



Glenn Seaborg and Edwin McMillan

Seaborg and McMillan shared the 1951 Nobel Prize in chemistry for their research on the transuranium elements





# The Discovery of Einsteinium and Fermium



In 1952, a team led by Seaborg discovered einsteinium and fermium in debris from the first thermonuclear (fusion) explosion (“MIKE”) detonated on Eniwetok Island in the South Pacific. The elements were named in honor of the *living* famous scientists.

# The Discovery of Mendelevium

Discovered in 1955 by Ghiorso, Harvey, Choppin, Thompson, and Seaborg at Berkeley by bombardment of Es with  $\text{He}^{2+}$  ions.



Seaborg: “It was fitting that the element be named for the Russian chemist Mendeleev who developed the periodic table. In discovering transuranium elements we depended on his table for predicting their chemical properties based on their position in the table.

During the Cold War naming an element for a Russian was a bold gesture that did not sit well with some Americans. However, Md was approved by IUPAC in August 1997

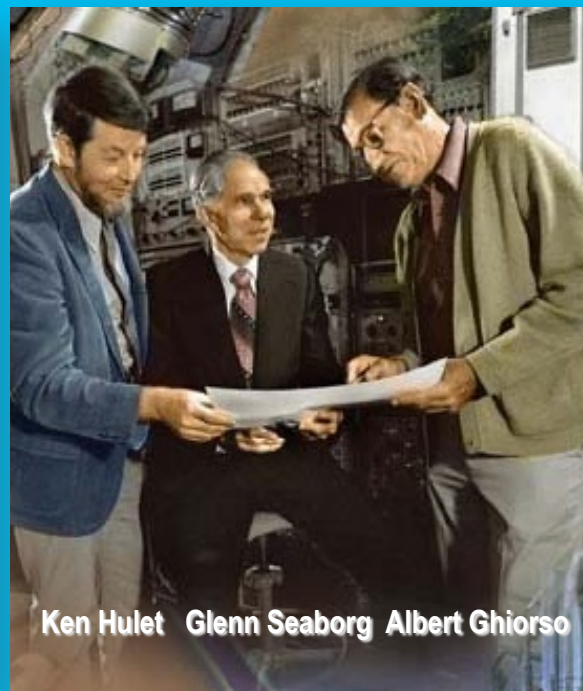
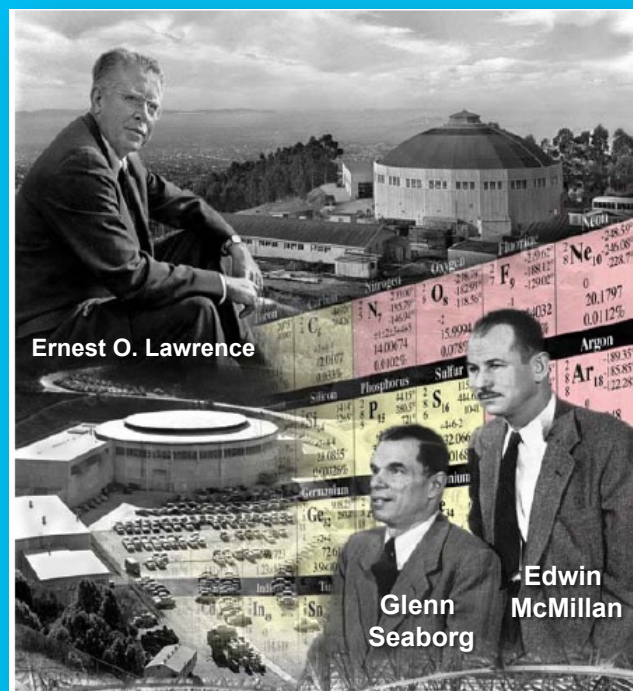


Gregory Choppin, Glenn Seaborg, Bernard Harvey,  
and Albert Ghiorso at the Berkeley Laboratory

Г	СКАНДИЙ	ТИТАН	ВАНАДИЙ	ХРОМ	МАРГАНЕЦ	ЖЕЛЕЗО
21	32	34	35	3		
Галлий	Германий	Мышьяк	Селен	Бром	Криптон	
38	40	41	42	43	44	
Иттрий	Цирконий	Никель	Медь	Технеций	Рубидий	
49	50	52				
Индий	Олово	Сурьма	Висмут	Полоний		
56	57	72	73	74	75	
Лантан	Гафний	Тантал	Вольфрам	Рений		

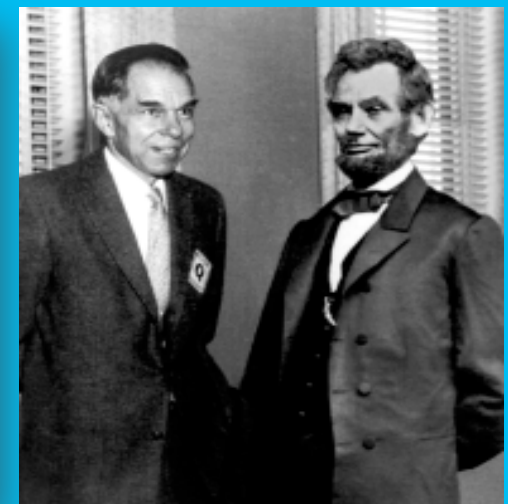
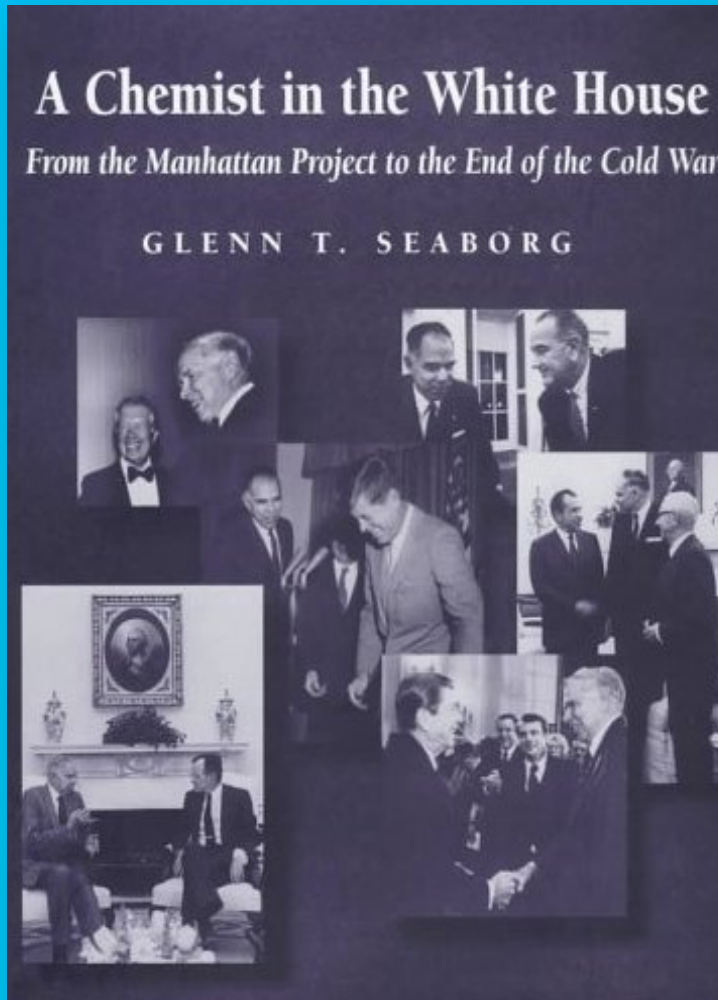
101 (258)  
Md  
 Mendelevium





From 1949 to 1999 Seaborg and other Berkeley scientists synthesized more than a dozen new elements beyond curium including berkelium through seaborgium along with many isotopes

# In the Service of Ten Presidents

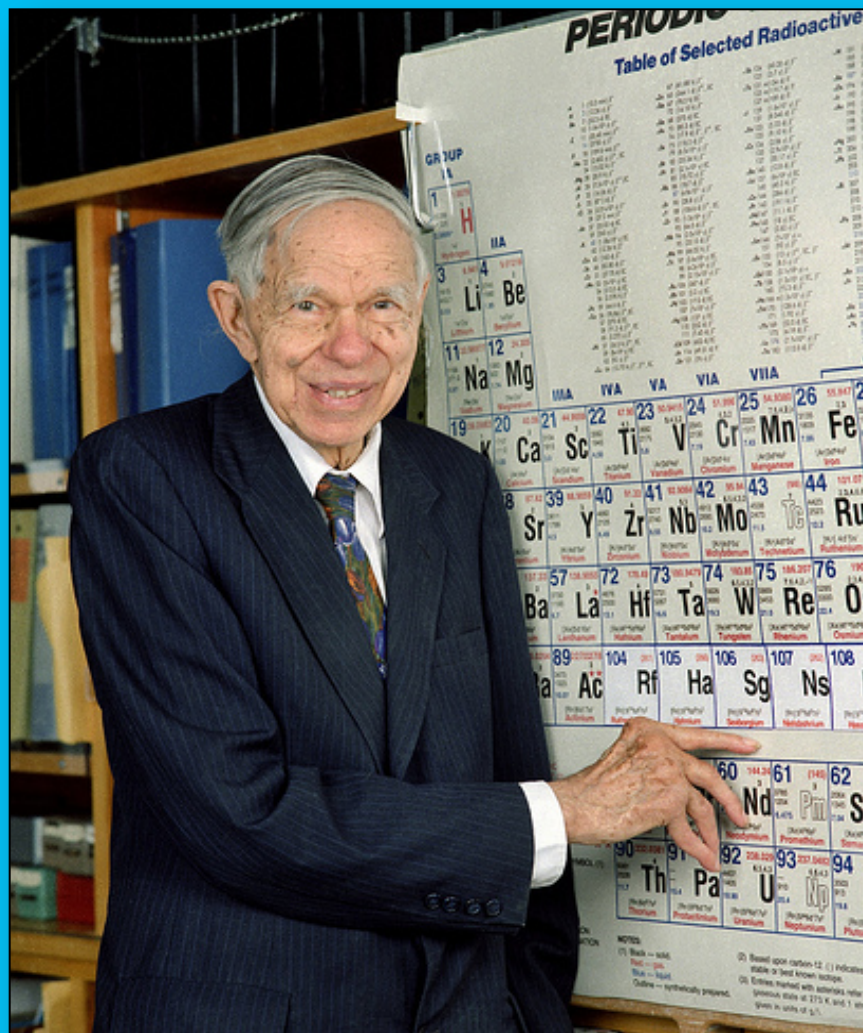




# Seaborg served as Chair of the Atomic Energy Commission 1961-1970



# Element 106 Named in Honor of Glenn T. Seaborg (LBL Research Review - August 1994)



Element 106, created at LBL in 1974 has been named "seaborgium" in honor of Nobel Laureate Glenn T. Seaborg.

"This is the greatest honor ever bestowed upon me--even better, I think, than winning the Nobel Prize,"

"Future students of chemistry, in learning about the periodic table, may have reason to ask why the element was named for me, and thereby learn more about my work."



# My Scientific Family Tree

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**SEABORG**

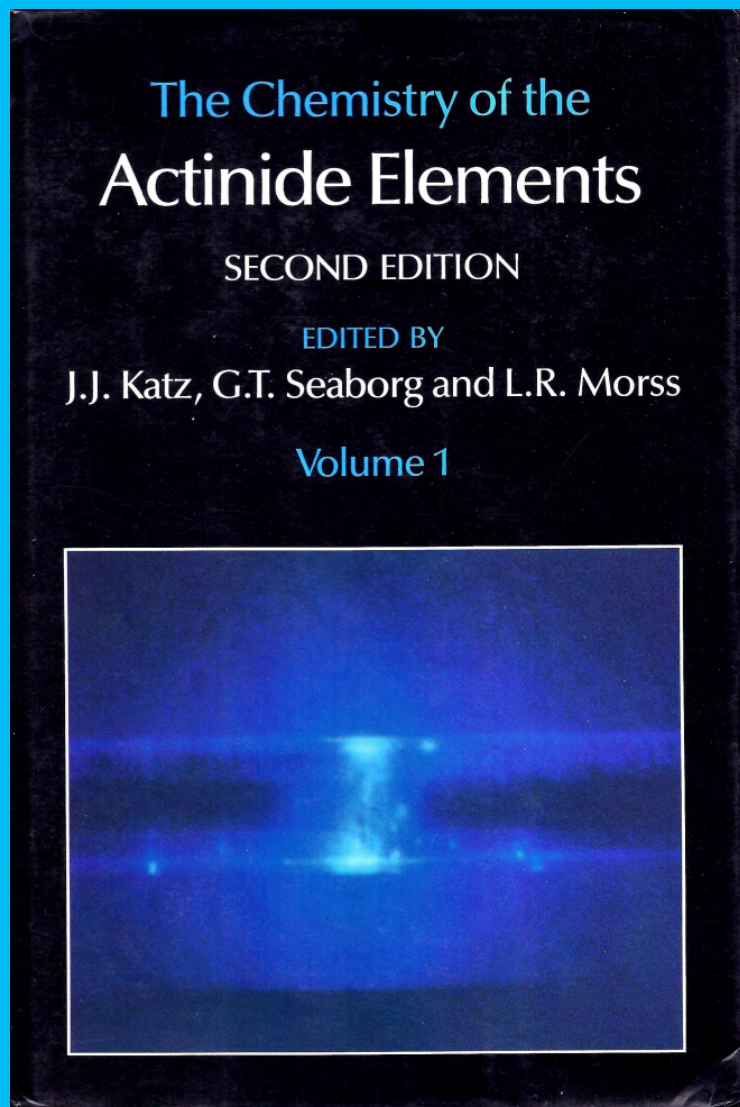
**CUNNINGHAM**

**PETERSON**

**HOBART**



# Chemistry of the Actinide Elements



## CHAPTER TEN

### BERKELIUM

David E. Hobart and Joseph R. Peterson

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#### 10.1 HISTORICAL

As was the case for the previously discovered transuranium elements, element 97 was first produced via a nuclear bombardment reaction. In December 1949 ion-exchange separation of the products formed by the bombardment of  $^{241}\text{Am}$  with accelerated alpha particles provided a new electron-capture activity eluting just ahead of curium (Thompson *et al.*, 1950a,b). This activity was assigned to an isotope (mass number 243) of element 97. The new element was named berkelium after Berkeley, California, USA, the city of its discovery, in a manner parallel to the naming of its lanthanide analog, terbium, after Ytterby, Sweden. The initial investigations of the chemical properties of berkelium were limited to tracer experiments (ion exchange and coprecipitation), and these were sufficient to establish the stability of  $\text{Bk(III)}$  and the accessibility of  $\text{Bk(IV)}$  in aqueous solution and to estimate the electrochemical potential of the  $\text{Bk(IV)/Bk(III)}$  couple (Thompson *et al.*, 1950b,c). Because a complete study of the chemistry of an element is not possible by tracer methods alone, a program for long-term neutron irradiation of about 8 g of  $^{239}\text{Pu}$  was initiated in 1952 in the Materials Testing Reactor (Arco, Idaho, USA) to provide macroquantities of berkelium (Cunningham, 1959). In 1958 about 0.6  $\mu\text{g}$  of  $^{249}\text{Bk}$  was separated, purified, and used in experiments to determine the absorption spectrum of  $\text{Bk(III)}$  in aqueous solution and to measure the magnetic susceptibility of  $\text{Bk(III)}$  (Cunningham, 1959). No  $\text{Bk(III)}$  absorption was observed over the wavelength range 450–750 nm, but an upper limit of about 20 was set for the molar absorptivity of any





David Hobart  
CHAIRMAN

ACTINIDES-93  
INTERNATIONAL CONFERENCE  
SANTA FE, NM, USA, SEPTEMBER 17-24, 1993

To Dave Hobart,  
Congratulations on a  
successful Actinides-93  
Conference,  
Steve Seaborg





To Dave Hoback,  
at the 50<sup>th</sup> anniversary of plutonium  
Salem Seabrook



# The Colors of Plutonium in Solution



Lawrence Berkeley Laboratory

1 Cyclotron Road Berkeley, California 94720

(415) 486-4000 • FTS 451-4000

Building 70A, Room 3307  
(415) 486-5661

August 16, 1988

David Hobart  
INC-Division  
Los Alamos National Laboratory  
P.O. Box 1663  
Los Alamos, NM 87545

Dear Dave:

I am sorry that I missed you on your visit to LBL.

I am immensely pleased to have the photos of plutonium in its various oxidation states, particularly the slides. These arrived at an opportune time for me to use them in a number of talks that I am giving in connection with the 50th anniversary of the discovery of fission and the discovery of the first transuranium elements.

I would also appreciate having the photos of neptunium in its various oxidation states, particularly in the form of slides.

Cordially yours,

A handwritten signature in dark ink, appearing to read "Glenn".

Glenn T. Seaborg

GTS/mm



THE  
WELCH FOUNDATION

## BULLETIN No. 53

## Actinide Research at Karlsruhe

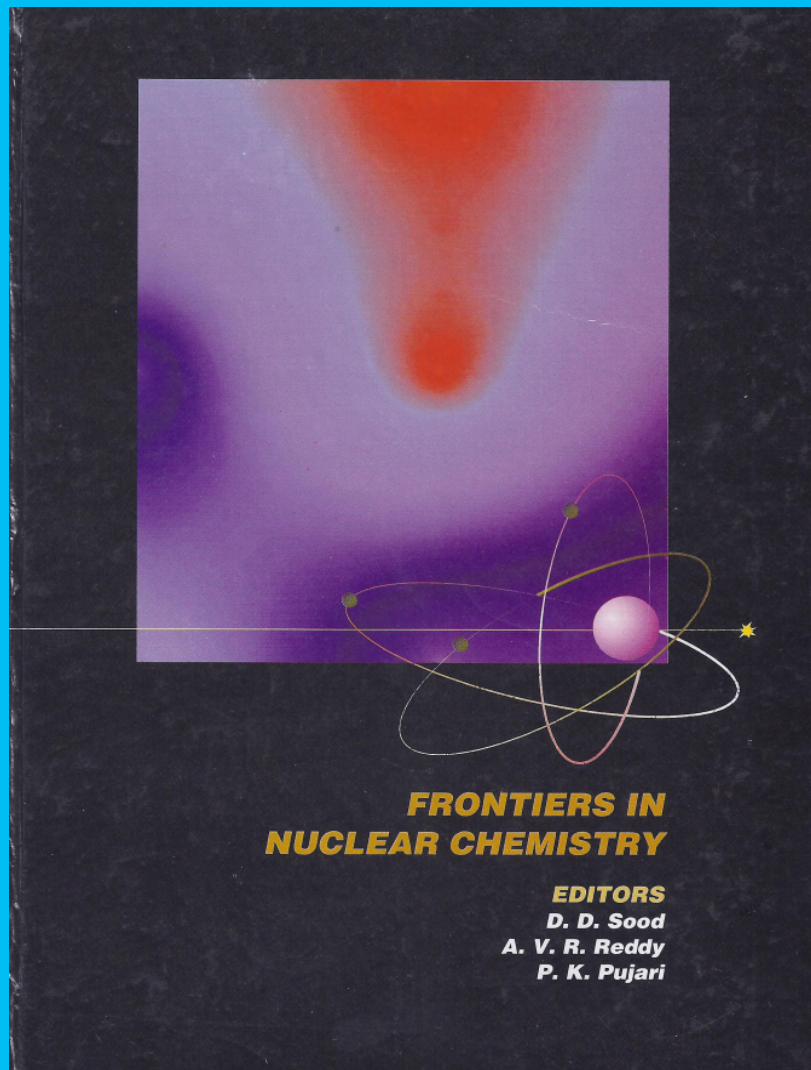








# Frontiers in Nuclear Chemistry



## Summary of the Properties of the Lanthanide and Actinide Elements

Glenn T. Seaborg and David E. Hobart

*Lawrence Berkeley Laboratory, One Cyclotron Road  
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### Abstract

The chemical properties, ion exchange behaviour, 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 on the practical applications of many of the lanthanides and actinides is also included.

### Key words

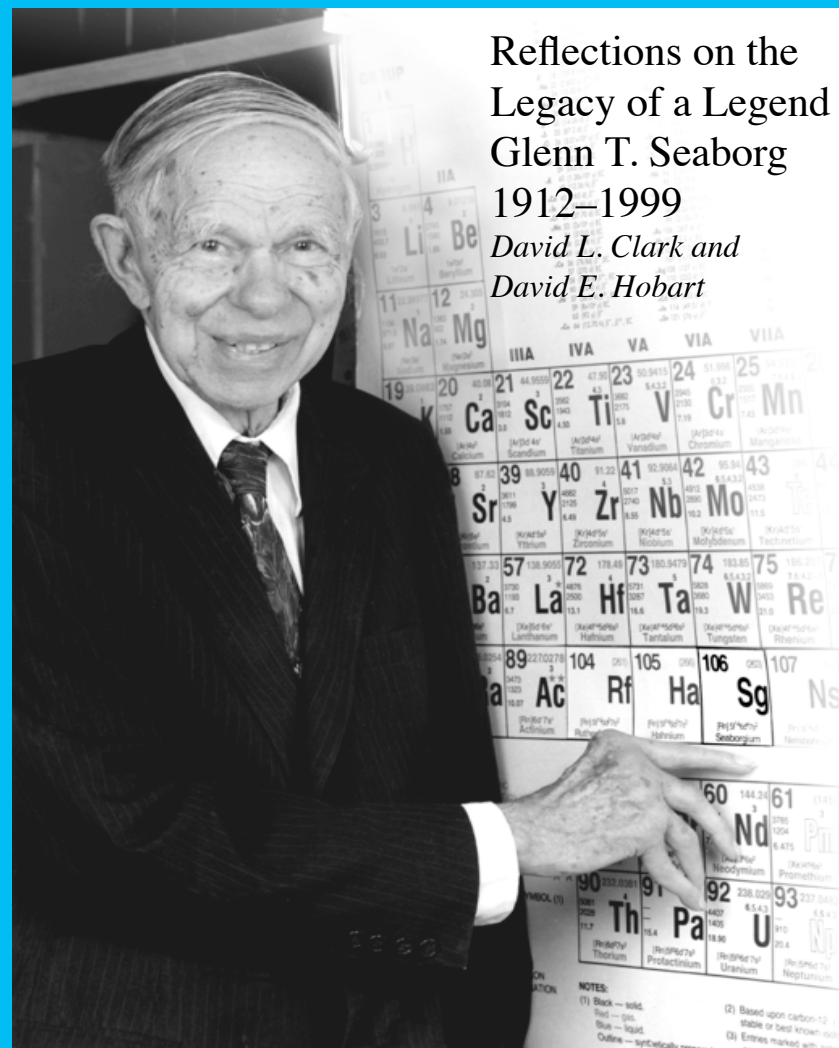
Lanthanide elements, actinide elements, f-electrons, periodic table, ion exchange behaviour, absorption and luminescence spectra

### Outline

- \* Introduction
- \* Position in the periodic table and electronic structure
- \* Properties
  - Metals*
  - Oxidation states*
  - Solid compounds*
  - Crystal structure and ionic radii*
  - Absorption, reflectance, and luminescence spectra*
  - Nuclear magnetic resonance and X-ray absorption spectra*
- \* Practical applications
- \* Concluding remarks



# The World has Lost a Legend

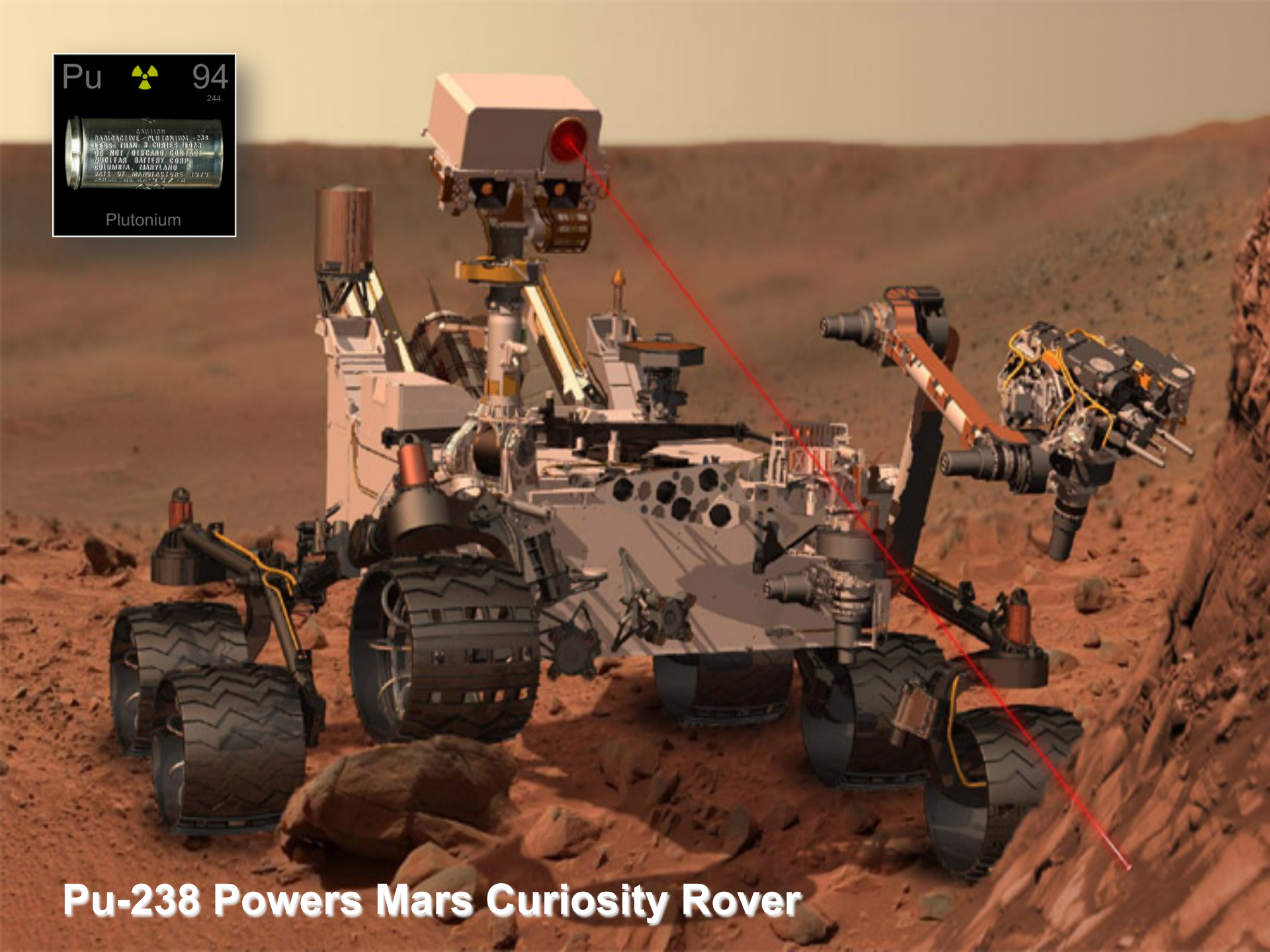
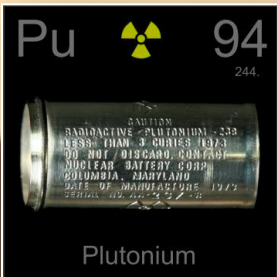


**Seaborg championed peaceful uses of plutonium**

**Pu-238 Powers Cassini at Saturn**







**Pu-238 Powers Mars Curiosity Rover**



Seaborg promoted Nuclear  
Power for Energy



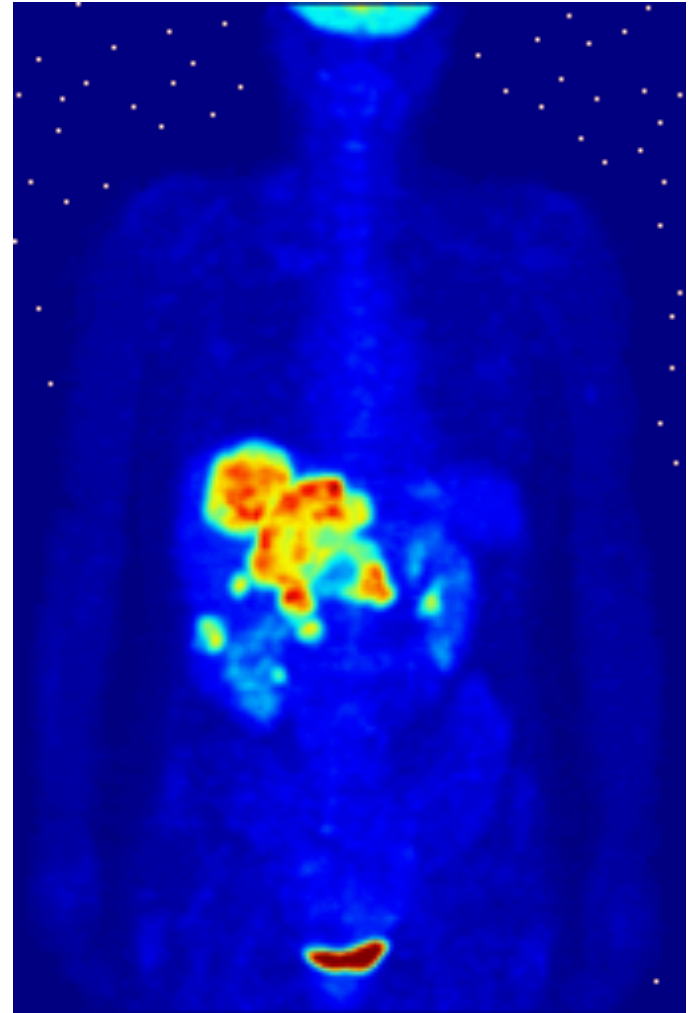
# Radionuclide Medical Applications

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“What is there to say about a man whose discoveries altered the course of history, immortalized his name on the periodic table of chemical elements and in the archives of the Nobel Prize Awards, and *extended the life of his own mother?*”

“Seaborg discovered more than 100 isotopes of existing elements including iron-59, cobalt-60 and iodine-131. The later, valuable for the diagnosis and treatment of thyroid and other diseases, was the most important to successfully prolong the life of his mother.”

“Glenn Seaborg: A Man in Full” - Lynn Yarris, *Science Beat*, March 5, 1999





# Transactinides and Superactinides

Seaborg theorized the transactinide series and the superactinide series of undiscovered synthetic elements. Seaborg also imagined an “island of stability” for isotopes of even heavier elements.



113	114	115	116	117	118
113	114	115	116	117	118





# PERIODIC TABLE OF THE ELEMENTS

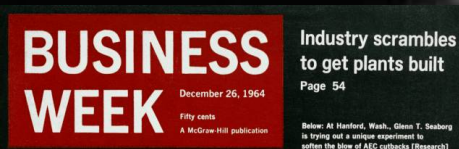
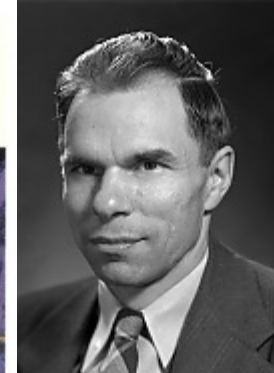
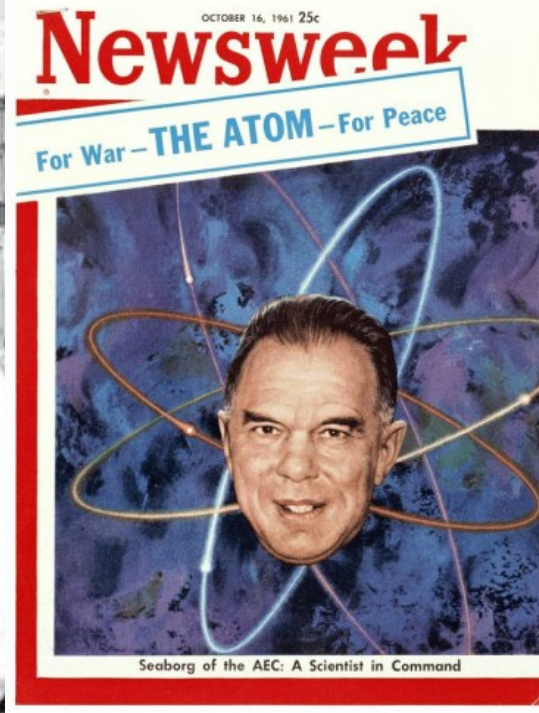
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7	37 Rb											38 Sr											39 Y											40 Zr											41 Nb											42 Mo											43 Tc											44 Ru											45 Rh											46 Pd											47 Ag											48 Cd											49 In											50 Sn											51 Sb											52 Te											53 I											54 Xe										
8	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										
9	87 Fr											88 Ra											89 +Ac											104 Rf											105 Db											106 Sg											107 Bh											108 Hs											109 Mt											110 Ds											111 Rg											112 Cn											113 113											114 114											115 115											116 116											117 117											118 118										

\**Lanthanides*

<sup>+</sup>*Actinides*

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







# Periodic Table of the Elements

