Role of the periodic table in discovery of new elements

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Summary. This year (2009) marks the 140th Anniversary of Mendeleev's original 1869 periodic table of the elements based on atomic weights. It also marks the 175th anniversary of his birth in Tolbosk, Siberia. The history of the development of periodic tables of the chemical elements is briefly reviewed beginning with the presentation by Dmitri Mendeleev and his associate Nikolai Menshutkin of their original 1869 table based on atomic weights. The value, as well as the sometimes negative effects, of periodic tables in guiding the discovery of new elements based on their predicted chemical properties is assessed. It is noteworthy that the element with $Z = 101$ (mendelevium) was identified in 1955 using chemical techniques. The discoverers proposed the name mendelevium to honor the predictive power of the Mendeleev Periodic Table. Mendelevium still remains the heaviest element to have been identified first by chemical rather than nuclear or physical techniques. The question concerning whether there will be a future role for the current form of the periodic table in predicting chemical properties and aid in the identification of elements beyond those currently known is considered.

1. Introduction

Ever since ancient times, humans have been investigating the composition of the earth around them and observing and even noting the behavior of the stars and other phenomena in the heavens beyond their reach. In the 4th century B.C. Aristotle proposed that all matter was composed of various proportions of the “elements” air, earth, fire, and water.

This year (2009) marks the 140th anniversary of the presentation to the Russian Chemical Society meeting in St. Petersburg by Dmitri Ivanovich Mendeleev and his associate Nikolai Menshutkin of their original Periodic Table of the Elements which was based on atomic weights. (It also marks the 175th anniversary of Mendeleev's birth in Tolbosk, Siberia as the youngest child in a family of 17!) As we consider how to synthesize new elements beyond those currently reported, it is appropriate to review the development of our modern periodic table of the chemical elements and whether or not it will help us in the future isolation and iden-

tification of new chemical elements beyond those currently known [1, 2].

2. Evolution of chemical periodic tables

Mendeleev and Menshutkin postulated that the 66 elements known in 1869 showed periodicity in their chemical properties when they were arranged in order of their masses as shown in Table 1.

Many chemists in other countries [3, 4] had earlier observed “orderliness” in the elements. A few examples are: (Germany) J. W. Dobereiner and his triads: 1829; (USA) O. W. Gibbs (1845) & J. P. Cooke Jr. (1854); (England) J. A. Newlands and the “Law of Octaves”; (France) A. de Chantcourtois and the “telluric screw” (1869).

The 1871 Periodic Table of Mendeleev shown in Fig. 1 includes subsequent changes to the original 1869 table.

Table 1. 1869 Periodic Table of Mendeleev and Menshutkin (included in text).

			Ti=50	Zr=90	?=180
			V=51	Nb=94	Ta=182
			Cr=52	Mo=96	W=186
			Mn=55	Rh=104,4	Pt=197,4
			Fe=56	Ru=104,4	Ir=198
			Ni=Co=59	Pd=106,6	Os=199
H=1			Cu=63,4	Ag=108	Hg=200
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	J=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204
		Ca=40	Sr=87,6	Ba=137	Pb=207
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

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1871 PERIODIC TABLE OF MENDELEEV, INCLUDING CHANGES TO ORIGINAL 1869 TABLE

[31]	Группа I	Группа II	Группа III	Группа IV	Группа V	Группа VI	Группа VII	Группа VIII. Переход к группе I
Типичские элементы	H = 1							
Первая серия	Li = 7	Be = 9,4	B = 11	C = 12	N = 14	O = 16	F = 19	
Ряд 1-й	Na = 23	Mg = 24	Al = 27,3	Si = 28	P = 31	S = 32	Cl = 35,5	
2-й	K = 39	Ca = 40	— ≈ 44	Ti = 50?	V = 51	Cr = 52	Mn = 55	Fe = 56, Co = 59, Ni = 59, Cu = 63
Вторая серия								
3-й	(Cu = 63)	Zn = 65	— ≈ 68	— ≈ 72	As = 75	Se = 78	Br = 80	
4-й	Rb = 85	Sr = 87	(? Yt = 88?)	Zr = 90	Nb = 94	Mo = 96	— = 100	Ru = 104, Rh = 104, Pd = 104, Ag = 108
Третья серия								
5-й	(Ag = 108)	Cd = 112	In = 113	Sn = 118	Sb = 122	Te = 128?	I = 127	
6-й	Cs = 133	Ba = 137	— ≈ 137	Ce = 138?	—	—	—	
Четвертая серия								
7-й	—	—	—	—	—	—	—	
8-й	—	—	—	—	Ta = 182	W = 184	—	Os = 199?, Ir = 198?
Пятая серия								Pt = 197?, Au = 197
9-й	(Au = 197)	Hg = 200	Tl = 204	Pb = 207	Bi = 208	—	—	
10-й	—	—	—	Th = 232	—	U = 240	—	
Высшая соли- ван окисъ	R ²⁰	R ²⁰ 2- или RO	R ²⁰ 3	R ²⁰ 4 или RO ²	R ²⁰ 5	R ²⁰ 6 или RO ³	R ²⁰ 7	R ²⁰ 8 или RO ⁴
Высшее водо- родное соеди- нение			(RH ² ?)	RH ⁴	RH ³	RH ²	RH	—

Fig. 1. 1871 Periodic Table of Mendeleev, including changes to original 1869 table.

Lothar Meyer in Germany proposed a similar scheme in 1870 so why did the Mendeleev Table gain such wide acceptance? This is probably because Mendeleev not only showed the periodicity of the known elements, but stated that his method of classification illustrated a fundamental law of nature. Furthermore, he claimed that apparent “deficiencies” in his table were actually due to gross inaccuracies in atomic weight measurements or to elements that had not yet been discovered! He even went so far as to predict new elements with atomic weights of 44, 68, and 72, their placement in his periodic table, and their general chemical properties. These were scandium-45, gallium-70, and germanium-73 as we now know them. These bold predictions were not completely accepted until scandium, gallium, and germanium were found in nature between 1875 and 1896. The many subsequent experimental proofs of his predictions of new elements gained general acceptance for his periodic system.

Quoting from Glenn Seaborg’s address [4] at the Mendeleev Centennial, November 1969, “Whenever one of my periodic tables has been published in a technical journal, a popular magazine, or even the New York Times, I receive a wealth of correspondence from those who are aficionados of periodic tables and who have invented their own versions. This must be one of the most popular hobbies of scientifically inclined people. I caution you that if you have a mind to make your own predictions of what the periodic table of the future will be like, you must be prepared to defend it against all comers, just as Mendeleev had to do one hundred years ago.”

By 1910, the number of known elements had risen to 85. Based on the discoveries of J. J. Thomson, E. Rutherford, Niels Bohr, H. G. J. Moseley and others, the atomic num-

Adapted from Moseley's original data (H. G. J. Moseley, Philos. Mag. (6) 27:703, 1914)

Fig. 2. Moseley figure.

PERIODIC TABLE OF 1923 SHOWING ELEMENTS BEYOND URANIUM AND WITH TRANSITION SERIES BEGINNING WITH ELEMENT 94

In 1920's, La and REs(4f) elements (Bohr's ideas) were properly placed between Ba & Hf; however, Th, Pa, U (heaviest elements known) were thought to be related to Hf, Ta, W. E-93 under Re. Bohr suggested the 5f shell would begin to fill at E-95 and end with E-108 and be similar to those of E-94 (eka-Os)!

Li 3	Be 4																	H 1	He 2
Na 11	Mg 12																	F 9	Ne 10
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36		
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	— 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	X 54		
Cs 55	Ba 56	*	— 72	Ta 73	W 74	— 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	— 85	Em 86		
— 87	Ra 88	Ac 89	Th 90	Pa 91	U 92	E-Re 93	X	109	110	111	112	113	114	115	116	117	118		
*Rare Earths:			La 57	Ce 58	Pr 59	Nd 60	— 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Cp 71	Note: Cp for E-71	
Possible Transition Group			E-Os 94	95	96	97	98	99	100	101	102	103	104	105	106	107	108		

Fig. 3. 1923 Periodic Table of Niels Bohr.

ber (proton number or electrical charge on the nucleus) soon replaced the atomic weight as the basis for ordering.

H. G. J. Moseley's ingenious experimental measurements of the characteristic X-rays emitted from an element when it is irradiated by cathode rays showed that their frequencies were related to whole numbers (see Fig. 2). Moseley then brilliantly concluded that these ordinal numbers were equal to the charge on the central nucleus. When the elements were arranged according to these numbers the order differed slightly from Mendeleev's arrangement by atomic weight, and accounted for some of the discrepancies in Mendeleev's periodic table. His original article [5] is a comprehensive masterpiece.

The 1923 periodic table shown in Fig. 3 incorporates Niels Bohr's ideas that the lanthanides and rare earth (4f) elements should be placed between Ba and Hf. Th, Pa, and U, the heaviest elements known then were believed to be related to Hf, Ta, and W and were placed under them, and the undiscovered element 93 was then placed under Re. N. Bohr suggested that the 5f shell would begin to fill at element 95 and end with 108 and have properties similar to those of element 94 (eka-osmium). In fact, the usual form of the periodic table just before World War II still placed Ac, Th, Pa, U, and elements 93-100 in the last row of the periodic table under Re, Os, Ir, through Pb.

In spite of this, E. M. McMillan and P. H. Abelson reported the first discovery of a transuranium element in 1940, identified in experiments performed when they were originally attempting to investigate the newly discovered phenomenon of nuclear fission. They found a new short-lived beta-activity and postdoc Phil Abelson devised a chemical procedure for its separation. The new element 93 was then identified and shown to have properties similar to uranium (not to Re) and was named neptunium, after the planet Neptune, next planet beyond Uranus. The article was published [6] in the 1940 issue of Physical Review, prior to the US entry into WW-II.

Table 2. List of IUPAC approved names for trans-fermium elements

IUPAC APPROVED HEAVY ELEMENT NAMES August 30, 1997, Geneva, Switzerland		
Element	Name	Symbol
101	Mendelevium	Md
102	Nobelium	No
103	Lawrencium	Lr
Transactinides (TANs)		
104	Rutherfordium	Rf
105	Dubnium (Hahnium)*	Db (Ha)*
106	Seaborgium	Sg
107	Bohrium	Bh
108	Hassium	Hs
109	Meitnerium	Mt
110 *	Darmstadtium	Ds
111**	Roentgenium	Rg
112***	Copernicium	Cn

*Many publications of chemical studies before 1997 use hahnium (Ha) for 105.
 *Approved by IUPAC, August 2003; **Approved by IUPAC, November 2004.
 ***Approval Spring 2010??

Plutonium (element 94) was identified [6] in 1940–41 by McMillan, J. W. Kennedy, A. C. Wahl, and G. T. Seaborg, but was the discovery was voluntarily withheld from publication until after the end of WW-II. It was named plutonium after Pluto, the next planet beyond Neptune, following the above convention. (Although recently it has been deemed that Pluto may not actually be a planet, it is unlikely that plutonium will be renamed!)

The properties of U, Np, and Pu were found to be quite similar and not like W, Re, and Os. The Seaborg group's original search for elements 95 and 96 based on chemical properties similar to those of U, Np, and Pu failed. Seaborg then conceived the idea that the elements beyond Ac were part of an actinide series that should be placed in the periodic table under the known lanthanide series. His original Periodic Table published in Chem. & Eng. News in 1945

PERIODIC TABLE SHOWING HEAVY ELEMENTS AS MEMBERS OF AN ACTINIDE SERIES																		I H 1.008	2 He 4.003															
3 Li 6.940	4 Be 9.02	Arrangement by Glenn T. Seaborg, 1945 Chem & Eng. News 1945, <u>23</u> , 2190-93.																5 B 10.82	6 C 12.01	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 Ar 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 Nb 92.91	42 Mo 95.95	43 Ru 101.7	44 Rh 102.91	45 Pd 106.7	46 Ag 107.868	47 Cd 112.41	48 In 114.76	49 Sn 118.70	50 Sb 121.76	51 Te 127.61	52 I 126.92	53 Xe 131.3	54 Cs 132.91	55 Ba 137.36	56 La 138.92	57 Ce 140.13	58 Pr 140.92	59 Nd 144.27	60 Pm 144.91	61 Sm 150.43	62 Eu 152.0	63 Gd 156.9	64 Tb 158.9	65 Dy 162.5	66 Ho 164.9	67 Er 167.3	68 Tm 168.9	69 Yb 173.04	70 Lu 174.99	
87 Fr 223	88 Ra 226	89 Ac 227	90 Th 232.04	91 Pa 231	92 U 238.03	93 Np 237	94 Pu 244	95 Am 243	96 Cm 247	97 Bk 247	98 Cf 251	99 Es 252	100 Fm 257	101 Md 258	102 Nv 261	103 Lv 263	104 Ts 267	105 Og 269	106 Lr 262	107 Hf 178.10	108 Ta 180.95	109 W 183.85	110 Re 186.21	111 Os 190.23	112 Ir 192.22	113 Pt 195.08	114 Au 196.97	115 Hg 200.59	116 Tl 204.38	117 Pb 207.2	118 Bi 208.98	119 Po 209	120 At 210	121 Rn 222

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							

Fig. 4. Original 1945 Seaborg Table showing actinide series.

is shown in Fig. 4. The group then quickly identified elements 96 (Cm) and 95 (Am) as trivalent species in 1944-1945. Thus, we have seen how different versions of the Periodic Table have both hindered and helped in the chemical separation and identification of new chemical elements.

3. Discovery of element 101 (Mendelevium)

The chemical separation and identification of the new element 101 in 1955 was a landmark experiment in many respects. It was the first transuranium element separated and identified using atom-at-a-time chemistry – 17 atoms in 8 experiments. It was also the last of the transuranium elements to be discovered and identified using direct radiochemical separation of the element itself. Higher Z transuranium elements since then have all been first identified using “physical separation techniques” and/or observation of “nuclear” decay properties. In addition, the highly radioactive ^{253}Es (~ 20 d half-life) target contained only a few picograms, one of the smallest targets ever used in such experiments.

The paper was published [8] in 1955 in Letters to the Editor of Physical Review by A. Ghiorso, B. G. Harvey, G. R. Choppin, S. G. Thompson, and G. T. Seaborg and was only 2 pages in length! On the second page, the authors wrote, “We would like to suggest the name Mendelev, symbol Mv , for the new element in recognition of the pioneering role of the great Russian chemist, Dmitri Mendelev, who was the first to use the periodic system of the elements to predict the chemical properties of undiscovered elements, a principle which has been a key to the discovery of the last seven transuranium (actinide) elements.” This name was finally officially approved by IUPAC in 1997 when the symbol was changed to Md .

Table 2 lists the IUPAC approved names for elements with $Z > 100$. Note that 112 is the heaviest element whose discovery has been approved by IUPAC and the proposed

name copernicium after the Polish astronomer Nicolaus Copernicus and symbol Cn are now awaiting final approval.

4. Future role of the periodic table

In 1968–69, Seaborg proposed a conventional form of the periodic table with a “superactinide” series placed at the bottom under the lanthanide and actinide series. This was done for simplicity’s sake to conform as closely as possible to then existing forms of the periodic tables. This 32-member series begins with element 122 and ends with element 153 after filling the $5g$ (18) and $6f$ (14) electronic shells, albeit in mixed configurations! Furthermore, intrusions from $7d$ and $8p$ electrons may cause significant deviations from expected trivalent properties of this series.

Half-lives and production rates are getting ever smaller although some longer species may be synthesized if we can approach nearer to predicted spherical even stable deformed regions. Much experimental information needs to be acquired and systematized before we abandon our periodic table representations although severe adjustments may be required.

Then what is the future role for a “conventional” periodic table and chemical experimentalists? If suitable isotopes for chemical studies can be produced beyond element 118, then we can determine if they are g -block elements or totally scrambled! It will be essential to compare theoretical predictions of both chemical and nuclear properties with experimental data to guide future experiments. Unique capabilities are now being built for conducting frontier explorations at the limits of both the chemical periodic table and the chart of the nuclides. Such complex and difficult experiments will certainly require international collaborations involving both facilities and personnel on all levels to successfully explore the regions that lie ahead.

In summary, Seaborg’s simple conventional periodic table has been a guide for ~ 40 years and is still widely used

in various forms. Other more complicated and “clever” representations have been formulated over the years but are now seldom seen.

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