The Discoverers of the Ruthenium Isotopes

Updated information on the discoveries of the six platinum group metals to 2010

http://dx.doi.org/10.1595/147106711X592448 http://www.platinummetalsreview.com/

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This review looks at the discovery and the discoverers of the thirty-eight known ruthenium isotopes with mass numbers from 87 to 124 found between 1931 and 2010. This is the sixth and final review on the circumstances surrounding the discoveries of the isotopes of the six platinum group elements. The first review on platinum isotopes was published in this Journal in October 2000 (1), the second on iridium isotopes in October 2003 (2), the third on osmium isotopes in October 2004 (3), the fourth on palladium isotopes in April 2006 (4) and the fifth on rhodium isotopes in April 2011 (5). An update on the new isotopes of palladium, osmium, iridium and platinum discovered since the previous reviews in this series is also included.

Naturally Occurring Ruthenium

Of the thirty-eight known isotopes of ruthenium, seven occur naturally with the authorised isotopic abundances (6) shown in **Table I**.

The isotopes were first detected in 1931 by Aston (7, 8) using a mass spectrograph at the Cavendish Laboratory, Cambridge University, UK. Because of difficult experimental conditions due to the use of poor quality samples, Aston actually only detected six of the isotopes and obtained very approximate

Table I

The Naturally Occurring Isotopes of Ruthenium

Mass number	Isotopic Abundance, %
^{96}Ru	5.54
^{98}Ru	1.87
^{99}Ru	12.76
^{100}Ru	12.60
^{101}Ru	17.06
^{102}Ru	31.55
^{104}Ru	18.62

percentage abundances. However, he did speculate on the existence of a seventh isotope with mass number 98. In 1943 Ewald (9) of the Aus dem Kaiser Wilhelm-Institut für Chemie, Berlin-Dahlem, Germany, carried out a more refined spectrographic analysis and obtained precision values for the isotopic abundances, including confirming the isotope of mass number 98.

Artificial Ruthenium Isotopes

Early investigations of activities associated with ruthenium tended to lead to half-life values which initially did not appear to be connected to each other. For example, in 1935 Kurchatov, Nemenov and Selinov (10) used slow neutron bombardment to obtain half-lives of 40 seconds, 100 seconds, 11 hours and 75 hours, and in 1936 Livingood (11) used deuteron bombardment to obtain different half-lives of 4 hours, 39 hours, 11 days and 46 days. In 1937, Pool, Cork and Thornton (12) used fast neutron bombardment and obtained activities with half-lives of 24 minutes and 3.6 hours and in 1940 Nishina *et al.* (13) also used fast neutron bombardment to obtain ruthenium activities of 4 hours and 60 hours and a rhodium activity of 34 hours. However, Nishina *et al.* (14) later speculated that the 60 hour activity was in reality a mixture of the 4 hour ruthenium and 34 hour rhodium activities plus a further long lived ruthenium activity which had not been identified. They also pointed out that in 1940 Segrè and Seaborg (15) had found a 4 hour half-life ruthenium activity in fission products. In 1938, De Vries and Veldkamp (16) used the different technique of slow neutron bombardment and had identified three activities: a 4 hour activity which they suggested was ^{103}Ru, a 20 hour activity which they suggested was ^{105}Ru and a 45 day half-life activity which they suggested was ^{105}Rh. All of these suggestions were incorrect but it would appear that all of the activities observed with an approximate 4 hour half-life were probably ^{105}Ru and the 46 day activity identified by Livingood and the equal 45 day activity identified by De Vries and Veldkamp were probably ^{103}Ru. None of these observations could be seriously considered as being contenders to the discovery of any isotopes since the discovery criterion of an accurate determination of the atomic mass number had not been met.

Discovery Date

As discussed in previous articles in the present series (1–5), the actual year of discovery is generally considered to be that when the details of the discovery were placed in the public domain such as manuscript dates or conference report dates. However, once again complications arise with the case of internal reports which may not be placed in the public domain until several years later. As with rhodium (5), several ruthenium isotopes were first identified during the highly secretive Plutonium Project of the Second World War which was not actually published until 1951 (17), although much of the information had become available in 1946 in the tables of Siegel (18, 19) or in the 1948 edition of the "Table of Isotopes" (20).

Discovery Acceptance

The discovery criteria used in this series of papers relate to the identification of the ground state and those isomers in which the half-life exceeds one millisecond, except in the very special circumstances where the ground state half-life is itself very short and the half-lives of corresponding isomers are of a similar order. This procedure was adopted to keep the tables succinct by avoiding the inclusion of the exceedingly large number of isomers with half-lives of less than one millisecond which are known for the isotopes of the platinum group elements and which would have greatly complicated the text.

Half-Lives

Selected half-lives used in **Table II** were generally those accepted in the revised NUBASE database (21) although literature values were used when either these were not available or had been superseded by later determinations.

An Update on the Discovery and Discoverers of the Platinum Group of Elements

Since the publication of the first four reviews in this series (1–4) a number of new isotopes have been discovered for palladium, osmium, iridium and platinum and the discovery circumstances for these isotopes are listed in **Table III**. The total number of isotopes for each element and their mass number ranges are now as shown in **Table IV**.

In addition the half-life of ^{199}Ir was unknown until determined to be 6 seconds by Kurtukian-Nieto (77).

The Number of Nuclides

If a nuclide is defined as being a unique combination of protons and neutrons, then the platinum group elements currently include 235 known nuclides out of a total for all elements of about 3200. Of these, 286 are primordial, that is they were present when the Earth was formed and are still present now. The

Table II

The Discoverers of the Ruthenium Isotopes

Mass number[a]	Half-life	Decay modes	Year of discovery	Discoverers	References	Notes
87	ps[b]	EC + β^+ ?	1994	Rykaczewski *et al*.	22, 23	
88	1.3 s	EC + β^+	1994	Hencheck *et al*.	24	A
89	1.38 s	EC + β^+	1992	Mohar *et al*.	25, 26	B
90	12 s	EC + β^+	1991	Zhou *et al*.	27, 28	C
91	7.9 s	EC + β^+	1983	Komninos, Nolte and Blasi	29	
91m	7.6 s	EC + β^+, IT ?	1982	Hagberg *et al*.	30	
92	3.65 min	EC + β^+	1971	(a) Arl't *et al*. (b) De Jesus and Neirinckx	(a) 31, 32 (b) 33	
93	59.7 s	EC + β^+	1955	Aten Jr. and De Vries-Hamerling	34	D
93m	10.8 s	EC + β^+, IT	1976	De Lange *et al*.	35	E
94	51.8 min	EC + β^+	1952	Van Der Wiel and Aten Jr.	36	
95	1.643 h	EC + β^+	1948	Eggen and Pool	37	F
96	Stable	–	1931	Aston	7, 8	
97	2.9 d	EC + β^+	1944	Sullivan, Sleight and Gladrow	38, 39	G
98	Stable	–	1943	Ewald	9	
99	Stable	–	1931	Aston	7, 8	
100	Stable	–	1931	Aston	7, 8	
101	Stable	–	1931	Aston	7, 8	
102	Stable	–	1931	Aston	7, 8	
103	39.25 d	β^-	1944	(a) Sullivan, Sleight and Gladrow (b) Bohr and Hole	(a) 38, 40 (b) 41	H
103m	1.69 ms	IT	1964	Brandi *et al*.	42	
104	Stable	–	1931	Aston	7, 8	
105	4.44 h	β^-	1944	(a) Sullivan, Sleight and Gladrow (b) Bohr and Hole	(a) 38, 43 (b) 41	H
106	371.8 d	β^-	1946	(a) Glendenin (b) Grummitt and Wilkinson	(a) 44, 45 (b) 46	I
107	3.75 min	β^-	1962	Pierson, Griffin and Coryell	47	J

(*Continued*)

Table II (Continued)

Mass number[a]	Half-life	Decay modes	Year of discovery	Discoverers	References	Notes
108	4.55 min	β^-	1955	Baró, Rey and Seelmann-Eggebert	48	
109	34.5 s	β^-	1966	Griffiths and Fritze	49, 50	K
110	11.6 s	β^-	1969	Wilhelmy *et al*.	51, 52	
111	2.12 s	β^-	1975	Fettweis and del Marmol	53	L
112	1.7 s	β^-	1969	Wilhelmy *et al*.	51, 52	
113	800 ms	β^-	1988	Penttilä *et al*.	54	M
113m	510 ms	IT ?, β^- ?	1998	Kurpeta *et al.*	55	
114	540 ms	β^-	1991	Leino *et al.*	56	
115	318 ms	β^-	1992	Äystö *et al.*	57, 58	
115m	76 ms	IT	2010	Kurpeta *et al.*	59	
116	204 ms	β^-	1994	Bernas *et al.*	60	N
117	142 ms	β^-	1994	Bernas *et al.*	60	N
118	123 ms	β^-	1994	Bernas *et al.*	60	N
119	ps[b]	β^- ?	1995	Czajkowski *et al.*	61, 62	
120	ps[b]	β^- ?	2010	Ohnishi *et al.*	63	P
121	ps[b]	β^- ?	2010	Ohnishi *et al.*	63	
122	ps[b]	β^- ?	2010	Ohnishi *et al.*	63	
123	ps[b]	β^- ?	2010	Ohnishi *et al.*	63	
124	ps[b]	β^- ?	2010	Ohnishi *et al.*	63	

[a]*m = isomeric state*

[b]*ps = particle stable (resistant to proton and neutron decay)*

Notes to Table II

A	^{88}Ru	Hencheck *et al.* (24) only proved that the isotope was particle stable. The half-life was first determined by Wefers *et al.* in 1999 (64).
B	^{89}Ru	Mohar *et al.* (25, 26) only proved that the isotope was particle stable. The half-life was first determined by Li Zhankui *et al.* in 1999 (65).
C	^{90}Ru	Mohar *et al.* (25, 26) also claimed the discovery of this isotope in 1992 and appeared to be unaware of the prior discovery by Zhou *et al.* (27, 28). However they only determined that the isotope was particle stable whereas Zhou *et al.* had already determined the half-life.

(*Continued*)

Notes to Table II (Continued)

D	^{93}Ru	The discovery by Aten Jr. and De Vries-Hamerling (34) is considered to be tentative but was confirmed by Doron and Lanford (66) in 1971.
E	^{93m}Ru	Doron and Lanford (66) also claimed to have discovered this isomer in 1971 but de Lange *et al.* (35) could not confirm their half-life of 45 s.
F	^{95}Ru	Mock *et al.* (67) appeared to independently claim the discovery even though their manuscript date was October 1948; the discovery claim by Eggen and Pool (37) had already been published in July 1948.
G	^{97}Ru	The 1944 discovery by Sullivan, Sleight and Gladrow (38) was not made public for this isotope until included in the 1946 public report (39).
H	^{103}Ru and ^{105}Ru	The 1944 discovery for these isotopes by Sullivan, Sleight and Gladrow (38) was not made public until included in the 1946 table of Siegel (18, 19).
I	^{106}Ru	Although produced in 1946, the results of Glendenin (44) were only made public at this time by including in the 1946 table of Siegel (18, 19).
J	^{107}Ru	A preliminary identification of this isotope by Glendenin (68, 69) in 1944 was made public in the 1946 table of Siegel (18, 19).
K	^{109}Ru	Franz and Herrmann (70) proposed the existence of a 12.9 s half-life isomer but this could not be found by Kaffrell *et al.* (71).
L	^{111}Ru	Franz and Herrmann (70) also tentatively identified this isotope in 1975.
M	^{113}Ru	Franz and Herrmann (70) tentatively claimed to have discovered this isotope in 1975 but Penttilä *et al.* (54) consider that the isotope observed was probably ^{113}Rh.
N	^{116}Ru to ^{118}Ru	Bernas *et al.* (60) only determined that these isotopes were particle stable. The half-lives were first measured by Montes *et al.* (72) in 2005.
P	^{120}Ru	A 1995 claim by Czajkowski *et al.* (61) to have discovered this isotope was highly preliminary and was not included in the later 1997 report by Bernas *et al.* (62). Ohnishi *et al.* (63) detected this isotope in 2010 but did not claim the discovery possibly under the impression that the isotope had already been found but they can be considered to be the actual discoverers.

Table III

New Discoveries

Element	Mass number[a]	Half-life	Decay mode	Year of discovery	Discoverers	References	Notes
Pd	125	ps[b]	β^- ?	2008	Ohnishi *et al.*	73	
	126	ps[b]	β^- ?	2008	Ohnishi *et al.*	73	
	127	ps[b]	β^- ?	2010	Ohnishi *et al.*	63	
	128	ps[b]	β^- ?	2010	Ohnishi *et al.*	63	

(*Continued*)

Table III (Continued)

Element	Mass number[a]	Half-life	Decay mode	Year of discovery	Discoverers	References	Notes
Os	161	570 μs	α	2008	Page *et al*.	74	
	195m	26 ns	IT	2002	Podolyák *et al*.	75	A1
	197	2.8 min	β^-	2003	Xu *et al*.	76	
	198	ps[b]	β^- ?	2006	Kurtukian-Nieto *et al*.	77, 78	B1
	199	5 s	β^-	2005	Kurtukian-Nieto *et al*.	79	
	200	6 s	β^-	2005	Kurtukian-Nieto *et al*.	79	
	201	ps[b]	β^- ?	2007	Kurtukian-Nieto	78	
Ir	200	ps[b]	β^- ?	2006	Kurtukian-Nieto *et al*.	77, 78	B1
	201	ps[b]	β^- ?	2006	Kurtukian-Nieto *et al*.	77, 78	B1
	202	11 s	β^-	2006	Kurtukian-Nieto *et al*.	77, 78	B1
	203	ps[b]	β^- ?	2006	Kurtukian-Nieto *et al*.	77, 78	B1
Pt	203	10.1 s	β^-	2005	Kurtukian-Nieto *et al*.	79	
	204	10.3 s	β^-	2006	Kurtukian-Nieto *et al*.	77, 78	B1, C1
	205	ps[b]	β^- ?	2010	Alvarez-Pol *et al*.	80	D1

[a]*m = isomeric state*

[b]*ps = particle stable (resistant to proton and neutron decay)*

Notes to Table III

A1	Although the ground state of ^{195}Os has not been discovered information on the very high level isomer is included to indicate that the isotope has been observed.
B1	Kurtukian-Nieto *et al.* (77) only showed results in the form of a chart with actual mass numbers being given by Kurtukian-Nieto (78) in 2007.
C1	Kurtukian-Nieto *et al.* (77) only determined the isotope to be particle stable. The half-life was first determined by Morales *et al.* (81) in 2008.
D1	Evidence for this isotope was also given by Benlliure *et al.* (82).

Table IV
Total Number of Isotopes and Mass Ranges Known for Each Platinum Group Element to 2010

Element	Number of known isotopes	Known mass number ranges
Ru	38	87–124
Rh	38	89–126
Pd	38	91–128
Os	41	161–201
Ir	40	164–203
Pt	40	166–205

Some of the Terms Used for This Review

Atomic number	The number of protons in the nucleus.
Mass number	The combined number of protons and neutrons in the nucleus.
Nuclide and isotope	A nuclide is an entity containing a unique number of protons and neutrons in the nucleus. For nuclides of the same element the number of protons remains the same but the number of neutrons may vary. Such nuclides are known collectively as the isotopes of the element. Although the term isotope implies plurality it is sometimes used loosely in place of nuclide.
Isomer/isomeric state	An isomer or isomeric state is a high energy state of a nuclide which may decay by isomeric transition (IT) as described in the table below, although certain low-lying states may decay independently to other nuclides rather than the ground state.
Half-life	The time taken for the activity of a radioactive nuclide to fall to half of its previous value.
Electron volt (eV)	The energy acquired by any charged particle carrying a unit (electronic) charge when it falls through a potential of one volt, equivalent to 1.602×10^{-19} J. The more useful unit is the mega (million) electron volt (MeV).

Decay Modes

α Alpha decay is the emission of alpha particles which are ^{4}He nuclei. Thus the atomic number of the daughter nuclide is two lower and the mass number is four lower.

β^- Beta or electron decay for neutron-rich nuclides is the emission of an electron (and an anti-neutrino) as a neutron in the nucleus decays to a proton. The mass number of the daughter nuclide remains the same but the atomic number increases by one.

β^+ Beta or positron decay for neutron-deficient nuclides is the emission of a positron (and a neutrino) as a proton in the nucleus decays to a neutron. The mass number of the daughter nuclide remains the same but the atomic number decreases by one. However this decay mode cannot occur unless the decay energy exceeds 1.022 MeV (twice the electron mass in energy units). Positron decay is always associated with orbital electron capture (EC).

EC Orbital electron capture in which the nucleus captures an extranuclear (orbital) electron which reacts with a proton to form a neutron and a neutrino, so that, as with positron decay, the mass number of the daughter nuclide remains the same but the atomic number decreases by one.

IT Isomeric transition in which a high energy state of a nuclide (isomeric state or isomer) usually decays by cascade emissions of γ (gamma) rays (the highest energy form of electromagnetic radiation) to lower energy levels until the ground state is reached.

p Proton decay in which a proton is emitted from the nucleus so both the atomic number and mass number decrease by one. Such a nuclide is said to be 'particle unstable'.

n Neutron decay in which a neutron is emitted from the nucleus so the atomic number remains the same but the atomic mass is decreased by one. Such a nuclide is said to be 'particle unstable'.

Fig. 1. Professor Michael Thoennessen

Professor Michael Thoennessen

Michael Thoennessen (**Figure 1**) is a Professor in the Department of Physics & Astronomy at Michigan State University (MSU), USA, and Associate Director at the National Superconducting Cyclotron Laboratory (NSCL) located on the campus of MSU. His main research interest is the study of exotic nuclei far from stability, concentrating on neutron-unbound nuclei beyond the neutron dripline. He performs most of his experiments at NSCL with the Modular Neutron Array (MoNA) – a large-area high efficiency neutron detector (**Figure 2**). He recently initiated a project to document the discovery of all isotopes. These reviews are currently being published in the journal *Atomic Data and Nuclear Data Tables*. The detailed description for each isotope has been carried out for about 70% and will be finished next year. Whilst some of the discovery criteria differ from these adopted here, there is generally good agreement as to assigning credit to the discoverers.

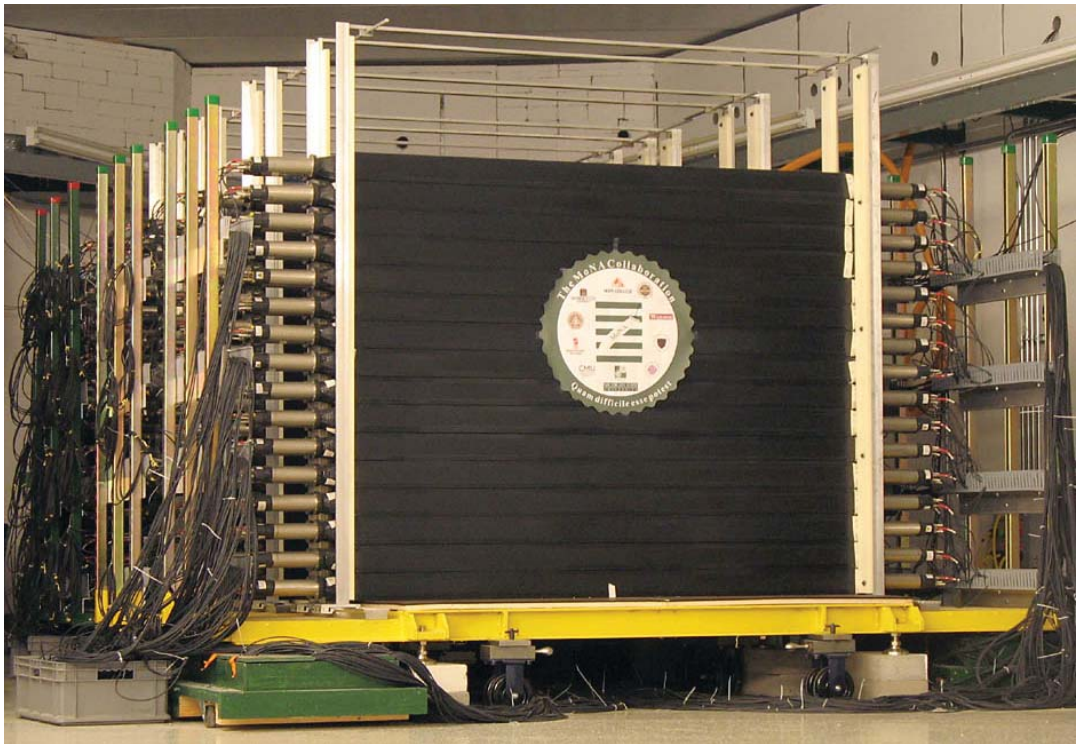

Fig. 2. The Modular Neutron Array (MoNA) at the National Superconducting Cyclotron Laboratory (NSCL) located on the campus of Michigan State University (MSU), USA (Courtesy of T. Baumann)

remaining ~2900 are described for these purposes as being 'artificial' radioactive nuclides, since a number of the primordial nuclides are also radioactive but with very long half-lives. There exist in nature a significant number of nuclides other than those of primordial origin due to various radioactive decay modes of naturally occurring thorium and uranium isotopes. The limits on the stability of the nuclides are defined by the proton and neutron drip lines beyond which the nuclides lose particle stability, become unbound and emit protons in the case of the proton drip line and neutrons in the case of the neutron drip line. Nuclides do exist beyond the drip lines but in the case of the light elements the half-lives immediately plunge to very short values. Thoennessen (83) has discussed the difficulties in producing nuclides close to the edges of the drip lines, and whilst for the lighter elements both the proton and neutron drip lines have been reached, only the proton drip line has been approached throughout the Periodic Table. For the medium to heavy elements, a large number of nuclides remain to be discovered before the neutron drip line is reached. Thoennessen and Sherrill (84) predict that up to the presently known limits of the Periodic Table the number of nuclides remaining to be discovered is likely to be at least equal to the number already known. There is optimism that at least 1000 of these will be discovered in the next ten years.

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