The Discoverers of the Rhodium Isotopes

The thirty-eight known rhodium isotopes found between 1934 and 2010

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This is the fifth in a series of reviews 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) and the fourth on palladium isotopes in April 2006 (4).

Naturally Occurring Rhodium

In 1934, at the University of Cambridge's Cavendish Laboratory, Aston (5) showed by using a mass spectrograph that rhodium appeared to consist of a single nuclide of mass 103 (^{103}Rh). Two years later Sampson and Bleakney (6) at Princeton University, New Jersey, using a similar instrument, suggested the presence of a further isotope of mass 101 (^{101}Rh) with an abundance of 0.08%. Since this isotope had not been discovered at that time, its existence in nature could not be discounted. Then in 1943 Cohen (7) at the University of Minnesota used an improved mass spectrograph to show that the abundance of ^{101}Rh must be less than 0.001%. Finally in 1963 Leipziger (8) at the Sperry Rand Research Center, Sudbury, Massachusetts, used an extremely sensitive double-focusing mass spectrograph to reduce any possible abundance to less than 0.0001%. However by that time ^{101}Rh had been discovered (see Table I) and although shown to be radioactive, no evidence was obtained for a long-lived isomer. This demonstrated conclusively that rhodium does in fact exist in nature as a single nuclide: ^{103}Rh.

Artificial Rhodium Isotopes

In 1934, using slow neutron bombardment, Fermi *et al.* (9) identified two rhodium activities with half-lives of 50 seconds and 5 minutes. A year later the same group (10) refined these half-lives to 44 seconds and 3.9 minutes. These discoveries were said to be 'non-specific' since the mass numbers were not

determined, although later measurements identified these activities to be the ground state and isomeric state of ^{104}Rh, respectively. In 1940 Nishina *et al*. (11, 12), using fast neutron bombardment, identified a 34 hour non-specific activity which was later identified as ^{105}Rh. In 1949 Eggen and Pool (13) confirmed the already known nuclide ^{101}Pd and identified the existence of a 4.7 day half-life rhodium daughter product. They did not comment on its mass although the half-life is consistent with the isomeric state of ^{101}Rh. Eggen and Pool also identified a 5 hour half-life activity which was never subsequently confirmed. Activities with half-lives of 4 minutes and 1.1 hours, obtained by fast neutron bombardment, were identified by Pool, Cork and Thornton (14) in 1937 but these also were never confirmed.

Although some of these measured activities represent the first observations of specific nuclides, the exact nuclide mass numbers were not determined and therefore they are not considered to represent actual discoveries. They are however included in the notes to Table I. The first unambiguous identification of a radioactive rhodium isotope was by Crittenden in 1939 (15) who correctly identified both ^{104}Rh and its principal isomer. Nuclides where only the atomic number and atomic mass number were identified are considered as satisfying the discovery criteria.

Discovery Dates

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, complications arise with internal reports which may not be placed in the public domain until several years after the discovery, and in these cases it is considered that the historical date takes precedence over the public domain date. Certain rhodium isotopes were discovered during the highly secretive Plutonium Project of the Second World War, the results of which were not actually published until 1951 (16) although much of the information was made available in 1946 by Siegel (17, 18) and in the 1948 "Table of Isotopes" (19).

Half-Lives

Selected half-lives used in Table I are generally those accepted in the revised NUBASE evaluation of nuclear and decay properties in 2003 (20) although literature values are used when the NUBASE data are not available or where they have been superseded by later determinations.

Table I

The Discoverers of the Rhodium Isotopes

Mass number[a]	Half-life	Decay modes	Year of discovery	Discoverers	References	Notes
89	ps[b]	EC + β^+ ?	1994	Rykaczewski *et al*.	21, 22	
90	15 ms	EC + β^+	1994	Hencheck *et al*.	23	A
90m	1.1 s	EC + β^+	2000	Stolz *et al*.	24	A
91	1.5 s	EC + β^+	1994	Hencheck *et al*.	23	B
91m	1.5 s	IT	2004	Dean *et al*.	25	B
92	4.7 s	EC + β^+	1994	Hencheck *et al*.	23	C
92m	0.5 s	IT?	2004	Dean *et al*.	25	C
93	11.9 s	EC + β^+	1994	Hencheck *et al*.	23	D
94	70.6 s	EC + β^+	1973	Weiffenbach, Gujrathi and Lee	26	
94m	25.8 s	EC + β^+	1973	Weiffenbach, Gujrathi and Lee	26	
95	5.02 min	EC + β^+	1966	Aten and Kapteyn	27	
95m	1.96 min	IT, EC + β^+	1974	Weiffenbach, Gujrathi and Lee	28	

Continued

Table I

The Discoverers of the Rhodium Isotopes *(Continued)*

Mass number[a]	Half-life	Decay modes	Year of discovery	Discoverers	References	Notes
96	9.90 min	EC + β^+	1966	Aten and Kapteyn	27	
96m	1.51 min	IT, EC + β^+	1966	Aten and Kapteyn	27	
97	30.7 min	EC + β^+	1955	Aten and de Vries-Hamerling	29	
97m	46.2 min	EC + β^+, IT	1971	Lopez, Prestwich and Arad	30	
98	8.7 min	EC + β^+	1955	Aten and de Vries-Hamerling	29	E
98m	3.6 min	EC + β^+	1966	Aten and Kapteyn	31	
99	16.1 d	EC + β^+	1956	Hisatake, Jones and Kurbatov	32	F
99m	4.7 h	EC + β^+	1952	Scoville, Fultz and Pool	33	
100	20.8 h	EC + β^+	1944	Sullivan, Sleight and Gladrow	34, 35	G
100m	4.6 min	IT, EC + β^+	1973	Sieniawski	36	
101	3.3 y	EC	1956	Hisatake, Jones and Kurbatov	32	F
101m	4.34 d	EC, IT	1944	Sullivan, Sleight and Gladrow	34, 37	G
102	207.0 d	EC + β^+, β^-	1941	Minakawa	38	
102m	3.742 y	EC + β^+, IT	1962	Born *et al*.	39	
103	Stable	–	1934	Aston	5	
103m	56.114 min	IT	1943	(a) Glendenin and Steinberg	(a) 40, 41	H
				(b) Flammersfeld	(b) 42	
104	42.3 s	β^-	1939	Crittenden	15	I
104m	4.34 min	IT, β^-	1939	Crittenden	15	I
105	35.36 h	β^-	1944	(a) Sullivan, Sleight and Gladrow	(a) 34, 43	J
				(b) Bohr and Hole	(b) 44	
105m	42.9 s	IT	1950	Duffield and Langer	45	
106	30.1 s	β^-	1943	(a) Glendenin and Steinberg	(a) 40, 41	K
				(b) Grummitt and Wilkinson	(b) 46	
				(c) Seelmann-Eggebert	(c) 47	
106m	2.18 h	β^-	1955	Baró, Seelmann-Eggebert and Zabala	48	L
107	21.7 min	β^-	1954	(a) Nervik and Seaborg	(a) 49	M
				(b) Baró, Rey and Seelmann-Eggebert	(b) 50	
108	16.8 s	β^-	1955	Baró, Rey and Seelmann-Eggebert	50	N
108m	6.0 min	β^-	1969	Pinston, Schussler and Moussa	51	

Continued

Table I

The Discoverers of the Rhodium Isotopes *(Continued)*

Mass number[a]	Half-life	Decay modes	Year of discovery	Discoverers	References	Notes
109	1.33 min	β^-	1969	Wilhelmy *et al*.	52, 53	
110	28.5 s	β^-	1969	(a) Pinston and Schussler	(a) 54	
				(b) Ward *et al.*	(b) 55	
110m	3.2 s	β^-	1963	Karras and Kantele	56	
111	11 s	β^-	1975	Franz and Herrmann	57	
112	3.4 s	β^-	1969	Wilhelmy *et al*.	52, 53	
112m	6.73 s	β^-	1987	Äystö *et al*.	58	
113	2.80 s	β^-	1988	Penttilä *et al*.	59	
114	1.85 s	β^-	1969	Wilhelmy *et al*.	52, 53	
114m	1.85 s	β^-	1987	Äystö *et al*.	58	
115	990 ms	β^-	1987	Äystö *et al*.	60, 61	
116	680 ms	β^-	1987	Äystö *et al*.	58, 60, 61	
116m	570 ms	β^-	1987	Äystö *et al*.	58, 60, 61	
117	394 ms	β^-	1991	Penttilä *et al*.	62	
118	266 ms	β^-	1994	Bernas *et al*.	63	O
119	171 ms	β^-	1994	Bernas *et al*.	63	P
120	136 ms	β^-	1994	Bernas *et al*.	63	Q
121	151 ms	β^-	1994	Bernas *et al*.	63	P
122	ps[b]	β^- ?	1997	Bernas *et al*.	64	
123	ps[b]	β^- ?	2010	Ohnishi *et al*.	65	See Figures 1 and 2
124	ps[b]	β^- ?	2010	Ohnishi *et al*.	65	See Figures 1 and 2
125	ps[b]	β^- ?	2010	Ohnishi *et al*.	65	See Figures 1 and 2
126	ps[b]	β^- ?	2010	Ohnishi *et al*.	65	See Figures 1 and 2

[a]*m = isomeric state*

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

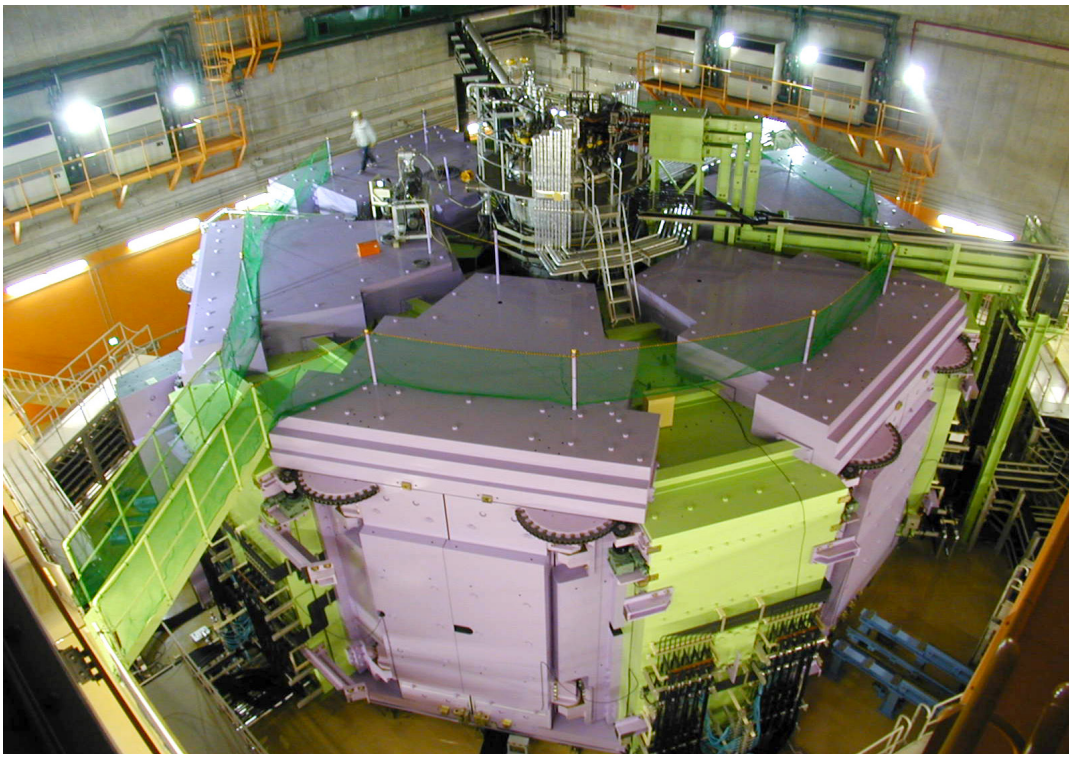

Fig. 1. The superconducting ring cyclotron (SRC) in the Radioactive Isotope Beam Factory (RIBF) at the RIKEN Nishina Center for Accelerator-Based Science where the newest isotopes of palladium, rhodium and ruthenium were discovered (65) (Copyright 2010 RIKEN)

Fig. 2. Dr Toshiyuki Kubo (Copyright 2010 RIKEN)

Dr Toshiyuki Kubo

Toshiyuki Kubo is the team leader of the Research Group at RIKEN. He was born in Tochigi, Japan, in 1956. He received his BS degree in Physics from The University of Tokyo in 1978, and his PhD degree from the Tokyo Institute of Technology in 1985. He joined RIKEN as an Assistant Research Scientist in 1980, and was promoted to Research Scientist in 1985 and to Senior Research Scientist in 1992. He spent time at the National Superconducting Cyclotron Laboratory of Michigan State University in the USA as a visiting physicist from 1992 to 1994. In 2001, he became the team leader for the in-flight separator, dubbed 'BigRIPS', which analyses the fragments produced in the RIBF. He was promoted to Group Director of the Research Instruments Group at the RIKEN Nishina Center in 2007. He is in charge of the design, construction, development and operation of major research instruments, as well as related infrastructure and equipment, at the RIKEN Nishina Center. His current research focuses on the production of rare isotope beams, in-flight separator issues, and the structure and reactions of exotic nuclei.

Notes to Table I

A	^{90}Rh and ^{90m}Rh	Hencheck *et al*. (23) only proved that the isotope was particle stable. Stolz *et al*. (24) in 2000 identified both the ground state and an isomer. The half-life determined by Wefers *et al*. in 1999 (66) appears to be consistent with the ground state. The discovery by Hencheck *et al*. is nominally assigned to the ground state.
B	^{91}Rh and ^{91m}Rh	Hencheck *et al*. (23) only proved that the isotope was particle stable. Wefers *et al*. (66) first determined a half-life in 1999 but Dean *et al*. (25) remeasured the half-life in 2004 and identified both a ground state and an isomer having identical half-lives within experimental limits. The discovery by Hencheck *et al*. is nominally assigned to the ground state.
C	^{92}Rh and ^{92m}Rh	Hencheck *et al*. (23) only proved that the isotope was particle stable. Wefers *et al*. (66) incorrectly determined the half-life in 1999 with more accurate values being determined by both Górska *et al*. (67) and Stolz *et al*. (24) in 2000. Dean *et al*. (25) showed that these determinations were for the ground state and not for the isomeric state which they also identified. The discovery by Hencheck *et al*. is nominally assigned to the ground state.
D	^{93}Rh	Hencheck *et al*. (23) only proved that the isotope was particle stable. Wefers *et al*. in (66) incorrectly measured the half-life in 1999 with more accurate values being obtained by both Górska *et al*. (67) and Stolz *et al*. (24) in 2000.
E	^{98}Rh	Aten *et al*. (68) observed this isotope in 1952 but could not decide if it was ^{96}Rh or ^{98}Rh.
F	^{99}Rh and ^{101}Rh	Farmer (69) identified both of these isotopes in 1955 but could not assign mass numbers.
G	^{100}Rh and ^{101m}Rh	For these isotopes the 1944 discovery by Sullivan, Sleight and Gladrow (34) was not made public until its inclusion in the 1948 "Table of Isotopes" (19).
H	^{103m}Rh	Although both Glendenin and Steinberg (40) and Flammersfeld (42) discovered the isomer in 1943 the results of Glendenin and Steinberg were not made public until their inclusion in the 1946 table compiled by Siegel (17, 18).
I	^{104}Rh and ^{104m}Rh	Both the ground state and isomer were first observed by Fermi *et al*. (9) in 1934 and by Amaldi *et al*. (10) in 1935 as non-specific activities. Pontecorvo (70, 71) discussed these activities in detail but assigned them to ^{105}Rh. EC + β^+ was also detected as a rare decay mode (0.45% of all decays) in ^{104}Rh by Frevert, Schöneberg and Flammersfeld (72) in 1965.
J	^{105}Rh	For this isotope the 1944 discovery by Sullivan, Sleight and Gladrow (34) was not made public until its inclusion in the 1946 table of Siegel (17, 18). The isotope was first identified by Nishina *et al*. (11, 12) in 1940 as a non-specific activity.
K	^{106}Rh	The discovery by Glendenin and Steinberg (40) in 1943 was not made public until

Continued

Notes to Table I (Continued)

		its inclusion in the 1946 table of Siegel (17, 18) and therefore the discovery of this isotope by both Grummitt and Wilkinson (46) and Seelmann-Eggebert (47) in 1946 are considered to be independent.
L	^{106m}Rh	Nervik and Seaborg (49) also observed this isotope in 1955 but tentatively assigned it to ^{107}Rh.
M	^{107}Rh	First observed by Born and Seelmann-Eggebert (73) in 1943 as a non-specific activity and also tentatively identified by Glendenin (74, 75) in 1944.
N	^{108}Rh	Although credited with the discovery, the claim by Baró, Rey and Seelmann-Eggebert (50) is considered to be tentative and a more definite claim to the discovery was made by Baumgärtner, Plata Bedmar and Kindermann (76) in 1957.
O	^{118}Rh	Bernas *et al*. (63) only confirmed that the isotope was particle stable. The half-life was first determined by Jokinen *et al*. (77) in 2000.
P	^{119}Rh and ^{121}Rh	Bernas *et al*. (63) only confirmed that the isotopes were particle stable. The half-lives were first determined by Montes *et al*. (78) in 2005.
Q	^{120}Rh	Bernas *et al*. (63) only confirmed that the isotope was particle stable. The half-life was first determined by Walters *et al*. (79) in 2004.

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 list of decay modes 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 emission 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'.

Erratum: In the previous reviews (1–4) the alpha and beta decay modes were described in terms of 'emittance'. This should read 'emission'.

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