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Autor: Pool, M.L.

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Radioactive X-Ray Emitters

by **M. L. Pool.**

The Ohio State University, Columbus, Ohio.

Some 725 different species of radioactive nuclei[1]) are now available for useful applications or for additional detailed study. Of these some 200 are distinguished by their ability to decay in such a way that the emission of characteristic x-rays result. This decay, leading to x-rays, is accomplished by either a K-electron capture process or by an internal conversion gamma-ray process. A nucleus of atomic number Z when experiencing the former process emits an x-ray characteristic of element Z-1, and when experiencing the latter process emits an x-ray characteristic of element Z. Table I shows a listing of x-ray emitting nuclei. The element of which the x-ray is characteristic is also shown. In addition it is evident that most of the x-ray emitting nuclear species also emit beta-rays and gamma-rays as well. There are only a few species which emit x-rays only and of these only a fraction can be made in great strength in a nuclear reactor (pile) or by a cyclotron.

A^{37}: One of the first recorded x-ray only emitting nuclei was A^{37}. It can be strongly and best produced by a cyclotron bombardment of KCl with deuterons[2]). Both reactions $K(d, \alpha)$ and $Cl(d, 2n)$ contribute to a high specific argon activity. This 34.1-day active gas is very useful in the calibration of proportional counters.

Ge^{71}: An 11.4-day x-ray activity can be obtained by the reactions Ga^{71} $(d, 2n)$, Ge^{70} (d, p) and Ge^{70} (n, γ). The former reaction with a cyclotron yields a high specific activity while the latter reaction with a pile yields a high total activity[3]). The decay is entirely by K-electron capture; no gamma- or beta-radiation is emitted. Since the x-rays are of 1.34 Angstrom wave-length, excellent contrast on x-ray films can be obtained when thin tissues or substances which have a surface density that varies from 0 to 0.15 gm/cm^2 are photographed with these "soft" x-rays.

Pd^{103}: A deuteron bombardment of Rh yields a very strong Pd activity of 17-day half-life[4]). X-rays only result in the decay. A Cauchois spectrograph shows that the x-rays are characteristic of Rh. A Rh fraction taken from the 17-day Pd activity decays with a 56-minute half-life. However, only about $^1/_{10}$ of the total Pd acti-

vity is obtained in the Rh fraction. Two internal conversion lines of energies 39.9 and 42.7 KeV are obtained with a magnetic spectrograph. L-conversion seems to be absent, which is unusual. The K-conversion seems to be complete since no gamma-rays of 63.1 or 65.9 KeV are present. The x-rays, two per disintegration, observed from Pd^{103} thus result from the processes of K-electron capture and of internal conversion[5]).

The above data can be interpreted by postulating two excited states of Rh^{103}, one of which has a half-life of 56 minutes and the other of much shorter duration. The K-electron capture process leading to the 56-minute level is about $^1/_{10}$ as frequent as capture leading to the short lived level.

Cb: When two species of long lived nuclei are present in the same element, the Cauchois spectrograph[6]) is very useful in clarifying the decay process. Cb^{92} has a half-life of 10.1 days, decays by K-electron capture and emits Zr x-rays. Cb^{95} has a half life of 3.75 days, decays by internal conversion and emits Cb x-rays. When these two activities are formed together by bombarding Zr with deuterons the 67.8-day Zr^{95} is readily found to decay into the 3.75-day Cb^{95} which then decays into the 35-day Cb^{95} isomer. A series of x-ray spectrograms supporting the above conclusions is shown in Fig. 1.

Mo^{93}: It may be difficult to discern the presence of x-ray emission when one or more strong gamma-rays accompany the decay. For x-rays, Geiger tubes have a sensitivity which is low compared with that for gamma-rays. Compton- and photo-electrons make simple ionization chamber detection unsatisfactory. The rate at which the x-rays are absorbed by foils can well be about equal to the rate at which Compton- and photo-electrons reach a saturation intensity in the foils. However, when the radioactive sample and also the various absorbing foils are both placed in a strong magnetic field, distinct x-rays, if they are really present, can be readily found with the aid of an ionization chamber.

The above difficulties in the detection of x-rays is exemplified by Mo^{93} which decays with a half-life of 6.7 hours. Under usual ionization measuring technique no x-radiation is found. However, using the magnetic field method, x-rays are easily observed and measured to be those characteristic of Mo. In addition this nucleus emits a 0.30-MeV gamma-ray which is 90% internally converted, a 0.70 MeV gamma-ray which is about 0.5% internally converted, and a 1.7 Mev gamma-ray which is not converted. By means of coincident Geiger counter measurements the three gamma-rays are found to be in tandem. Since the x-rays are characteristic of Mo, a long lived Mo^{93}

ground state must be inferred which is isomeric with the 6.7-hour Mo^{93} excited state[7]).

Mo^{93} is unusual in another respect. It is not possible to produce this 6.75-hour activity by the common (d, p) or (n, γ) reactions. The assignment of the activity to Mo^{93} is not in question, however, since the activity can be produced by the reactions $Zr^{90}(\alpha, n)$, Zr^{91}

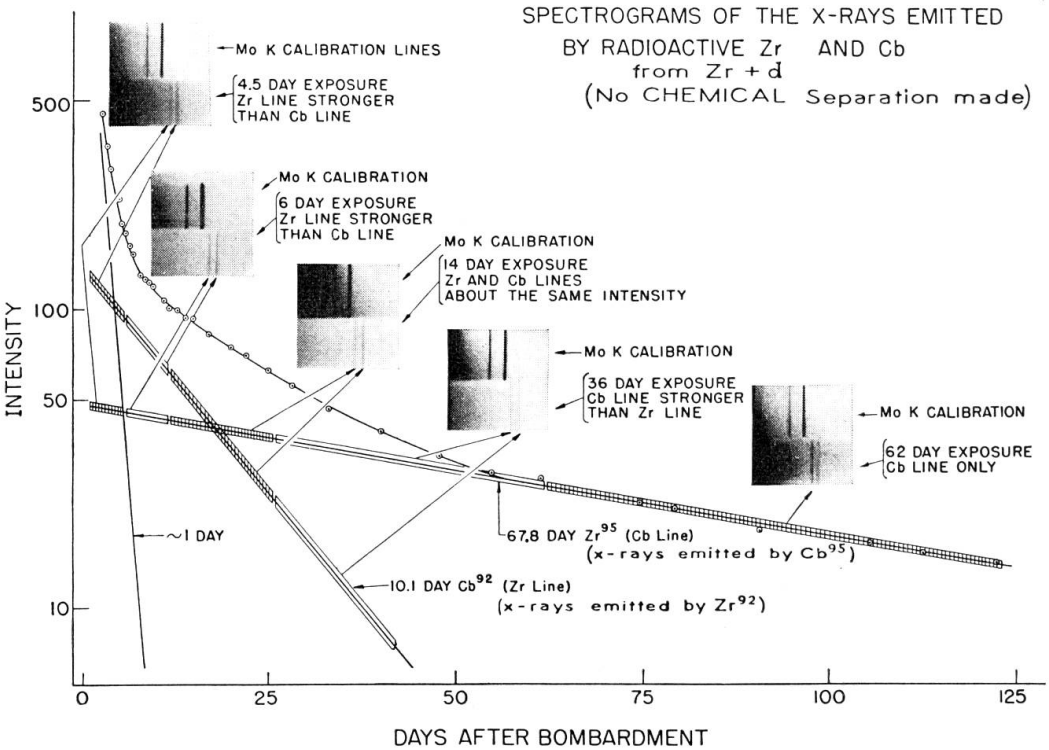

Fig. 1.
Cauchois spectograms taken at various times of a Zr sample subsequent to a bombardment with deuterons. The lengths of exposures are indicated on the resolved decay curve.

$(\alpha, 2\,n)$, $Cb^{94}\,(d, 2\,n)$, $Cb^{94}\,(p, n)$ and $Mo^{94}\,(n, 2\,n)$*). It is to be noted that Mo^{92} is one of the magic number nuclei and probably has a very low neutron capture cross section. $Mo^{92}\,(d, p)\,Mo^{93}$ is the only reaction of the (d, p) type that our cyclotron, furnishing 10 MeV deuterons, has failed to produce.

Cd^{107}: This 6.7-hour activity is useful as an x-ray source since it can be so easily produced by the Ag $(d, 2\,n)$ reation. The few positrons[8]) which are present to only 0.3% and of energy of 0.32 Mev, can be removed with an aluminium foil.

*) Enriched isotopes were supplied by the Y-12 plant, Carbide and Carbon Chemicals Corporation through the Isotopes Division, U. S. Atomic Energy Commission, Oak Ridge, Tennessee.

These x-rays are of about the correct wavelength to render good detail in thin flesh and bone structures.

Cs^{131}: In order to see in an x-ray shadow photograph, details in the bone structure itself, a "harder" x-ray is required. Cs^{131} seems to be a very satisfactory source. The half-life is 10.2 days; no gamma- or beta-rays are emitted. The activity can be produced by the reaction Ba^{130} (d, p) or Ba^{130} (n, γ). The latter reaction is recommended since pile neutrons can be used. From the barium the caesium is

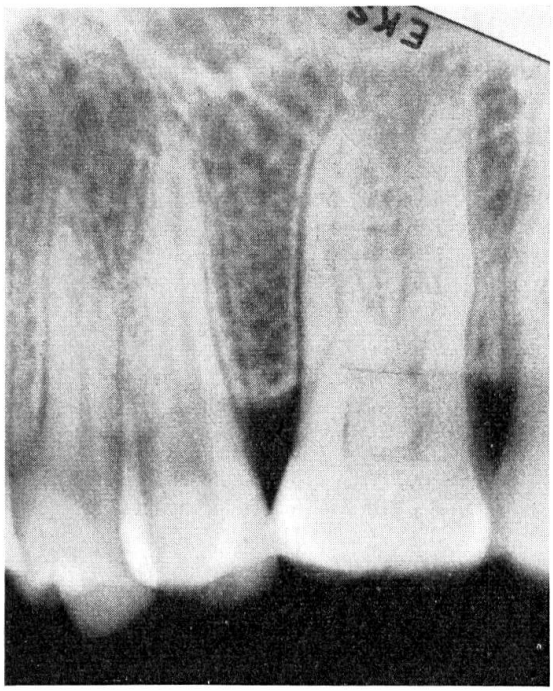

Fig. 2.
Dental picture obtained with a radioactive x-ray source placed in the back portion of the mouth. The view is from the inside outward.

easily extracted in sub-microchemical quantities. A point x-ray source can then be prepared. Since the decay is by K-capture, the x-rays are those of Xe.

Fig. 2 shows a dental picture obtained by putting the x-ray source in the back portion of the mouth. The view is therefore from the inside outward. There is shown in this figure the first and second premolars and first molar, a small portion of the floor of the maxilary sinus, and the contiguous bone structure[9]).

With the new availability of minute but strong monoergic x-ray sources the future surely holds in store many interesting anatomical views and perhaps many important new methods in x-ray therapy.

Table I.

List of radioactive x-ray emitters. μS, S, M, H, D, Y are respectively microseconds, seconds, minutes, hours, days, and years. Class A, B, etc., are same as those used by SEABORG and PERLMAN. Under column marked radiations, the characteristic x-rays emitted are listed together with accompanying beta- and gamma-ray emission, if any.

Element	Half-Life		Class	Radiations
Be 7	43	D	A	X(Li), γ
Cl 36	2×10^6	Y	A	X(S), β
A 37	34.1	D	A	X(Cl)
K 40	1.5×10^9	Y	A	X(A), β, γ
Sc 44	3.92	H	A	X(Ca), β, γ
Sc 44	2.44	D	A	X(Sc), γ
Sc 46	20	S	A	X(Sc), γ
Sc 46	85	D	A	X(Ca), β, γ
V 48	16.0	D	A	X(Ti), β, γ
V 49	1.65	Y	B	X(Ti)
Cr 51	26.5	D	A	X(V), γ
Mn 52	6.5	D	A	X(Cr), β, γ
Mn 54	310	D	A	X(Cr), γ
Fe 55	4	Y	A	X(Mn)
Co 56	72	D	A	X(Fe), β, γ
Co 57	270	D	A	X(Fe), β, γ
Co 58	72	D	A	X(Fe), β, γ
Co 60	10.7	M	A	X(Co), β, γ
Ni 59	5×10^4	Y	B	X(Co), β
Cu 61	3.4	H	B	X(Ni), β, γ
Cu 64	12.8	H	A	X(Ni), β, γ
Zn 62	9.5	H	A	X(Cu)
Zn 63	38.3	M	A	X(Cu), β, γ
Zn 65	250	D	A	X(Cu), β, γ
Zn 69	13.8	H	A	X(Zn), β, γ
Ga 65	15	M	A	X(Zn), γ
Ga 67	3.26	D	A	X(Zn), γ
Ga 70	19.8	M	A	X(Zn), β
Ge 68	250	D	A	X(Ga)
Ge 69	1.65	D	B	X(Ga), β, γ
Ge 71	11.4	D	A	X(Ga)
Ge 72	0.5	μS	A	X(Ge)
As 71	2.08	D	B	X(Ge), β
As 72	1.08	D	A	X(Ge), β, γ
As 73	76	D	A	X(Ge), γ
Se 72	9.5	D	A	X(As)
Se 73	7.1	H	A	X(As), β
Se 75	127	D	A	X(As), γ
Se 77	17.5	S	A	X(Se), γ
Se 81	57	M	B	X(Se), γ
Br 75	1.7	H	A	X(Se), β
Br 77	2.4	D	B	X(Se), β, γ
Br 80	4.54	H	A	X(Br), γ
Kr 77	1.1	H	A	X(Br), β, γ
Kr 79	1.44	D	A	X(Br), β, γ

Element		Half-Life		Class	Radiations
Kr	83	113	M	A	X(Kr)
Sr	85	66	D	A	X(Rb), γ
Sr	85	1.15	H	A	X(Sr), γ
Sr	87	2.75	H	A	X(Sr), γ
Y	87	3.3	D	B	X(Sr)
Y	87	14	H	B	X(Y), γ
Y	88	105	D	A	X(Sr), β, γ
Y	91	50	M	A	X(Y), γ
Zr	89	4.5	M	A	X(Zr), γ
Cb	91	62	D	A	X(Cb), γ
Cb	92	9.8	D	A	X(Zr), β, γ
Cb	93	42	D	F	X(Cb)
Cb	94	6.6	M	B	X(Cb), β, γ
Cb	95	3.75	D	A	X(Cb), β, γ
Mo	93	6.7	H	A	X(Mo), γ
Tc	92	47	M	B	X(Mo), γ
Tc	93	2.75	H	B	X(Mo), β, γ
Tc	94	50	M	B	X(Mo), β. γ
Tc	95	20	H	A	X(Mo), γ
Tc	95	52	D	A	X(Mo), γ
Tc	96	4.2	D	A	X(Mo), γ
Tc	97	91	D	A	X(Tc), γ
Ru	95	1.65	H	A	X(Tc), β, γ
Ru	97	2.8	D	A	X(Tc) γ
Rh	100	19.4	H	B	X(Ru), β, γ
Rh	101	4.3	D	B	X(Ru), γ
Rh	102	210	D	A	X(Ru), β, γ
Rh	103	52	M	A	X(Rh), γ
Rh	104	4.34	M	A	X(Rh), γ
Pd	100	4.0	D	B	X(Rh), γ
Pd	101	9	H	B	X(Rh), β, γ
Pd	103	17	D	A	X(Rh)
Pd	111	26	M	A	X(Rh), β
Ag	105	45	D	D	X(Pd), γ
Ag	106	8.2	D	A	X(Pd), γ
Ag	107	44.3	S	A	X(Ag), γ
Ag	109	39.2	S	A	X(Ag), γ
Ag	110	225	D	A	X(Pd), β, γ
Cd	107	6.7	H	A	X(Ag), β, γ
Cd	109	330	D	A	X(Ag), γ
Cd	111	48.7	M	A	X(Cd), γ
Cd	113	2.3	M	A	X(Cd)
In	109	5.2	H	A	X(Cd), γ
In	111	2.7	D	A	X(Cd), γ
In	112	9	M	B	X(Cd), β, γ
In	112	23	M	B	X(In), γ
In	113	1.74	H	A	X(In), γ
In	114	48.5	D	A	X(In), γ
In	115	4.5	H	A	X(In), γ
Sn	113	105	D	A	X(In), γ
Sb	117	2.8	H	B	X(Sn), γ
Sb	118	5.1	H	B	X(Sn), γ
Sb	119	1.63	D	A	X(Sn), γ

Element	Half-Life		Class	Radiations
Sb 120	6.0	D	A	X(Sn), γ
Sb 122	3.5	M	A	X(Sb), γ
Sb 124	21	M	A	X(Sb), β, γ
Te 118	6.0	D	D	X(Sb)
Te 119	4.5	D	B	X(Sb), γ
Te 121	17	D	A	X(Sb), γ
Te 121	0.05	μS	A	X(Te), γ
Te 121	143	D	A	X(Te), γ
Te 122	30	D	C	X(Te), γ
Te 125	60	D	B	X(Te), γ
Te 127	90	D	A	X(Te), γ
Te 129	35.5	D	A	X(Te), γ
Te 131	1.2	D	A	X(Te), γ
I 125	56	D	B	X(Te)
Xe 127	1.25	M	B	X(Xe), γ
Cs 131	10.2	D	B	X(Xe)
Cs 132	7.1	D	B	X(Xe), γ
Cs 134	3.15	H	A	X(Cs), β, γ
Ba 131	11.7	D	B	X(Cs), γ
Ba 133	20	Y	C	X(Cs), γ
Ba 133	1.67	D	A	X(Ba), γ
Ba 135	1.2	D	D	X(Ba), γ
Ba 137	2.64	M	A	X(Ba), γ
La 135	17.5	H	B	X(Ba), γ
Ce 137	1.5	D	A	X(La), γ
Ce 139	140	D	B	X(La), γ
Eu 152	9.2	H	A	X(Sm), β, γ
Eu 154	20	Y	A	X(Sm), β, γ
Gd 153	155	D	B	X(Eu), β, γ
Tb 152	4.5	H	D	X(Gd)
Tb 153	5.1	D	D	X(Gd)
Tb 154	17.2	H	D	X(Gd), β, γ
Tb 155	1	Y	D	X(Gd)
Dy 165	1.25	M	A	X(Gd)
Ho 161	4.5	H	C	X(Dy), β. γ
Ho 163	7	D	B	X(Dy)
Tm 166	7.7	H	B	X(Er), β, γ
Tm 167	9	D	B	X(Er), γ
Tm 167	100	D	C	X(Er), γ
Tm 169	1	μS	B	X(Tm)
Yb 169	33	D	B	X(Tm), γ
Lu 170	2.15	D	B	X(Yb), β, γ
Lu 171	9	D	B	X(Yb), β
Lu 176	2.4×10^{10}	Y	A	X(Yb), β, γ
Lu 177	6.8	D	A	X(Yb), β, γ
Hf 177	19	S	C	X(Hf), γ
Ta 176	8	D	B	X(Hf), γ
Ta 177	2.66	D	B	X(Hf), γ
Ta 177	16	D	C	X(Hf), β
Ta 180	8.2	H	A	X(Hf)
Ta 181	20	μS	A	X(Ta), β, γ
Ta 182	16.2	M	B	X(Ta), β, γ
W 178	2.25	H	C	X(Ta), γ

Element	Half-Life		Class	Radiations
W 181	140	D	B	X(Ta), γ
Re 182	2.7	D	B	X(W), β, γ
Re 183	80	D	C	X(W), γ
Re 184	50	D	A	X(W), β, γ
Re 187	0.65	μS	A	X(Re)
Os 185	94.7	D	C	X(Re), γ
Ir 190	10.7	D	B	X(Os), γ
Ir 192	1.42	M	A	X(Ir), γ
Pt 191	3	D	D	X(Ir), γ
Pt 193	4.33	D	B	X(Ir), γ
Pt 195	1.3	H	D	X(Pt), γ
Au 192	4.7	H	D	X(Pt), γ
Au 193	15.8	H	B	X(Pt), γ
Au 194	165	D	D	X(Pt), γ
Au 195	195	D	D	X(Pt), γ
Au 196	14	H	B	X(Pt)
Au 196	5.55	D	B	X(Pt), γ
Au 197	7.4	S	A	X(Au), γ
Hg 197	23	H	A	X(Au), γ
Hg 197	2.66	D	A	X(Au), γ
Hg 198	0.3	μS	F	X(Hg), γ
Hg 199	44.4	M	C	X(Hg), γ
Tl 198	1.8	H	D	X(Hg), γ
Tl 199	7	H	D	X(Hg), γ
Tl 200	1.12	D	B	X(Hg), γ
Tl 202	11.8	D	B	X(Hg), γ
Pb 201	5	H	D	X(Tl), γ
Pb 203	2.16	D	A	X(Tl), β, γ
Pb 204	1.1	H	A	X(Pb), γ
Pb 207	1.6	M	D	X(Pb), γ
Bi 204	12	H	A	X(Pb), γ
Bi 206	6.4	D	A	X(Pb), γ
Po 206	9	D	A	X(Bi), α, γ
At 210	8.3	H	A	X(Po), γ
Ac 223	2.2	M	A	X(Ra), β
Ac 224	2.5	H	A	X(Ra), α
Pa 229	1.5	H	B	X(Th), α
Pa 230	17	D	A	X(Th), β, γ
Pa 234	1.14	M	A	X(Pa), β, γ
U 231	4.2	D	B	X(Pa)
Np 234	4.4	D	A	X(U), γ
Np 235	240	D	A	X(U), α, γ
Pu 234	8	H	A	X(Np), β
Pu 237	40	D	B	X(Np)
Am 239	12	H	B	X(Pu), α, γ
Am 240	2.1	D	B	X(Pu), γ
Cm 241	55	D	E	X(Am)

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