



4.2 Absorption of photons

4.2.1 X-ray absorption edges, characteristic X-ray lines and fluorescence yields

For a given absorbing element, the general fall in X-ray absorption coefficient with increasing energy of incident photon is interrupted by a sharp rise when the energy is equal to the binding energy of an electron shell (K, L, M, etc.) in the absorber; this energy is the least at which a vacancy can be created in the particular shell and is referred to as the 'edge' or 'critical excitation' energy. Characteristic X-ray lines are generated when an 'initial' vacancy in an inner shell, created by X-ray or electron excitation, is filled by transfer of an electron from another shell, thus leaving a 'final' vacancy in that shell; the energy of the line is equal to the difference in binding energies of the shells with the 'initial' and 'final' vacancies. Depending on atomic number, the X-ray spectra from the elements can include lines from the K, L, M, N and O series corresponding to excitation of the K, L, M, N or O levels; the table lists the energies—in keV—of the principal lines of the common K, L and M series along with the corresponding edge, or excitation, energy. Lines are identified both by the common labels—e.g. $K\alpha_1$, $K\alpha_2$, etc.—and the term labels giving in order the shells with the 'initial' and 'final' vacancies—e.g. KL_{III} , KL_{II} , etc. With the exception of the elements 92–103 the table has been prepared by calculation of line energies from the compilation of smoothed edge energies given by Dewey, Mapes and Reynolds, which in turn drew extensively on the compilation by Bearden; the edge data for elements 92–103 are taken directly from Bearden. The energies of the softer radiations may be affected by the chemical state of the elements concerned; generally the shifts do not exceed a few electron volts. The wavelength λ , in pm, can be derived from the tabulated energy E , in keV, by the relationship $\lambda = 1239.81/E$.

Approximate K and L line intensities are given at the head of the columns in the table, relative to the line in the series which is normally the strongest. Where a range of values is indicated, the first number represents the value for lowest Z, the second number that for the highest Z, in the section of the table to which it refers. The values given are based on the compilation of experimental relative intensities of Salem, Panossian and Krause and the intensities calculated by Scofield (Salem *et al.*, pp. 121–37). The values are intended only as a rough guide and the original references should be consulted for details. The accompanying figure gives a plot of the relative intensities for the commonly encountered $K\beta$ line.

In addition to the lines given in the table, satellite, or non-diagram, lines also occur; these are generally only of significance in the case of the K-satellites or the lighter elements Al, Mg, Si, etc. where their intensities may be a few per cent of that of the $K\alpha$ line (see Clark or Sandström).

The transition of an electron to fill, for example, a vacancy in the K-shell may be accompanied by either the emission of an X-ray photon or the transfer of energy to another electron which is then emitted (an Auger electron); the probability that a vacancy in a given shell will result in emission of an X-ray is the fluorescence yield of that shell.

The accompanying figures give plots of the fluorescence yield ω_K for the K shell and an effective yield γ_{LII} for the L_{II} shell versus Z; the effective yield for the L_{III} is similar to that for the L_{II} . The K and L plots are based on the extensive survey by Krause, the validity of which is discussed in papers by Mitchell and Barfoot, and Singh *et al.* which consider additional experimental data including L_I yields. A few values for the average M shell fluorescence yield taken from *The Handbook of Spectroscopy* (ed. J. W. Robinson) are also given in the figure.

References

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- Salem, Panossian and Krause (1974) *Atomic and Nuclear Data Tables* 1A, 91–109.
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X-ray adsorption edges and characteristic X-ray line energies (keV)

Atomic number and element	K-series					L-series										M-series											
	K edge	KN _{III}	KM _{III}	KM _{II}	KL _{III}	KL _{II}	L _I edge	L _I N _{III}	L _I M _{III}	L _I M _{II}	L _{II} edge	L _{II} N _{IV}	L _{II} M _{IV}	L _{III} edge	L _{III} N _V	L _{III} M _V	L _{III} M _{IV}	L _{III} M _I	M _{II} N _{IV}	M _{III} edge	M _{III} N _V	M _{IV} edge	M _{IV} N _{VI}	M _V edge	M _V N _{VII}	M _V N _{VI}	
		K β_2	K β_1	K β_3	K α_1	K α_2		L γ_3	L β_3	L β_4		L γ_1	L β_1		L β_2	L α_1	L α_2	L ι									
Intensity	—	2–5	~20	~10	100	50–53	—	~5	50–35	20	—	~5	~50	—	~5	~5	~90	10	20–5	—	—	—	—	—	—	—	
4 Be	0.115					0.109										0.006											
5 B	0.188					0.183										0.005											
6 C	0.282					0.277										0.005											
7 N	0.397					0.393										0.004											
8 O	0.533					0.525										0.008											
9 F	0.692					0.677										0.015											
10 Ne	0.874		0.858			0.848										0.026											
11 Na	1.080		1.071			1.041										0.039											
12 Mg	1.309		1.302			1.253	0.062									0.056											
13 Al	1.562		1.557	1.487	1.486	0.087						0.076				0.075											
14 Si	1.840		1.836	1.740	1.739	0.118						0.101				0.100											
15 P	2.143		2.139	2.014	2.013	0.153						0.130				0.129											
16 S	2.471		2.464	2.308	2.307	0.193						0.164				0.163											
17 Cl	2.824		2.816	2.622	2.620	0.237						0.204				0.202											
18 Ar	3.203		3.190	2.958	2.956	0.286						0.247				0.245											
19 K	3.607		3.590	3.314	3.311	0.340						0.296				0.293											
20 Ca	4.034		4.013	3.692	3.688	0.403						0.346				0.342											
21 Sc	4.486		4.461	4.090	4.086	0.462						0.400				0.400	0.396			0.395	0.348						
22 Ti	4.965		4.932	4.511	4.505	0.529						0.460				0.458	0.454			0.452	0.395						
23 V	5.463		5.427	4.952	4.944	0.626						0.585	0.519			0.519	0.511			0.511	0.446						
24 Cr	5.987		5.947	5.415	5.405	0.694						0.654	0.582			0.583	0.572			0.573	0.500						
25 Mn	6.537		6.490	5.899	5.888	0.768						0.721	0.649			0.649	0.638			0.637	0.556						
26 Fe	7.112		7.058	6.404	6.391	0.846						0.792	0.721			0.719	0.708			0.705	0.615						
27 Co	7.712		7.649	6.930	6.915	0.929						0.870	0.797			0.791	0.782			0.776	0.678						
28 Ni	8.339		8.265	7.478	7.461	1.016						0.941	0.878			0.869	0.861			0.852	0.743						
29 Cu	8.993		8.905	8.903	8.048	8.028	1.109	1.023	1.019	0.965					0.950	0.945			0.930	0.811			0.015				
30 Zn	9.673	9.658 ¹	9.572	9.567	8.639	8.616	1.208	1.107	1.102	1.057					1.035	1.034			1.012	0.884			0.022				
31 Ga	10.386	10.366 ¹	10.271	10.261	9.252	9.231	1.316	1.197	1.191	1.155					1.125	1.134			1.098	0.957	0.115	0.030					
32 Ge	11.115	11.101 ¹	10.983	10.978	9.887	9.856	1.426	1.294	1.289	1.259					1.218	1.228			1.188	1.036	0.132	0.041					
33 As	11.877	11.864 ¹	11.727	11.721	10.544	10.509	1.536	1.386	1.380	1.368					1.316	1.333			1.282	1.120	0.150	0.052					
34 Se	12.666	12.652 ¹	12.496	12.489	11.222	11.181	1.662	1.492	1.485	1.485					1.419	1.444			1.379	1.204	0.170	0.066					
35 Br	13.483	13.470 ¹	13.292	13.285	11.924	11.878	1.791	1.600	1.593	1.605					1.523	1.559			1.480	1.294	0.191	0.082					
36 Kr	14.330	14.315 ¹	14.113	14.105	12.650	12.598	1.923	1.706	1.698	1.732					1.637	1.680			1.586	1.386	0.217	0.095					

37 Rb	15.202	15.185 ¹	14.962	14.952	13.396	13.336	2.067	2.051 ²	1.827	1.817	1.866		1.752	1.806		1.694	1.692	1.482		0.240	0.114	0.112	
38 Sr	16.106	16.085 ¹	15.836	15.826	14.166	14.098	2.217	2.197 ²	1.947	1.937	2.008		1.872	1.940		1.806	1.804	1.582		0.270	0.136	0.134	
39 Y	17.037	17.015 ¹	16.737	16.725	14.958	14.882	2.372	2.347 ²	2.072	2.060	2.155		1.996	2.079		1.923	1.920	1.685		0.300	0.159	0.156	
40 Zr	17.997	17.963 ¹	17.662	17.649	15.770	15.692	2.535	2.503 ²	2.200	2.187	2.305	2.292	2.118	2.227	2.215	2.043	2.040	1.792		0.335	0.323	0.187	0.184
41 Nb	18.985	18.947 ¹	18.623	18.606	16.615	16.521	2.698	2.660 ²	2.336	2.319	2.464	2.449	2.257	2.370	2.357	2.166	2.163	1.902		0.362	0.349	0.207	0.204
42 Mo	20.002	19.960	19.608	19.590	17.479	17.374	2.867	2.825 ²	2.473	2.455	2.628	2.611	2.396	2.523	2.508	2.295	2.291	2.016		0.394	0.379	0.232	0.228
43 Tc	21.048	21.002	20.619	20.599	18.367	18.251	3.047	3.001 ²	2.618	2.598	2.797	2.778	2.537	2.681	2.664	2.424	2.421	2.131		0.429	0.412	0.260	0.257
44 Ru	22.123	22.072	21.656	21.637	19.279	19.150	3.230	3.179 ²	2.763	2.744	2.973	2.952	2.683	2.844	2.825	2.556	2.554	2.253		0.467	0.448	0.290	0.288
45 Rh	23.229	23.173	22.723	22.698	20.216	20.073	3.421	3.365 ²	2.915	2.890	3.156	3.132	2.835	3.013	2.992	2.698	2.692	2.377		0.506	0.485	0.321	0.315
46 Pd	24.365	24.303	23.819	23.792	21.178	21.021	3.619	3.557	3.073	3.046	3.344	3.318	2.990	3.187	3.163	2.838	2.833	2.503		0.546	0.522	0.354	0.349
47 Ag	25.531	25.463	24.943	24.912	22.163	21.991	3.822	3.754	3.234	3.203	3.540	3.511	3.151	3.368	3.342	2.985	2.979	2.634		0.588	0.562	0.389	0.383
48 Cd	26.727	26.653	26.095	26.061	23.173	22.985	4.034	3.960	3.402	3.368	3.742	3.710	3.319	3.554	3.525	3.134	3.131	2.767		0.632	0.603	0.423	0.420
49 In	27.953	27.872	27.275	27.237	24.209	24.002	4.250	4.169	3.572	3.534	3.951	3.915	3.487	3.744	3.712	3.288	3.280	2.905		0.678	0.646	0.464	0.456
50 Sn	29.211	29.122	28.491	28.439	25.272	25.044	4.475	4.377	3.750	3.703	4.167	4.127	3.661	3.939	3.903	3.442	3.433	3.045		0.720	0.684	0.506	0.497
<i>Intensity</i>	—	5–15	~20	~10	100	53–65	—	~5	35–20	20	—	5–25	100	—	5–20	~90	10	20–5	—	—	—	—	
51 Sb	30.499	30.402	29.725	29.677	26.359	26.110	4.706	4.609	3.932	3.884	4.389	4.345	3.843	4.140	4.101	3.604	3.594	3.189		0.774	0.735	0.537	0.527
52 Te	31.817	31.712	30.995	30.944	27.472	27.201	4.942	4.837	4.120	4.069	4.616	4.568	4.030	4.345	4.302	3.770	3.759	3.336		0.822	0.779	0.583	0.572
53 I	33.168	33.054	32.295	32.239	28.612	28.317	5.186	5.072	4.313	4.257	4.851	4.799	4.221	4.556	4.509	3.938	3.926	3.485		0.873	0.826	0.631	0.619
54 Xe	34.551	34.428	33.625	33.562	29.779	29.459	5.442	5.319	4.516	4.453	5.092	5.035	4.415	4.772	4.720	4.110	4.095	3.625		0.926	0.874	0.678	0.672
55 Cs	35.966	35.833	34.985	34.918	30.973	30.625	5.700	5.567	4.719	4.652	5.341	5.278	4.619	4.993	4.936	4.289	4.271	3.795		0.981	0.924	0.740	0.726
56 Ba	37.414	37.270	36.378	36.303	32.194	31.817	5.964	5.820	4.928	4.853	5.597	5.529	4.827	5.220	5.158	4.470	4.450	3.954		1.036	0.974	0.796	0.781
57 La	38.894	38.739	37.802	37.721	33.442	33.034	6.235	6.080	5.143	5.062	5.860	5.786	5.037	5.452	5.385	4.651	4.629	4.122		1.092	1.025	0.854	0.833
58 Ce	40.410	40.243	39.258	39.170	34.720	34.279	6.516	6.349	5.364	5.276	6.131	6.051	5.261	5.690	5.617	4.839	4.820	4.289		1.152	1.079	0.902	0.883
59 Pr	41.958	41.778	40.748	40.653	36.026	35.550	6.802	6.622	5.592	5.497	6.408	6.321	5.485	5.932	5.853	5.034	5.009	4.455		1.210	1.131	0.951	0.931
60 Nd	43.538	43.345	42.272	42.166	37.361	36.847	7.095	6.902	5.829	5.723	6.691	6.597	5.722	6.177	6.091	5.231	5.208	4.633		1.266	1.180	1.000	0.978
61 Prm	45.152	44.947	43.825	43.713	38.725	38.171	7.398	7.193	6.071	5.959	6.981	6.880	5.962	6.427	6.334	5.433	5.408	4.785		1.327	1.234	1.052	1.027
62 Sm	46.801	46.584	45.413	45.289	40.118	39.523	7.707	7.490	6.319	6.195	7.278	7.169	6.205	6.683	6.582	5.635	5.610	4.995		1.388	1.287	1.106	1.081
63 Eu	48.486	48.256	47.036	46.902	41.542	40.902	8.024	7.794	6.574	6.440	7.584	7.467	6.455	6.944	6.835	5.843	5.815	5.177		1.450	1.341	1.161	1.131
64 Gd	50.207	49.964	48.696	48.554	42.996	42.309	8.343	8.100	6.832	6.690	7.898	7.772	6.713	7.211	7.034	6.058	6.026	5.362		1.511	1.334	1.217	1.209
65 Tb	51.965	51.709	50.382	50.228	44.481	43.744	8.679	8.423	7.096	6.942	8.221	8.086	6.976	7.484	7.358	6.273	6.239	5.547		1.583	1.457	1.275	1.240
66 Dy	53.761	53.491	52.119	51.956	45.999	45.208	9.013	8.743	7.371	7.208	8.553	8.409	7.249	7.762	7.627	6.496	6.458	5.743		1.642	1.507	1.333	1.325
67 Ho	55.593	55.308	53.878	53.707	47.547	46.699	9.365	9.080	7.650	7.479	8.894	8.740	7.529	8.046	7.901	6.719	6.681	5.944		1.715	1.570	1.392	1.351
68 Er	57.464	57.164	55.681	55.491	49.128	48.221	9.725	9.425	7.942	7.752	9.243	9.078	7.813	8.336	8.180	6.951	6.906	6.153		1.783	1.627	1.453	1.443
69 Tm	59.374	59.059	57.513	57.303	50.742	49.773	10.097	9.782	8.236	8.026	9.601	9.426	8.103	8.632	8.465	7.181	7.134	6.342		1.861	1.694	1.515	1.503
70 Yb	61.322	60.991	59.374	59.157	52.389	51.354	10.479	10.148	8.531	8.314	9.968	9.781	8.402	8.933	8.755	7.415	7.367	6.546		1.948	1.770	1.576	1.568
71 Lu	63.311	62.960	61.286	61.049	54.070	52.965	10.869	10.518	8.844	8.607	10.346	10.144	8.709	9.241	9.049	7.655	7.604	6.753		2.025	1.833	1.637	1.623
72 Hf	65.345	64.973	63.236	62.979	55.790	54.611	11.262	10.890	9.153	8.896	10.734	10.517	9.016	9.555	9.348	7.891	7.837	6.960		2.109	1.902	1.718	1.700
73 Ta	67.405	67.011	65.221	64.946	57.533	56.277	11.672	11.278	9.488	9.213	11.128	10.894	9.345	9.872	9.649	8.147	8.089	7.173		2.184	1.961	1.783	1.760
74 W	69.517	69.100	67.244	66.951	59.318	57.982	12.092	11.675	9.819	9.526	11.535	11.284	9.671	10.199	9.959	8.396	8.335	7.388		2.273	2.033	1.864	1.835
75 Re	71.670	71.230	69.309	68.994	61.140	59.718	12.522	12.082	10.161	9.846	11.952	11.682	10.006	10.530	10.273	8.651	8.584	7.604		2.361	2.104	1.946	1.910
																							1.843

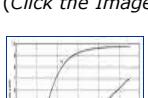
76 Os	73.869	73.404	71.416	71.077	63.001	61.487	12.968	12.503	10.515	10.176	12.382	12.092	10.349	10.868	10.592	8.905	8.835	7.822		2.453	2.177	2.033	1.988	1.963.	1.921	1.918	
77 Ir	76.111	75.620	73.560	73.203	64.896	63.287	13.416	12.925	10.865	10.508	12.824	12.514	10.705	11.215	10.919	9.175	9.096	8.046		2.551	2.255	2.119	2.062	2.040	1.988	1.983	
78 Pt	78.400	77.883	75.751	75.364	66.832	65.123	13.880	13.363	11.231	10.844	13.277	12.944	11.073	11.568	11.251	9.439	9.364	8.271		2.649	2.332	2.204	2.134	2.129	2.065	2.059	
79 Au	80.729	80.182	77.985	77.580	68.804	66.990	14.353	13.806	11.609	11.204	13.739	13.383	11.432	11.925	11.585	9.705	9.618	8.494		2.744	2.404	2.307	2.220	2.220	2.142	2.133	
80 Hg	83.109	82.532	80.261	79.822	70.819	68.894	14.835	14.258	11.987	11.548	14.215	13.834	11.823	12.290	11.927	9.999	9.898	8.722		2.848	2.485	2.392	2.285	2.291	2.195	2.184	
81 Tl	83.532	84.924	82.575	82.384	72.872	70.832	15.344	14.736	13.387	12.196	14.700	14.293	12.217	12.660	12.272	10.271	10.117	8.953	3.012	2.957	2.569	2.483	2.360	2.389	2.270	2.266	
82 Pb	88.008	87.367	84.936	84.450	74.969	72.804	15.863	15.222	12.791	12.305	15.204	14.769	12.618	13.039	12.625	10.555	10.453	9.185	3.125	3.072	2.658	2.586	2.442	2.484	2.345	2.340	
83 Bi	90.540	89.866	87.354	86.831	77.118	74.815	16.391	15.717	13.205	12.682	15.725	15.261	13.031	13.422	12.981	10.836	10.728	9.421	3.234	3.186	2.745	2.694	2.534	2.586	2.422	2.426	
84 Po	93.113	92.403	89.801	89.250	79.301	76.863	16.940	16.230	13.628	13.077	16.250	15.756	13.452	13.812	13.342	11.131	11.014	9.664	3.354	3.312	2.842	2.798	2.620	2.681	2.501	2.503	
85 At	95.730	94.983	92.302	91.722	81.523	78.943	17.495	16.748	14.067	13.487	16.787	16.262	13.882	14.207	13.708	11.427	11.302	9.858	3.475	3.428	2.929	2.905	2.707	2.780	2.581	2.582	
86 Rn	98.402	97.617	94.866	94.246	83.793	81.065	18.047	17.262	14.511	13.891	17.337	16.777	14.323	14.609	14.079	11.727	11.595	10.085	3.593	3.536	3.006	3.014	2.794	2.882	2.663	2.662	
87 Fr	101.131	100.306	97.477	96.807	86.114	83.231	18.630	17.805	14.976	14.306	17.900	17.307	14.775	15.017	14.456	12.031	11.892	10.340	3.724	3.654	3.093	3.125	2.881	2.986	2.746	2.742	
88 Ra	103.909	103.039	100.130	99.432	88.476	85.434	19.222	18.352	15.443	14.745	18.475	17.848	15.238	15.433	14.839	12.340	12.196	10.622	3.853	3.779	3.185	3.237	2.967	3.093	2.829	2.823	
89 Ac	106.738	105.837	102.846	102.101	90.884	87.675	19.823	18.922	15.931	15.186	19.063	18.402	15.711	15.854	15.227	12.652	12.502	10.835	3.981	3.892	3.265	3.352	3.054	3.202	2.913	2.904	
90 Th	109.641	108.690	105.611	104.831	93.358	89.952	20.449	19.498	16.419	15.639	16.689	18.993	16.215	16.283	15.622	12.970	12.809	11.119	4.118	4.030	3.369	3.474	3.145	3.313	2.996	2.984	
91 Pa	112.599	111.606	108.435	107.606	95.883	92.287	21.088	20.095	16.924	16.095	20.312	19.581	16.715	16.716	16.022	13.300	13.119	11.366	4.261	4.164	3.470	3.597	3.251	3.416	3.083	3.070	
92 U	115.606	114.561	111.303	110.424	98.440	94.659	21.757	20.712	17.454	16.575	20.947	20.167	17.219	17.166	16.429	13.614	13.438	11.619	4.401	4.303	3.566	3.728	3.337	3.552	3.171	3.161	
93 Np	118.678	117.591	114.243	113.312	101.068	97.077	22.427	21.340	17.992	17.061	21.601	20.785	17.751	17.610	16.840	13.944	13.760	11.890	4.543	4.435	3.665	3.850	3.435	3.666	3.262	3.251	
94 Pu	121.818	120.703	117.261	116.277	103.761	99.552	23.097	21.982	18.540	17.556	22.266	21.417	18.293	18.057	17.256	14.279	14.084	12.124	4.699	4.557	3.756	3.973	3.527	3.778	3.346	3.332	
95 Am	125.027	123.891	120.360	119.317	106.523	102.083	23.773	22.637	19.106	18.063	22.944	22.065	18.852	18.504	17.676	14.617	14.412	12.384		4.667	3.839	4.092	0.0	3.887	0.0	0.0	
Intensity	—	~15	~20	~10	100	~65	—	~5	~20	20	—	~25	~100	—	~20	~90	10	20-5	—	—	—	—	—	—	—	—	
96 Cm	128.220	127.066	123.423	122.325	109.290	104.441	24.460	23.306	19.663	18.565	23.779		19.552	18.930		14.959	14.703			4.797	4.227			3.971			
97 Bk	131.590	130.355	126.663	125.443	112.138	107.205	25.275	24.040	20.348	19.128	24.385		20.019	19.452		15.320	15.086			4.927	4.366			4.132			
98 Cf	135.960	134.681	130.851	129.601	116.030	110.710	26.110	24.831	21.001	19.751	25.250		20.763	19.930		15.677	15.443			5.109	4.487			4.253			
99 Es	139.490	138.169	134.238	132.916	119.080	113.470	26.900	25.579	21.648	20.326	26.020		21.390	20.410		16.036	15.780			5.252	4.630			4.374			
100 Fm	143.090	141.724	137.693	136.347	122.190	116.280	27.700	26.334	22.303	20.957	26.810		22.044	20.900		16.402	16.134			5.397	4.766			4.498			
101 Md	146.780	145.370	141.234	139.761	125.390	119.170	28.530	27.120	22.984	21.511	27.610		22.707	21.390		16.768	16.487			5.546	4.903			4.622			
102 No	150.540	149.092	144.852	143.295	128.660	122.100	29.380	27.932	23.692	22.135	28.440		23.403	21.880		17.139	16.843			5.688	5.037			4.741			
103 Lw	154.380	152.900	148.670	146.920	132.020	125.100	30.240	28.760	24.530	22.780	29.280		24.130	22.360		17.500	17.210			5.710	5.150			4.860			

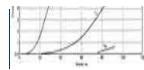
Unresolved lines:

1—KN_{II,III} (K β_2); 2—L₁N_{II,III} (Ly_{2,3})

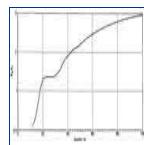
Depending on the resolving power of the dispersing system used (e.g. crystal spectrometer, solid state energy dispersive detector) line pairs shown separately in the table may not be resolved and the effective energy of the doublet will be close to the mean value weighted by the relative intensity of the components.

(Click the Images to view Larger Images)

Variations of the fluorescence yields ω_K and ω_M for the K-shell and M-shell respectively and



of the effective
fluorescence yield γ_{L1} for the L_{II} shell with atomic number.



Variations of K_β / K_α with atomic number

D.M. Poole

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