# Chapter 11

# *Atomic physics*


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***Spectroscopic terminology***

| Orbital angular momentum $L$ or $l$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| $L$ | $S$ | $P$ | $D$ | $F$ | $G$ | $H$ | $I$ | $K$ | $L$ |
| $l$ | $s$ | $p$ | $d$ | $f$ | $g$ | $h$ | $i$ | $k$ | $l$ |

$L = \sum l$ (individual electrons), orbital angular momentum,
$S = \sum s$ (individual electrons), spin angular momentum,
$J = L + S$ (LS coupling), total angular momentum,
$J = \sum j$; $j = l + s$ (jj coupling),
$M$ = magnetic quantum number; components of $J$ in magnetic field.

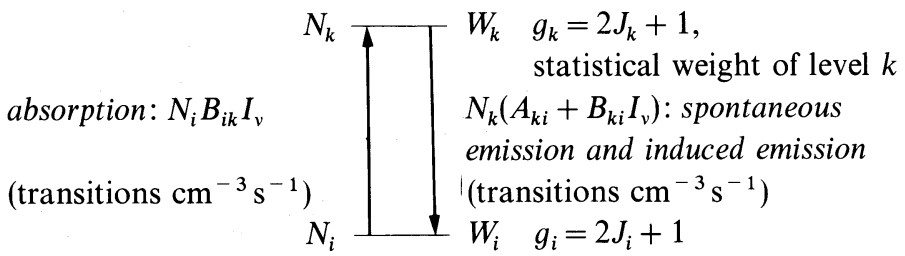
| $n$ (total quantum number) | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Shell | $K$ | $L$ | $M$ | $N$ | $O$ | $P$ | $Q$ |

The quantities $n, l, S, L, J, M$ define a Zeeman *state*.
The quantities $n, l, S, L, J$ define a *level* which includes $2J + 1$ *states*, e.g., the atomic level $2p^3\ {}^4S^0_{3/2}$.
Interpretation:

- 2: outer electrons, $n = 2$ ($L$ shell).
- $p^3$: 3 outer electrons, $l = 1$.
- 4: multiplicity = 4 ($2S + 1 = 4$, $S = 3/2$, the spin).
- $S$: orbital momentum $L = 0$.
- 3/2: $J = 3/2$.
- 0: the level has odd parity.

The quantities $n, l, S, L$ define an atomic *term*, the set of $(2S + 1) \times (2L + 1)$ states characterized by given values of $L$ and $S$.
A transition between two *levels* is called a spectral *line*.
The totality of transitions between two *terms* is a *multiplet*.

***Emission and absorption of radiation (cgs units)***

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where

$A_{ki}$ = Einstein coefficient of spontaneous emission,
$N_k$ = number of atoms per unit volume in level $k$,
$B_{ik}$ = induced transition probability from level $i$ to level $k$,
$I_\nu$ = specific intensity of radiation field at frequency $\nu$,
$h\nu = W_k - W_i$, transition energy.

$$g_k B_{ki} = g_i B_{ik},$$

$$\frac{g_k}{g_i} A_{ki} = \frac{2h\nu^3}{c^2} B_{ik} = \frac{8\pi^2 e^2 \nu^2}{mc^3} f_{ik},$$

where $f_{ik}$ = absorption oscillator strength.

$$\sigma_i = \int \sigma_\nu \, d\nu = \frac{\pi e^2}{mc} f_{ik} N_i, \text{ is the}$$

integrated atomic scattering coefficient for a spectrum line.
$\sigma_\nu$ = atomic scattering coefficient near an absorption line.

*Thermal equilibrium*

$$\frac{N_k}{N_i} = \frac{g_k}{g_i} e^{-(W_k - W_i)/kT} \quad \text{(Boltzmann's formula).}$$

*Doppler shift*

$$\Delta\lambda/\lambda \approx v/c \quad (v = \text{velocity of source}).$$

*Doppler width of spectral line* (FWHM, Maxwellian distribution)

$$\frac{\Delta\lambda_D}{\lambda} = \frac{2[(2\ln 2)kT/M]^{1/2}}{c} = 7.162 \times 10^{-7} \sqrt{\left[\frac{T\,(\mathrm{K})}{\text{at. wt.}}\right]},$$

where $M$ is the mass of the radiating atom.

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## X-ray atomic energy levels (eV)

| Z | element | K | $L_I$ | $L_{II,III}$ |
|---|---|---|---|---|
| 1 | H | 13.598 | | |
| 2 | He | 24.587 | | |
| 3 | Li | 54.75 | | |
| 4 | Be | 111.0 | | |
| 5 | B | 188.0 | | 4.7 |
| 6 | C | 283.8 | | 6.4 |
| 7 | N | 401.6 | | 9.2 |
| 8 | O | 532.0 | 23.7 | 7.1 |
| 9 | F | 685.4 | 31 | 8.6 |
| 10 | Ne | 866.9 | 45 | 18.3 |
| 11 | Na | 1072.1 | 63.3 | 31.1 |
| 12 | Mg | 1305.0 | 89.4 | 51.4 |
| 13 | Al | 1559.6 | 117.7 | 73.1 |
| 14 | Si | 1838.9 | 148.7 | 99.2 |
| 15 | P | 2145.5 | 189.3 | 132.2 |
| 16 | S | 2472.0 | 229.2 | 164.8 |

### *Permitted transitions*

| K series | L series |
|---|---|
| $K\alpha_1 = K - L_{III}$ | $L\alpha_1 = L_{III} - M_V$ |
| $K\alpha_2 = K - L_{II}$ | $L\alpha_2 = L_{III} - M_{IV}$ |
| $K\beta_1 = K - M_{III}$ | $L\beta_1 = L_{II} - M_{IV}$ |
| $K\beta_3 = K - M_{II}$ | |
| $K\beta_2 = K - N_{II,III}$ | |

| Z | element | K | $L_I$ | $L_{II}$ | $L_{III}$ | $M_I$ | $M_{II,III}$ | $M_{IV,V}$ |
|---|---|---|---|---|---|---|---|---|
| 17 | Cl | 2822.4 | 270.2 | 201.6 | 200.0 | 17.5 | 6.8 | |
| 18 | Ar | 3202.9 | 320. | 247.3 | 245.2 | 25.3 | 12.4 | |
| 19 | K | 3607.4 | 377.1 | 296.3 | 293.6 | 33.9 | 17.8 | |
| 20 | Ca | 4038.1 | 437.8 | 350.0 | 346.4 | 43.7 | 25.4 | |
| 21 | Sc | 4492.8 | 500.4 | 406.7 | 402.2 | 53.8 | 32.3 | 6.6 |
| 22 | Ti | 4966.4 | 563.7 | 461.5 | 455.5 | 60.3 | 34.6 | 3.7 |
| 23 | V | 5465.1 | 628.2 | 520.5 | 512.9 | 66.5 | 37.8 | 2.2 |
| 24 | Cr | 5989.2 | 694.6 | 583.7 | 574.5 | 74.1 | 42.5 | 2.3 |
| 25 | Mn | 6539.0 | 769.0 | 651.4 | 640.3 | 83.9 | 48.6 | 3.3 |
| 26 | Fe | 7112.0 | 846.1 | 721.1 | 708.1 | 92.9 | 54.0 | 3.6 |

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| Z | element | K | $L_I$ | $L_{II}$ | $L_{III}$ | $M_I$ | $M_{II}$ | $M_{III}$ | $M_{IV,V}$ |
|---|---|---|---|---|---|---|---|---|---|
| 27 | Co | 7708.9 | 925.6 | 793.6 | 778.6 | 100.7 | 59.5 | 2.9 | |
| 28 | Ni | 8332.8 | 1008.1 | 871.9 | 854.7 | 111.8 | 68.1 | 3.6 | |
| 29 | Cu | 8978.9 | 1096.6 | 951.0 | 931.1 | 119.8 | 73.6 | 1.6 | |
| 30 | Zn | 9658.6 | 1193.6 | 1042.8 | 1019.7 | 135.9 | 86.6 | 8.1 | |
| 31 | Ga | 10 367.1 | 1297.7 | 1142.3 | 1115.4 | 158.1 | 106.8 | 102.9 | 17.4 |
| 32 | Ge | 11 103.1 | 1414.3 | 1247.8 | 1216.7 | 180.0 | 127.9 | 120.8 | 28.7 |

| Z | element | K | $L_I$ | $L_{II}$ | $L_{III}$ | $M_I$ | $M_{II}$ | $M_{III}$ | $M_{IV}$ | $M_V$ | $N_I$ | $N_{II}$ | $N_{III}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 47 | Ag | 25 514.0 | 3805.8 | 3523.7 | 3351.1 | 717.5 | 602.4 | 571.4 | 372.8 | 366.7 | 95.2 | 62.6 | 55.9 |
| 53 | I | 33 169.4 | 5188.1 | 4852.1 | 4557.1 | 1072.1 | 930.5 | 874.6 | 631.3 | 619.4 | 186.4 | 122.7 | |
| 54 | Xe | 34 561.4 | 5452.8 | 5103.7 | 4782.2 | | 999.0 | 937.0 | | 672.3 | | 146.7 | |
| 55 | Ca | 35 984.6 | 5714.3 | 5359.4 | 5011.9 | 1217.1 | 1065.0 | 997.6 | 739.5 | 725.5 | 230.8 | 172.3 | 161.6 |
| 74 | W | 69 525.0 | 12 099.8 | 11 544.0 | 10 206.8 | 2819.6 | 2574.9 | 2281.0 | 1871.6 | 1809.2 | 595.0 | 491.6 | 425.3 |
| 78 | Pt | 78 394.8 | 13 879.9 | 13 272.6 | 11 563.7 | 3296.0 | 3026.5 | 2645.4 | 2201.9 | 2121.6 | 722.0 | 609.2 | 519.0 |
| 79 | Au | 80 724.9 | 14 352.8 | 13 733.6 | 11 918.7 | 3424.9 | 3147.8 | 2743.0 | 2291.1 | 2205.7 | 758.8 | 643.7 | 545.4 |
| 82 | Pb | 88 004.5 | 15 860.8 | 15 200.0 | 13 035.2 | 3850.7 | 3554.2 | 3066.4 | 2585.6 | 2484.0 | 893.6 | 763.9 | 644.5 |
| 92 | U | 115 606.1 | 21757.4 | 20 947.6 | 17 166.3 | 5548.0 | 5182.2 | 4303.4 | 3727.6 | 3551.7 | 1440.8 | 1272.6 | 1044.9 |

| Z | element | $N_{IV}$ | $N_V$ | $N_{VI}$ | $N_{VII}$ | $O_I$ | $O_{II}$ | $O_{III}$ | $O_{IV}$ | $O_V$ | $P_I$ | $P_{II}$ | $P_{III}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 47 | Ag | 3.3 | | | | | | | | | | | |
| 53 | I | 49.6 | | | | 13.6 | | | | | | | |
| 54 | Xe | | | | | | | 3.3 | | | | | |
| 55 | Ca | 78.8 | 76.5 | | | 22.7 | 13.1 | 11.4 | | | | | |
| 74 | W | 258.8 | 245.4 | 36.5 | 33.6 | 77.1 | 46.8 | 35.6 | 6.1 | | | | |
| 78 | Pt | 330.8 | 313.3 | 74.3 | 71.1 | 101.7 | 65.3 | 51.7 | 2.2 | | | | |
| 79 | Au | 352.0 | 333.9 | 86.4 | 82.8 | 107.8 | 71.7 | 53.7 | 2.5 | | | | |
| 82 | Pb | 435.2 | 412.9 | 142.9 | 138.1 | 147.3 | 104.8 | 86.0 | 21.8 | 19.2 | 3.1 | 0.7 | |
| 92 | U | 780.4 | 737.7 | 391.3 | 380.9 | 323.7 | 259.3 | 195.1 | 105.0 | 96.3 | 70.7 | 42.3 | 32.3 |

(List from Bearden, J. A. and Burr, A. F., *Rev. Mod. Phys.*, **39**, 125, 1967.)



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## X-ray atomic energy levels (*cont.*)

### *Notation for X-ray lines*

| Siegbahn notation | Transition | Siegbahn notation | Transition | Siegbahn notation | Transition | Siegbahn notation | Transition |
|---|---|---|---|---|---|---|---|
| $K\alpha_1$ | $KL_{III}$ | $L\gamma_2$ | $L_IN_{II}$ | $LV$ | $L_{II}N_{VI}$ | $L\beta_2$ | $L_{III}N_V$ |
| $K\alpha_2$ | $KL_{II}$ | $L\gamma_3$ | $L_IN_{III}$ | $L\gamma_8$ | $L_{II}O_I$ | $Lu$ | $L_{III}N_{VI,VII}$ |
| $K\beta_3$ | $KM_{II}$ | $L\gamma_{11}$ | $L_IN_V$ | $L\gamma_6$ | $L_{II}O_{IV}$ | $L\beta_7$ | $L_{III}O_I$ |
| $K\beta_1$ | $KM_{III}$ | $L\gamma_4$ | $L_IO_{III}$ | $Ll$ | $L_{III}M_I$ | $L\beta_3$ | $L_{III}O_{IV,V}$ |
| $K\beta_5$ | $KM_{IV,V}$ | $L\gamma_{13}$ | $L_IP_{II,III}$ | $Lt$ | $L_{III}M_{II}$ | $M\gamma$ | $M_{III}N_V$ |
| $K\beta_2$ | $KN_{II,III}$ | $L\eta$ | $L_{II}M_I$ | $Ls$ | $L_{III}M_{III}$ | $M\beta$ | $M_{IV}N_{VI}$ |
| $K\beta_4$ | $KN_{IV,V}$ | $L\beta_{17}$ | $L_{II}M_{III}$ | $L\alpha_2$ | $L_{III}M_{IV}$ | $M\zeta_2$ | $M_{IV}N_{II}$ |
| $L\beta_4$ | $L_IM_{II}$ | $L\beta_1$ | $L_{II}M_{IV}$ | $L\alpha_1$ | $L_{III}M_V$ | $M\zeta_1$ | $M_{IV}N_{III}$ |
| $L\beta_3$ | $L_IM_{III}$ | $L\gamma_5$ | $L_{II}N_I$ | $L\beta_6$ | $L_{III}N_I$ | $M\alpha_2$ | $M_VN_{VII}$ |
| $L\beta_{10}$ | $L_IM_{IV}$ | $L\gamma_1$ | $L_{II}N_{IV}$ | $L\beta_{13}$ | $L_{III}N_{IV}$ | $M\alpha_1$ | $M_VN_{VII}$ |
| $L\beta_9$ | $L_IM_V$ | | | | | | |

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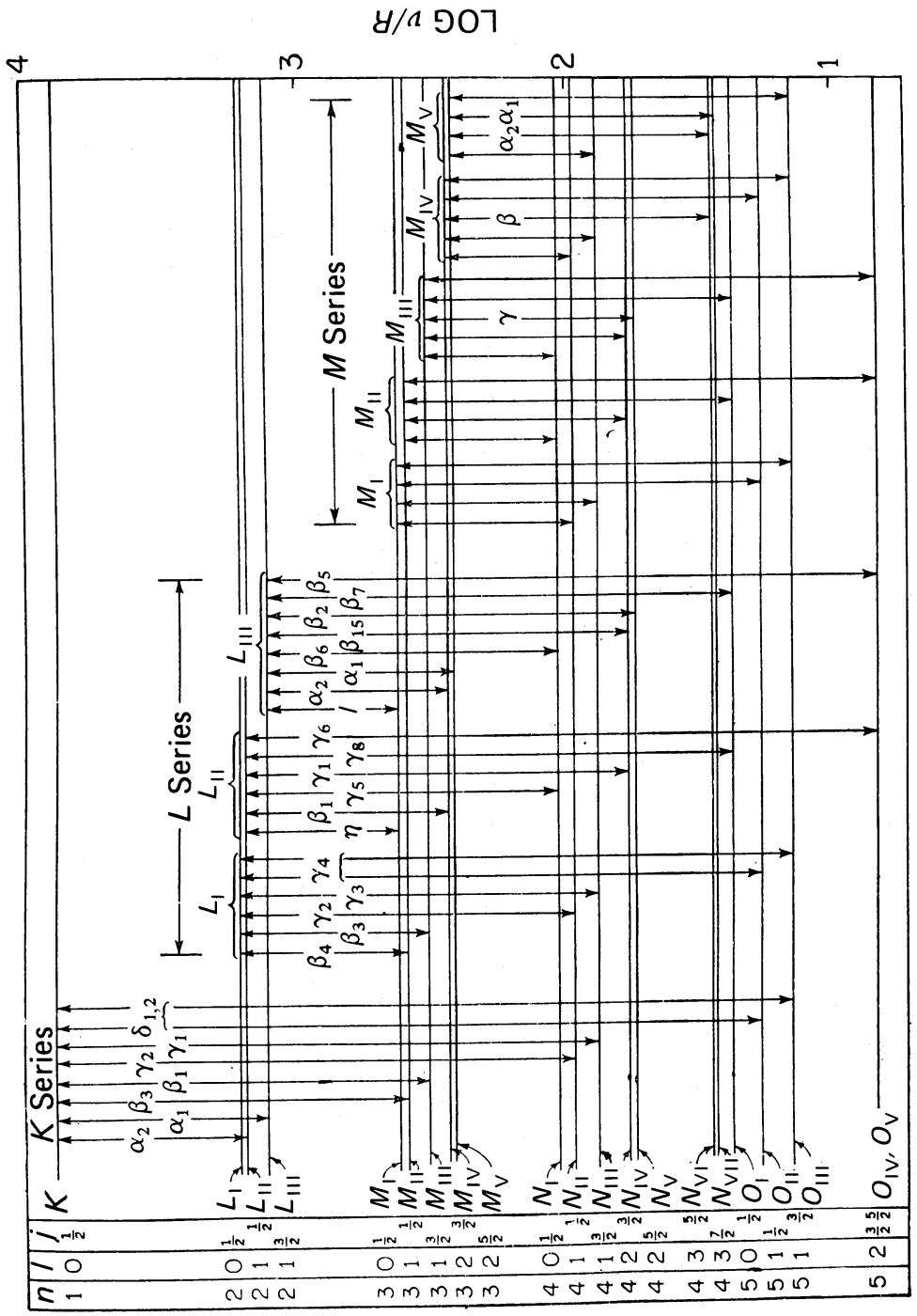
## X-ray energy level diagram

X-ray energy-level diagram for $^{92}U$, showing the transitions permitted by the selection rules $\Delta l = \pm 1$; $\Delta j = \pm 1, 0$. (Adapted from Richtmyer, F. K., Kennard, E. H. & Lauritsen, T., *Introduction to Modern Physics*, McGraw-Hill Book Company, 1955.)

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*Wavelengths of K series lines representing transitions in the ordinary X-ray energy-level diagram allowed by the selection principles (Ångstrom)*

| Siegbahn<br>Sommerfeld<br>transition | | $K\alpha_2$<br>$K\alpha'$<br>$K-L_{II}$ | $K\alpha_1$<br>$K\alpha$<br>$K-L_{III}$ | $K\beta$<br>$K\beta_2$<br>$K-M_{II}$ | $K\beta_1$<br>$K\beta$<br>$K-M_{III}$ | $K\beta_2$<br>$K\gamma$<br>$K-L_{II}N_{III}$ |
|---|---|---|---|---|---|---|
| 4 | Be | 115.7 | | | | |
| 5 | B | 67.71 | | | | |
| 6 | C | 44.54 | | | | |
| 7 | N | 31.557 | | | | |
| 8 | O | 23.567 | | | | |
| 9 | F | 18.275 | | | | |
| 11 | Na | 11.885 | | 11.594 | | |
| 12 | Mg | 9.869 | | 9.539 | | |
| 13 | Al | 8.3205 | | 7.965 | | |
| 14 | Si | 7.111 06 | | 6.7545 | | |
| 15 | P | 6.1425 | | 5.7921 | | |
| 16 | S | 5.3637 | 5.3613 | 5.0211 | | |
| 17 | Cl | 4.7212 | 4.7182 | 4.3942 | | |
| 19 | K | 3.737 07 | 3.733 68 | 3.4468 | | |
| 20 | Ca | 3.354 95 | 3.351 69 | 3.0834 | | |
| 21 | Sc | 3.028 40 | 3.025 03 | 2.7739 | | |
| 22 | Ti | 2.746 81 | 2.743 17 | 2.5090 | | |
| 23 | V | 2.502 13 | 2.498 35 | 2.2797 | | |
| 24 | Cr | 2.288 91 | 2.285 03 | 2.0806 | | |
| 25 | Mn | 2.101 49 | 2.097 51 | 1.906 20 | | |
| 26 | Fe | 1.936 012 | 1.932 076 | 1.753 013 | | |
| 27 | Co | 1.789 19 | 1.785 29 | 1.617 44 | | |
| 28 | Ni | 1.658 35 | 1.654 50 | 1.479 05 | | 1.485 61 |
| 29 | Cu | 1.541 232 | 1.537 395 | 1.389 35 | | 1.378 24 |
| 30 | Zn | 1.436 03 | 1.432 17 | 1.292 55 | | 1.281 07 |
| 31 | Ga | 1.340 87 | 1.337 15 | 1.205 20 | | 1.1938 |
| 32 | Ge | 1.255 21 | 1.251 30 | 1.126 71 | | 1.114 59 |
| 33 | As | 1.177 43 | 1.173 44 | 1.055 10 | | 1.042 81 |
| 34 | Se | 1.106 52 | 1.102 48 | 0.990 13 | | 0.977 91 |
| 35 | Br | 1.041 66 | 1.037 59 | 0.930 87 | | 0.918 53 |
| 36 | Kr | 0.9821 | 0.9781 | 0.8767 | | 0.8643 |
| 37 | Rb | 0.927 76 | 0.923 64 | 0.827 49 | 0.826 96 | 0.814 76 |
| 38 | Sr | 0.877 61 | 0.873 45 | 0.781 83 | 0.781 30 | 0.769 21 |
| 39 | Y | 0.831 32 | 0.827 12 | 0.739 72 | 0.739 19 | 0.727 13 |
| 40 | Zr | 0.788 51 | 0.784 30 | 0.700 83 | 0.700 28 | 0.688 50 |
| 41 | Nb | 0.748 89 | 0.744 65 | 0.664 96 | 0.664 38 | 0.652 80 |
| 42 | Mo | 0.712 105 | 0.707 831 | 0.631 543 | 0.630 978 | 0.619 698 |
| 43 | Te | 0.675 | 0.672 | 0.601 | | |
| 44 | Ru | 0.646 06 | 0.641 74 | 0.571 93 | 0.571 31 | 0.560 51 |
| 45 | Rh | 0.616 37 | 0.612 02 | 0.545 09 | 0.544 49 | 0.533 96 |
| 46 | Pd | 0.588 63 | 0.584 27 | 0.520 09 | 0.519 47 | 0.509 18 |
| 47 | Ag | 0.562 67 | 0.558 28 | 0.496 65 | 0.496 01 | 0.486 03 |

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***Wavelengths of K series lines representing transitions in the ordinary X-ray energy-level diagram allowed by the selection principles*** (*cont.*)

| Siegbahn<br>Sommerfeld<br>transition | $K\alpha_2$<br>$K\alpha'$<br>$K$–$L_{II}$ | $K\alpha_1$<br>$K\alpha$<br>$K$–$L_{III}$ | $K\beta$<br>$K\beta_2$<br>$K$–$M_{II}$ | $K\beta_1$<br>$K\beta$<br>$K$–$M_{III}$ | $K\beta_2$<br>$K\gamma$<br>$K$–$L_{II}N_{III}$ |
|---|---|---|---|---|---|
| 48 Cd | 0.538 32 | 0.533 90 | 0.474 71 | 0.474 08 | 0.464 20 |
| 49 In | 0.515 48 | 0.511 06 | 0.454 23 | 0.453 58 | 0.444 08 |
| 50 Sn | 0.494 02 | 0.489 57 | 0.434 95 | 0.434 30 | 0.424 99 |
| 51 Sb | 0.473 87 | 0.469 31 | 0.416 23 | | 0.407 10 |
| 52 Te | 0.454 91 | 0.450 37 | 0.399 26 | | 0.390 37 |
| 53 I | 0.437 03 | 0.432 49 | 0.382 92 | 0.383 15 | 0.374 71 |
| 54 Xe | 0.417 | | 0.360 | | |
| 55 Cs | 0.404 11 | 0.399 59 | 0.354 36 | 0.353 60 | 0.345 16 |
| 56 Ba | 0.388 99 | 0.384 43 | 0.340 89 | 0.340 22 | 0.332 22 |
| 57 La | 0.374 66 | 0.370 04 | 0.328 09 | 0.327 26 | 0.319 66 |
| 58 Ce | 0.361 10 | 0.356 47 | 0.315 72 | 0.315 01 | 0.307 70 |
| 59 Pr | 0.348 05 | 0.343 40 | 0.304 39 | 0.303 60 | 0.296 25 |
| 60 Nd | 0.335 95 | 0.331 25 | 0.293 51 | 0.292 75 | 0.285 73 |
| 62 Sm | 0.313 02 | 0.308 33 | 0.273 25 | 0.272 50 | 0.265 75 |
| 63 Eu | 0.302 65 | 0.297 90 | 0.263 86 | 0.263 07 | 0.256 45 |
| 64 Gd | 0.292 61 | 0.287 82 | 0.254 71 | 0.253 94 | 0.247 62 |
| 65 Tb | 0.282 86 | 0.278 20 | 0.246 29 | 0.245 51 | 0.239 12 |
| 66 Dy | 0.273 75 | 0.269 03 | 0.237 87 | 0.237 10 | 0.231 28 |
| 67 Ho | 0.264 99 | 0.260 30 | | | |
| 68 Er | 0.256 64 | 0.251 97 | 0.223 00 | 0.222 15 | 0.216 71 |
| 69 Tm | 0.248 61 | 0.243 87 | 0.215 58 | 0.214 87 | |
| 70 Yb | 0.240 98 | 0.230 28 | 0.209 16 | 0.208 34 | 0.203 22 |
| 71 Lu | 0.233 58 | 0.2282 | 0.202 52 | 0.201 71 | 0.196 49 |
| 72 Hf | 0.226 53 | 0.221 73 | 0.195 83 | 0.195 15 | 0.190 42 |
| 73 Ta | 0.219 73 | 0.214 88 | 0.189 91 | | 0.184 52 |
| 74 W | 0.213 37 | 0.208 56 | 0.184 75 | 0.183 97 | 0.179 06 |
| 76 Os | 0.201 31 | 0.196 45 | 0.173 61 | | 0.168 75 |
| 77 Ir | 0.195 50 | 0.190 65 | 0.168 50 | | 0.163 76 |
| 78 Pt | 0.190 04 | 0.182 23 | 0.163 70 | | 0.158 87 |
| 79 Au | 0.184 83 | 0.179 96 | 0.159 02 | | 0.154 26 |
| 81 Tl | 0.174 66 | 0.169 80 | 0.150 11 | | 0.145 39 |
| 82 Pb | 0.170 04 | 0.165 16 | 0.146 06 | | 0.141 25 |
| 83 Bi | 0.165 25 | 0.160 41 | 0.142 05 | | 0.136 21 |
| 92 U | 0.130 95 | 0.126 40 | 0.111 87 | | 0.108 42 |

(From *Smithsonian Physical Tables.*)

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*Wavelengths of the more prominent L group lines (Ångstrom)*

| Siegbahn | | $\alpha_2$ | $\alpha_1$ | $\beta_1$ | $l$ | $\eta$ |
|---|---|---|---|---|---|---|
| Sommerfeld | | $\alpha'$ | $\alpha$ | $\beta$ | $\varepsilon$ | $\eta$ |
| transition | | $L_{III}$–$M_{IV}$ | $L_{III}$–$M_V$ | $L_{II}$–$M_V$ | $L_{III}$–$M_I$ | $L_{II}$–$M_I$ |
| 16 | S | ... | | ... | 83.75 | |
| 20 | Ca | 36.27 | | ... | 40.90 | |
| 21 | Sc | 31.37 | | ... | 35.71 | |
| 22 | Ti | 27.37 | | ... | 31.33 | |
| 23 | V | 24.31 | | ... | 27.70 | |
| 24 | Cr | 21.53 | | 21.19 | 23.84 | 23.28 |
| 25 | Mn | 19.40 | | 19.04 | 22.34 | |
| 26 | Fe | 17.57 | | 17.23 | 20.09 | 19.76 |
| 27 | Co | 15.93 | | 15.63 | 18.25 | 17.86 |
| 28 | Ni | 14.53 | | 14.25 | 16.66 | 16.28 |
| 29 | Cu | 13.306 | | 13.027 | 15.26 | 14.87 |
| 30 | Zn | 12.229 | | 11.960 | 13.97 | 13.61 |
| 31 | Ga | 11.27 | | 11.01 | 12.89 | 12.56 |
| 32 | Ge | 10.415 | | 10.153 | 11.922 | 11.587 |
| 33 | As | 9.652 | | 9.395 | 11.048 | 10.711 |
| 34 | Se | 8.972 | | 8.718 | 10.272 | 9.939 |
| 35 | Br | 8.358 | | 8.109 | 9.564 | 9.235 |
| 37 | Rb | 7.3027 | | | | |
| 38 | Sr | 6.8486 | | 6.610 | 7.822 | 7.506 |
| 39 | Y | 6.4357 | | 6.2039 | ... | 7.0310 |
| | | | | | $\beta_2$ | $\gamma_1$ |
| | | | | | $\gamma$ | $\delta$ |
| | | | | | $L_{III}$–$N_V$ | $L_{II}$–$N_{IV}$ |
| 40 | Zr | 6.057 | | 5.8236 | 5.5742 | 5.3738 |
| 41 | Nb | 5.718 | 5.7120 | 5.4803 | 5.2260 | 5.0248 |
| 42 | Mo | 5.401 | 5.3950 | 5.1665 | 4.9100 | |
| 44 | Ru | 4.8437 | 4.8357 | 4.6110 | 4.3619 | 4.1728 |
| 45 | Rh | 4.5956 | 4.5878 | 4.3640 | 4.1221 | 3.9357 |
| 46 | Pd | 4.3666 | 4.3585 | 4.1373 | 3.9007 | 3.7164 |
| 47 | Ag | 4.1538 | 4.1456 | 3.9266 | 3.6938 | 3.5149 |
| 48 | Cd | 3.9564 | 3.9478 | 3.7301 | 3.5064 | 3.3280 |
| 49 | In | 3.7724 | 3.7637 | 3.5478 | 3.3312 | 3.1553 |
| 50 | Sn | 3.601 51 | 3.592 57 | 3.3779 | 3.168 61 | 2.994 94 |
| 51 | Sb | 3.4408 | 3.4318 | 3.2184 | 3.0166 | 2.8451 |
| 52 | Te | 3.2910 | 3.2820 | 3.0700 | 2.8761 | 2.7065 |
| 53 | I | 3.1509 | 3.1417 | 2.9309 | 2.7461 | 2.5775 |
| 55 | Cs | 2.8956 | 2.8861 | 2.6778 | 2.5064 | 2.3425 |
| 56 | Ba | 2.7790 | 2.7696 | 2.5622 | 2.3993 | 2.2366 |
| 57 | La | 2.6689 | 2.6597 | 2.4533 | 2.2980 | 2.1372 |
| 58 | Ce | 2.5651 | 2.5560 | 2.3510 | 2.2041 | 2.0443 |
| 59 | Pr | 2.4676 | 2.4577 | 2.2539 | 2.1148 | 1.9568 |
| 60 | Nd | 2.3756 | 2.3653 | 2.1622 | 2.0314 | 1.8738 |
| 62 | Sm | 2.2057 | 2.1950 | 1.9936 | 1.8781 | 1.7231 |
| 63 | Eu | 2.1273 | 2.1163 | 1.9163 | 1.8082 | 1.6543 |

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***Wavelengths of the more prominent L group lines*** *(cont.)*

| Siegbahn<br>Sommerfeld<br>transition | $\alpha_2$<br>$\alpha'$<br>$L_{III}$–$M_{IV}$ | $\alpha_1$<br>$\alpha$<br>$L_{III}$–$M_V$ | $\beta_1$<br>$\beta$<br>$L_{II}$–$M_V$ | $l$<br>$\varepsilon$<br>$L_{III}$–$M_I$ | $\eta$<br>$\eta$<br>$L_{II}$–$M_I$ |
|---|---|---|---|---|---|
| 64 Gd | 2.0526 | 2.0419 | 1.8425 | 1.7419 | 1.5886 |
| 65 Tb | 1.9823 | 1.9715 | 1.7727 | 1.6790 | 1.5266 |
| 66 Dy | 1.9156 | 1.9046 | 1.7066 | 1.6198 | 1.4697 |
| 67 Ho | 1.8521 | 1.8410 | 1.6435 | 1.5637 | 1.4142 |
| 68 Er | 1.792 02 | 1.780 68 | 1.584 09 | 1.510 94 | 1.3611 |
| 69 Tm | 1.7339 | 1.7228 | 1.5268 | 1.4602 | 1.3127 |
| 70 Yb | 1.679 42 | 1.668 44 | 1.4725 | 1.412 61 | 1.265 12 |
| 71 Lu | 1.6270 | 1.616 17 | 1.420 67 | 1.367 31 | 1.219 74 |
| 72 Hf | 1.577 04 | 1.566 07 | 1.3711 | 1.3235 | 1.1765 |
| 73 Ta | 1.529 78 | 1.518 85 | 1.324 23 | 1.281 90 | 1.135 58 |
| 74 W | 1.484 38 | 1.473 36 | 1.279 17 | 1.242 03 | 1.096 30 |
| 75 Re | 1.4410 | 1.429 97 | 1.236 03 | 1.2041 | 1.0587 |
| 76 Os | 1.398 66 | 1.388 59 | 1.194 90 | 1.168 84 | 1.022 96 |
| 77 Ir | 1.3598 | 1.348 47 | 1.155 40 | 1.132 97 | 0.988 76 |
| 78 Pt | 1.321 55 | 1.310 33 | 1.117 58 | 1.099 74 | 0.955 99 |
| 79 Au | 1.285 02 | 1.273 77 | 1.081 28 | 1.068 01 | 0.924 61 |
| 80 Hg | 1.249 51 | 1.238 63 | 1.046 52 | 1.037 70 | 0.8946 |
| 81 Tl | 1.216 26 | 1.204 93 | 1.012 99 | 1.008 22 | 0.865 71 |
| 82 Pb | 1.184 08 | 1.172 58 | 0.980 83 | 0.980 83 | 0.838 01 |
| 83 Bi | 1.153 01 | 1.141 50 | 0.950 02 | 0.953 24 | 0.811 43 |
| 90 Th | 0.965 85 | 0.954 05 | 0.763 56 | 0.791 92 | 0.651 76 |
| 91 Pa | 0.9427 | 0.9309 | 0.7407 | 0.7721 | 0.6325 |
| 92 U | 0.920 62 | 0.908 74 | 0.718 51 | 0.753 07 | 0.613 59 |

(From *Smithsonian Physical Tables*.)

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