Exam Materials Science

January 30, 2023, 8:30 - 10:30
Exam Hall 1 Blauwborgje 4

- *Separate Exercise 1 sheet from others, write your name and s-number on the top, mark correct answers and use it as your first answer sheet.*
- *Make the exercises 2 to 4 each on a separate two-sheets paper.*
- *Clearly indicate your name and student number on each separate sheet of paper.*
- *Indicate on the first sheet the total number of papers you hand in.*

Mark for the exam = 1 + 9*((sum of total points scored) / (max. number of points (65))

Suggestions:

- *Work fast and write down answers concisely.*
- *When you have difficulty to find an answer and to formulate it, do not keep on thinking for a long time, but move to the next question. Then, come back to this (skipped and unanswered) question later when you still have time.*

Exercise 1: Quiz (15p: maximal number of points 30 divided by 2)
Mark by cross the correct answer(s). Separate this page from others, write your name and s-number on the top and use it as your first answer sheet.

1. **What is the highest number of covalent bonds that Carbon atom may offer?**
   ☐ 3
   ☒ 4
   ☐ 5

2. **What value of electrical conductivity would you expect for solid having dominantly:**

	high	low
metallic bonding	☒	☐
ionic bonding	☐	☒
covalent bonding	☐	☒

3. **Grain boundary is 2D structural defect existing in:**
   ☐ amorphous material
   ☐ single crystal
   ☒ polycrystalline material

4. **Sort different arrangements of atoms in solids, according to value of atomic packing fraction!**

	high	middle	low
face centred cubic	☒	☐	☐
body centred cubic	☐	☒	☐
close packed hexagonal	☒	☐	☐
amorphous	☐	☐	☒

5. **Typical precipitation hardening process consists of following subsequent steps:**
   ☒ 1. Heating at higher temperature; 2. Fast quenching; 3. Heating at lower temperature
   ☐ 1. Fast cooling from liquid state; 2. Heating at middle temperature
   ☐ 1. Long-time heating just under eutectoid temperature; 2. Fast quenching

6. **Polymers are exclusively synthetic materials formed by additional or condensation polymerization.**
   ☐ true
   ☒ false

7. **Indicate typical mechanical characteristics for three different groups of materials:**

	Strength		**Ductility**		**Young's mod.**	
	High	Low	High	Low	High	Low
Ceramics	☒	☐	☐	☒	☒	☐
Metals	☒	☐	☒	☐	☒	☐
Plastics	☐	☒	☒	☐	☐	☒

8. **Classify following defects in solids according their dimensionality!**

	point	linear	planar	volume
surface crack	☐	☐	☐	☒
vacancy	☒	☐	☐	☐
stacking fault	☐	☐	☒	☐
edge dislocation	☐	☒	☐	☐
interstitial atom	☒	☐	☐	☐
grain boundary	☐	☐	☒	☐
precipitate	☐	☐	☐	☒

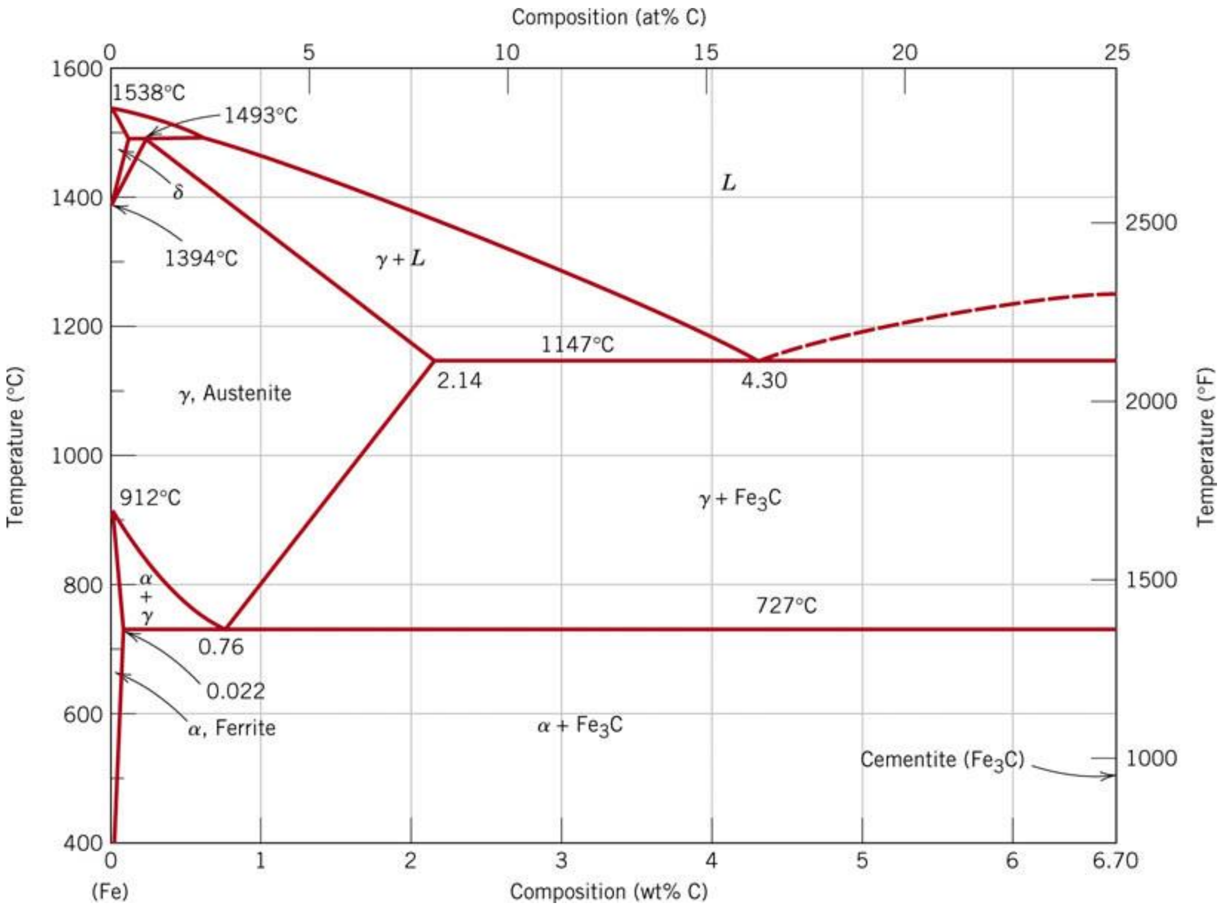
9. **We observe a huge difference in electrical conductivity in different types of materials? It is mainly due to a large difference in:**
   ☒ density of their free charge carriers
   ☐ size of electric charge of their charge free carriers
   ☐ mobility of their free charge carriers

10. **The size of the energetic band gap between the Valence and the Conduction band in insulators is typically:**
    ☐ ~ 1 eV
    ☒ > 3 eV
    ☐ may be any value because the position of Fermi energy level is important

11. **The presence of dielectric material between plates of a capacitor in comparison with the vacuum between them:**
    ☐ decreases its capacity
    ☒ increases its capacity
    ☐ has no influence

Exercise 2 (15p)

Attached figure shows a part of Fe-Fe$_3$C phase diagram, the base of steel.



a) Name all the areas in this phase diagram that contain only a single phase. (2p)
These are: area with liquid phase L and 3 areas with solid phase: δ, γ and α. (1/2p for each named area)

b) We have an Fe-C alloy with 2 wt.% C slowly cooling down from 1 600 °C to room temperature. At what temperature does the first (tiny amount of) solid form? Give the composition (value) of this solid. (2p)
About 1380 ºC, clearly above 1360 and below 1394 ºC. The composition is about 0.8 wt.% C (0.7 and 0.9 can be accepted, but not outside this range). (2p)

c) At what temperature does the last liquid drop disappear in this 2 wt.% C alloy upon further cooling? What is the composition (value) of this last liquid? (2p)
About 1180 ºC (plus min max 10 ºC). About 4.0-4.2 wt.% C. (2p)

d) Suppose a Fe-C alloy with a certain amount of C is cooled down to 728 °C. Only austenite and cementite phases are observed, and the weight fraction of austenite is measured to be 0.9. What is the concentration of C in the alloy? Show how you compute your answer. (2p)
Using the lever rule at 728 ºC: 0.9 = (6.7- x)/(6.7-0.76) or also 0.1 = (x-0.76)/(6.7-0.76), which both lead to x =1.354 wt.% C. (2p)

e) At what temperature will the eutectoid pearlite be formed from austenite? Compute the fractions of the phases present in pearlite. (3p)
At temperature just below 727 ºC (1p). Pearlite fractions: α = (6.7 - 0.76)/(6.7 - 0.022) = 0.889 (1p), fraction Fe$_3$C = (0.76 - 0.022)/(6.7 - 0.022) = 0.111. (1p)

f) Cold rolling and after annealing can be used to strengthen low Carbon steels. Explain how cold rolling can strengthen the steel (1p). Why can it be necessary to anneal cold rolled steel? (2p) Still, also few various cycles of cold-rolling and recrystallizing the steel can be strengthened compared to the original material. Explain how this is possible. (1p)
Cold rolling increases strength, because it increases the dislocation density and since dislocations are mutual obstacles during their movement, it also decreases dislocation mobility and thereby increases (yield) strength. (1p)

Cold rolling creates texture and this leads to anisotropic properties (i.e. properties are not the same in different directions. This is often not acceptable. (1p) Annealing leads to recrystallization and thereby it removes texture and anisotropy. (1p)

Cycles of cold rolling and recrystallization generally are used to refine the grains of the material. Smaller grain size leads to relative more grain boundary density (per unit volume) and since boundaries are obstacles for dislocations movement, it decreases dislocation mobility and thereby increases (yield) strength. (1p)

Exercise 3 (16p)

We have a crane whose vertical arm has a cross-sectional area of $5x5\ cm^2$, and a length of $5\ m$. This arm is loaded parallel to its length. We know that it behaves according to linear elasticity for the regime we are working. The manufacturer told us that this behavior will stop when the load exceeds $100\ 000\ kg$, i.e. 100 tons. This load will produce an elongation of the arm of the crane of $1\ cm$.

a) Calculate the yield strength of the material. (2p)

$\sigma_y = \frac{F}{A} = \frac{100\ 000\ kg}{25\ cm^2} = 4\ 000\ {}^{kg}/{}_{cm^2} = 4\ 000\ x\ 9.81\ N/(0.01x0.01)m^2 \approx 400\ MPa$ (2p)

b) Calculate the yield strain of the crane arm material. (2p)

$\varepsilon_{\parallel} = \frac{\Delta l}{l} = \frac{0.01\ m}{5\ m} = 0.002 = 0.2\ \%$ (2p)

c) Calculate the Young's modulus of the crane arm material. (1p)

$\sigma = E\ .\ \varepsilon_{\parallel} \Longrightarrow E = \frac{\sigma}{\varepsilon_{\parallel}} = \frac{400\ MPa}{0.002} = 200\ GPa$ (1p)

d) If the Poisson ratio is 0.3, calculate in terms of percentage the reduction in cross-sectional area due to a loading of $100\ 000\ kg$. (3p)

$((1 + \varepsilon_{\perp})^2 - 1^2) * 100\ \% = (2\varepsilon_{\perp} + \varepsilon_{\perp}{}^2) * 100\ \% \approx 2\varepsilon_{\perp} * 100\ \%$

$\varepsilon_{\perp} = -\nu . \varepsilon_{\parallel} \Rightarrow 2\varepsilon_{\perp} * 100\ \% = 2 * (-0.3) * 0.002 * 100\ \% = -0.12\ \%$

The minus means the reduction of cross-sectional area. (3p)

e) What happens both on a macroscopic and an atomic scale in the metal when the load exceeds yield strength? Each of the two answers is possible in one sentence. (4p)

On a macroscopic scale the length of the arm will increase permanently after the loading beyond yield strength, because of plastic deformation. (2p) Up to yield strength the loading is fully elastic.

On an atomic scale the plastic deformation normally means that atomic planes start sliding with respect to each other. (2p) This sliding occurs by the movement of dislocations.

f) Would it make a difference for the mechanical behavior of material near yielding if it has a crystalline or an amorphous structure? Motivate your answer. (4p)

Yes, it makes a large difference, because in crystalline systems plastic deformation and thus strengthening can occur by sliding of crystal planes with respect to each other. (2p)

In amorphous materials slip along planes is impossible (there are no planes) and therefore such materials are very resistant to plastic deformation (are very hard), but also very brittle (very low fracture toughness) and cannot be used with any reliability under tensile loading. (2p)

Exercise 4 (19p)

a) At room temperature, the resistivity of diamond is 10^{20} times higher than the one of pure Ag. Explain how this is possible and which physical quantity is responsible for it. (2p)
For the conductivity in case of electron conduction it holds: $\sigma = n|e|\mu_e$. The huge difference in resistivity (1/conductivity) between diamond and Ag is caused by the huge difference in *n*, i.e., the number of free electrons, i.e., conduction electrons. (1p) This difference is caused by the strong localization of electrons in diamond, i.e., each valence electron is really strongly bound to its own carbon atoms such that *n* is extremely low, whereas in a metal like Ag, each atom donates at least one electron to a sea of delocalized electrons which can move relatively freely throughout the material giving a very high *n*. (1p)

b) What will happen to the difference in resistivity of these two materials if the temperature is increased for example to 300 ºC? Explain this by discussing how temperature affects the resistivity of both discussed types of materials. (4p)
This huge difference will reduce (1p), because for semiconductors or insulators the resistivity decreases with increasing temperature, whereas for metals it will increase. (1p) The reason for decreasing resistivity of diamond is that the number of free charge carriers (conduction electrons) will increase, because more electrons obtain now sufficient thermal energy to jump across the band gap with increasing temperature. (1p) The reason for increasing resistivity of Ag is that the number of free charge carriers (conduction electrons) will not change, but the mobility μ_e will decrease because electrons will be scattered more strongly on atoms which due the higher temperature vibrate more heavily (electron/phonon interaction becomes stronger at higher temperatures). (1p)

c) Natural blue diamonds are semiconductors due to substitutional boron impurities replacing carbon atoms. Nowadays we can also make these semiconductors synthetically. What type of semiconductor do we have here, i.e., an electron or hole conductor? Explain why the resistivity of these boron doped diamond at room temperature can be many orders of magnitude lower than of pure diamond (which is transparent and colourless). (3p)
Boron doped diamond is a p-type semiconductor, i.e., a hole type conductor, because B has one valence electron less than C. (1p) The resistivity of these boron doped diamond can be many orders of magnitude lower than of pure diamond, because the boron atoms create an acceptor level in the band gap at an energy not much higher than the top of the valence band. Electrons from the C atoms can therefore jump easily into these acceptor level and leave holes behind which can travel relatively freely throughout the material. (1p) This is not possible in pure diamond, because its valence electrons have to jump across the total bandgap and thus need much more energy for this jump. At a certain limited temperature like room temperature thermal energy is thus sufficient to create a large number of charge carriers in B-doped diamond, whereas this is not possible for pure diamond. (1p)

d) We have silicon doped with gallium, where on average for each 10^7 crystal unit cells (lattice parameter of the cell a_{Si}=0.543 nm) 1 gallium atom is present. What type of semiconductor do we have here, i.e., intrinsic, extrinsic p-type or extrinsic n-type? At room temperature, the mobility of electrons μ_e= 0.19 m^2/(Vs) and of holes μ_h= 0.045 m^2/(Vs). The unit charge e = - 0.16 x10^{-18} C. Compute the conductivity of this semiconductor you expect at room temperature (e.g. in extrinsic temperature region). (3p)

Ga-doped Si is a p-type extrinsic semiconductor, because Ga has one valence electron less than Si (1p). The expected conductivity at room temperature (all holes are activated) is:

$$\sigma = p|e|\mu_h = \frac{1}{10^7(0.543\,x10^{-9})^3}\,x\,0.16\,x10^{-18}\,x\,0.045 = 4.5\,(\Omega m)^{-1}.\ (2p)$$

e) We now dope the sample of exercise d) (i.e., including the gallium atoms) with arsenic atoms such that 1 arsenic atom is added to each 2 x10^7 unit cells. What type of semiconductor do we have now? Compute the conductivity you expect now at room temperature (where we assume that the additional arsenic doping does not affect the mobilities, although this is not strictly correct). (3p)

As is an n-type dopant that will compensate the p-type Ga. However, the amount of added As is only half of the amount of Ga. Therefore, the Si remains a p-type semiconductor (only in case the concentration of As would have been larger than of Ga it would change Si into n-type). (1p) Since only half of the holes remain uncompensated compared to question d), the conductivity becomes a factor 2 lower:

$$\sigma = p|e|\mu_h = \frac{1}{2\,x10^7(0.543\,x10^{-9})^3}\,x\,0.16\,x10^{-18}\,x\,0.045 = 2.25\,(\Omega m)^{-1}\ .\ (2p)$$

f) At room temperature the electrical conductivity and the electron mobility for Aluminium are 3.8 x10^7 (Ω m)$^{-1}$ and 0.0012 m^2/(V.s), respectively. Compute the number of free electrons per cubic meter for Aluminium at room temperature and determine the number of free electrons per one Aluminium atom?

Use for charge of single electron: -1.602 x10^{-19} C, Avogadro number N_A= *6.022 x10*^{23} atoms/mol, for density and atomic weight of Aluminium: $\rho' =$ 2.7 g/cm^3 and $A_{Al} =$ 26.98 g/mol, respectively. (4p)

The number of free electrons per cubic meter for aluminium at room temperature may be computed using the equation:

$$n = \frac{\sigma}{|e|\,\mu_e} =$$

$$= \frac{3.8\,x10^7\,(\Omega\,.\,m)^{-1}}{(1.602\,x10^{-19}\,C)\big(0.0012\,m^2/(V.s)\big)} = 1.98\,x10^{29}\,m^{-3}\quad (2p)$$

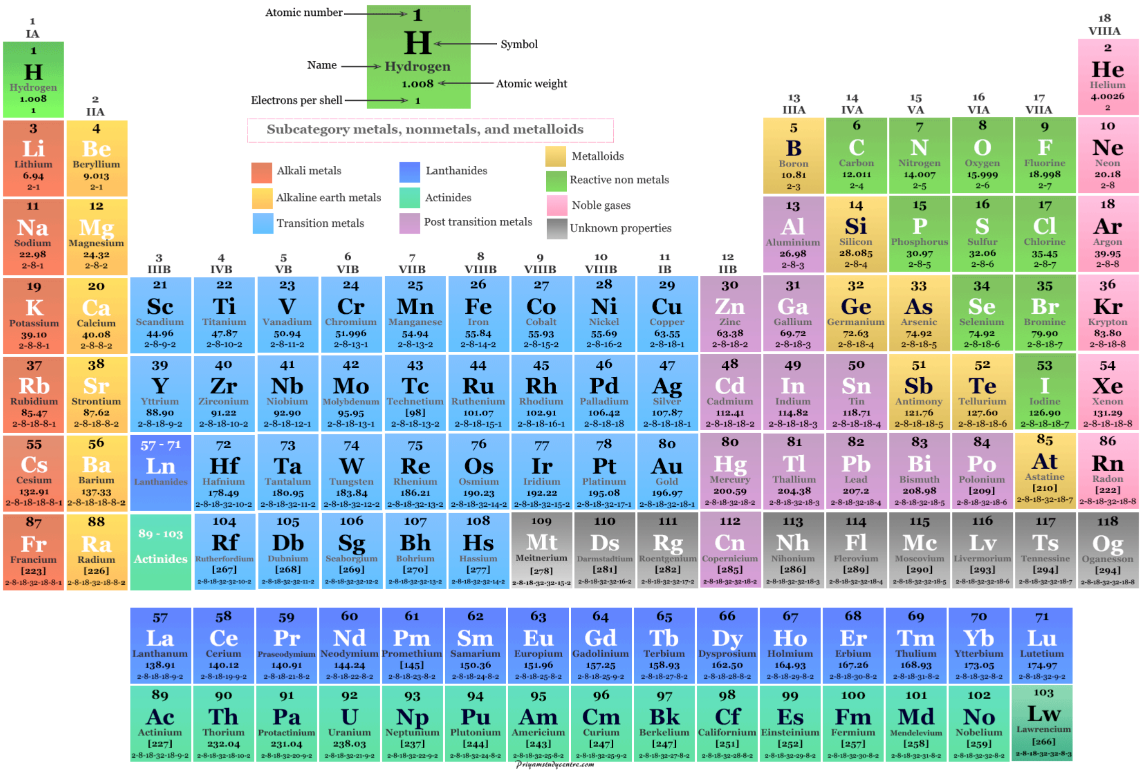
In order to calculate the number of free electrons per aluminium atom, we must first determine the number of aluminium atoms per cubic meter, N_{Al}:

$$N_{Al} = \frac{N_A\,.\,\rho'}{A_{Al}} = \frac{(6.022\,x10^{23}\,atoms/mol).(2.7\,g/cm^3).(10^6\,cm^3/m^3)}{26.98\,g/mol} =$$

$$= 6.03\,x10^{28}\,m^{-3}$$

And, finally the number of free electrons per copper atom is just n/N_{Cu}:

$$\frac{n}{N_{Al}} = \frac{1.98\ x10^{29}\ m^{-3}}{6.03\ x10^{28}\ m^{-3}} = 3.28. \quad (2p)$$



Atomic number → 1
Symbol ← H
Name → Hydrogen
Atomic weight ← 1.008
Electrons per shell → 1

Subcategory metals, nonmetals, and metalloids

- 🟥 Alkali metals
- 🟨 Alkaline earth metals
- 🟦 Transition metals
- 🟦 Lanthanides
- 🟩 Actinides
- 🟪 Post transition metals
- 🟨 Metalloids
- 🟩 Reactive non metals
- 🟥 Noble gases
- ⬜ Unknown properties

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.008 1																	2 He Helium 4.0026 2
3 Li Lithium 6.94 2-1	4 Be Beryllium 9.013 2-1											5 B Boron 10.81 2-3	6 C Carbon 12.011 2-4	7 N Nitrogen 14.007 2-5	8 O Oxygen 15.999 2-6	9 F Fluorine 18.998 2-7	10 Ne Neon 20.18 2-8
11 Na Sodium 22.98 2-8-1	12 Mg Magnesium 24.32 2-8-2											13 Al Aluminium 26.98 2-8-3	14 Si Silicon 28.085 2-8-4	15 P Phosphorus 30.97 2-8-5	16 S Sulfur 32.06 2-8-6	17 Cl Chlorine 35.45 2-8-7	18 Ar Argon 39.95 2-8-8
19 K Potassium 39.10 2-8-8-1	20 Ca Calcium 40.08 2-8-8-2	21 Sc Scandium 44.96 2-8-9-2	22 Ti Titanium 47.87 2-8-10-2	23 V Vanadium 50.94 2-8-11-2	24 Cr Chromium 51.996 2-8-13-1	25 Mn Manganese 54.94 2-8-13-2	26 Fe Iron 55.84 2-8-14-2	27 Co Cobalt 55.93 2-8-15-2	28 Ni Nickel 55.69 2-8-16-2	29 Cu Copper 63.55 2-8-18-1	30 Zn Zinc 63.38 2-8-18-2	31 Ga Gallium 69.72 2-8-18-3	32 Ge Germanium 72.63 2-8-18-4	33 As Arsenic 74.92 2-8-18-5	34 Se Selenium 74.92 2-8-18-6	35 Br Bromine 79.90 2-8-18-7	36 Kr Krypton 83.80 2-8-18-8
37 Rb Rubidium 85.47 2-8-18-8-1	38 Sr Strontium 87.62 2-8-18-8-2	39 Y Yttrium 88.90 2-8-18-9-2	40 Zr Zirconium 91.22 2-8-18-10-2	41 Nb Niobium 92.90 2-8-18-12-1	42 Mo Molybdenum 95.95 2-8-18-13-1	43 Tc Technetium [98] 2-8-18-13-2	44 Ru Ruthenium 101.07 2-8-18-15-1	45 Rh Rhodium 102.91 2-8-18-16-1	46 Pd Palladium 106.42 2-8-18-18	47 Ag Silver 107.87 2-8-18-18-1	48 Cd Cadmium 112.41 2-8-18-18-2	49 In Indium 114.82 2-8-18-18-3	50 Sn Tin 118.71 2-8-18-18-4	51 Sb Antimony 121.76 2-8-18-18-5	52 Te Tellurium 127.60 2-8-18-18-6	53 I Iodine 126.90 2-8-18-18-7	54 Xe Xenon 131.29 2-8-18-18-8
55 Cs Cesium 132.91 2-8-18-18-8-1	56 Ba Barium 137.33 2-8-18-18-8-2	57 - 71 Ln Lanthanides	72 Hf Hafnium 178.49 2-8-18-32-10-2	73 Ta Tantalum 180.95 2-8-18-32-11-2	74 W Tungsten 183.84 2-8-18-32-12-2	75 Re Rhenium 186.21 2-8-18-32-13-2	76 Os Osmium 190.23 2-8-18-32-14-2	77 Ir Iridium 192.22 2-8-18-32-15-2	78 Pt Platinum 195.08 2-8-18-32-17-1	80 Au Gold 196.97 2-8-18-32-18-1	80 Hg Mercury 200.59 2-8-18-32-18-2	81 Tl Thallium 204.38 2-8-18-32-18-3	82 Pb Lead 207.2 2-8-18-32-18-4	83 Bi Bismuth 208.98 2-8-18-32-18-5	84 Po Polonium [209] 2-8-18-32-18-6	85 At Astatine [210] 2-8-18-32-18-7	86 Rn Radon [222] 2-8-18-32-18-8
87 Fr Francium [223] 2-8-18-32-18-8-1	88 Ra Radium [226] 2-8-18-32-18-8-2	89 - 103 Actinides	104 Rf Rutherfordium [267] 2-8-18-32-32-10-2	105 Db Dubnium [268] 2-8-18-32-32-11-2	106 Sg Seaborgium [269] 2-8-18-32-32-12-2	107 Bh Bohrium [270] 2-8-18-32-32-13-2	108 Hs Hassium [277] 2-8-18-32-32-14-2	109 Mt Meitnerium [278] 2-8-18-32-32-15-2	110 Ds Darmstadtium [281] 2-8-18-32-32-16-2	111 Rg Roentgenium [282] 2-8-18-32-32-17-2	112 Cn Copernicium [285] 2-8-18-32-32-18-2	113 Nh Nihonium [286] 2-8-18-32-32-18-3	114 Fl Flerovium [289] 2-8-18-32-32-18-4	115 Mc Moscovium [290] 2-8-18-32-32-18-5	116 Lv Livermorium [293] 2-8-18-32-32-18-6	117 Ts Tennessine [294] 2-8-18-32-32-18-7	118 Og Oganesson [294] 2-8-18-32-32-18-8
		57 La Lanthanum 138.91 2-8-18-18-9-2	58 Ce Cerium 140.12 2-8-18-19-9-2	59 Pr Praseodymium 140.91 2-8-18-21-8-2	60 Nd Neodymium 144.24 2-8-18-22-8-2	61 Pm Promethium [145] 2-8-18-23-8-2	62 Sm Samarium 150.36 2-8-18-24-8-2	63 Eu Europium 151.96 2-8-18-25-8-2	64 Gd Gadolinium 157.25 2-8-18-25-9-2	65 Tb Terbium 158.93 2-8-18-27-8-2	66 Dy Dysprosium 162.50 2-8-18-28-8-2	67 Ho Holmium 164.93 2-8-18-29-8-2	68 Er Erbium 167.26 2-8-18-30-8-2	69 Tm Thulium 168.93 2-8-18-31-8-2	70 Yb Ytterbium 173.05 2-8-18-32-8-2	71 Lu Lutetium 174.97 2-8-18-32-9-2	
		89 Ac Actinium [227] 2-8-18-32-18-9-2	90 Th Thorium 232.04 2-8-18-32-18-10-2	91 Pa Protactinium 231.04 2-8-18-32-20-9-2	92 U Uranium 238.03 2-8-18-32-21-9-2	93 Np Neptunium [237] 2-8-18-32-22-9-2	94 Pu Plutonium [244] 2-8-18-32-24-8-2	95 Am Americium [243] 2-8-18-32-25-8-2	96 Cm Curium [247] 2-8-18-32-25-9-2	97 Bk Berkelium [247] 2-8-18-32-27-8-2	98 Cf Californium [251] 2-8-18-32-28-8-2	99 Es Einsteinium [252] 2-8-18-32-29-8-2	100 Fm Fermium [257] 2-8-18-32-30-8-2	101 Md Mendelevium [258] 2-8-18-32-31-8-2	102 No Nobelium [259] 2-8-18-32-32-8-2	103 Lw Lawrencium [266] 2-8-18-32-32-8-3	

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