Student Number  |__|__|__|__|__|__|__|__|

Family Name  _____

First Name  _____

# School of Mathematics & Physics

# EXAMINATION

Semester One Final Examinations, 2020

## PHYS2020 Thermodynamics and Condensed Matter Physics

*This paper is for St Lucia Campus students.*

**For Examiner Use Only**

| Question | Mark |
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Total  _____

**Examination Duration:** 120 minutes (+ additional 30 mins encompassing reading time, and time to scan and upload solutions). You must commence your exam at the time listed in your personalised timetable. The exam will remain open **only** for the duration shown

**Materials Permitted In The Exam Venue:** This is an Open Book exam. Students are allowed to use a computer and all forms of calculator. No consultation or collaboration is allowed on the exam questions, whether face-to-face, over the phone, over the internet, through social media or otherwise.

**Instructions To Students:** You can print the exam and write on the exam paper, or write your answers on blank paper, or write electronically on a suitable device. Scan or photograph your work if necessary and upload your answers to Blackboard as a single pdf file.

The exam consists of two parts. Complete **all four** questions in Part A. Complete **two of three** questions in Part B.

Each question will be marked with a grade between 1 and 7. Overall exam grades will be calculated as a weighted average, with each question in Part B receiving twice the weighting of those in Part A (so that Parts A and B contribute equally overall).

**Who to Contact:** Course staff will not be able to respond to academic queries during the exam. If you have any concerns or queries about a particular question, or need to make any assumptions to answer the question, state these at the start of your solution to that question. You may also include queries you might have made with respect to a particular question, were you able to 'raise your hand' in an examination room.

If you experience any technical difficulties during the exam, contact the Library AskUs service via the Live Chat or Phone for advice (open 7:00am – 10:00pm AEST every day during the final exam period). You should ask the library staff for an email documenting the advice provided so you can provide this to the course coordinator.

**Certification (must be signed before submission):**
*I certify that my submitted answers are entirely my own work and that I have neither given nor received any unauthorised assistance on this assessment item.*

Signed:_____Date:_____

# Part A

*Answer all questions in this section*

## Question 1

Four kilograms of water vapour (corresponding to 221 moles) is heated from 300 K to 800 K at a constant pressure of 10 kPa.

(a) How many quadratic degrees of freedom would you expect to be active for each water molecule? Explain.

(b) Assuming that the water vapour behaves as an ideal gas with this number of degrees of freedom, calculate its heat capacity at constant pressure $C_P$. From this determine the heat $Q$ required to increase the temperature to 800 K.

(c) Check your calculation by also calculating $Q$ from the data in the superheated steam table below. Discuss the level of agreement, and what might cause any discrepancies.

| $T$ (°C) | $1/\rho$ (m³ kg⁻¹) | $u$ (kJ kg⁻¹) | $h$ (kJ kg⁻¹) | $s$ (kJ kg⁻¹ K⁻¹) |
|---|---|---|---|---|
| sat | 14.674 | 2437.9 | 2584.6 | 8.1501 |
| 50 | 14.869 | 2443.9 | 2592.6 | 8.1749 |
| 100 | 17.196 | 2515.5 | 2687.5 | 8.4479 |
| 150 | 19.513 | 2587.9 | 2783.0 | 8.6881 |
| 200 | 21.825 | 2661.3 | 2879.5 | 8.9037 |
| 250 | 24.136 | 2736.0 | 2977.3 | 9.1002 |
| 300 | 26.445 | 2812.1 | 3076.5 | 9.2812 |
| 400 | 31.063 | 2968.9 | 3279.5 | 9.6076 |
| 500 | 35.679 | 3132.3 | 3489.0 | 9.8977 |
| 600 | 40.295 | 3302.5 | 3705.4 | 10.1608 |
| 700 | 44.911 | 3479.6 | 3928.7 | 10.4028 |
| 800 | 49.526 | 3663.8 | 4159.1 | 10.6281 |
| 900 | 54.141 | 3855.0 | 4396.4 | 10.8395 |
| 1000 | 58.757 | 4053.0 | 4640.6 | 11.0392 |
| 1100 | 63.372 | 4257.5 | 4891.2 | 11.2287 |
| 1200 | 67.987 | 4467.9 | 5147.8 | 11.4090 |
| 1300 | 72.603 | 4683.7 | 5409.7 | 11.5810 |

Figure 1: Superheated steam table at $P = 10$ kPa. $T$, temperature; $\rho$, density; $u$, energy density; $h$, specific enthalphy; $s$, specific entropy.

## Question 2

Two copper blocks have masses $m_A$ and $m_B$, and initial temperatures $T_A$ and $T_B$, respectively. They are placed in thermal contact while being kept well insulated from the environment.

(a) By considering the heat transfer between the blocks and assuming that their specific heat capacity at constant pressure $c_P$ is constant over the temperature range of interest, show that in equilibrium they reach a temperature of

$$T_F = \frac{m_A T_A + m_B T_B}{m_A + m_B}.$$

Check that this expression gives sensible results in appropriate limits.

(b) If $m_A = 1$ kg, $m_B = 2$ kg, $T_A = 300$ K and $T_B = 305$ K, how much does the entropy of the universe change after the blocks are placed in contact? Discuss this result. Note: over this range of temperatures the specific heat capacity at constant pressure of copper can be well approximated as $c_P = 386$ J K$^{-1}$ kg$^{-1}$.

## Question 3

(a) Using the thermodynamic identity and Maxwell's relations show that changes in the internal energy $U$ of a substance can be related to changes in temperature $T$, volume $V$ and pressure $P$ via

$$dU = C_V dT + \left( T \left( \frac{\partial P}{\partial T} \right)_V - P \right) dV,$$

where $C_V$ is the heat capacity at constant volume. Hint: an incremental change in entropy $dS$ may be expanded as

$$dS = \left( \frac{\partial S}{\partial T} \right)_V dT + \left( \frac{\partial S}{\partial V} \right)_T dV.$$

(b) Consider a van der Waals gas that undergoes a change in volume and pressure at constant temperature. Use the relationship given in (a) to show that the change internal energy is

$$\Delta U_T = an^2 \left( \frac{1}{V_i} - \frac{1}{V_f} \right),$$

where $a$ is the constant used to introduce attractive forces in van der Waals equation, $n$ is the number of moles of gas, and the subscripts $i$ and $f$ label the state variables in the initial and final states, respectively.

(c) Compare your result from (b) to what you would expect for an ideal gas, and suggest reasons for any differences.

## Question 4

(a) In your own words, briefly explain how you would distinguish a phase transformation from other changes in the properties of a pure substance.

(b) Sketch a qualitatively accurate graph of $G$ versus $T$ for a pure substance as it changes from solid to liquid to gas at fixed pressure. Think carefully about the slope of the line in each region of the graph and briefly discuss its main features.

# Part B

*Answer any 2 out of the 3 questions in this section.*

## Question 5

Heat pumps use work to transfer heat from a cold reservoir to a hot reservoir. Design your own thermodynamic cycle for a heat pump (do not replicate a cycle you have seen elsewhere). You could, for example, build the heat pump from some different combination of quasistatic isobaric, isochoric, isothermal and adiabatic processes, or from some other closed loop on a $PV$ or $TS$ diagram.

(a) Draw either the $PV$ diagram or the $TS$ diagram for the thermodynamic cycle.

(b) Identify the processes in the cycle (or regions of the cycle) for which the heat pump does positive work on its environment, and for which the environment does positive work on the heat pump.

(c) Identify the processes in the cycle (or regions of the cycle) for which heat is transferred into the heat pump, and for which it is transferred out.

(d) Calculate the ideal coefficient of performance of your heat pump and compare this to the Carnot limit. Note: the coefficient of performance of a heat pump is defined as the heat transferred to the hot reservoir (the effect we want) divided by the input work, and the Carnot limit for a heatpump is

$$COP_{\mathrm{C}} = \frac{1}{1 - T_C/T_H}.$$

(e) Discuss the advantages and disadvantages of this heat pump, and how you might build it.

## Question 6

Consider a fuel cell that uses methane ("natural gas") as fuel. The reaction is

$$\mathrm{CH_4 + 2O_2 \rightarrow 2H_2O + CO_2}$$
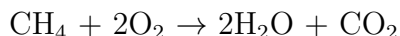
(a) Using the table of thermodynamic properties at the back of the exam, determine the values of $\Delta H$ and $\Delta G$ for this reaction for one mole of methane. Assume that the reaction takes place at room temperature and atmospheric pressure.

(b) Assuming ideal performance, how much electrical work can you get out of the cell for each mole of methane fuel?

(c) How much waste heat is produced for each mole of fuel?

(d) The chemical reaction equations at the two electrodes are:

     Negative electrode: $\mathrm{CH_4 + 2H_2O \rightarrow CO_2 + 8H^+ + 8e^-}$.

     Positive electrode: $\mathrm{2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O}$.

What is the voltage of the cell?

# Question 7

This question considers the thermodynamics of seawater.

(a) Seawater has a salinity of 3.5% meaning that if you boil away a kilogram of seawater, when you're finished 35 grams of solids will remain (mostly NaCl). Calculate the osmotic pressure difference between seawater and fresh water. For simplicity, assume that all the dissolved salts in seawater are NaCl.

(b) Briefly discuss the concept of reverse osmosis and calculate the minimum work required to desalinate one litre of seawater.

(c) Discuss some reasons why the realistic work required to desalinate the seawater would be greater than the minimum value calculated in (b).

(d) Calculate the boiling and freezing temperatures of seawater.

## END OF EXAMINATION

# PHYS2020 Formula Sheet

**Units and constants:**

$$
\begin{aligned}
1 \text{ atm} &= 101.3 \text{ kPa} = 1.013 \text{ bar} \\
&= 1.013 \times 10^5 \text{ N/m}^2 \\
0 \text{ °C} &= 273.15 \text{ K} \\
1 \text{ cal} &= 4.186 \text{ J} \\
N_A &= 6.022 \times 10^{23} \\
R &= 8.315 \text{ J/(mol·K)} \\
k_B = R/N_A &= 1.381 \times 10^{-23} \text{ J/K} \\
e &= 1.602 \times 10^{-19} \text{ C} \\
F = N_A e &= 96485 \text{ J/V·mol}
\end{aligned}
$$

**Ideal gas equation of state:**

$$ PV = nRT = NkT $$

**Van der Waals equation of state:**

$$ P = \frac{nRT}{V - nb} - a\left(\frac{n}{V}\right)^2 $$

**Virial equation of state:**

$$
\begin{aligned}
PV_m &= RT(1 + BP + CP^2 + \dots) \\
PV_m &= RT\left(1 + \frac{B}{V_m} + \frac{C}{V_m^2} + \dots\right)
\end{aligned}
$$

**Compression factor:**

$$ Z = PV/NkT $$

**Work and heat:**

$$ \Delta U = Q + W $$

$$ W = -\int P\, dV $$

$$ Q = \int T\, dS $$

**Heat capacities:**

$$ C_m = C/n, \quad c = C/m $$

$$ C_V = \left(\frac{\partial U}{\partial T}\right)_V, \quad C_P = \left(\frac{\partial H}{\partial T}\right)_P $$

$$ C_V = \frac{f}{2}Nk = \frac{f}{2}nR \quad \text{(ideal gas)} $$

$$ C_P - C_V = nR \quad \text{(ideal gas)} $$

**Adiabatic expansion of an ideal gas:**

$$ PV^\gamma = \text{const}; \quad TV^{\gamma-1} = \text{const}; \quad \gamma = \frac{f+2}{f} $$

**Equipartition theorem:**

$$ U(T) = U(0) + \frac{f}{2}nRT = U(0) + \frac{f}{2}NkT $$

**Entropy:**

$$ S = k \ln \Omega $$

$$ dS = \frac{Q_{\text{rev}}}{T} $$

$$ \Delta_{\text{trs}}S = \frac{\Delta_{\text{trs}}H}{T_{\text{trs}}} $$

$$ S(T_f) = S(T_i) + \int_{T_i}^{T_f} \frac{C_P dT}{T} $$

**Clausius-Clapeyron equation:**

$$ \frac{dP}{dT} = \frac{\Delta S}{\Delta V} = \frac{L}{T\Delta V} $$

**Clausius inequality:**

$$ \oint \frac{dQ}{T_{\text{env}}} \leq 0 $$

**Entropy of mixing:**

$$ \Delta S_{\text{mixing}} = -nR\left[x \ln x + (1-x)\ln(1-x)\right] $$

**Efficiency of a heat engine:**

$$ \epsilon \equiv \frac{\text{work performed}}{\text{heat absorbed}} = \frac{W}{Q_h} $$

**Carnot efficiency:**

$$ \epsilon_C = 1 - \frac{T_c}{T_h} $$

**Coefficient of performance:**

$$ \text{COP} \equiv \frac{\text{energy transferred as heat}}{\text{work performed}} = \frac{Q_c}{W} $$

**Carnot refrigerator:**

$$ \text{COP}_C = \frac{1}{T_h/T_c - 1} $$

**Thermodynamic potentials:**

$$
\begin{aligned}
H &= U + PV \\
F &= U - TS \\
G &= H - TS
\end{aligned}
$$

**Thermodynamic identity:**

$$
\begin{aligned}
dU &= TdS - PdV + \mu dN \\
dG &= -SdT + VdP + \mu dN
\end{aligned}
$$

**Maxwell relations:**

$$
\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P
$$

$$
\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V
$$

$$
\left(\frac{\partial V}{\partial T}\right)_P = -\left(\frac{\partial S}{\partial P}\right)_T
$$

$$
\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T
$$

**Gibbs-Helmholtz equations:**

$$
\left(\frac{\partial}{\partial T}\frac{G}{T}\right)_P = -\frac{H}{T^2}
$$

$$
\left(\frac{\partial}{\partial T}\frac{F}{T}\right)_V = -\frac{U}{T^2}
$$

**Partial derivatives:**

$$
\left(\frac{\partial x}{\partial y}\right)_z \left(\frac{\partial y}{\partial z}\right)_x \left(\frac{\partial z}{\partial x}\right)_y = -1
$$

$$
\left(\frac{\partial x}{\partial y}\right)_z = \left[\left(\frac{\partial y}{\partial x}\right)_z\right]^{-1}
$$

# Thermodynamic Properties of Selected Substances

All of the values in this table are for one mole of material at 298 K and 1 bar. Following the chemical formula is the form of the substance, either solid (s), liquid (l), gas (g), or aqueous solution (aq). When there is more than one common solid form, the mineral name or crystal structure is indicated. Data for aqueous solutions are at a standard concentration of 1 mole per kilogram water. The enthalpy and Gibbs free energy of formation, $\Delta_f H$ and $\Delta_f G$, represent the changes in $H$ and $G$ upon forming one mole of the material starting with elements in their most stable pure states (e.g., C (graphite), $O_2$ (g), etc.). To obtain the value of $\Delta H$ or $\Delta G$ for another reaction, subtract $\Delta_f$ of the reactants from $\Delta_f$ of the products. For ions in solution there is an ambiguity in dividing thermodynamic quantities between the positive and negative ions; by convention, $H^+$ is assigned the value zero and all others are chosen to be consistent with this value. Data from Atkins (1998), Lide (1994), and Anderson (1996). Please note that, while these data are sufficiently accurate and consistent for the examples and problems in this textbook, not all of the digits shown are necessarily significant; for research purposes you should always consult original literature to determine experimental uncertainties.

| Substance (form) | $\Delta_f H$ (kJ) | $\Delta_f G$ (kJ) | $S$ (J/K) | $C_P$ (J/K) | $V$ (cm$^3$) |
|---|---|---|---|---|---|
| Al (s) | 0 | 0 | 28.33 | 24.35 | 9.99 |
| $Al_2SiO_5$ (kyanite) | −2594.29 | −2443.88 | 83.81 | 121.71 | 44.09 |
| $Al_2SiO_5$ (andalusite) | −2590.27 | −2442.66 | 93.22 | 122.72 | 51.53 |
| $Al_2SiO_5$ (sillimanite) | −2587.76 | −2440.99 | 96.11 | 124.52 | 49.90 |
| Ar (g) | 0 | 0 | 154.84 | 20.79 | |
| C (graphite) | 0 | 0 | 5.74 | 8.53 | 5.30 |
| C (diamond) | 1.895 | 2.900 | 2.38 | 6.11 | 3.42 |
| $CH_4$ (g) | −74.81 | −50.72 | 186.26 | 35.31 | |
| $C_2H_6$ (g) | −84.68 | −32.82 | 229.60 | 52.63 | |
| $C_3H_8$ (g) | −103.85 | −23.49 | 269.91 | 73.5 | |
| $C_2H_5OH$ (l) | −277.69 | −174.78 | 160.7 | 111.46 | 58.4 |
| $C_6H_{12}O_6$ (glucose) | −1273 | −910 | 212 | 115 | |
| CO (g) | −110.53 | −137.17 | 197.67 | 29.14 | |
| $CO_2$ (g) | −393.51 | −394.36 | 213.74 | 37.11 | |
| $H_2CO_3$ (aq) | −699.65 | −623.08 | 187.4 | | |
| $HCO_3^-$ (aq) | −691.99 | −586.77 | 91.2 | | |
| $Ca^{2+}$ (aq) | −542.83 | −553.58 | −53.1 | | |
| $CaCO_3$ (calcite) | −1206.9 | −1128.8 | 92.9 | 81.88 | 36.93 |
| $CaCO_3$ (aragonite) | −1207.1 | −1127.8 | 88.7 | 81.25 | 34.15 |
| $CaCl_2$ (s) | −795.8 | −748.1 | 104.6 | 72.59 | 51.6 |
| $Cl_2$ (g) | 0 | 0 | 223.07 | 33.91 | |
| $Cl^-$ (aq) | −167.16 | −131.23 | 56.5 | −136.4 | 17.3 |
| Cu (s) | 0 | 0 | 33.150 | 24.44 | 7.12 |
| Fe (s) | 0 | 0 | 27.28 | 25.10 | 7.11 |

| Substance (form) | $\Delta_f H$ (kJ) | $\Delta_f G$ (kJ) | $S$ (J/K) | $C_P$ (J/K) | $V$ (cm$^3$) |
|---|---|---|---|---|---|
| H$_2$ (g) | 0 | 0 | 130.68 | 28.82 | |
| H (g) | 217.97 | 203.25 | 114.71 | 20.78 | |
| H$^+$ (aq) | 0 | 0 | 0 | 0 | |
| H$_2$O (l) | $-285.83$ | $-237.13$ | 69.91 | 75.29 | 18.068 |
| H$_2$O (g) | $-241.82$ | $-228.57$ | 188.83 | 33.58 | |
| He (g) | 0 | 0 | 126.15 | 20.79 | |
| Hg (l) | 0 | 0 | 76.02 | 27.98 | 14.81 |
| N$_2$ (g) | 0 | 0 | 191.61 | 29.12 | |
| NH$_3$ (g) | $-46.11$ | $-16.45$ | 192.45 | 35.06 | |
| Na$^+$ (aq) | $-240.12$ | $-261.91$ | 59.0 | 46.4 | $-1.2$ |
| NaCl (s) | $-411.15$ | $-384.14$ | 72.13 | 50.50 | 27.01 |
| NaAlSi$_3$O$_8$ (albite) | $-3935.1$ | $-3711.5$ | 207.40 | 205.10 | 100.07 |
| NaAlSi$_2$O$_6$ (jadeite) | $-3030.9$ | $-2852.1$ | 133.5 | 160.0 | 60.40 |
| Ne (g) | 0 | 0 | 146.33 | 20.79 | |
| O$_2$ (g) | 0 | 0 | 205.14 | 29.38 | |
| O$_2$ (aq) | $-11.7$ | 16.4 | 110.9 | | |
| OH$^-$ (aq) | $-229.99$ | $-157.24$ | $-10.75$ | $-148.5$ | |
| Pb (s) | 0 | 0 | 64.81 | 26.44 | 18.3 |
| PbO$_2$ (s) | $-277.4$ | $-217.33$ | 68.6 | 64.64 | |
| PbSO$_4$ (s) | $-920.0$ | $-813.0$ | 148.5 | 103.2 | |
| SO$_4^{2-}$ (aq) | $-909.27$ | $-744.53$ | 20.1 | $-293$ | |
| HSO$_4^-$ (aq) | $-887.34$ | $-755.91$ | 131.8 | $-84$ | |
| SiO$_2$ ($\alpha$ quartz) | $-910.94$ | $-856.64$ | 41.84 | 44.43 | 22.69 |
| H$_4$SiO$_4$ (aq) | $-1449.36$ | $-1307.67$ | 215.13 | 468.98 | |

## Periodic Table of the Elements

The atomic number (top left) is the number of protons in the nucleus. The atomic mass (bottom) is weighted by isotopic abundances in the earth's surface. Atomic masses are relative to the mass of the carbon-12 isotope, defined to be exactly 12 unified atomic mass units (u). Uncertainties range from 1 to 9 in the last digit quoted. Relative isotopic abundances often vary considerably, both in natural and commercial samples. A number in parentheses is the mass of the longest-lived isotope of that element—no stable isotope exists. However, although Th, Pa, and U have no stable isotopes, they do have characteristic terrestrial compositions, and meaningful weighted masses can be given. For elements 110–112, the mass numbers of known isotopes are given. From the Review of Particle Physics by the Particle Data Group, *The European Physical Journal* **C3**, 73 (1998).

| Group | 1 IA | 2 IIA | 3 IIIB | 4 IVB | 5 VB | 6 VIB | 7 VIIB | 8 VIII | 9 VIII | 10 VIII | 11 IB | 12 IIB | 13 IIIA | 14 IVA | 15 VA | 16 VIA | 17 VIIA | 18 VIIIA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 H Hydrogen 1.00794 | | | | | | | | | | | | | | | | | 2 He Helium 4.002602 |
| | 3 Li Lithium 6.941 | 4 Be Beryllium 9.012182 | | | | | | | | | | | 5 B Boron 10.811 | 6 C Carbon 12.0107 | 7 N Nitrogen 14.00674 | 8 O Oxygen 15.9994 | 9 F Fluorine 18.9984032 | 10 Ne Neon 20.1797 |
| | 11 Na Sodium 22.989770 | 12 Mg Magnesium 24.3050 | | | | | | | | | | | 13 Al Aluminum 26.981538 | 14 Si Silicon 28.0855 | 15 P Phosph. 30.973761 | 16 S Sulfur 32.066 | 17 Cl Chlorine 35.4527 | 18 Ar Argon 39.948 |
| | 19 K Potassium 39.0983 | 20 Ca Calcium 40.078 | 21 Sc Scandium 44.955910 | 22 Ti Titanium 47.867 | 23 V Vanadium 50.9415 | 24 Cr Chromium 51.9961 | 25 Mn Manganese 54.938049 | 26 Fe Iron 55.845 | 27 Co Cobalt 58.933200 | 28 Ni Nickel 58.6934 | 29 Cu Copper 63.546 | 30 Zn Zinc 65.39 | 31 Ga Gallium 69.723 | 32 Ge German. 72.61 | 33 As Arsenic 74.92160 | 34 Se Selenium 78.96 | 35 Br Bromine 79.904 | 36 Kr Krypton 83.80 |
| | 37 Rb Rubidium 85.4678 | 38 Sr Strontium 87.62 | 39 Y Yttrium 88.90585 | 40 Zr Zirconium 91.224 | 41 Nb Niobium 92.90638 | 42 Mo Molybd. 95.94 | 43 Tc Technet. (97.907215) | 44 Ru Ruthen. 101.07 | 45 Rh Rhodium 102.90550 | 46 Pd Palladium 106.42 | 47 Ag Silver 107.8682 | 48 Cd Cadmium 112.411 | 49 In Indium 114.818 | 50 Sn Tin 118.710 | 51 Sb Antimony 121.760 | 52 Te Tellurium 127.60 | 53 I Iodine 126.90447 | 54 Xe Xenon 131.29 |
| | 55 Cs Cesium 132.90545 | 56 Ba Barium 137.327 | 57–71 Lantha-nides | 72 Hf Hafnium 178.49 | 73 Ta Tantalum 180.9479 | 74 W Tungsten 183.84 | 75 Re Rhenium 186.207 | 76 Os Osmium 190.23 | 77 Ir Iridium 192.217 | 78 Pt Platinum 195.078 | 79 Au Gold 196.96655 | 80 Hg Mercury 200.59 | 81 Tl Thallium 204.3833 | 82 Pb Lead 207.2 | 83 Bi Bismuth 208.98038 | 84 Po Polonium (208.982415) | 85 At Astatine (209.987131) | 86 Rn Radon (222.017570) |
| | 87 Fr Francium (223.019731) | 88 Ra Radium (226.025402) | 89–103 Actinides | 104 Rf Rutherford. (261.1089) | 105 Db Dubnium (262.1144) | 106 Sg Seaborg. (263.1186) | 107 Bh Bohrium (262.1231) | 108 Hs Hassium (265.1306) | 109 Mt Meitner. (266.1378) | 110 (269, 273) | 111 (272) | 112 (277) | | | | | | |

**Lanthanide series**

| 57 La Lanthanum 138.9055 | 58 Ce Cerium 140.116 | 59 Pr Praseodym. 140.90765 | 60 Nd Neodym. 144.24 | 61 Pm Prometh. (144.912745) | 62 Sm Samarium 150.36 | 63 Eu Europium 151.964 | 64 Gd Gadolin. 157.25 | 65 Tb Terbium 158.92534 | 66 Dy Dyspros. 162.50 | 67 Ho Holmium 164.93032 | 68 Er Erbium 167.26 | 69 Tm Thulium 168.93421 | 70 Yb Ytterbium 173.04 | 71 Lu Lutetium 174.967 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

**Actinide series**

| 89 Ac Actinium (227.027747) | 90 Th Thorium 232.0381 | 91 Pa Protactin. 231.03588 | 92 U Uranium 238.0289 | 93 Np Neptunium (237.048166) | 94 Pu Plutonium (244.064197) | 95 Am Americium (243.061372) | 96 Cm Curium (247.070346) | 97 Bk Berkelium (247.070298) | 98 Cf Californ. (251.079579) | 99 Es Einstein. (252.08297) | 100 Fm Fermium (257.095096) | 101 Md Mendelev. (258.098427) | 102 No Nobelium (259.1011) | 103 Lr Lawrenc. (262.1098) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|