NATIONAL UNIVERSITY OF SINGAPORE

CM2142 – Analytical Chemistry 1

SEMESTER II : AY2014/15

TIME ALLOWED: 2 HOURS

INSTRUCTIONS TO STUDENTS

1. This assessment paper contains **FOUR (4)** questions and comprises **THIRTEEN (13)** printed pages.

2. Students are required to answer **ALL** questions.

3. Students should write the answers for each question on a new page.

4. **2 A4, double sided sheets of notes** are allowed.

5. Non-programmable calculators are allowed.

6. Formula Sheet and Periodic Table are attached at the back.

Question 1

(a) The mass (in g) of a sample was determined by two different methods, gravimetric and volumetric. The values are given below:

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**
Gravimetric	2.310	2.309	2.308	2.310	2.311	2.309	2.307
Volumetric	2.301	2.298	2.299	2.301	2.299	2.299	2.297

Are the methods equivalent at 95% confidence level? Confirm by performing an appropriate significance test. Explain why the Paired t-test is *not* an appropriate test.

(7 marks)

(b) In a binary resin mixture, 20% of the particles have a 30% by weight coating (analyte) and a density of 0.48 g/cm^3, whereas the remaining have 1% by weight coating (analyte) and a density of 0.24 g/cm^3. Assume that the average particle in the batch being sampled is about 1 mm in diameter.

(i) What should the mass of the gross sample be if the sampling relative uncertainty is 0.5%?

(7 marks)

(ii) If the maximum sample loading is 1 g, determine the final diameter in mm of the resin before analysis.

(4 marks)

(iii) The results below were obtained:

Run	**Laboratory Sample 1**	**Laboratory Sample 2**	**Laboratory Sample 3**	**Laboratory Sample 4**	**Laboratory Sample 5**
1	10.3	9.5	12.1	9.6	11.6
2	9.8	8.6	13.0	8.3	12.5
3	11.4	8.9	12.4	8.2	11.4

If the relative uncertainty of 15% is required, what is the appropriate number of laboratory samples that should be analysed, at the 95% confidence level?

(7 marks)

Question 2

(a) Describe, with diagrams where appropriate, a suitable extraction technique for:

(i) limonene, which smells like lemon/oranges, from dish washing liquid

(ii) caffeine from coffee beans

(7 marks)

(b) A sample that is soluble in hexane is to be separated using HPLC. Describe the specific instrument parameters, including values where appropriate, and a common detector that you would recommend.

(10 marks)

(c) Describe an appropriate HPLC method that would separate sodium and calcium ions, given that the method uses a conductivity detector. In your description, include a schematic of the column set up and also list the factors that determine the order of elution.

(8 marks)

Question 3

(a) A 1.0 g sample of zinc metal is dissolved in 50 mL of 6.0 M HCl solution and diluted to the mark in a 250 mL volumetric flask. A 25 mL portion is transferred to a polarographic cell and oxygen is flushed out. A polarogram recorded in the range 0 to -1 V vs. SCE has $E_{1/2}$ = -0.65 V and i_d = 32.0 μA. A 5 mL portion of 5.0 x 10^{-4} M $CdCl_2$ solution is added directly to the polarography cell which already contains the Zn solution, oxygen is again flushed out, and a second polarogram is recorded. The polarogram shows the same $E_{1/2}$ but the i_d = 77.5 μA. What is the % weight of Cd impurity in the metal? Sketch the polarograms that would be obtained, labelling the axes, $E_{1/2}$ and i_d.

(12 marks)

(b) For the silver/silver chloride RE vs. SHE, what is the chloride ion concentration in the filling solution if the potential measured is 0.20 V, given that K_{sp}(AgCl) = 1.8 x 10^{-10} and $E^o_{Ag/Ag+}$ = 0.80 V. Explain the role of the RE in a 3-electrode voltammetry set up.

(6 marks)

(c) Describe the working principle of the scanning electron microscopy (SEM) in secondary electron imaging mode. Include a schematic diagram in your description.

(7 marks)

Question 4

(a) Acetate buffer is a common buffer. From its K_a expression, determine the Buffer equation. Write a procedure for the preparation of 250 mL of pH 5.0 acetate buffer using 1 M acetic acid and solid sodium acetate, given that $K_a = 1.8 \times 10^{-5}$.

(8 marks)

(b) Determine the concentration of calcium in a solution of calcium sulphate that has been buffered to pH 1. Given that $K_{sp}(CaSO_4) = 2.4 \times 10^{-5}$; Sulphuric acid K_{a1} = large and $K_{a2} = 1.02 \times 10^{-2}$.

(10 marks)

(c) Calculate the concentration of Ca^{2+} in a solution of 0.01 M CaY^{2-} at pH 6 ($\alpha_4 = 2.3 \times 10^{-5}$) given that $K_{CaY^{2-}} = 5.0 \times 10^{10}$. Define and write an expression for α_4.

(7 marks)

END OF PAPER

CM2142 Formula Sheet

Statistical Analysis

$$\mu = \frac{\sum_{i=1}^{N} x_i}{N}$$

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \mu)^2}{N}} \qquad \sigma = \sqrt{\frac{\sum_{i=1}^{N} x_i^2 - \frac{\left(\sum_{i=1}^{N} x_i\right)^2}{N}}{N}}$$

$$s = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1}} \qquad s = \sqrt{\frac{\sum_{i=1}^{N} x_i^2 - \frac{\left(\sum_{i=1}^{N} x_i\right)^2}{N}}{N-1}}$$

$$s^2 = \sigma^2 = \frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1}$$

$$RSD = \frac{s}{\bar{x}}$$

$$CV = \frac{s}{\bar{x}} \times 100\%$$

$$z = \frac{x - \mu}{\sigma}$$

$$t = \frac{x - \mu}{s}$$

$$s_m = \frac{s}{\sqrt{N}}$$

$$\mu = \bar{x} \pm \frac{z\sigma}{\sqrt{N}}$$

$$\mu = \bar{x} \pm \frac{ts}{\sqrt{N}}$$

Significance Tests

$$CL = (1 - \alpha) \text{ x } 100\%$$

$$z = (\bar{x} - \mu_0)\frac{\sqrt{N}}{\sigma}$$

$$t = (\bar{x} - \mu_0)\frac{\sqrt{N}}{s}$$

$$s_{pooled} = \sqrt{\frac{(N_1 - 1)s_1^2 + (N_2 - 1)s_2^2}{N_1 + N_2 - 2}}$$

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s_{pooled}\sqrt{\left(\frac{N_1 + N_2}{N_1 N_2}\right)}}$$

$$t = (\bar{d} - \Delta_0)\frac{\sqrt{N}}{s_d}$$

$$F = \frac{s_1^2}{s_2^2}$$

$$Q = \frac{|x_q - x_n|}{(\text{highest value} - \text{lowest value})} = \frac{|x_q - x_n|}{w}$$

$$\bar{\bar{x}} = \left(\frac{N_1}{N}\right)\overline{x_1} + \left(\frac{N_2}{N}\right)\overline{x_2} + \left(\frac{N_3}{N}\right)\overline{x_3} + \ldots + \left(\frac{N_i}{N}\right)\overline{x_i}$$

$$SSF = N_1(\overline{x_1} - \bar{\bar{x}})^2 + N_2(\overline{x_2} - \bar{\bar{x}})^2 + N_3(\overline{x_3} - \bar{\bar{x}})^2 + \ldots + N_i(\overline{x_i} - \bar{\bar{x}})^2$$

$$SSE = (N_1 - 1)s_1^2 + (N_2 - 1)s_2^2 + (N_3 - 1)s_3^2 + \ldots + (N_i - 1)s_i^2$$

$$SST = SSF + SSE = (N-1)s^2$$

where s^2 is the sample variance of all data points.

$$SST = SSF + SSE$$

$$(N - 1) = (i - 1) + (N - i)$$

$$MSF = \frac{SSF}{i-1}$$

$$MSE = \frac{SSE}{N-i}$$

$$F = \frac{MSF}{MSE}$$

Sampling and Calibration

$$N = \frac{(1-p)}{p\sigma_r^2}$$

$$LOD = \bar{y}_B + 3s_B$$

$$LOQ = \bar{y}_B + 10s_B$$

$$N = p(1-p)\left(\frac{d_A d_B}{d^2}\right)^2\left(\frac{X_A - X_B}{\sigma_r X}\right)^2$$

$$\sqrt{N} = \frac{ts_s}{\bar{x}\sigma_r}$$

$$SS_{resid} = \sum_{i=1}^{N}(y_i - y)^2 = \sum_{i=1}^{N}[y_i - (mx_i + c)]^2$$

$$R^2 = 1 - \frac{SS_{resid}}{SS_{total}}$$

$$SS_{total} = \sum_{i=1}^{N}(y_i - \bar{y})^2 \text{ where } \bar{y} = \frac{\sum_{i=1}^{N} y_i}{N}$$

$$s_c = \frac{\sqrt{\frac{\sum_{i=1}^{N}(y_i - \bar{y})^2 - m^2\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-2}}}{m}\sqrt{\frac{1}{U} + \frac{1}{N} + \frac{\left(\overline{y_U} - \bar{y}\right)^2}{m^2\sum_{i=1}^{N}(x_i - \bar{x})^2}}$$

TABLE 6-4

Error Propagation in Arithmetic Calculations

Type of Calculation	Example*	Standard Deviation of y†	
Addition or subtraction	$y = a + b - c$	$s_y = \sqrt{s_a^2 + s_b^2 + s_c^2}$	(1)
Multiplication or division	$y = a \times b/c$	$\frac{s_y}{y} = \sqrt{\left(\frac{s_a}{a}\right)^2 + \left(\frac{s_b}{b}\right)^2 + \left(\frac{s_c}{c}\right)^2}$	(2)
Exponentiation	$y = a^x$	$\frac{s_y}{y} = x\left(\frac{s_a}{a}\right)$	(3)
Logarithm	$y = \log_{10} a$	$s_y = 0.434\frac{s_a}{a}$	(4)
Antilogarithm	$y = \text{antilog}_{10}\, a$	$\frac{s_y}{y} = 2.303\, s_a$	(5)

*a, b, and c are experimental variables with standard deviations of s_a, s_b, and s_c, respectively
†These relationships are derived in Appendix 9. The values for s_y/y are absolute values if y is a negative number.

*

TABLE 7-1

Confidence Levels for Various Values of z

Confidence Level, %	z
50	0.67
68	1.00
80	1.28
90	1.64
95	1.96
95.4	2.00
99	2.58
99.7	3.00
99.9	3.29

*

TABLE 7-3

Values of t for Various Levels of Probability

Degrees of Freedom	80%	90%	95%	99%	99.9%
1	3.08	6.31	12.7	63.7	637
2	1.89	2.92	4.30	9.92	31.6
3	1.64	2.35	3.18	5.84	12.9
4	1.53	2.13	2.78	4.60	8.61
5	1.48	2.02	2.57	4.03	6.87
6	1.44	1.94	2.45	3.71	5.96
7	1.42	1.90	2.36	3.50	5.41
8	1.40	1.86	2.31	3.36	5.04
9	1.38	1.83	2.26	3.25	4.78
10	1.37	1.81	2.23	3.17	4.59
15	1.34	1.75	2.13	2.95	4.07
20	1.32	1.73	2.09	2.84	3.85
40	1.30	1.68	2.02	2.70	3.55
60	1.30	1.67	2.00	2.62	3.46
∞	1.28	1.64	1.96	2.58	3.29

*

TABLE 7-4

Critical Values of F at the 5% Probability Level (95% confidence level)

Degrees of Freedom (Denominator)	Degrees of Freedom (Numerator)								
	2	3	4	5	6	10	12	20	∞
2	19.00	19.16	19.25	19.30	19.33	19.40	19.41	19.45	19.50
3	9.55	9.28	9.12	9.01	8.94	8.79	8.74	8.66	8.53
4	6.94	6.59	6.39	6.26	6.16	5.96	5.91	5.80	5.63
5	5.79	5.41	5.19	5.05	4.95	4.74	4.68	4.56	4.36
6	5.14	4.76	4.53	4.39	4.28	4.06	4.00	3.87	3.67
10	4.10	3.71	3.48	3.33	3.22	2.98	2.91	2.77	2.54
12	3.89	3.49	3.26	3.11	3.00	2.75	2.69	2.54	2.30
20	3.49	3.10	2.87	2.71	2.60	2.35	2.28	2.12	1.84
∞	3.00	2.60	2.37	2.21	2.10	1.83	1.75	1.57	1.00

*

TABLE 7-5

Critical Values for the Rejection Quotient, Q*

Number of Observations	Q_{crit} (Reject if $Q > Q_{crit}$) 90% Confidence	95% Confidence	99% Confidence
3	0.941	0.970	0.994
4	0.765	0.829	0.926
5	0.642	0.710	0.821
6	0.560	0.625	0.740
7	0.507	0.568	0.680
8	0.468	0.526	0.634
9	0.437	0.493	0.598
10	0.412	0.466	0.568

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* Adapted from *Fundamentals of Analytical Chemistry (8th Edition)* Douglas A. Skoog, et. al. Thomson Brooks / Cole

Extraction Techniques

$$[A]_i = \left(\frac{V_{aq}}{K_D V_{org} + V_{aq}}\right)^i [A]_0 \quad \text{or} \quad [A]_i^T = \left(\frac{V_{aq}}{DV_{org} + V_{aq}}\right)^i [A]_0^T$$

$$F_A = \frac{K_D R_v}{K_D R_v + 1} \quad \text{or} \quad \frac{D_A R_V}{D_A R_V + 1}$$

where $R_v = \text{phase-volume ratio}, \frac{V_{org}}{V_{aq}}$

$$G_A = 1 - F_A$$

$$D = \frac{[HA]_{org}^T}{[HA]_{aq}^T} = \frac{K_D[H^+]}{[H^+] + K_a} = K_D \alpha_{HA}$$

$$D = \frac{[B]_{org}^T}{[B]_{aq}^T} = \frac{K_D[OH^-]}{[OH^-] + K_b} = K_D \alpha_B$$

$$D_M = K_{DM} K_{ML} \left(\frac{K_a}{K_{DL}}\right)^n \left(\frac{[HL]_{org}}{[H^+]_{aq}}\right)^n = K'' \left(\frac{[HL]_{org}}{[H^+]_{aq}}\right)^n$$

$$\text{Masking Factor} = -\log \frac{\alpha_{M_2}}{\alpha_{M_1}} \quad \text{where} \quad \alpha_M = \frac{[M^{n+}]_{aq}}{[M^{n+}]_{aq}^T}$$

Chromatography

$$t_R = t_S + t_M$$

$$\bar{v} = \frac{L}{t_R}$$

$$u = \frac{L}{t_M}$$

$$F = \frac{V_M}{t_M}$$

Open column: $F = u_o A = u_o \times \pi r^2$

Packed column: $F = \pi r^2 u_o \varepsilon$

$$\bar{v} = u \times \frac{1}{1 + K\frac{V_S}{V_M}}$$

$$k = \frac{t_R - t_M}{t_M} = \frac{t_S}{t_M}$$

$$\alpha = \frac{(t_R)_B - t_M}{(t_R)_A - t_M} = \frac{(t_S)_B}{(t_S)_A}$$

$$N = \frac{L}{H}$$

$$H = \frac{\sigma^2}{L}$$

$$N = 16\frac{t_R^{\ 2}}{W^2} \qquad N = 5.54\frac{t_R^{\ 2}}{W_{1/2}^{\ 2}}$$

$$H = A + \frac{B}{u} + C_s u$$

$$H = \frac{B}{u} + C_s u + C_M u$$

$$A = 2\,\lambda\,d_p$$

$$B = 2\,\gamma\,D_M$$

$$C_S = \frac{2k}{3(k+1)^2}\frac{d^2}{D_S}$$

$$C_M = \frac{1+6k+11k^2}{96(k+1)^2}\frac{d^2}{D_M}$$

$$R_S = \frac{2[(t_R)_B - (t_R)_A]}{W_A + W_B}$$

$$R_S = 1.175\frac{[(t_R)_B - (t_R)_A]}{[W_{1/2A} + W_{1/2B}]}$$

$$R_s = \left(\frac{\sqrt{N}}{4}\right)\left(\frac{\alpha-1}{\alpha}\right)\left(\frac{k_B}{1+k_B}\right)$$

Gas Chromatography

$$I = 100\left[n + (N-n)\frac{\log t'_{R(unk)} - \log t'_{R(n)}}{\log t'_{R(N)} - \log t'_{R(n)}}\right]$$

Electrophoresis

$$u_{ep} = \frac{Q}{f}E = \mu_{ep}E$$

$$f = 6\pi\,r\,\eta$$

$$E = \frac{V}{L}$$

$$u_{eo} = \mu_{eo}E$$

$$\mu_{eo} = \frac{u_{eo,\,neutral}}{E} = \frac{L_d/t_{neutral}}{V/L}$$

$$\mu_{app} = \mu_{ep} + \mu_{eo} = \frac{L_d/t}{V/L}$$

$$N = \frac{L_d^2}{2Dt} = \frac{\mu_{app}V}{2D}\frac{L_d}{L}$$

$$R_S = \frac{2[t_B - t_A]}{W_A + W_B}$$

$$R_s = \left(\frac{\sqrt{N}}{4}\right)(\gamma - 1)$$

Electrochemistry

A = C / s

V = J / C

V = i R

Q = n F = i t

w = nFE = Q E

P = w / t = i E

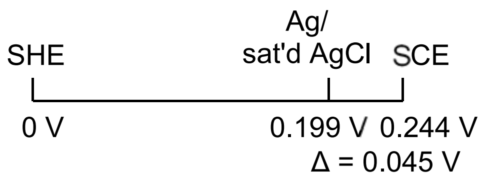
$\Delta G = -nFE = -w$

$$E_{cell} = E^{\circ}_{cell} - \frac{RT}{nF}\ln Q$$

$$E_{cell} = E^{\circ}_{cell} - \frac{0.059}{n}\log Q$$

Potentiometry

$E_{cell} = E_{ind} - E_{ref} + E_j$



$$E_{outside} = \frac{\Delta G_{solvation}}{nF} - \left(\frac{RT}{nF}\right)\ln\left(\frac{a_m}{a_o}\right)$$

$$E_{cell} = k + \left(\frac{RT}{nF}\right)\ln a_o = k + \frac{0.059}{n}\log a_{sample} \text{ at 298 K}$$

where $k = \frac{\Delta G_{solvation}}{nF} - \left(\frac{RT}{nF}\right)\ln a_m - E_{inside}$

$$E_{cell} = k - 0.059 \text{ pH at 298 K}$$

$$(V_0 + V_s)10^{\frac{E_{cell}}{Y}} = 10^{\frac{k}{Y}} c_a V_0 + 10^{\frac{k}{Y}} c_s V_s$$

where $Y = \beta\left(\frac{RT}{nF}\ln 10\right)$

Voltammetry

$$i = \frac{nFAD([\text{analyte}]_{bulk} - [\text{analyte}]_{x=0})}{\delta}$$

$$\frac{Q}{E} = C$$

$$i_p = 2.686 \times 10^5\, n^{3/2}\, A\, c\, D^{1/2}\, v^{1/2}$$

$\Gamma = Q / nFA$

$$(i_d)_{max} = 708\, n\, D^{1/2}\, m^{2/3}\, t^{1/6}\, c$$

Chemical Equilibrium

$\Delta G = \Delta H - T\Delta S$

$\Delta G = RT \ln Q/K = RT \ln Q - RT \ln K$

$\Delta G^{o} = -RT \ln K$

$\Delta G = \Delta G^{o} + RT \ln Q$

$$\ln\frac{K_2}{K_1} = \left(\frac{-\Delta H^{\circ}}{R}\right)\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$$K_p = (RT)^{\Delta n} K_c$$

Acid Base Equilibrium

$K_a \times K_b = K_w$

$$pH = pK_a + \log_{10}\frac{[base]}{[acid]}$$

$$\mu = \frac{1}{2}([A]Z_A^2 + [B]Z_B^2 + [C]Z_C^2 + ...)$$

$$a_X = [X]\gamma_X$$

$$-\log\gamma_X = \frac{0.51 Z_X^2 \sqrt{\mu}}{1 + 3.3\alpha_X\sqrt{\mu}}$$

TABLE 14-1

Some Important Acid/Base Indicators

Common Name	Transition Range, pH	pK_a*	Color Change†	Indicator Type‡
Thymol blue	1.2–2.8	1.65§	R–Y	1
	8.0–9.6	8.96§	Y–B	
Methyl yellow	2.9–4.0		R–Y	2
Methyl orange	3.1–4.4	3.46§	R–O	2
Bromocresol green	3.8–5.4	4.66§	Y–B	1
Methyl red	4.2–6.3	5.00§	R–Y	2
Bromocresol purple	5.2–6.8	6.12§	Y–P	1
Bromothymol blue	6.2–7.6	7.10§	Y–B	1
Phenol red	6.8–8.4	7.81§	Y–R	1
Cresol purple	7.6–9.2		Y–P	1
Phenolphthalein	8.3–10.0		C–R	1
Thymolphthalein	9.3–10.5		C–B	1
Alizarin yellow GG	10–12		C–Y	2

*At ionic strength of 0.1.
†B = blue; C = colorless; O = orange; P = purple; R = red; Y = yellow.
‡(1) Acid type: $HIn + H_2O \rightleftharpoons H_3O^+ + In^-$; (2) Base type: $In + H_2O \rightleftharpoons InH^+ + OH^-$.
§For the reaction $InH^+ + H_2O \rightleftharpoons H_3O^+ + In$.

* Adapted from *Fundamentals of Analytical Chemistry (8th Edition)* Douglas A. Skoog, et. al. Thomson Brooks / Cole

Periodic Table of the Elements

Main groups | Transition metals | Main groups

Period	1A[a] 1	2A 2	3B 3	4B 4	5B 5	6B 6	7B 7	8B 8	8B 9	8B 10	1B 11	2B 12	3A 13	4A 14	5A 15	6A 16	7A 17	8A 18
1	1 **H** 1.00794																	2 **He** 4.002602
2	3 **Li** 6.941	4 **Be** 9.012182											5 **B** 10.811	6 **C** 12.0107	7 **N** 14.0067	8 **O** 15.9994	9 **F** 18.998403	10 **Ne** 20.1797
3	11 **Na** 22.989770	12 **Mg** 24.3050											13 **Al** 26.981538	14 **Si** 28.0855	15 **P** 30.973761	16 **S** 32.065	17 **Cl** 35.453	18 **Ar** 39.948
4	19 **K** 39.0983	20 **Ca** 40.078	21 **Sc** 44.955910	22 **Ti** 47.867	23 **V** 50.9415	24 **Cr** 51.9961	25 **Mn** 54.938049	26 **Fe** 55.845	27 **Co** 58.933200	28 **Ni** 58.6934	29 **Cu** 63.546	30 **Zn** 65.39	31 **Ga** 69.723	32 **Ge** 72.64	33 **As** 74.92160	34 **Se** 78.96	35 **Br** 79.904	36 **Kr** 83.80
5	37 **Rb** 85.4678	38 **Sr** 87.62	39 **Y** 88.90585	40 **Zr** 91.224	41 **Nb** 92.90638	42 **Mo** 95.94	43 **Tc** [98]	44 **Ru** 101.07	45 **Rh** 102.90550	46 **Pd** 106.42	47 **Ag** 107.8682	48 **Cd** 112.411	49 **In** 114.818	50 **Sn** 118.710	51 **Sb** 121.760	52 **Te** 127.60	53 **I** 126.90447	54 **Xe** 131.293
6	55 **Cs** 132.90545	56 **Ba** 137.327	71 **Lu** 174.967	72 **Hf** 178.49	73 **Ta** 180.9479	74 **W** 183.84	75 **Re** 186.207	76 **Os** 190.23	77 **Ir** 192.217	78 **Pt** 195.078	79 **Au** 196.96655	80 **Hg** 200.59	81 **Tl** 204.3833	82 **Pb** 207.2	83 **Bi** 208.98038	84 **Po** [208.98]	85 **At** [209.99]	86 **Rn** [222.02]
7	87 **Fr** [223.02]	88 **Ra** [226.03]	103 **Lr** [262.11]	104 **Rf** [261.11]	105 **Db** [262.11]	106 **Sg** [266.12]	107 **Bh** [264.12]	108 **Hs** [269.13]	109 **Mt** [268.14]	110 [271.15]	111 [272.15]	112 [277]		114 [285]		116 [289]		

*Lanthanide series	57 ***La** 138.9055	58 **Ce** 140.116	59 **Pr** 140.90765	60 **Nd** 144.24	61 **Pm** [145]	62 **Sm** 150.36	63 **Eu** 151.964	64 **Gd** 157.25	65 **Tb** 158.92534	66 **Dy** 162.50	67 **Ho** 164.93032	68 **Er** 167.259	69 **Tm** 168.93421	70 **Yb** 173.04
†Actinide series	89 **†Ac** [227.03]	90 **Th** 232.0381	91 **Pa** 231.03588	92 **U** 238.02891	93 **Np** [237.05]	94 **Pu** [244.06]	95 **Am** [243.06]	96 **Cm** [247.07]	97 **Bk** [247.07]	98 **Cf** [251.08]	99 **Es** [252.08]	100 **Fm** [257.10]	101 **Md** [258.10]	102 **No** [259.10]