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Ph.D. Qualifying Examination in Materials Science
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This test includes 8 problems on 5 pages. Please answer any **four** of these 8 problems in the blue book(s) provided. The attached Periodic Table of the Elements includes information on the atomic masses of the elements.

Problem 1 (100%)

Describe an effective experimental method for performing each of the following tasks.

(a) (10%) Distinguishing between amorphous silicon and polycrystalline silicon.

(b) (10%) Distinguishing between a metal and a semiconductor.

(c) (10%) Distinguishing between the lead-rich and tin-rich phases in a tin-lead eutectic alloy.

(d) (10%) Distinguishing between carbon monoxide gas and nitrogen gas.

(e) (10%) Determining the thickness of a copper thin film on a silicon substrate.

(f) (10%) Determining the energy band gap of a semiconductor.

(g) (10%) Determining the phase of the copper-tin compound at the interface between tin and copper.

(h) (10%) Determining the activation energy of the reaction between copper and tin.

(i) (10%) Determining the frequency of a lattice vibrational mode of a material.

(j) (10%) Determining the crystallographic texture of a metal sheet.

Problem 2 (100%)

Explain each of the following statements by giving the scientific origin.

(a) (10%) A solid expands upon heating.

(b) (10%) Diamond is an excellent thermal conductor.

(c) (10%) The modulus of elasticity of a carbon fiber is higher along the axis of the fiber than in the transverse direction.

(d) (10%) A semicrystalline polymer tends to be able to withstand higher temperatures than a conventional polymer.

(e) (10%) An electrostrictive material strains in the presence of an electric field.

(f) (10%) The yield stress of a magnetorheological fluid increases in the presence of a magnetic field.

(g) (10%) A laser is superior to a light emitting diode as a light source for an optical fiber sensor.

(h) (10%) An optical fiber sensor can be used to monitor the curing of epoxy.

(i) (10%) A shape memory alloy can remember its shape.

(j) (10%) The electrical resistivity of a metal increases with increasing temperature.

Problem 3 (100%)

The primitive translation vectors of a simple cubic lattice may be taken as:

a=a**x**; **b**=b**x**; **c**=c**x**, where **x**, **y**, and **z** are unit vectors.

What are the primitive translation vectors **A**, **B**, and **C** of its reciprocal lattice?

Problem 4 (100%)

Fig. 1 shows a simple method of estimating the theoretical shear strength of a perfect crystal. For small elastic strains, the stress σ is related to the displacement x by: $\sigma=Gx/d$, where d is the interplanar distance between atom in rows A and B, and G is the shear modulus (derived from the broken line in stress versus displacement at the initial slope). At first approximation, stress-displacement relation for large displacements may be written as:

$$\sigma=(Ga/2\pi d)\sin(2\pi x/d),$$

where 'a' is the interatomic spacing in the shear direction.

(a) (80%) What is the critical shear stress σ_c at which the lattice becomes unstable (that is when the atoms in row A are directly above B corresponding to zero stress)?

(b) (20%) What is the value of σ_c when $a \approx d$?

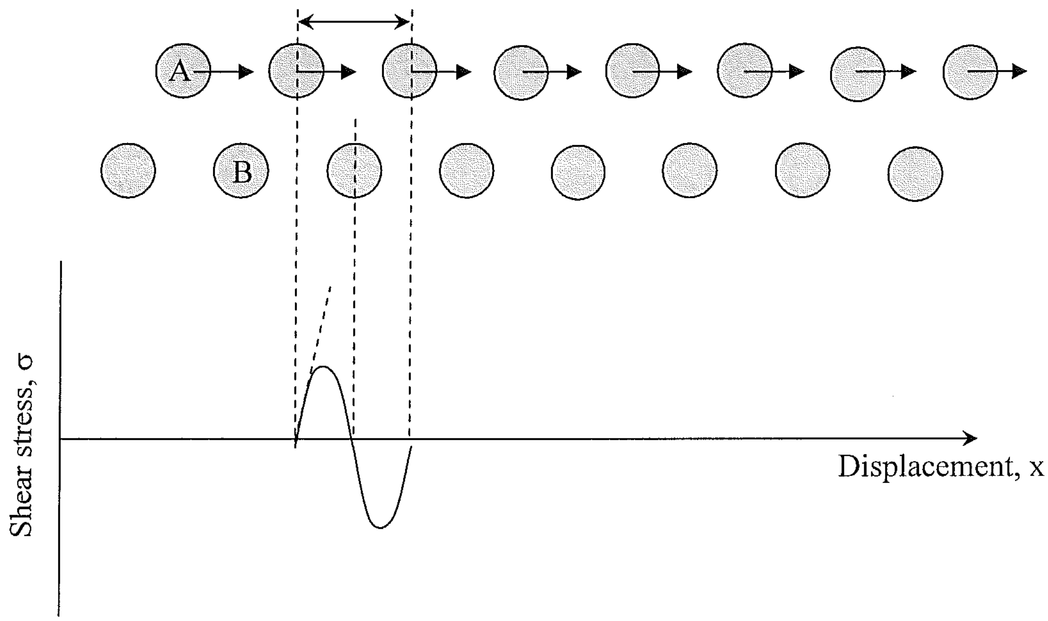

Fig. 1

Problem 5 (100%)

(a) (20%) Derive the Maxell relationships for Helmholtz energy, A; Gibbs energy, G; Enthalpy, H; and Free energy, E.

(b) (60%) Show that C_p-C_v=α^2VT/β, where C_p and C_v are the respective hear capacities at constant pressure and volume, α is the coefficient of thermal expansion, β is compressibility, V is the volume of the system, and T is the temperature.

(c) (20%) What does this expression reduces to for the case of an ideal gas?

Problem 6 (100%)

Classical Thermodynamics – isotropic, non-ferromagnetic material.

The variation of the entropy, *S*, with temperature, *T*, and magnetic field, *H*, is given by:

$$dS(T,H) = \left(\frac{C_H}{T}\right) dT - (V\gamma_H)\, dH$$

where $C_H = \left(\delta Q_{rev} / dT\right)\big|_H$, heat capacity at constant magnetic field

and $\gamma_H = -\left(\partial B / \partial T\right)\big|_H$

Magnetic cooling is commonly used during the process of achieving sub-Kelvin temperatures. The procedure consists of the following steps:

Step 1. While being held *isothermal* at a low temperature (i.e., liquid helium, $T_0 = 4K$), the material is placed in a magnet whose *field strength* is *increased* to *H.*

Step 2. The material is *thermally insulated* while in the magnet and then the *field strength* is *reduced* to *zero.*

(a) In Step 1, write an expression for the heat transfer and determine whether the heat is flowing into or out of the material.

(b) Determine an expression for the temperature of the material after Step 2.

Problem 7 (100%)

Statistical Thermodynamics – crystal defects.

A Schottky defect is an intrinsic imperfection in a crystal lattice in which both a cation and anion site are vacant. To form this defect requires an energy ε. Consider the perfect lattice as the 'ground state' with each site having an energy $\varepsilon_0 = 0$. Each Schottky defect then has an energy $\varepsilon_1 = \varepsilon$. There are N total sites in the crystal.

Nomenclature: (n_0, n_1) designate the number of sites having energies (ε_0, ε_1), respectively;

U is the total crystal energy *above* the ground state;

T is the temperature (absolute)

Ω is the number of *microstates* corresponding to a given *macrostate*.

(a) Determine the entropy of the crystal, S, as a function of (U, ε, N).

(b) Determine the energy of the crystal, U, as a function of (T, ε, N).

(a) Determine the heat capacity of the crystal, C_v, as a function of (T, ε, N).

Problem 8 (100%)

Classical Thermodynamics – binary solution.

The *partial molal heat of mixing* of species A associated with binary mixtures of A and B is given by:

$$\Delta \bar{H}_A = a_0 X_A X_B^2$$

where

$$X_i = \textit{mole fraction} \text{ of species } i$$

Determine the *heat of mixing*, $\Delta \bar{H}_{mix}$, in terms of X_A, X_B, a_0.

PERIODIC TABLE OF THE ELEMENTS

Table of Radioactive Isotopes

Ac 227(22y)β^-,α
Ag 110(24s)β^-,γ; 111(7.5d)β^-,γ
Am 241(458y)α,γ,e^-; 242(16.0h)β^-,K,α,γ; 243(8000y)α,γ
As 76(26.7h)β^-,γ; 77(39h)β^-,γ
At 210(8.3h)K,α,γ; 211(7.2h),Kα,γ
Au 198(2.69d)β^-,γ
Ba 131(12d)K,γ; 133(7.2y)K,γ,e^-
Bi 210(5d)β^-,α
Bk 245(4.9d)K,α,γ; 249(314d)β^-,α,SF
Br 82(36h)β^-,γ
C 14(5700y)β^-
Ca 41(8x10^{4}y)K; 45(165d)β^-; 47(4.5d)β^-,γ
Cd 115(43d)β^-,γ
Ce 141(32d)β^-,γ; 143(33h)β^-,γ; 144(285d)β^-,γ
Cf 246(35h)α,γ,SF; 249(360y)α,γ,SF; 251(800y)γ
Cl 36(3x10^{5}y)β^-
Cm 243(35y),α,γ; 245(9300y),α,γ; 247(10^{7}y)
Co 58(71d),K,β^+,γ; 60(5.27y)β^-,γ
Cr 51(27d),K,γ
Cs 134(2.0y)β^-,γ; 135(3x10^{6}y)β^-; 137(30y)β^-,γ
Cu 64(12.8h)K,β^-,β^+,γ
Es 253(20d)α,γ,SF; 254(1y)α,SF
Eu 154(16y)β^-,γ; 155(1.8y)β^-,γ
Fe 55(2.6y)K; 59(45d)β^-,γ
Fm 255(20h)α
Fr 223(22m)β^-,γ,α
Ga 72(14.1h),β^-,γ
Gd 153(236d)K,γ,e^-; 159(18h)β^-,γ
Ge 71(11d)K
H 3(12.3y)β^-
Hf 181(45d)β^-,γ,e^-
Hg 197(65h)K,γ,e^-; 203(47d)β^-,γ,e^-
Ho 166(27.3h)β^-,γ
I 129(10^{7}y)β^+,γ,e; 131(8.05d)β^-,γ
In 114(50d)γ
Ir 192(74.4d)β^-,γ
K 40(10^{9}y)β^+,K,γ; 42(12.4h),β^-,γ
La 140(40.2h)β^-,γ
Lu 176(10^{10}y)β^-,K,γ; 177(6.8d)β^-,γ
Md 256(90m)K,SF
Mo 99(67h)β^-,γ
Na 22(2.6y)β^+,K,γ; 24(15h)β^-,γ
Nd 147(11.1d)β^-,γ
Ni 63(125y)β^-; 59(8x10^{4}y),K
Np 237(2.2x10^{6}y)α,γ; 239(2.33d)β^-,γ
Os 191(15d)β^-,γ,e^-
P 32(14.2d)β^-
Pa 231(34000y)α,γ
Pb 210(19.4y)β^-,γ,e^-; 202(10^{5}y)L
Pd 103(17d)K,γ
Pm 147(2.6y)β^-
Po 210(138.4d)α,γ; 209(103y)α,K,γ
Pr 143(13.8d)β^-
Pt 197(18h)β^-,γ
Pu 242(3.8 × 10^{5}y)α,SF; 241(13y)β^-,α,γ; 239(24300y)α,γ,SF
Ra 226(1620y)α,γ
Rb 86(18.6d)β^-,γ
Re 188(16.7h)β^-,γ; 186(3.7d)β^-,γ
Rn 222(3.82d)α
Ru 103(40d)β^-,γ; 97(2.9d),K,γ,e^-
S 35(88d)β^-
Sb 122(2.8d)β^-,K,β^+,γ; 124(60d)β^-,γ
Sc 46(84d)β^-,γ
Se 75(120d)K,γ
Sm 153(47h)β^-,γ; 145(340d)K,γ
Sn 113(119d)K,L,γ,e^-
Sr 90(28y)β^-; 89(51d)β^-,γ; 85(64d)K,γ
Ta 182(115d)β^-,γ
Tb 160(73d)β^-,γ
Tc 99(2x10^{5}y)β^-; 97(10^{6}y)K
Te 127(9.3h)β^-
Th 232(1.4x10^{10}y)α,γ,SF; 228(1.91y)β^-
Tl 204(3.81y)β^-,K
Tm 170(134d)β^-,γ,e^-
U 238(4.5x10^{9}y)α,γ,SF; 234(2.5x10^{5}y)α,γ,SF; 235(7.1x10^{8}y)α,γ,SF; 233(1.6x10^{5}y)α,γ
W 185(75d)β^-
Y 90(64h)β^-,e^-
Yb 175(4.2d)β^-,γ; 169(31d)K,γ,e^-
Zn 65(245d)K,β^+,γ
Zr 95(65d)β^-,γ,e^-; 93(9x10^{5}y)β^-,γ

Naturally occurring radioactive isotopes are indicated by a blue mass number. Half lives are in parentheses where s, m, h, d and y stand for seconds, minutes, hours, days and years respectively. The symbols describing the mode of decay and resulting radiation are defined as follows:

α	alpha particle	L	L-electron capture
β^-	beta particle	SF	spontaneous fission
β^+	positron	γ	gamma ray
K	K-electron capture	e^-	internal electron conversion

Elements

Group	Atomic number	Symbol	Name	Atomic weight (2)	Oxidation states	Boiling point, °C	Melting point, °C	Density (g/ml) (3)	Electron structure
IA	1	H	Hydrogen	1.00797	1	−252.7	−259.2	0.071	$1s^1$
VIIIA	2	He	Helium	4.0026		−268.9	−269.7	0.126	$1s^2$
IA	3	Li	Lithium	6.939	1	1330	180.5	0.53	$1s^2 2s^1$
IIA	4	Be	Beryllium	9.0122	2	2770	1277	1.85	$1s^2 2s^2$
IIIA	5	B	Boron	10.811	3	—	(2030)	2.34	$1s^2 2s^2 2p^1$
IVA	6	C	Carbon	12.01115	±4,2	4830	3727	2.26	$1s^2 2s^2 2p^2$
VA	7	N	Nitrogen	14.0067	±3,5,4,2	−195.8	−210	0.81	$1s^2 2s^2 2p^3$
VIA	8	O	Oxygen	15.9994	−2	−183	−218.8	1.14	$1s^2 2s^2 2p^4$
VIIA	9	F	Fluorine	18.9984	−1	−188.2	−219.6	1.505	$1s^2 2s^2 2p^5$
VIIIA	10	Ne	Neon	20.183		−246	−248.6	1.20	$1s^2 2s^2 2p^6$
IA	11	Na	Sodium	22.9898	1	892	97.8	0.97	$[Ne]3s^1$
IIA	12	Mg	Magnesium	24.312	2	1107	650	1.74	$[Ne]3s^2$
IIIA	13	Al	Aluminum	26.9815	3	2450	660	2.70	$[Ne]3s^2 3p^1$
IVA	14	Si	Silicon	28.086	4	2680	1410	2.33	$[Ne]3s^2 3p^2$
VA	15	P	Phosphorus	30.9738	±3,5,4	280w	44.2w	1.82w	$[Ne]3s^2 3p^3$
VIA	16	S	Sulfur	32.064	±2,4,6	444.6	119.0	2.07	$[Ne]3s^2 3p^4$
VIIA	17	Cl	Chlorine	35.453	±1,3,5,7	−34.7	−101.0	1.56	$[Ne]3s^2 3p^5$
VIIIA	18	Ar	Argon	39.948		−185.8	−189.4	1.40	$[Ne]3s^2 3p^6$
IA	19	K	Potassium	39.102	1	760	63.7	0.86	$[Ar]4s^1$
IIA	20	Ca	Calcium	40.08	2	1440	838	1.55	$[Ar]4s^2$
IIIB	21	Sc	Scandium	44.956	3	2730	1539	3.0	$[Ar]3d^1 4s^2$
IVB	22	Ti	Titanium	47.90	4,3	3260	1668	4.51	$[Ar]3d^2 4s^2$
VB	23	V	Vanadium	50.942	5,4,3,2,	3450	1900	6.1	$[Ar]3d^3 4s^2$
VIB	24	Cr	Chromium	51.996	6,3,2	2665	1875	7.19	$[Ar]3d^5 4s^1$
VIIB	25	Mn	Manganese	54.938	7,6,4,2,3	2150	1245	7.43	$[Ar]3d^5 4s^2$
VIII	26	Fe	Iron	55.847	2,3	3000	1536	7.86	$[Ar]3d^6 4s^2$
VIII	27	Co	Cobalt	58.933	2,3	2900	1495	8.9	$[Ar]3d^7 4s^2$
VIII	28	Ni	Nickel	58.71	2,3	2730	1453	8.9	$[Ar]3d^8 4s^2$
IB	29	Cu	Copper	63.54	2,1	2595	1083	8.96	$[Ar]3d^{10} 4s^1$
IIB	30	Zn	Zinc	65.37	2	906	419.5	7.14	$[Ar]3d^{10} 4s^2$
IIIA	31	Ga	Gallium	69.72	3	2237	29.8	5.91	$[Ar]3d^{10} 4s^2 4p^1$
IVA	32	Ge	Germanium	72.59	4	2830	937.4	5.32	$[Ar]3d^{10} 4s^2 4p^2$
VA	33	As	Arsenic	74.922	±3,5	613*	817	5.72	$[Ar]3d^{10} 4s^2 4p^3$
VIA	34	Se	Selenium	78.96	−2,4,6	685	217	4.79	$[Ar]3d^{10} 4s^2 4p^4$
VIIA	35	Br	Bromine	79.909	±1,5	58	−7.2	3.12	$[Ar]3d^{10} 4s^2 4p^5$
VIIIA	36	Kr	Krypton	83.80		−152	−157.3	2.6	$[Ar]3d^{10} 4s^2 4p^6$
IA	37	Rb	Rubidium	85.47	1	688	38.9	1.53	$[Kr]5s^1$
IIA	38	Sr	Strontium	87.62	2	1380	768	2.6	$[Kr]5s^2$
IIIB	39	Y	Yttrium	88.905	3	2927	1509	4.47	$[Kr]4d^1 5s^2$
IVB	40	Zr	Zirconium	91.22	4	3580	1852	6.49	$[Kr]4d^2 5s^2$
VB	41	Nb	Niobium	92.906	5,3	3300	2468	8.4	$[Kr]4d^4 5s^1$
VIB	42	Mo	Molybdenum	95.94	6,5,4,3,2	5560	2610	10.2	$[Kr]4d^5 5s^1$
VIIB	43	Tc	Technetium	(98)	7	—	2140	11.5	$[Kr]4d^5 5s^2$
VIII	44	Ru	Ruthenium	101.07	2,3,4,6,8	4900	2500	12.2	$[Kr]4d^7 5s^1$
VIII	45	Rh	Rhodium	102.905	2,3,4	4500	1966	12.4	$[Kr]4d^8 5s^1$
VIII	46	Pd	Palladium	106.4	2,4	3980	1552	12.0	$[Kr]4d^{10} 5s^0$
IB	47	Ag	Silver	107.870	1	2210	960.8	10.5	$[Kr]4d^{10} 5s^1$
IIB	48	Cd	Cadmium	112.40	2	765	320.9	8.65	$[Kr]4d^{10} 5s^2$
IIIA	49	In	Indium	114.82	3	2000	156.2	7.31	$[Kr]4d^{10} 5s^2 5p^1$
IVA	50	Sn	Tin	118.69	4,2	2270	231.9	7.30	$[Kr]4d^{10} 5s^2 5p^2$
VA	51	Sb	Antimony	121.75	±3,5	1380	630.5	6.62	$[Kr]4d^{10} 5s^2 5p^3$
VIA	52	Te	Tellurium	127.60	−2,4,6	989.8	449.5	6.24	$[Kr]4d^{10} 5s^2 5p^4$
VIIA	53	I	Iodine	126.904	±1,5,7	183	113.7	4.94	$[Kr]4d^{10} 5s^2 5p^5$
VIIIA	54	Xe	Xenon	131.30		−108.0	−111.9	3.06	$[Kr]4d^{10} 5s^2 5p^6$
IA	55	Cs	Cesium	132.905	1	690	28.7	1.90	$[Xe]6s^1$
IIA	56	Ba	Barium	137.34	2	1640	714	3.5	$[Xe]6s^2$
IIIB	57 ★	La	Lanthanum	138.91	3	3470	920	6.17	$[Xe]5d^1 6s^2$
★	58	Ce	Cerium	140.12	3,4	3468	795	6.67	$[Xe]4f^2 5d^0 6s^2$
★	59	Pr	Praseodymium	140.907	3,4	3127	935	6.77	$[Xe]4f^3 5d^0 6s^2$
★	60	Nd	Neodymium	144.24	3	3027	1024	7.00	$[Xe]4f^4 5d^0 6s^2$
★	61	Pm	Promethium	(147)	3	—	(1027)	—	$[Xe]4f^5 5d^0 6s^2$
★	62	Sm	Samarium	150.35	3,2	1900	1072	7.54	$[Xe]4f^6 5d^0 6s^2$
★	63	Eu	Europium	151.96	3,2	1439	826	5.26	$[Xe]4f^7 5d^0 6s^2$
★	64	Gd	Gadolinium	157.25	3	3000	1312	7.89	$[Xe]4f^7 5d^1 6s^2$
★	65	Tb	Terbium	158.924	3,4	2800	1356	8.27	$[Xe]4f^9 5d^0 6s^2$
★	66	Dy	Dysprosium	162.50	3	2600	1407	8.54	$[Xe]4f^{10} 5d^0 6s^2$
★	67	Ho	Holmium	164.930	3	2600	1461	8.80	$[Xe]4f^{11} 5d^0 6s^2$
★	68	Er	Erbium	167.26	3	2900	1497	9.05	$[Xe]4f^{12} 5d^0 6s^2$
★	69	Tm	Thulium	168.934	3,2	1727	1545	9.33	$[Xe]4f^{13} 5d^0 6s^2$
★	70	Yb	Ytterbium	173.04	3,2	1427	824	6.98	$[Xe]4f^{14} 5d^0 6s^2$
★	71	Lu	Lutetium	174.97	3	3327	1652	9.84	$[Xe]4f^{14} 5d^1 6s^2$
IVB	72	Hf	Hafnium	178.49	4	5400	2222	13.1	$[Xe]4f^{14} 5d^2 6s^2$
VB	73	Ta	Tantalum	180.948	5	5425	2996	16.6	$[Xe]4f^{14} 5d^3 6s^2$
VIB	74	W	Wolfram	183.85	6,5,4,3,2	5930	3410	19.3	$[Xe]4f^{14} 5d^4 6s^2$
VIIB	75	Re	Rhenium	186.2	7,6,4,2,−1	5900	3180	21.0	$[Xe]4f^{14} 5d^5 6s^2$
VIII	76	Os	Osmium	190.2	2,3,4,6,8	5500	3000	22.6	$[Xe]4f^{14} 5d^6 6s^2$
VIII	77	Ir	Iridium	192.2	2,3,4,6	5300	2454	22.5	$[Xe]4f^{14} 5d^7 6s^2$
VIII	78	Pt	Platinum	195.09	2,4	4530	1769	21.4	$[Xe]4f^{14} 5d^9 6s^1$
IB	79	Au	Gold	196.967	3,1	2970	1063	19.3	$[Xe]4f^{14} 5d^{10} 6s^1$
IIB	80	Hg	Mercury	200.59	2,1	357	−38.4	13.6	$[Xe]4f^{14} 5d^{10} 6s^2$
IIIA	81	Tl	Thallium	204.37	3,1	1457	303	11.85	$[Xe]4f^{14} 5d^{10} 6s^2 6p^1$
IVA	82	Pb	Lead	207.19	4,2	1725	327.4	11.4	$[Xe]4f^{14} 5d^{10} 6s^2 6p^2$
VA	83	Bi	Bismuth	208.980	3,5	1560	271.3	9.8	$[Xe]4f^{14} 5d^{10} 6s^2 6p^3$
VIA	84	Po	Polonium	(210)	2,4	—	254	(9.2)	$[Xe]4f^{14} 5d^{10} 6s^2 6p^4$
VIIA	85	At	Astatine	(210)	±1,3,5,7	—	(302)	—	$[Xe]4f^{14} 5d^{10} 6s^2 6p^5$
VIIIA	86	Rn	Radon	(222)		(−61.8)	(−71)	—	$[Xe]4f^{14} 5d^{10} 6s^2 6p^6$
IA	87	Fr	Francium	(223)	1	—	(27)	—	$[Rn]7s^1$
IIA	88	Ra	Radium	(226)	2	—	700	5.0	$[Rn]7s^2$
IIIB	89 ★★	Ac	Actinium	(227)	3	—	1050	—	$[Rn]6d^1 7s^2$
★★	90	Th	Thorium	232.038	4	3850	1750	11.7	$[Rn]5f^0 6d^2 7s^2$
★★	91	Pa	Protactinium	(231)	5,4	—	(1230)	15.4	$[Rn]5f^2 6d^1 7s^2$
★★	92	U	Uranium	238.03	6,5,4,3	3818	1132	19.07	$[Rn]5f^3 6d^1 7s^2$
★★	93	Np	Neptunium	(237)	6,5,4,3	—	637	19.5	$[Rn]5f^4 6d^1 7s^2$
★★	94	Pu	Plutonium	(242)	6,5,4,3	3235	640	—	$[Rn]5f^6 6d^0 7s^2$
★★	95	Am	Americium	(243)	6,5,4,3	—	—	11.7	$[Rn]5f^7 6d^0 7s^2$
★★	96	Cm	Curium	(247)	3	—	—	—	$[Rn]5f^7 6d^1 7s^2$
★★	97	Bk	Berkelium	(247)	4,3	—	—	—	$[Rn]5f^9 6d^0 7s^2$
★★	98	Cf	Californium	(249)	3	—	—	—	$[Rn]5f^{10} 6d^0 7s^2$
★★	99	Es	Einsteinium	(254)	—	—	—	—	$[Rn]5f^{11} 6d^0 7s^2$
★★	100	Fm	Fermium	(253)	—	—	—	—	$[Rn]5f^{12} 6d^0 7s^2$
★★	101	Md	Mendelevium	(256)	—	—	—	—	$[Rn]5f^{13} 6d^0 7s^2$
★★	102	No	Nobelium	(254)	—	—	—	—	$[Rn]5f^{14} 6d^0 7s^2$
★★	103	Lw	Lawrencium	(257)	—	—	—	—	$[Rn]5f^{14} 6d^1 7s^2$
	104								

KEY

ATOMIC NUMBER: 30; ATOMIC WEIGHT (2): 65.37; OXIDATION STATES (Bold most stable): 2; BOILING POINT, °C: 906; MELTING POINT, °C: 419.5; DENSITY (g/ml) (3): 7.14; SYMBOL (1): Zn; ELECTRON STRUCTURE: $[Ar]3d^{10}4s^2$; NAME: Zinc

NOTES:

(1) Black — solid.
Red — gas.
Blue — liquid.
Outline — synthetically prepared.

(2) Based upon carbon – 12. ( ) indicates most stable or best known isotope.

(3) Values for gaseous elements are for liquids at the boiling point.

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