Exam Kaleidoscope of Modern Physics

3 November 2015, 14:00-17:00

- Put your name and student number on each answer sheet.
- Answer all questions short and to the point, but complete; write legible.
- Use of a calculator is not allowed.
- Final grade = total number of points/10 + 1

NAME : .... STUDENT NUMBER : ....

1. Read the following propositions carefully and indicate if they are true (T) or false (F) by checking the appropriate box. **(15 points)**

T☐ **F**☐ According to the de Broglie relation, the higher the momentum, the shorter the wavelength.
TRUE, the de Broglie relation states that $\lambda = h/p$, with λ the wavelength, p the momentum and h Planck's constant.

T☐ **F**☐ The wave nature of particles mainly shows up when the particle has a small energy or when considered at small length scales.
TRUE, the de Broglie wavelength of a particle is either very short and thus only visible at small length scales. At smaller energies, the wavelength is longer and thus also visible at larger length scales.

T☐ **F**☐ Although the energy of an electron bound in an atom can only take discrete values, the corresponding photon emission spectrum may be continuous.
FALSE, photons get emitted when the electron jumps from one state to another. Energy conservation dictates that the photon carries away the difference in electron energy, which is thus also discrete.

T☐ **F**☐ Photons with a wavelength of 410 nm have a higher energy than photons with a wavelength of 750 nm.
TRUE, the energy of a photon is given by $E = hc/\lambda$, with λ the wavelength.

T☐ **F**☐ If an electron and a proton travel at the same speed, the proton has a shorter wavelength because the proton is much heavier than the electron.
TRUE, the de Broglie wavelength is defined as $\lambda = h/p = h/(m \cdot v)$. If the velocity is the same, but the mass larger, the momentum is larger and hence the wavelength shorter.

T☐ **F**☐ It is impossible to measure exactly where a particle is, unless it is at rest.
FALSE, the uncertainty relation states that if a particle has a well defined momentum and hence velocity, the position uncertainty becomes large.

T☐ **F**☐ A probability amplitude can be negative.
TRUE, the probability amplitude is given by a complex number and can taken any value, positive and negative, as well as imaginary and any combination.

T☐ **F**☐ Using Quantum Mechanics you can very precisely calculate the probability for some event, but you cannot predict when an event will actually happen.
TRUE, all you can do is calculate the probability, not the actual moment of occurence.

T☐ **F**☐ A free particle with a precisely defined momentum has a poorly defined location.
TRUE, this is a consequence of the uncertainty principle, $\Delta p \cdot \Delta x \geq \hbar/2$.

T☐ **F**☐ A wavefunction must be normalized according to $\int_{\text{all space}} \psi(x)dx = 1$.
FALSE, the probability density $P(x) = |\psi(x)|^2$ should be normalised, and hence $\int_{\text{all space}} |\psi(x)|^2 dx = 1$

T☐ **F**☐ If Planck's constant were a lot larger, we would eventually notice quantum effects in every day life.
TRUE, the magnitude of quantum effects is related to the magnitude of Planck's constant.

T☐ **F**☐ The photon energies for transitions to the $n = 1$ state in a hydrogen atom are generally larger than those for transitions to the $n = 2$ state.
TRUE, the photon energy is determined by the difference of the energy of the initial electron state and that of the final electron state. The energies of the intial states are essentially the same, but the energies of the final state quite different. For $n = 1$ this energy is much lower, than for $n = 2$.

T☐ **F**☐ Materials with a larger work function require photons with longer wavelengths to release an electron via the photoelectric effect.
FALSE, if the work function is larger, photons need to have a higher energy to release an electron. Higher energy means a smaller wavelength.

T☐ **F**☐ If nothing else changes, the zero-point energy of a wider box is smaller than that of a narrower box.
TRUE, for a wider box, the wavefunction can have a larger wavelength, and hence a lower energy.

T☐ **F**☐ Without Pauli's exclusion principle, all atomic electrons would occupy the $n = 1, l = 0, m_l = 0$ state.
TRUE; then electron could share the same quantum numbers.

T☐ **F**☐ The energy of an electron in an atom is primarily determined by the orbital quantum number l.
FALSE; it is mainly the principal quantum number n that determines the energies.

T☐ **F**☐ The energies of the electron states in an atom scale with $1/Z^2$, with Z the charge of the nucleus.
FALSE; it scales as Z^2.

T☐ **F**☐ A subshell can contain $2(2l + 1)$ electrons.
TRUE; a sub-shell is defined by electrons sharing a particular value of n and l. In a subshell m_l can take $(2l + 1)$ values, and m_s two, totalling $2(2l + 1)$ possible states.

T☐ **F**☐ A shell can contain $2n^2$ electrons.
TRUE; a shell is defined as the collection of states that share the same value of n. For the same n, l can take a value from zero to $n - 1$ (forming a sub-shell). Then refer to the previous question.

T☐ **F**☐ For noble gases in the ground state all electronic shells are full.
TRUE; this defines noble gases.

T☐ **F**☐ A molecule primarily held together by the attraction between the nuclei to the electron cloud between them is said to have an ionic bond.
FALSE; this is a covalent bond.

T☐ **F**☐ Burning gasoline releases more energy than burning wood. The activation energy for burning gasoline is thus larger than for burning wood.
FALSE; activation energy is a reaction threshold. The binding energy determines the energy release.

T☐ **F**☐ For a semiconductor the valence band is completely filled, just like for an insulator.
TRUE; the only difference is the size of the band gap.

T☐ **F**☐ The electrons in a metal are not subject to the exclusion principle.
FALSE; they are fermions and thus always have to obey the exclusion principle.

T☐ **F**☐ Isotopes have the same number of protons.
TRUE; by definition.

T☐ **F**☐ Isotones have the same chemical properties.
FALSE; isotones share the same number of neutrons. The chemical properties are determined by the number of electrons, which is equal to the number of protons.

T☐ **F**☐ Protons and neutrons are fermions.
TRUE; both have spin-1/2.

T☐ **F**☐ An atomic nucleus contains almost all the mass of an atom.
TRUE; electrons are about 2000 times lighter than protons, of which there are an equal number. And there are typically a similar number of neutrons, which have a similar weight as protons.

T☐ **F**☐ In an elastic scattering experiment the particles in the initial and final state are the same.
TRUE; by definition.

T☐ **F**☐ All isotopes heavier than Iron-56 can fission spontaneously.
FALSE; that depends on the Q-valu.

T☐ **F**☐ The binding energy of an electron in an atom is of order 1/1,000th of that of a proton or neutron in a nucleus.
FALSE; atomic binding energies are of order $10 - 100\,\text{eV}$. Nuclear binding energies are of order $10\,\text{MeV}$.

T☐ **F**☐ The strong nuclear force has infinity range.
FALSE; from the approximate constancy of the binding energy per nucleon it follows that the nucleons don't "see" all the other nucleons in a nucleus. This is only possible if the range of the force is limited.

T☐ **F**☐ A radioactive nucleus has less mass than the combination of particles and nuclei it decays into.
FALSE; to be radioactive the nucleus must decau spontaneously, and for this a mass-excess, $Q > 0$, is necessary. This means that a radioactive nucleus is *heavier* that its daughters.

T☐ **F**☐ Spontaneous decay requires a Q-value smaller than zero.
FALSE; $Q > 0$.

T☐ **F**☐ In α-decay N and Z will change, but A remains the same.
FALSE; the total number of nucleons goes down by 4.

T☐ **F**☐ In two-body decay the kinetic energies of the daughters are discrete; in three-body decay they are continuous.
TRUE; several combination of momenta and their relative orientation can guarantee energy and momentum conservation.

T☐ **F**☐ After one half-life 50% of a radioactive substance has disappeared; after two half-lives 100% is gone.
FALSE; after two half-lives 50% + 50% of the remaining 50% has decayed. So 25% is still left over.

T☐ **F**☐ It is possible to find natural (*i.e.* not man-made) short-lived isotopes on earth, of which the lifetime is much shorter than the age of the earth.
TRUE; they could be produced in the decay chain of a longer living isotope.

T☐ **F**☐ Gluons are the particles associated with the strong interaction between quarks.
TRUE;

T☐ **F**☐ The weak interaction is only weak at large distances; at (very) short distances it is about as strong as the electromagnetic interaction.
TRUE; the weakness is caused by the large mass of the transmitting boson.

T☐ **F**☐ A particle and its antiparticle have precisely the same mass.
TRUE; only the other properties have opposite values.

T☐ **F**☐ Neutrinos only interact via the weak interaction.
TRUE

T☐ **F**☐ ”Color” is like the electric charge, but then for the weak interaction.
FALSE; color is the ”charge” for the strong interaction.

2. Consider a particle with mass m in a one-dimensional *rigid* box with width w. **(12 points)**

   a) Formulate the de Broglie relation showing how the wavelength and the momentum $p = mv$ of a particle are related.
   The de Broglie relation states that the wavelength and the momentum are inversely proportional, with Planck's constant as the proportionallity constant. So $\lambda = h/p = h/(m \cdot v)$.

   b) What condition does the wavefunction have to meet at the wall of the box? Briefly explain.
   A particle in a rigid box cannot be outside the box. Because the square of (the norm of) the wavefunction gives the probability (density) to be at some location, the wavefunction has to be zero outside the box, and thus also at the wall. Only inside the box the wavefunction can (must) have non-zero values.

   c) Explain why only discrete values of the particle energy are allowed. *Hint:* use that $E = p^2/2m$.
   A whole number of half-waves have to fit in between the two walls, because only then the wavefunction can be zero at both walls. This means that only a discrete number of wavelengths are actually allowed inside the box, namely those for which $n \cdot \lambda/2 = w$, with n an integer number. Because of the de Broglie relation, this means that also the momentum can only have specific discrete values and therefore also $E = p^2/2m$.

   d) What is the interpretation of the wave function?
   As in the book: The square of the norm of the wave function, $|\Psi|^2$, at a certain point in space and time represents the probability (density) of finding the electron (better: physical system) at the given position and time (better: in a given state).

3. Use dimensional analysis to find the relation between the force F (in N = kg·m/s^2) needed to keep a ball with mass M at the end of a piece of string with length R and going around with velocity V. **(12 points)**

We have to find the way the force F depends on M, R and V. Assume therefore that

$$F = M^\alpha R^\beta V^\gamma.$$

As the force is given in Newton (1 N = 1 kg·m/s^2, the dimension of the lefthand side of the equation is [mass][length]/[time]^2. The righthand side has dimension

$$[\text{mass}]^\alpha[\text{length}]^\beta([\text{length}]/[\text{time}])^\gamma.$$

To match the mass dimension, $\alpha = 1$. To match the time dimension, $\gamma = 2$. This brings in a length-squared, so $\beta = -1$, giving the solution

$$F = M \cdot V^2/R$$

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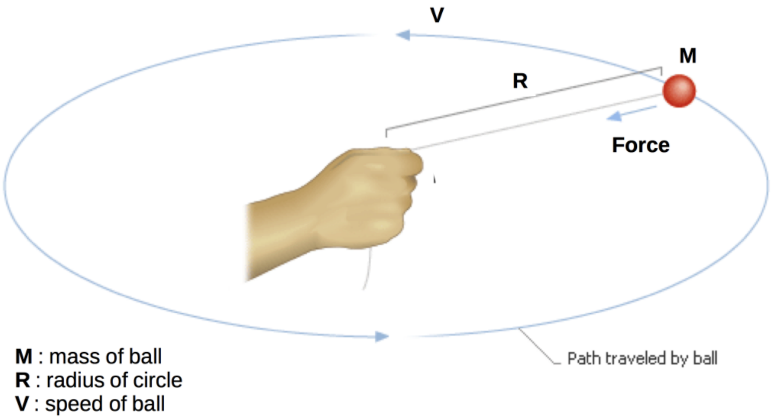

4. Atomic Physics : **(12 points)**

   a) How many electrons are there in a chlorine atom (Cl)? And in a sodium atom (Na)?
   From the periodic system in the appendix: Na: 11, Cl: 17

   b) Use the appendix "Sodium and Chlorine energy levels". (*i*) Indicate for the left and right spectrum which one represents Na and which Cl. Distribute the number of electrons found in a)[1] over the available states to form each atom in its ground state. Indicate for each state (*ii*) how many electrons it holds (if more than zero) and (*iii*) label the corresponding state (as in the bottom left corner) (*iv*) give the complete electron configuration for Na and Cl.
   The (single-electron) energies in an atom scale as Z^2, so that of Cl are larger (in absolute sense). So the left scheme belongs to Cl, the right to Na. The Na system has 2 electrons in the 1S state, 2 in the 2S, 6 in 2P, and 1 in 3S. Cl is 1s2 2s2 2p6 3s2 3p5.

   c) If you would knock out one of the electrons in the 1s shell, X-rays are emitted. Explain how the wavelength of this X-ray can be used to identify the emitting atom.
   One of the other atomic electrons would make a jump to fill the vacancy, and emit a photon with an energy that is equal to the difference in the energy levels. The level spacing in Na and Cl are different, and hence photons with different energies are emitted. The 1S state of Cl is more strongly bound, so for Cl the emitted photons have shorter wavelengths than for Na.

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[1] If you don't know the answer, take a number anywhere between 10 and 20.

5. Nuclear Physics & Radioactivity: **(12 points)**

   a) Which two interactions determine the binding energy of an atomic nucleus? Indicate for each interaction whether it is attractive, repulsive or absent for *pp*, *pn*, and *nn* pairs. Use these observations to explain why very heavy nuclei generally have $N > Z$, while light ones have $N \simeq Z$.
   The two relevant interactions are the EM and strong nuclear interaction (SNI). The SNI is attractive for all three pairs. The EM interaction is only repulseive for a *pp* pair, and absent for the other two. The binding energy per nucleon due to the electromagnetic respulsion grows with Z, whereas the energy per nucleon due to the strong interaction is approximately constant. To compensate for the loss in binding for larger Z addition neutron are needed to increase the distance between the protons, and hence lower the repulsion.

   b) Briefly explain the principle of ^{14}C-dating. Can it be used for dating: *(i)* wine, *(ii)* rock walls of an old civilization, *(iii)* wall paintings of *homo sapiens*, *(iv)* dinosaur bones? Why (not)?
   I. Carbon-14 is continuously produced in the upper atmosphere by cosmic radiation. It is absorbed by living organisms and incorported into their system. Once they die, the intake of C-14 stops and the accumulated amount slowly drops because of radioactive decay. C-14 has a halflife of about 6000 years. **II.** *i* wine: consists of grapes, which accumulate C-14 while they are on the plant. Wine is kept in closed bottles, thus no new carbon is accumulated. Hence it can be carbon-dated. *ii* rock walls: do not "grow" and hence do not accumulate C-14 during their "life". Hence: no. *iii* wall paintings: if the used paint is organic (plants, ashes), then yes, otherwise: no. After-the-fact accumulation may affect the result though. *iv* dinosaur bones can in principle be radio-dated, because they contain carbon, but they are much older than the half-life, so: no.

   c) Write down the reaction equations for the following processes (identify all particles involved!): β^- decay of $^{200}_{78}$Pt; electron capture of $^{163}_{67}$Ho; α decay of $^{8}_{4}$Be.
   β^-: A remains the same, Z goes up by 1: $^{200}_{78}\mathrm{Pt} \rightarrow ^{200}_{79}\mathrm{Au} + e^- + \bar{\nu}_e$; Electron capture: equivalent to β^+ decay, $^{163}_{67}\mathrm{Ho} + e^- \rightarrow ^{163}_{66}\mathrm{Dy} + \nu_e$; a neutrino is generated; α decay: A goes down by 4, Z by 2, $^{8}_{4}\mathrm{Be} \rightarrow ^{4}_{2}\mathrm{He} + \alpha$ (or 2α).

6. Particle Physics : **(12 points)**

   a) Name the four fundamental interactions and the corresponding carrier bosons. What makes the weak interaction "weak"?
   Strong, gluons; EM, photons; Weak, W$^+$,W$^-$,Z; Gravity, gravitons. The weak interaction is weak because the mass of the W and Z boson are so large. This makes the range of the WI very short, and thus very weak.

   b) Which (kinds of) fundamental fermions are subject to the strong interaction? Electromagnetic interaction? Weak interaction?
   SI: only the quarks; EM: quarks and charged leptons; Weak: all particles.

   c) Put the following systems in the correct order of their first appearance after the Big Bang: deuterium nucleus, electron, helium atom, DNA molecule, neutron, star. Motivate your ordering, using *e.g.* temperature or the strenght of the various forces binding the object.
   I. electron: this is an elementary particles that can be created immediately after the Big Bang. No binding is required, so these particles can have high energies;
   II. neutron: requires the binding of quarks using the strong force. The temperature needs to be low enough that the kinetic energy is smaller than the binding energy;
   III. deuterium nucleus: requires the binding between a proton and a neutron, which thus first

have to be formed. Nuclear binding energies are of order MeV (here it's 2.2 MeV), which has to be below the thermal energy of the protons and neutrons;

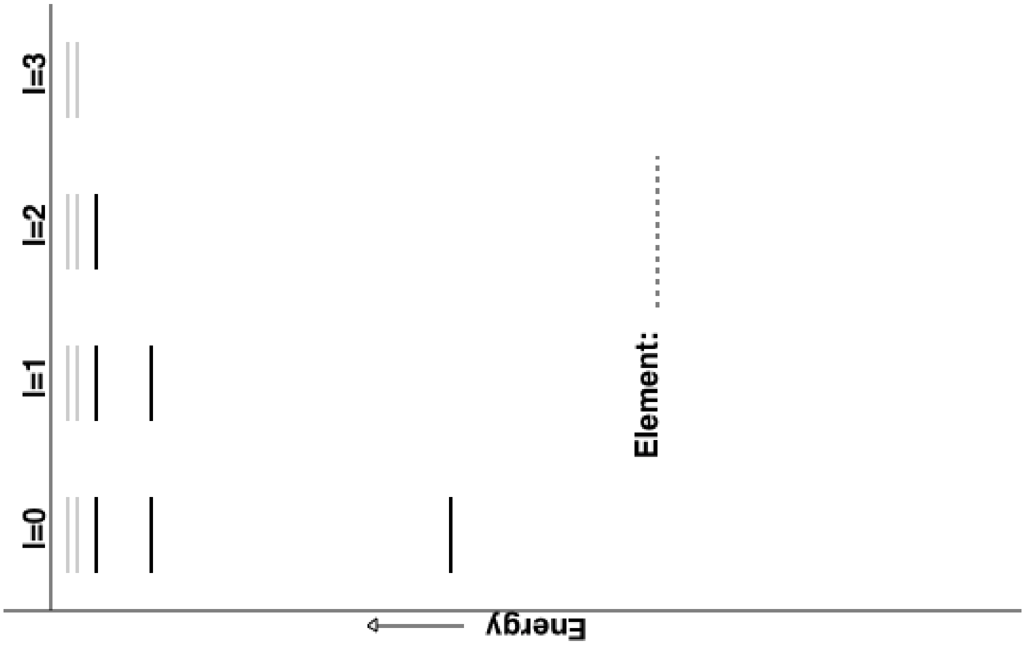
IV. helium atom: electrons and nuclei are bound into an atom due to the electromagnetic interaction. Typical binding energies are of order eV, with correspondingly lower temperature.

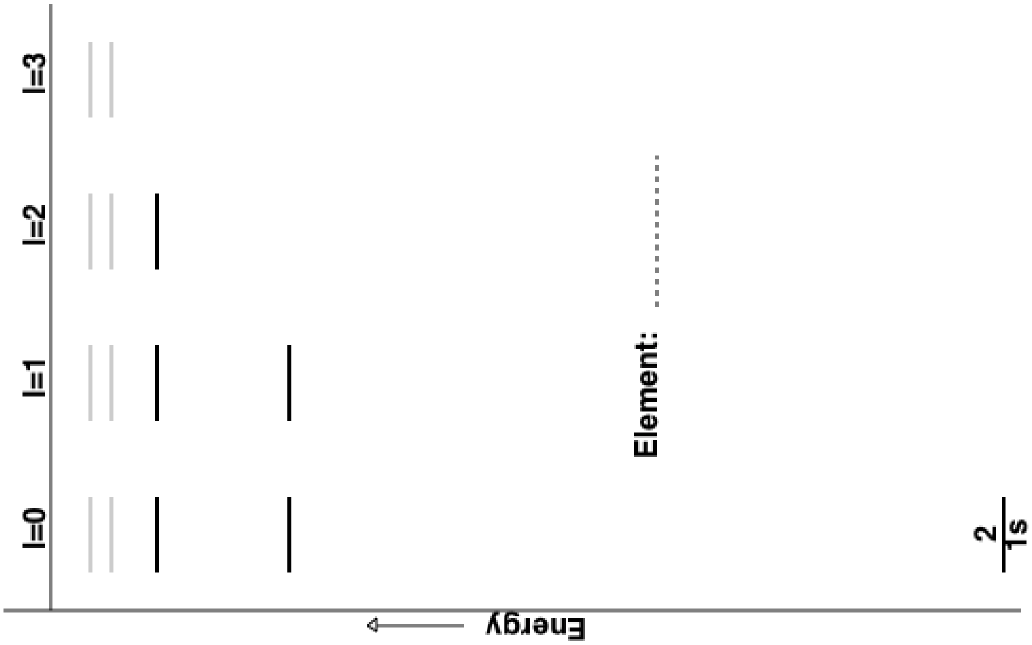
V. star: may consist of hydrogen atoms, bound by the gravitational attaction. Binding is exceedingly weak (10^{36} times weaker than the EM interaction), hence star formation can only occur once the temperature of the universe has dropped a lot.

VI. DNA molecule: requires heavy elements formed in supernovae to accumulate on a cold planet such that complicated molecular processes can take place.

7. Fermi problem: **(15 points)**
   How far away could you be from the nearest windmill if the Netherlands would produce all its electricity from windmills on land?
   Many answers possible. Items to address include: estimation of energy needs in the Netherlands (approx. 1 kW/household), population of the Netherlands (17 million), power output of a windmill (typically 1 MW), size of the Netherlands (33,000 km^2).

Sodium and Chlorine energy levels





Fundamental Constants

Quantity	Symbol	Approximate Value	Current Best Value†
Speed of light in vacuum	c	$3.00 \times 10^8 \mathrm{~m/s}$	$2.99792458 \times 10^8 \mathrm{~m/s}$
Gravitational constant	G	$6.67 \times 10^{-11} \mathrm{~N \cdot m^2/kg^2}$	$6.6728(67) \times 10^{-11} \mathrm{~N \cdot m^2/kg^2}$
Avogadro's number	N_{A}	$6.02 \times 10^{23} \mathrm{~mol^{-1}}$	$6.02214179(30) \times 10^{23} \mathrm{~mol^{-1}}$
Gas constant	R	$8.314 \mathrm{~J/mol \cdot K} = 1.99 \mathrm{~cal/mol \cdot K}$ $= 0.0821 \mathrm{~L \cdot atm/mol \cdot K}$	$8.314472(15) \mathrm{~J/mol \cdot K}$
Boltzmann's constant	k	$1.38 \times 10^{-23} \mathrm{~J/K}$	$1.3806504(24) \times 10^{-23} \mathrm{~J/K}$
Charge on electron	e	$1.60 \times 10^{-19} \mathrm{~C}$	$1.602176487(40) \times 10^{-19} \mathrm{~C}$
Stefan-Boltzmann constant	σ	$5.67 \times 10^{-8} \mathrm{~W/m^2 \cdot K^4}$	$5.670400(40) \times 10^{-8} \mathrm{~W/m^2 \cdot K^4}$
Permittivity of free space	$\epsilon_0 = (1/c^2\mu_0)$	$8.85 \times 10^{-12} \mathrm{~C^2/N \cdot m^2}$	$8.854187817 \ldots \times 10^{-12} \mathrm{~C^2/N \cdot m^2}$
Permeability of free space	μ_0	$4\pi \times 10^{-7} \mathrm{~T \cdot m/A}$	$1.2566370614 \ldots \times 10^{-6} \mathrm{~T \cdot m/A}$
Planck's constant	h	$6.63 \times 10^{-34} \mathrm{~J \cdot s}$	$6.62606896(33) \times 10^{-34} \mathrm{~J \cdot s}$
Electron rest mass	m_{e}	$9.11 \times 10^{-31} \mathrm{~kg} = 0.000549 \mathrm{~u}$ $= 0.511 \mathrm{~MeV}/c^2$	$9.10938215(45) \times 10^{-31} \mathrm{~kg}$ $= 5.4857990943(23) \times 10^{-4} \mathrm{~u}$
Proton rest mass	m_{p}	$1.6726 \times 10^{-27} \mathrm{~kg} = 1.00728 \mathrm{~u}$ $= 938.27 \mathrm{~MeV}/c^2$	$1.672621637(83) \times 10^{-27} \mathrm{~kg}$ $= 1.00727646677(10) \mathrm{~u}$
Neutron rest mass	m_{n}	$1.6749 \times 10^{-27} \mathrm{~kg} = 1.008665 \mathrm{~u}$ $= 939.57 \mathrm{~MeV}/c^2$	$1.674927211(84) \times 10^{-27} \mathrm{~kg}$ $= 1.00866491597(43) \mathrm{~u}$
Atomic mass unit (1 u)		$1.6605 \times 10^{-27} \mathrm{~kg} = 931.49 \mathrm{~MeV}/c^2$	$1.660538782(83) \times 10^{-27} \mathrm{~kg}$ $= 931.494028(23) \mathrm{~MeV}/c^2$

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† CODATA (3/07), Peter J. Mohr and Barry N. Taylor, National Institute of Standards and Technology. Numbers in parentheses indicate one-standard-deviation experimental uncertainties in final digits. Values without parentheses are exact (i.e., defined quantities).

Other Useful Data

Joule equivalent (1 cal)	4.186 J
Absolute zero (0 K)	−273.15°C
Acceleration due to gravity at Earth's surface (avg.)	$9.80 \mathrm{~m/s^2}$ $(= g)$
Speed of sound in air (20°C)	343 m/s
Density of air (dry)	$1.29 \mathrm{~kg/m^3}$
Earth: Mass	$5.98 \times 10^{24} \mathrm{~kg}$
Radius (mean)	$6.38 \times 10^3 \mathrm{~km}$
Moon: Mass	$7.35 \times 10^{22} \mathrm{~kg}$
Radius (mean)	$1.74 \times 10^3 \mathrm{~km}$
Sun: Mass	$1.99 \times 10^{30} \mathrm{~kg}$
Radius (mean)	$6.96 \times 10^5 \mathrm{~km}$
Earth–Sun distance (mean)	$149.6 \times 10^6 \mathrm{~km}$
Earth–Moon distance (mean)	$384 \times 10^3 \mathrm{~km}$

The Greek Alphabet

Alpha	A	α	Nu	N	ν
Beta	B	β	Xi	Ξ	ξ
Gamma	Γ	γ	Omicron	O	o
Delta	Δ	δ	Pi	Π	π
Epsilon	E	ϵ, ε	Rho	P	ρ
Zeta	Z	ζ	Sigma	Σ	σ
Eta	H	η	Tau	T	τ
Theta	Θ	θ	Upsilon	Υ	υ
Iota	I	ι	Phi	Φ	ϕ, φ
Kappa	K	κ	Chi	X	χ
Lambda	Λ	λ	Psi	Ψ	ψ
Mu	M	μ	Omega	Ω	ω

Values of Some Numbers

$\pi = 3.1415927$

$e = 2.7182818$

$\sqrt{2} = 1.4142136$

$\sqrt{3} = 1.7320508$

$\ln 2 = 0.6931472$

$\ln 10 = 2.3025851$

$\log_{10} e = 0.4342945$

$1 \text{ rad} = 57.2957795°$

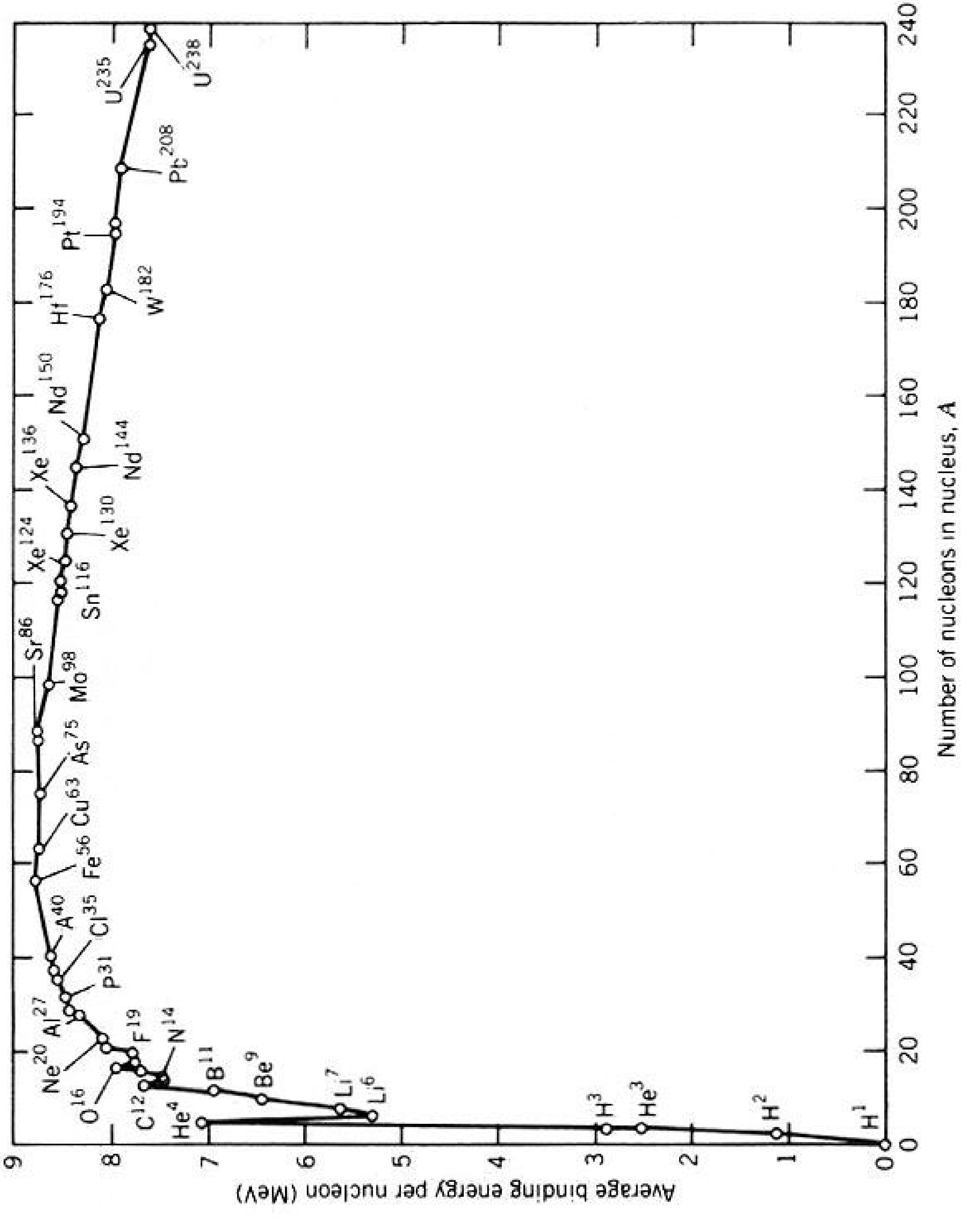
Mathematical Signs and Symbols

$\propto$	is proportional to	$\leq$	is less than or equal to
$=$	is equal to	$\geq$	is greater than or equal to
$\approx$	is approximately equal to	Σ	sum of
$\neq$	is not equal to	$\bar{x}$	average value of x
$>$	is greater than	Δx	change in x
$\gg$	is much greater than	$\Delta x \rightarrow 0$	Δx approaches zero
$<$	is less than	$n!$	$n(n-1)(n-2) \ldots (1)$
$\ll$	is much less than		

Properties of Water

Density (4°C)	$1.000 \times 10^3 \mathrm{~kg/m^3}$
Heat of fusion (0°C)	333 kJ/kg (80 kcal/kg)
Heat of vaporization (100°C)	2260 kJ/kg (539 kcal/kg)
Specific heat (15°C)	4186 J/kg·C° (1.00 kcal/kg·C°)
Index of refraction	1.33

Average Nuclear Binding Energy per Nucleon



Periodic Table of the Elements[§]

Symbol — **Cl** 17 — Atomic Number
Atomic Mass[§] — 35.453
$3p^5$ — Electron Configuration (outer shells only)

Group I	Group II	Transition Elements										Group III	Group IV	Group V	Group VI	Group VII	Group VIII
H 1 1.00794 $1s^1$																	**He** 2 4.002602 $1s^2$
Li 3 6.941 $2s^1$	**Be** 4 9.012182 $2s^2$											**B** 5 10.811 $2p^1$	**C** 6 12.0107 $2p^2$	**N** 7 14.0067 $2p^3$	**O** 8 15.9994 $2p^4$	**F** 9 18.9984032 $2p^5$	**Ne** 10 20.1797 $2p^6$
Na 11 22.98976928 $3s^1$	**Mg** 12 24.3050 $3s^2$											**Al** 13 26.9815386 $3p^1$	**Si** 14 28.0855 $3p^2$	**P** 15 30.973762 $3p^3$	**S** 16 32.065 $3p^4$	**Cl** 17 35.453 $3p^5$	**Ar** 18 39.948 $3p^6$
K 19 39.0983 $4s^1$	**Ca** 20 40.078 $4s^2$	**Sc** 21 44.955912 $3d^14s^2$	**Ti** 22 47.867 $3d^24s^2$	**V** 23 50.9415 $3d^34s^2$	**Cr** 24 51.9961 $3d^54s^1$	**Mn** 25 54.938045 $3d^54s^2$	**Fe** 26 55.845 $3d^64s^2$	**Co** 27 58.933195 $3d^74s^2$	**Ni** 28 58.6934 $3d^84s^2$	**Cu** 29 63.546 $3d^{10}4s^1$	**Zn** 30 65.409 $3d^{10}4s^2$	**Ga** 31 69.723 $4p^1$	**Ge** 32 72.64 $4p^2$	**As** 33 74.92160 $4p^3$	**Se** 34 78.96 $4p^4$	**Br** 35 79.904 $4p^5$	**Kr** 36 83.798 $4p^6$
Rb 37 85.4678 $5s^1$	**Sr** 38 87.62 $5s^2$	**Y** 39 88.90585 $4d^15s^2$	**Zr** 40 91.224 $4d^25s^2$	**Nb** 41 92.90638 $4d^45s^1$	**Mo** 42 95.94 $4d^55s^1$	**Tc** 43 (98) $4d^55s^2$	**Ru** 44 101.07 $4d^75s^1$	**Rh** 45 102.90550 $4d^85s^1$	**Pd** 46 106.42 $4d^{10}5s^0$	**Ag** 47 107.8682 $4d^{10}5s^1$	**Cd** 48 112.411 $4d^{10}5s^2$	**In** 49 114.818 $5p^1$	**Sn** 50 118.710 $5p^2$	**Sb** 51 121.760 $5p^3$	**Te** 52 127.60 $5p^4$	**I** 53 126.90447 $5p^5$	**Xe** 54 131.293 $5p^6$
Cs 55 132.9054519 $6s^1$	**Ba** 56 137.327 $6s^2$	57–71†	**Hf** 72 178.49 $5d^26s^2$	**Ta** 73 180.94788 $5d^36s^2$	**W** 74 183.84 $5d^46s^2$	**Re** 75 186.207 $5d^56s^2$	**Os** 76 190.23 $5d^66s^2$	**Ir** 77 192.217 $5d^76s^2$	**Pt** 78 195.084 $5d^96s^1$	**Au** 79 196.966569 $5d^{10}6s^1$	**Hg** 80 200.59 $5d^{10}6s^2$	**Tl** 81 204.3833 $6p^1$	**Pb** 82 207.2 $6p^2$	**Bi** 83 208.98040 $6p^3$	**Po** 84 (209) $6p^4$	**At** 85 (210) $6p^5$	**Rn** 86 (222) $6p^6$
Fr 87 (223) $7s^1$	**Ra** 88 (226) $7s^2$	89–103‡	**Rf** 104 (267) $6d^27s^2$	**Db** 105 (268) $6d^37s^2$	**Sg** 106 (271) $6d^47s^2$	**Bh** 107 (272) $6d^57s^2$	**Hs** 108 (277) $6d^67s^2$	**Mt** 109 (276) $6d^77s^2$	**Ds** 110 (281) $6d^97s^1$	**Rg** 111 (280) $6d^{10}7s^1$	112 (285) $6d^{10}7s^2$						

†Lanthanide Series	**La** 57 138.90547 $5d^16s^2$	**Ce** 58 140.116 $4f^15d^16s^2$	**Pr** 59 140.90765 $4f^35d^06s^2$	**Nd** 60 144.242 $4f^45d^06s^2$	**Pm** 61 (145) $4f^55d^06s^2$	**Sm** 62 150.36 $4f^65d^06s^2$	**Eu** 63 151.964 $4f^75d^06s^2$	**Gd** 64 157.25 $4f^75d^16s^2$	**Tb** 65 158.92535 $4f^95d^06s^2$	**Dy** 66 162.500 $4f^{10}5d^06s^2$	**Ho** 67 164.93032 $4f^{11}5d^06s^2$	**Er** 68 167.259 $4f^{12}5d^06s^2$	**Tm** 69 168.93421 $4f^{13}5d^06s^2$	**Yb** 70 173.04 $4f^{14}5d^06s^2$	**Lu** 71 174.967 $4f^{14}5d^16s^2$
‡Actinide Series	**Ac** 89 (227) $6d^17s^2$	**Th** 90 232.03806 $6d^27s^2$	**Pa** 91 231.03588 $5f^26d^17s^2$	**U** 92 238.0289 $5f^36d^17s^2$	**Np** 93 (237) $5f^46d^17s^2$	**Pu** 94 (244) $5f^66d^07s^2$	**Am** 95 (243) $5f^76d^07s^2$	**Cm** 96 (247) $5f^76d^17s^2$	**Bk** 97 (247) $5f^96d^07s^2$	**Cf** 98 (251) $5f^{10}6d^07s^2$	**Es** 99 (252) $5f^{11}6d^07s^2$	**Fm** 100 (257) $5f^{12}6d^07s^2$	**Md** 101 (258) $5f^{13}6d^07s^2$	**No** 102 (259) $5f^{14}6d^07s^2$	**Lr** 103 (262) $5f^{14}6d^17s^2$

[§] Atomic mass values averaged over isotopes in percentages they occur on Earth's surface. For many unstable elements, mass of the longest-lived known isotope is given in parentheses. 2006 revisions. (See also Appendix F.) Preliminary evidence (unconfirmed) has been reported for elements 113, 114, 115, 116 and 118.