Preparing for the Physics GRE: Day 4
Advanced Topics: Atomic, Particle, and Nuclear Physics

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Atomic Physics

The Periodic Table

- A few things worth memorizing:
  - Fact: Z ranges from 1 to (about) 100
  - Noble gases, in order by weight
  - Alkali metals
  - Z for Carbon, Iron (as well as H, He)

The Hydrogen Atom

- Most complicated system completely solved by quantum: one electron and one proton

- Bohr radius: most probable distance between p and e in hydrogen ground state

$$a_0 = \frac{4\pi\varepsilon_0\hbar^2}{m_e e^2} \cong .5 \cdot 10^{-10}m$$

- Allowed energies, where n is the quantum number of the radial state of the atom:

$$E_n = -\left[\frac{m}{2\hbar^2}\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\right]\frac{1}{n^2} = \frac{-13.6eV}{n^2}$$

- It is worth knowing these formulae so you know how they scale as mass or charge is changed (or at least be able to reason them out using dimensional analysis)

Positronium

- Electron-positron bound state

- Mass that appears in H spectrum is *reduced* e-p mass:

$$m_{reduced} = \left(\frac{1}{m_p} + \frac{1}{m_e} \right)^{-1}$$

- Since $m_p \gg m_e$, the reduced mass is set to m_e

- But for positronium, what is the new reduced mass?

- How does the energy spectrum change?

- How does the Bohr radius change?

99. The positronium "atom" consists of an electron and a positron bound together by their mutual Coulomb attraction and moving about their center of mass, which is located halfway between them. Thus the positronium "atom" is somewhat analogous to a hydrogen atom. The ground-state binding energy of hydrogen is 13.6 electron volts. What is the ground-state binding energy of positronium?

(A) $\left(\frac{1}{2} \right)^2 \times 13.6$ eV

(B) $\frac{1}{2} \times 13.6$ eV

(C) 13.6 eV

(D) 2×13.6 eV

(E) $(2)^2 \times 13.6$ eV

Spectrum for Hydrogen (and for Higher-Z atoms)

- Photons are emitted when atomic electrons fall from high n to low n states

- Photon energy is equal to the energy difference between the two energy states

- As a first approximation, can treat high-Z atoms as having effective charge Ze

$$\hbar\omega = -13.6eV\cdot Z^2\left(\frac{1}{n_f^{\,2}} - \frac{1}{n_o^{\,2}}\right)$$

9. In the spectrum of hydrogen, what is the ratio of the longest wavelength in the Lyman series ($n_f = 1$) to the longest wavelength in the Balmer series ($n_f = 2$) ?

   (A) 5/27
   (B) 1/3
   (C) 4/9
   (D) 3/2
   (E) 3

Spectrum for Hydrogen (and for Higher-Z atoms)

9. In the spectrum of hydrogen, what is the ratio of the longest wavelength in the Lyman series ($n_f = 1$) to the longest wavelength in the Balmer series ($n_f = 2$) ?

(A) 5/27
(B) 1/3
(C) 4/9
(D) 3/2
(E) 3

$$\hbar\omega = -13.6eV\cdot Z^2 \left(\frac{1}{n_f^{\,2}} - \frac{1}{n_o^{\,2}} \right)$$

- Long wavelength => small frequency
- n_f and n_0 must be close to one another
- Balmer n_0 = 3, n_f = 2: -5/36
- Lyman n_0 = 2, n_f = 1: -3/4
- Take the ratio…

Ionization energy

- How much energy does it take to ionize an atom, so that one (or more) electrons are removed from their orbits completely?

- Think of the energy required as an atomic transition from n_0 to $n_f \to \infty$:

$$E_{ionization} = \frac{13.6eV \cdot Z^2}{n_o^2}$$

18. The energy required to remove both electrons from the helium atom in its ground state is 79.0 eV. How much energy is required to ionize helium (i.e., to remove one electron) ?

(A) 24.6 eV
(B) 39.5 eV
(C) 51.8 eV
(D) 54.4 eV
(E) 65.4 eV

Helium Ionization Energy

18. The energy required to remove both electrons from the helium atom in its ground state is 79.0 eV. How much energy is required to ionize helium (i.e., to remove one electron) ?

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   (B) 39.5 eV
   (C) 51.8 eV
   (D) 54.4 eV
   (E) 65.4 eV

$$E_{ionization} = \frac{13.6 eV \cdot Z^2}{n_o^2}$$

- The energy to remove two He electrons equals the energy required to ionize He (remove the first) plus the energy required to remove the second

- Treat ionized Helium as a hydrogen-like atom with Z = 2

- What is the ionization energy of ionized Helium?
  - 4 * 13.6 eV = 54.4 eV
  - => 79 eV-54.4 eV = 24.6 eV

Ionization energy

- Generally, ionization energy is highest for noble gases, lowest for alkali metals

First Electron Ionization Energy

Legend:
- Alkali metal
- Alkaline earth metal
- Transition metal
- Post-transition metal
- Metalloid
- Nonmetal
- Halogen
- Noble gas
- Lanthanide
- Actinide

Chart: Ionization Energy [eV] vs Atomic Number, with labeled points He, Ne, Ar, Kr, Xe, Hg, Rn, Li, Na, K, Rb, Cs, Fr
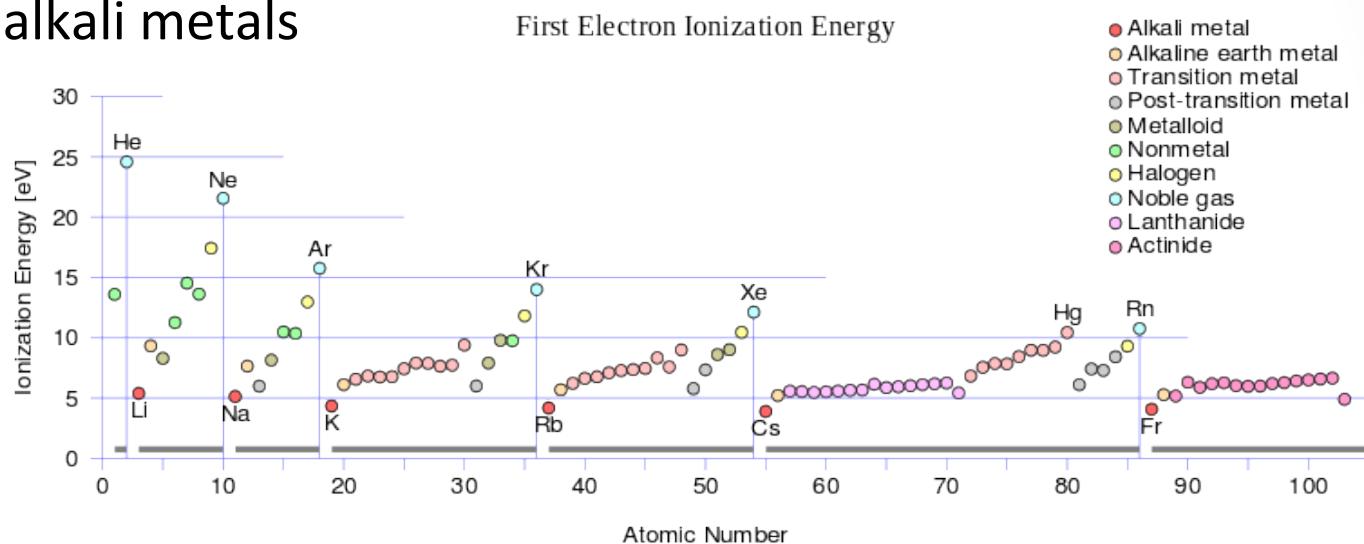
39. Which of the following atoms has the lowest ionization potential?

(A) $^{2}_{4}$ He

(B) $^{7}_{14}$ N

(C) $^{8}_{16}$ O

(D) $^{18}_{40}$ Ar

(E) $^{55}_{133}$ Cs

Orbitals

http://chemistry.beloit.edu/Stars/pages/orbitals.html
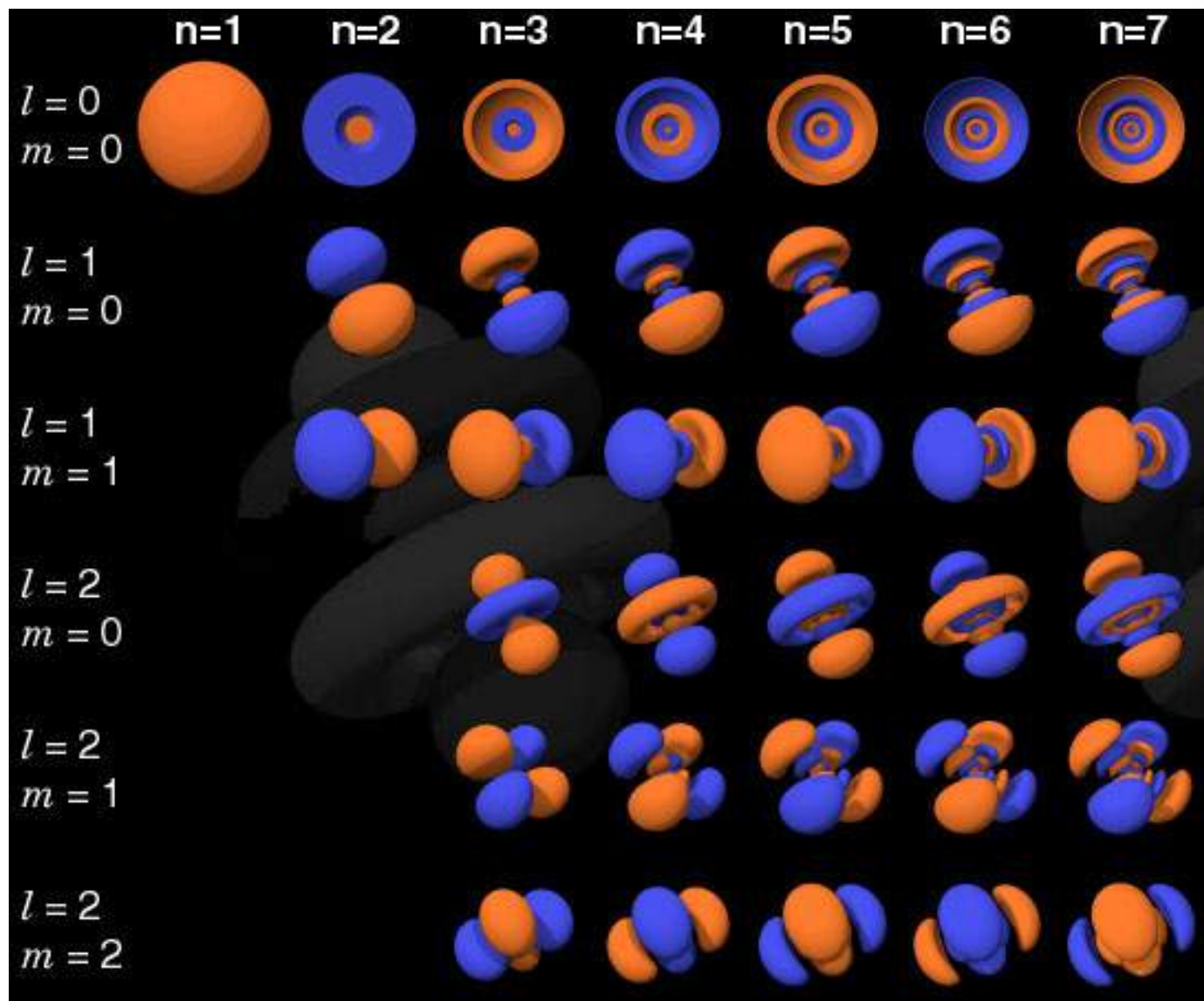
Orbitals

- Orbitals are denoted by their quantum numbers
- **n** is the **radial** quantum number, determines energy eigenstate
- **l** is the **azimuthal** quantum number: 0, 1, 2, … n-1
- **m is the magnetic** quantum number: -l, -l+1, … l-1, l
  - l > 0 states are 2l+1-fold degenerate
- l, m = 0 states are spherically symmetric: nonzero l, m states have nonzero angular momentum and break symmetry
- For each n, there are n^2 - n possible states to fill
- We distinguish these angular momentum states as follows:
  - s: l = 0 (**s**harp)
  - p: l = 1 (**p**rincipal)
  - d: l = 2 (**d**iffuse)
  - f: l = 3 (**f**undamental)
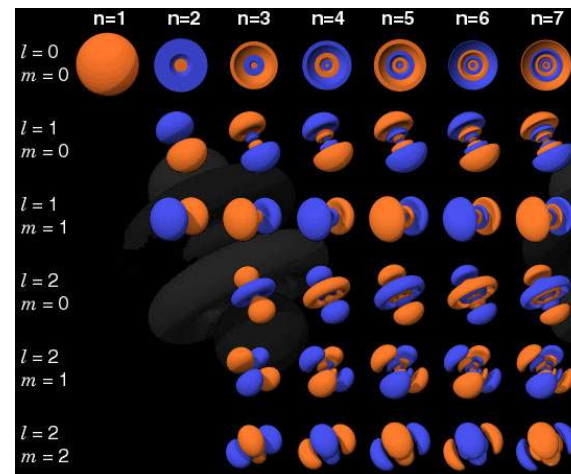
How ground state orbitals are filled

- I have Z electrons in an atomic ground state, which orbitals do they fill?
- Notation: (n, l-state label, number of electrons in state, up to 2)
- Filling is as follows, from left to right:

 1s2 2s2 2p6 3s2 3p6 4s2 3d10 …

- (Note, for example, that 4s are filled before 3d)
- After Helium, noble gases occur when p-orbitals are filled:
  - He: 1s2, Ne: 1s2 2s2 2p6,
  - Ar: 1s2 2s2 2p6 3s2 3p6, etc.
- Sometimes this notation is abbreviated:
  - Ca: 1s2 2s2 2p6 3s2 3p6 4s2= Ar 4s2

1s
2s 2p
3s 3p 3d
4s 4p 4d 4f
5s 5p 5d 5f
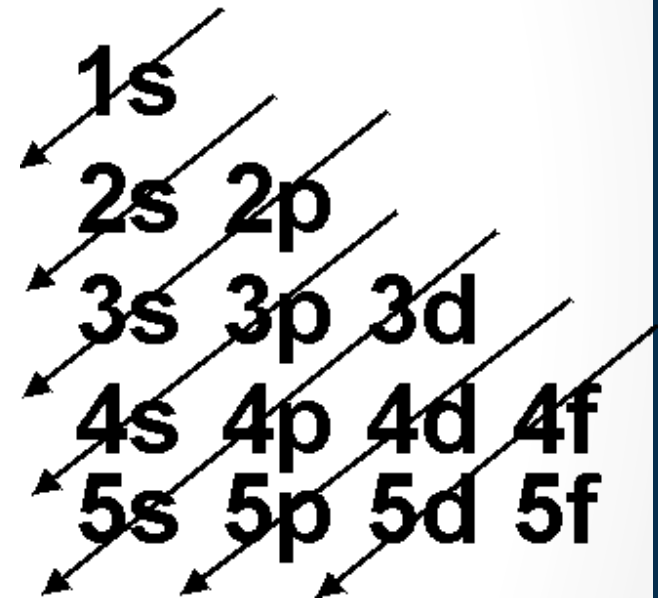
How ground state orbitals are filled

- Notation: (n, l-state label, number of electrons in state, up to 2)

  1s2 2s2 2p6 3s2 3p6 4s2 3d10 4p6

- (A) What about 3d?
- (B) Only 1 electron in 4s
- (C) No l = 4 electrons here
- (D) I count 19 orbitals filled
- (E) s-orbitals have 0 net angular momentum and are spherically symmetric

30. The configuration of the potassium atom in its ground state is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^1$. Which of the following statements about potassium is true?

   (A) Its $n = 3$ shell is completely filled.
   (B) Its $4s$ subshell is completely filled.
   (C) Its least tightly bound electron has $\ell = 4$.
   (D) Its atomic number is 17.
   (E) Its electron charge distribution is spherically symmetrical.

Spectroscopic notation $^{2S+1}L_J$

- There's yet another notation for the state of atoms, that can also account for states above the ground state
- S is the total spin momentum of the electrons
  - Electrons paired together in the same state have 0 net spin
  - Spin-up and spin-down half-shells are filled separately
  - That is to say, three p states (px, py, pz) are filled as follows: (1,0,0), (1,1,0), (1,1,1), (1,1,2), (1,2,2), (2,2,2)
  - Only unpaired electrons contribute to S
- L is the l-state label of the atom (S, P, D, F, etc)
  - Each half-shell is filled in order: l, l-1, l-2, … 1-l, -l
- J is the total angular momentum, ranging from L+S to |L-S|
  - |L-S| if outermost subshell is only half filled
  - L+S if outermost subshell is completely filled

Spectroscopic notation $^{2S+1}L_J$

- S is the total spin momentum of the electrons
  - Electrons paired together in the same state have 0 net spin
- L is the l-state label of the atom (S, P, D, F, etc)
  - Each half-shell is filled in order: l, l-1, l-2, … 1-l, -l
- J is the total angular momentum, ranging from L+S to |L-S|
  - |L-S| if outermost subshell is only half filled
  - L+S if outermost subshell is completely filled
- Examples:
- Mg: 1s2 2s2 2p6 3s2 -> s = 0, l = 0, j = 0 => $^1S_0$
  - Example of an atom with all shells filled
- C: He 2p2 -> s = 1, l = 1 + 0, j = l-s = 0 => $^1P_0$

- F: He 2p5 -> s = ½, l = 1+0-1+1+0 = 1, j = l+s = 3/2 => $^2P_{3/2}$

- P: Ne 3s2 3p3 -> s = 3/2, l = 1+0-1= 0, j = l-s = 3/2 => $^4S_{3/2}$

Spectroscopic notation $^{2S+1}L_J$

- Two examples:
- Note the atom is out of its ground state
  - S = 3/2
  - l = 0+1+1 = 2

76. The configuration of three electrons ls2p3p has which of the following as the value of its maximum possible total angular momentum quantum number?

(A) $\frac{7}{2}$

(B) 3

(C) $\frac{5}{2}$

(D) 2

(E) $\frac{3}{2}$

- Na: Fill up to 11 electrons:
  - 1s2 2s2 2p6 3s1
  - l = 0
  - S = ½
  - J = |l-s|

84. Sodium has eleven electrons and the sequence in which energy levels fill in atoms is $1s$, $2s$, $2p$, $3s$, $3p$, $4s$, $3d$, etc. What is the ground state of sodium in the usual notation $^{2S+1}L_J$?

(A) $^1S_0$ (B) $^2S_{\frac{1}{2}}$ (C) $^1P_0$

(D) $^2P_{\frac{1}{2}}$ (E) $^3P_{\frac{1}{2}}$

Selection Rules

- For a hydrogen-like atom to undergo a transition from a higher energy state to a lower energy state (thus emitting a photon), there are restrictions on the transitions that are allowed

- Specifically, the angular momentum quantum numbers must change:
  - Δl = +1 or -1
  - Δm = +1, -1, or 0

- When working in spectroscopic notation:
  - ΔJ = +1, -1, or 0
  - Δs = 0 (no restrictions due to spin, outside of Pauli)

- "Electric dipole transition"

Selection Rules - Examples

48. A transition in which one photon is radiated by the electron in a hydrogen atom when the electron's wave function changes from ψ_1 to ψ_2 is forbidden if ψ_1 and ψ_2

   (A) have opposite parity
   (B) are orthogonal to each other
   (C) are zero at the center of the atomic nucleus
   (D) are both spherically symmetrical
   (E) are associated with different angular momenta

41. A $3p$ electron is found in the $^3P_{3/2}$ energy level of a hydrogen atom. Which of the following is true about the electron in this state?

   (A) It is allowed to make an electric dipole transition to the $^2S_{1/2}$ level.
   (B) It is allowed to make an electric dipole transition to the $^2P_{1/2}$ level.
   (C) It has quantum numbers $\ell = 3$, $j = 3/2$, $s = 1/2$.
   (D) It has quantum numbers $n = 3$, $j = \ell$, $s = 3/2$.
   (E) It has exactly the same energy as it would in the $^3D_{3/2}$ level.

- Two examples:
- Spherically symmetric wave functions are both S-type orbitals
- There must be some change in angular momentum for radiation to occur

- Need to use spectroscopic notation here as well!
  - S = 1/2, L = 1, J = L+S = 3/2
- (A) Seems possible
- (B) Angular momentum hasn't changed
- (C) Not true
- (D) An electron with spin 3/2?
- (E) Need an n=4 state to have a d-orbital

Atomic Physics Summary

- Know parts of the periodic table
- Understand and be able to recognize the spectrum and orbitals of hydrogen-like atoms
- Be able to calculate spectrum and ionization energies
- Know the order in which orbitals are filled
- Recognize spectroscopic notation
- Remember selection rules for dipole transitions
- Other topics
  - Basic chemistry
  - Types of chemical bonds
  - What causes spectra to change? (Pressure, Temperature, etc.)

Particle Physics

Some Experimental Context

- Where do "particles" come from?
  - Radioactive decay (n, e⁺, etc)
  - The environment, such as products from Cosmic Rays (muons, etc)
  - Accelerators, such as the LHC (quarks, etc)
- How do we "see" them?
  - Cloud chambers
  - Bubble chambers
  - Scintillators
- How do we measure their properties?
  - Interactions with matter
  - Indirectly through decay products
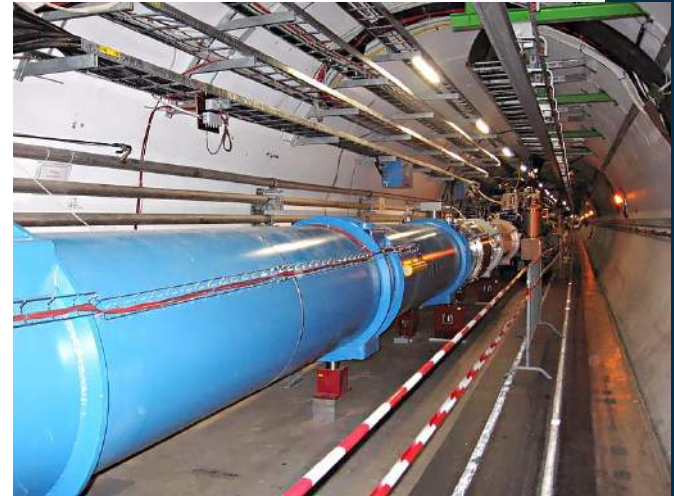
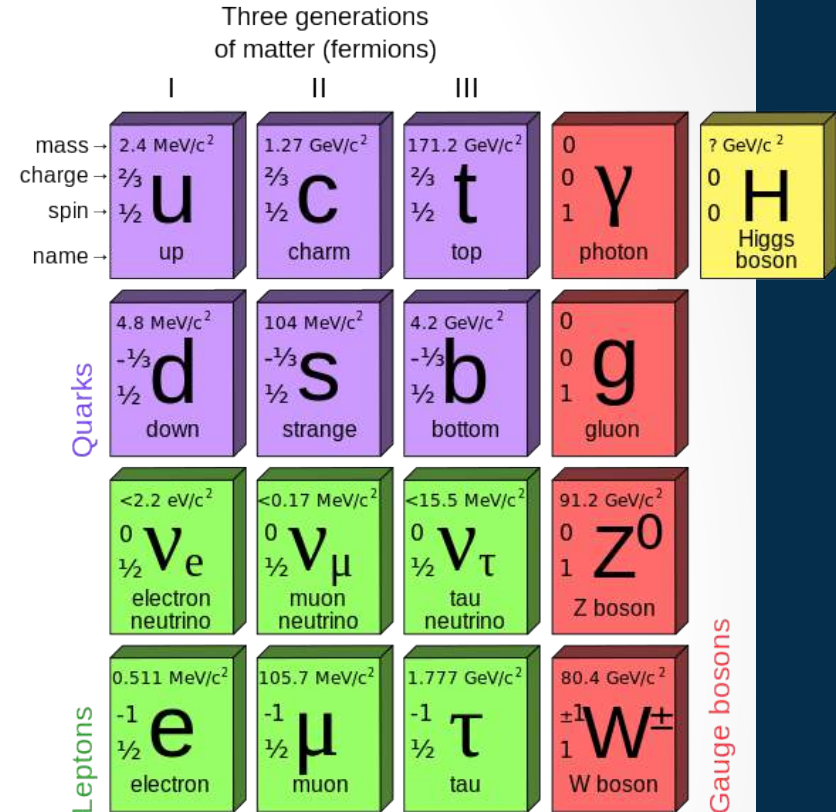http://en.wikipedia.org/wiki/File:CERN_LHC_Tunnel1.jpg

http://en.wikipedia.org/wiki/Cloud_chamber

The Standard Model

Three generations of matter (fermions)

The Standard Model

- All elementary, non-composite particles that we know of (so far)
- Quarks
  - 6 flavors
  - Fractional charge
  - Fermions
  - Up/Down make up protons, neutrons
- Leptons
  - 3 flavors
  - Fermions
  - Electrons and heavier electrons
  - Neutrinos, chargeless and (practically) massless
- Force Carriers
  - Bosons
  - Photons – carry Electromagnetic Force
  - Gluons – carry Strong Nuclear Force
  - W/Z – carry Weak Nuclear Force
- (Probably don't need Higgs physics for test)

Three generations
of matter (fermions)

I   II   III

mass → 2.4 MeV/c^2 charge → 2/3 spin → 1/2 **u** name → up	1.27 GeV/c^2 2/3 1/2 **c** charm	171.2 GeV/c^2 2/3 1/2 **t** top	0 0 1 **γ** photon	? GeV/c^2 0 0 **H** Higgs boson
4.8 MeV/c^2 -1/3 1/2 **d** down	104 MeV/c^2 -1/3 1/2 **s** strange	4.2 GeV/c^2 -1/3 1/2 **b** bottom	0 0 1 **g** gluon	
<2.2 eV/c^2 0 1/2 **ν$_e$** electron neutrino	<0.17 MeV/c^2 0 1/2 **ν$_\mu$** muon neutrino	<15.5 MeV/c^2 0 1/2 **ν$_\tau$** tau neutrino	91.2 GeV/c^2 0 1 **Z^0** Z boson	
0.511 MeV/c^2 -1 1/2 **e** electron	105.7 MeV/c^2 -1 1/2 **μ** muon	1.777 GeV/c^2 -1 1/2 **τ** tau	80.4 GeV/c^2 ±1 1 **W$^\pm$** W boson	

Quarks

Leptons

Gauge bosons

63. According to the Standard Model of elementary particles, which of the following is NOT a composite object?

(A) Muon
(B) Pi-meson
(C) Neutron
(D) Deuteron
(E) Alpha particle

Conserved Quantities

- Most particle physics GRE questions deal with nuclear reactions and other types of decay processes

- Typically, reactions obey **conservation laws**

- What you probably already know:
  - Momentum and Energy
  - Charge
  - Angular momentum (spin)

- New concepts from particle physics:
  - Lepton Number
  - Baryon Number
  - Other quantities violated in Weak interactions only:
    - Strangeness
    - Parity
    - Charge-Parity

Lepton Number

- 3 flavors of lepton (electron, muon, tauon)
  - Note: each electron-like particle has a corresponding neutrino with the same flavor, eg muon and muon neutrino
- The number of particles belonging to each flavor of lepton is conserved
- **NB**: anti-particles contribute *negative* lepton number
  - Example: anti-electrons (e^+) have electron number -1

98. Which of the following is the principal decay mode of the positive muon μ^+ ?

(A) $\mu^+ \rightarrow e^+ + v_e$

(B) $\mu^+ \rightarrow p + v_\mu$

(C) $\mu^+ \rightarrow n + e^+ + v_e$

(D) $\mu^+ \rightarrow e^+ + v_e + \overline{v}_\mu$

(E) $\mu^+ \rightarrow \pi^+ + \overline{v}_e + v_\mu$

<2.2 eV/c² 0 ½ V_e electron neutrino	<0.17 MeV/c² 0 ½ V_μ muon neutrino	<15.5 MeV/c² 0 ½ V_τ tau neutrino
0.511 MeV/c² -1 ½ e electron	105.7 MeV/c² -1 ½ μ muon	1.777 GeV/c² -1 ½ τ tau

Leptons

Lepton Number Example

- Need to conserve charge (doesn't eliminate any results)
- Need to conserve muon number and electron number:
  - (A) -1 mu -> -1 e + 1 e
  - (B) -1 mu -> proton? + 1 mu
  - (C) -1 mu -> neutron? -1 e + 1 e
  - (D) -1 mu -> -1 e + 1 e -1 mu
  - (E) -1 mu -> pion? - 1 e + 1 mu

- Additional example:

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(B) $\mu^+ \rightarrow p + v_\mu$

(C) $\mu^+ \rightarrow n + e^+ + v_e$

(D) $\mu^+ \rightarrow e^+ + v_e + \bar{v}_\mu$

(E) $\mu^+ \rightarrow \pi^+ + \bar{v}_e + v_\mu$

78. The muon decays with a characteristic lifetime of about 10^{-6} second into an electron, a muon neutrino, and an electron antineutrino. The muon is forbidden from decaying into an electron and just a single neutrino by the law of conservation of

(A) charge
(B) mass
(C) energy and momentum
(D) baryon number
(E) lepton number

Baryons

- Composite particles made up of **3 quarks**
- Examples:
  - Proton = 2 up + 1 down
  - Neutron = 2 down + 1 up
  - Most matter consists of baryons
- All baryons are **fermions**
- Baryon number = (number of quarks – number of antiquarks)/3
  - So protons and neutrons have B = +1
  - Anti-protons have B = -1
- Other (more exotic examples)
  - Δ (3 up/down quarks)
  - Λ, Σ (2 up/down quarks)
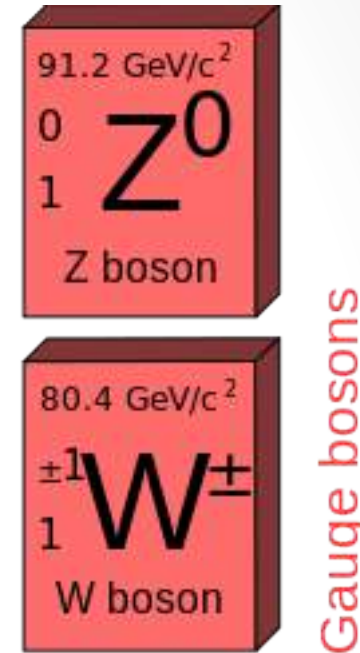 - Ξ (1 up/down quark)
  - Ω (0 up/down quarks)

I	II	III
2.4 MeV/c^2 $\frac{2}{3}$ $\frac{1}{2}$ **u** up	1.27 GeV/c^2 $\frac{2}{3}$ $\frac{1}{2}$ **c** charm	171.2 GeV/c^2 $\frac{2}{3}$ $\frac{1}{2}$ **t** top
4.8 MeV/c^2 $-\frac{1}{3}$ $\frac{1}{2}$ **d** down	104 MeV/c^2 $-\frac{1}{3}$ $\frac{1}{2}$ **s** strange	4.2 GeV/c^2 $-\frac{1}{3}$ $\frac{1}{2}$ **b** bottom

… as opposed to Mesons

- Composite particles made up of one quark and one antiquark
  - These particles appear as decay products (for example from cosmic rays)
- Examples:
  - Pions: π^+ π^- π^0, consist of up/down quarks
  - Kaons: K^+ K^- K^0 , consist of one up/down quark, one strange quark
- Baryon number is 0
- (Side note: Older literature may refer to muons as mesons, though now we know they are leptons.)

The Weak Interaction

- Interacts with all fermions
- Mediated by Z, W^+, W^- bosons
- Responsible for all decay of subatomic particles
  - Produces a whole zoo of possible interactions
- Certain symmetries are violated by Weak Interactions:
  - **Quarks change flavor**
  - Parity (also charge-parity)
- Example: Beta decay
  - Nuclear scale: n-> p^+ + e^- - v_e
  - Sub-nuclear (quark) scale:
        d-> u + e^- - v_e

91.2 GeV/c^2

0
1 Z^0

Z boson

80.4 GeV/c^2

± 1 $W^\pm$
1

W boson

Gauge bosons

$$^{13}\text{N} \rightarrow {}^{13}\text{C} + e^+ + v_e$$

63. The nuclear decay above is an example of a process induced by the

(A) Mössbauer effect
(B) Casimir effect
(C) photoelectric effect
(D) weak interaction
(E) strong interaction

Weak Interaction Example

91. The particle decay $\Lambda \to p + \pi^-$ must be a weak interaction because

(A) the π^- is a lepton
(B) the Λ has spin zero
(C) no neutrino is produced in the decay
(D) it does not conserve angular momentum
(E) it does not conserve strangeness

- (A) Pions are mesons, not leptons
- (B) Weak interactions only affect fermions (Λ and p have spin ½)
- (C) Only need neutrinos to conserve lepton number, not necessary for every weak interaction
- (D) Looks like angular momentum *is* conserved
- (E) Strangeness counts number of strange quarks. Since quarks can change flavor under weak interactions, this could be right

Strong Interaction
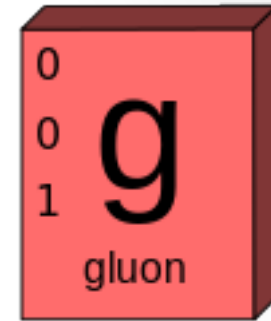
- Responsible for holding quarks together
  - Hadrons: includes mesons and baryons
- Mediated by gluons
- "Massive photons" follow the Yukawa potential

$$V(r) \propto \frac{e^{-kr}}{r}$$

- (Same as charge-screened potential for electrons in matter)

How do particles interact with matter?

- Treat the interaction between incident particles and matter probabilistically, with some probability of scattering occurring
  - Probability: Cross sections are measured in units of **area**
- Not totally necessary to memorize rules for cross sections, but can list some rules of thumb that build on physical intuition
  - *Charged* particles interact with electrons in matter, so the higher Z of the matter, the more likely they are to interact
  - *Lighter* particle mass scatter more easily (less inertia => easier to change momentum)

25. In experiments located deep underground, the two types of cosmic rays that most commonly reach the experimental apparatus are

(A) alpha particles and neutrons
(B) protons and electrons
(C) iron nuclei and carbon nuclei
(D) muons and neutrinos
(E) positrons and electrons

How do photons interact with matter?

- Photons primarily interact with atomic electrons
- Three primary processes (which you **need** to know for the test)
  - Compton Scattering
  - Photoelectric effect
  - Pair production
- Important to know:
  - Why does the photoelectric effect only occur with atomic electrons (as opposed to free)?
  - Why can't pair production occur in vacuum?
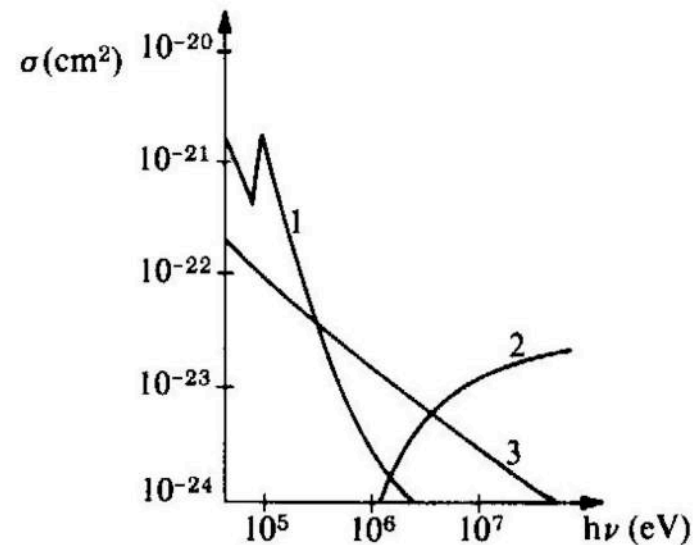
85. The figure above shows the photon interaction cross sections for lead in the energy range where the Compton, photoelectric, and pair production processes all play a role. What is the correct identification of these cross sections?

(A) 1 = photoelectric, 2 = Compton, 3 = pair production

(B) 1 = photoelectric, 2 = pair production, 3 = Compton

(C) 1 = Compton, 2 = pair production, 3 = photoelectric

(D) 1 = Compton, 2 = photoelectric, 3 = pair production

(E) 1 = pair production, 2 = photoelectric, 3 = Compton

Particle Physics Summary

- Begin with the Standard Model
  - Know the different properties of fundamental particles
- What quantities are conserved?
  - Charge, spin angular momentum
  - Lepton number
  - Baryon number
- Weak interactions
  - Interacts with fermions
  - Mediates particle decay
  - Quarks can change flavor
- Interactions between particles and matter
- Other topics:
  - Additional symmetries: Parity, Charge-parity
  - Zoo of subatomic mesons and baryons
 - Interaction cross sections

Nuclear Physics

Notation

- Atomic nucleus consists of protons and neutrons
- A nucleus of X has Z protons and A total nucleons (n + p)

$$X_Z^A \quad \leftarrow \ Total \ \# \ nucleons$$
$$_Z \ \leftarrow \ Total \ \# \ protons$$

- For small nuclei, same number of neutrons as protons, A = 2 Z
- For large nuclei (and isotopes) the number of neutrons may vary
- Example:
  - Ordinary Carbon: 6 protons, 6 neutrons, 12 nucleons C_6^{12}
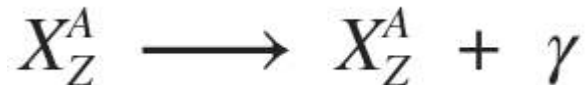 - Carbon-14: 6 protons, 8 neutrons, 14 nucleons C_6^{14}

Radioactive Decay Modes

- Alpha decay: the nucleus emits a Helium nucleus

$$X_Z^A \longrightarrow X'^{A-4}_{Z-2} + He_2^4$$
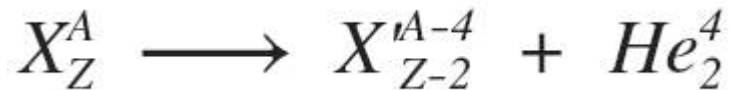
- Beta decay: the nucleus emits an electron and antineutrino

$$X_Z^A \longrightarrow X'^A_{Z+1} + \beta^0_{-1} + \overline{v}_e$$
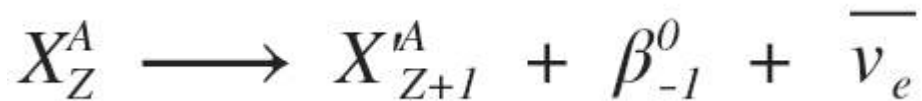
- Gamma decay: the nucleus emits a photon (loses some energy, but does not change otherwise)

$$X_Z^A \longrightarrow X_Z^A + \gamma$$

- Deuteron decay (very rare):
  the nucleus emits a deuteron

$$X_Z^A \longrightarrow X'^{A-2}_{Z-1} + H_1^2$$

- An example problem ->

17. Suppose that $^A_Z X$ decays by natural radioactivity in two stages to $^{A-4}_{Z-1} Y$. The two stages would most likely be which of the following?

| First Stage	Second Stage
(A) β^- emission with an antineutrino	α emission
(B) β^- emission	α emission with a neutrino
(C) β^- emission	γ emission
(D) Emission of a deuteron	Emission of two neutrons
(E) α emission	γ emission

Radioactive Decay Modes Example

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(E)	α emission	γ emission

- Alpha decay takes away 4 nucleons and 2 protons (A->A-4, Z->Z-2)
- Beta decay adds one proton (Z -> Z+ 1)
- Beta decay followed by alpha decay: A-> A-4, Z-> Z-1
- If you don't remember the details of beta decay, how do you know whether (A) or (B) is correct?

Nuclear Binding Energy

- Nucleons repel electromagnetically, but are bound in place by the Strong force

- Can define a binding energy per nucleon, varies with size

- Iron (Z = 26) has max energy per nucleon

  - Much larger nuclei are so big that the strong force has smaller effect
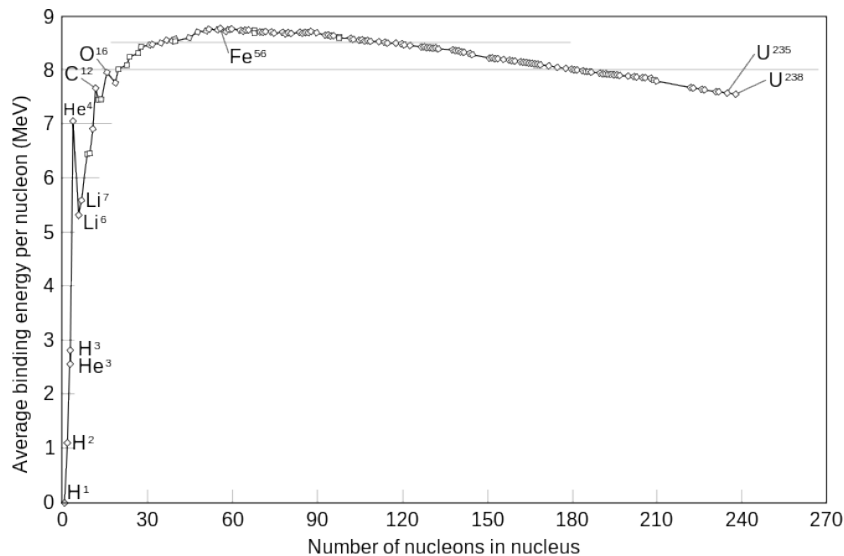
http://en.wikipedia.org/wiki/File:Binding_energy_curve_-_common_isotopes.svg

64. The binding energy of a heavy nucleus is about 7 million electron volts per nucleon, whereas the binding energy of a medium-weight nucleus is about 8 million electron volts per nucleon. Therefore, the total kinetic energy liberated when a heavy nucleus undergoes symmetric fission is most nearly

(A) 1876 MeV
(B) 938 MeV
(C) 200 MeV
(D)   8 MeV
(E)   7 MeV

Radioactivity

- Radioactive substances break down over time
- The process occurs at random, but we can model what fraction N radioactive atoms will break down
- The change in the number of radioactive atoms (ie, the atoms that undergo decay) in time dt is proportional to the number of atoms N:
$$dN = -\lambda N dt$$
- Solving, we find exponential decay:
$$N(t) = N(0)e^{-\lambda t}$$
- Radioactive half-life is the time required for half of the N atoms to decay (an invariant, since the decay process is exponential)
$$\tau_{1/2} = \frac{\log 2}{\lambda} \cong \frac{.69}{\lambda}$$

Radioactivity

- How do half-lives add?

- Think: there are **two** processes that are contributing to the disappearance of the material

- Total half-life must be smaller than either of the half-lives of the individual decay processes

- 1/t is the rate at which half of the material disappears

- The rates **add**:

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_1} + \frac{1}{\tau_2}$$

66. A sample of radioactive nuclei of a certain element can decay only by γ-emission and β-emission. If the half-life for γ-emission is 24 minutes and that for β-emission is 36 minutes, the half-life for the sample is

(A) 30 minutes
(B) 24 minutes
(C) 20.8 minutes
(D) 14.4 minutes
(E)   6 minutes

Nuclear Physics Summary

- Recognize the notation used

- Radioactive decay processes

- Nuclear binding energy

- Radioactive half-life

- Other topics:

  - Examples of radioactive decays

  - Fusion, as in stars

Other Topics

- Laboratory methods
  - Reading log-log and semilog graphs
  - Reading oscilloscope screens
  - Precision vs. accuracy
  - Statistics – sampling, adding uncertainties
- Band theory of solids
  - Valence and conduction bands
  - Conductors, insulators, semiconductors
- Fluid statics
  - Incompressibility – flux conservation
  - Buoyant forces
  - Streamline equation: $P + \frac{1}{2}\rho v^2 + \rho g h = Constant$