Physics 29000 – Quarknet/Service Learning

Lecture 3: Ionizing Radiation

Purdue University
Department of Physics

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Resources

- Particle Data Group:

  http://pdg.lbl.gov

- Summary tables of particle properties:

  http://pdg.lbl.gov/2012/tables/contents_tables.html

- Table of atomic and nuclear properties of materials:

  http://pdg.lbl.gov/2012/reviews/rpp2012-rev-atomic-nuclear-prop.pdf

Some Subatomic Particles

- **electron**, e^- and **positron**, e^+
- **proton**, p and **neutron**, n
- **muon**, μ^- and **anti-muon**, μ^+
  - When we don't care which we usually just call them "muons" or write $\mu^\pm$
- **photon**, γ
- **electron neutrino**, ν_e and **muon neutrino**, ν_μ
- **charged pions**, $\pi^\pm$ and **charged kaons**, $K^\pm$
- **neutral pions**, π^0 and **neutral kaons**, K^0
- "**lambda hyperon**", Λ

Some are fundamental (no substructure) while others are not.

Subatomic Particles

- Fundamental particles (as far as we know):

$$\begin{matrix} Q = +2/3 \\ Q = -1/3 \end{matrix} \quad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \Bigg\} \text{ Quarks}$$

$$\begin{matrix} Q = 0 \\ Q = -1 \end{matrix} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \Bigg\} \text{ Leptons}$$

- electrons, muons and neutrinos are fundamental.
- protons, neutrons, kaons, pions are made of quarks:
  - baryons have 3 quarks: $p = (uud)$, $n = (udd)$, $\Lambda^0 = (uds)$
  - mesons are $q\bar{q}$ pairs: $\pi^+ = (u\bar{d})$, $\pi^- = (d\bar{u})$, $K^+ = (u\bar{s})$
- what about the photon?

Subatomic Particles

- fundamental particles of matter interact with fundamental "force carriers" called "gauge bosons":
  - Electromagnetic force: photon (γ)
  - Weak nuclear force, responsible for β-decay: W^+, W^-
  - Strong nuclear force: gluons (g)
- The force carriers "couple" to the "charge" of the matter particle:
  - photons couple to electric charge (not neutrinos)
  - W's couple to "weak hypercharge" (all particles)
  - gluons couple to "color charge" (only quarks)
  - mesons and baryons are "colorless" so they only interact strongly when they get close enough to see the individual quarks.

Particle Interactions

- Particle interactions must always conserve energy/momentum and angular momentum.
- Particle interactions must conserve electric charge.
- For practical purposes, they conserve lepton number.
- The strong interaction conserves quark flavor number
- Examples:
  - Electric charge: $\gamma \rightarrow e^+e^-$
  - Lepton number: $\mu^- \rightarrow e^-\nu_\mu\bar{\nu}_e$
  - Quark number: $\pi^- + p \rightarrow n \quad (\bar{u}d) + (uud) = (udd)$
- The weak interaction does not conserve quark number:
  - Pion decay: $\pi^- \rightarrow \mu^-\bar{\nu}_\mu$
  - Neutron decay: $n \rightarrow p\ e^-\bar{\nu}_e$
  - Lambda decay: $\Lambda \rightarrow p\pi^- \qquad (uds) \rightarrow (uud) + (\bar{u}d)$

Particle Masses

- Mass/energy relation: $E = mc^2$
- Mass is usually expressed in units of energy/c^2
- Mass is a fundamental characteristic of particles:
  - photon: massless
  - neutrinos: essentially massless
  - electron: $m_e = 0.511\ MeV/c^2$
  - muon: $m_\mu = 106\ MeV/c^2$
  - pion: $m_\pi = 139\ MeV/c^2$
  - kaon: $m_K = 494\ MeV/c^2$
  - proton: $m_p = 938.3\ MeV/c^2$
  - neutron: $m_n = 939.6\ MeV/c^2$

Particle Decays

- The only stable particles are:
  - proton, electron, photon and neutrinos
- Other particles decay into lighter particles:
  - muon decay: $\mu^- \to e^- \nu_\mu \bar{\nu}_e$
  - pion decay: $\pi^- \to \mu^- \bar{\nu}_\mu$
- The "lifetime" is defined by

$$N(t) = N_0 e^{-t/\tau}$$

- We usually don't use "half-life" in particle physics but it is frequently used in nuclear physics:

$$N(t) = N_0 2^{-t/\tau_{1/2}}$$

- After some simple algebra,

$$\tau_{1/2} = \tau \log 2$$

Unstable Particles

Particle lifetimes:

- The photon is stable
- The proton is stable, $\tau > 2.1 \times 10^{29}$ years
- The electron is stable, $\tau > 4.6 \times 10^{26}$ years
- The neutron is unstable, $\tau = 880.1 \pm 1.1$ sec
- The muon is unstable, $\tau = 2.1969811(22)\ \mu s$
- Charged pions are unstable, $\tau = 2.6033(5) \times 10^{-8}$ sec
- Charged kaons are unstable, $\tau = 1.2380(21) \times 10^{-8}$ sec
- Everything else has even shorter lifetimes

Distance travelled before decay:

$$d = vt = \beta ct = \gamma\beta c\tau = \frac{\beta c\tau}{\sqrt{1-\beta^2}}$$

Special Relativity

- All the special relativity you need for Physics 290:

$$\beta = \frac{v}{c}$$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

$$E = T + mc^2 = \gamma mc^2$$

$$p = \gamma\beta mc$$

$$\gamma = \frac{E}{mc^2}$$

$$\beta = \frac{pc}{E}$$

$$\gamma\beta = \frac{p}{mc}$$

Unstable Particles

Example:

– What is the distance that a muon travels in one lifetime if it has a momentum of 1 GeV/c?

$$d = \gamma\beta c\tau$$

$$= \frac{p}{mc}\,c\tau$$

$$= \frac{(1000\,MeV/c)}{(106\,MeV/c^2)}(2.20\times 10^{-6}\,s)$$

$$= \frac{(1000\ MeV)}{(106\ MeV)}(2.998\times 10^{8}\,m/s)(2.20\times 10^{-6}\ s)$$

$$= 6.222\ km$$

Observing Fundamental Particles

- Ultimately, all particles are detected by means of the electromagnetic interaction:
  - A charged particle moving at high speed produces an electric field that can ionize matter or excite atomic electrons
  - The rate of energy loss depends on the velocity but not on the type of particle
  - Rate of energy loss is proportional to Q^2
  - Neutral particles do not produce an electric field and are not detected…
    - unless they interact in a way that produces charged particles.
    - but the original particle is destroyed in the process.

Observing Fundamental Particles

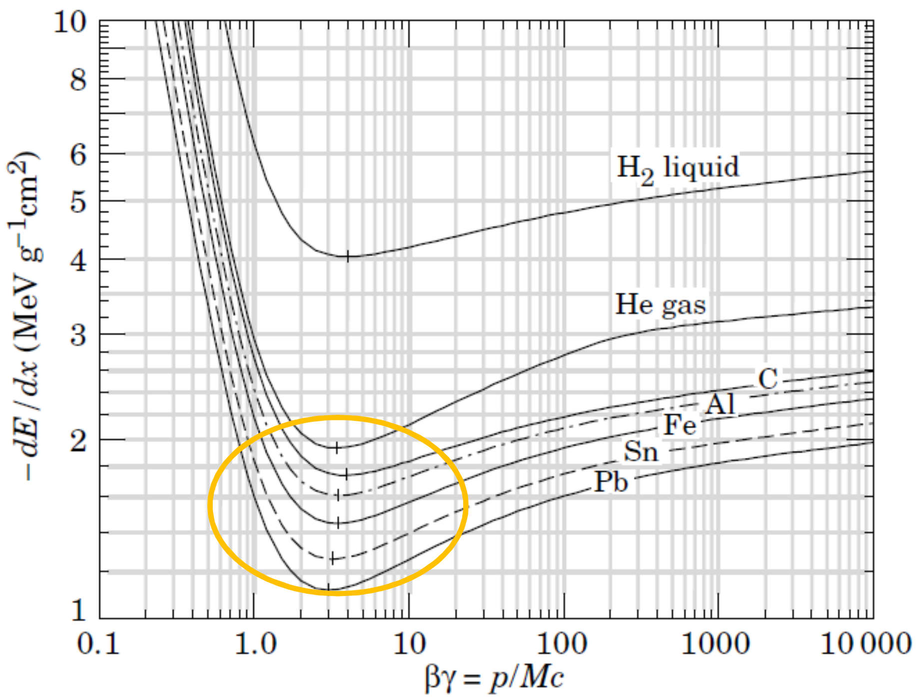
- Examples:
  - An α-particle is doubly-charged. It is heavy and moves slowly: it deposits a more energy in a short distance.
  - A β-particle (ie, an electron) is singly charged. It is less highly ionizing than an α-particle.
  - A photon does not ionize matter directly.
    - It can transfer energy to electrons via Compton scattering: $\gamma + e^- \rightarrow \gamma + e^-$
    - A photon can be converted into an e^+e^- pair in the strong electric field surrounding a nucleus: $\gamma + Z \rightarrow e^+ + e^-$
    - The secondary charged particles do deposit energy
  - Neutrinos are very weakly interacting. They have no electromagnetic interactions.
    - Occasionally, $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$
    - The muon deposits energy

Rate of Energy Loss

- The electric field of a charged particle interacts with the electrons in the surrounding medium
- Rate of energy loss is proportional to electron density
- Electron density is closely related to the mass density
- Energy loss per unit length is roughly proportional to mass density

Rate of Energy Loss

- Energy loss per unit length (divided by density):
  - Units are [MeV/cm]/[g/cm^3] = [MeV cm^2/g]



Minimum is always near $\beta\gamma \approx 3$

For carbon, $dE/dx|_{min}$=1.8 MeV cm^2/g

Increases only slowly with increasing momentum above minimum

Rises rapidly below the minimum

Energy Loss Data

- Table of atomic and nuclear properties of materials:

  http://pdg.lbl.gov/2012/reviews/rpp2012-rev-atomic-nuclear-prop.pdf

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1 Abridged from `pdg.lbl.gov/AtomicNuclearProperties` by D. E. Groom (2007). See web pages for more detail about entries in this table including chemical formulae, and for several hundred other entries. Quantities in parentheses are for NTP (20° C and 1 atm), and square brackets indicate quantities evaluated at STP. Boiling points are at 1 atm. Refractive indices n are evaluated at the sodium D line blend (589.2 nm); values ≫1 in brackets are for $(n-1)\times 10^6$ (gases).

Material	Z	A	$\langle Z/A\rangle$	Nucl.coll. length λ_T {g cm^{-2}}	Nucl.inter. length λ_I {g cm^{-2}}	Rad.len. X_0 {g cm^{-2}}	$dE/dx\|_{min}$ { MeV g^{-1}cm^2}	Density {g cm^{-3}} ({gℓ^{-1}})	Melting point (K)	Boiling point (K)	Refract. index (@ Na D)
H_2	1	1.00794(7)	0.99212	42.8	52.0	63.04	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.01410177803(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.941(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.012182(3)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.42
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210			
N_2	7	14.0067(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O_2	8	15.9994(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F_2	9	18.9984032(5)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Al	13	26.9815386(8)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	1687.	3538.	3.95
Cl_2	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	171.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	1941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	1811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	1358.	2835.	
Ge	32	72.64(1)	0.44053	86.9	143.0	12.25	1.370	5.323	1211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	505.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	

Example

- A charged particle is called "minimum ionizing" if $\beta\gamma \geq 3$. What momentum is this for a muon?

$$p = \beta\gamma mc$$
$$= (3)(106\, MeV/c^2) \cdot c$$
$$= 318\, MeV/c$$

- How much energy is deposited if a minimum ionizing muon passes through 1 cm of iron?

$$dE/dx|_{min} = 1.451\, MeV \cdot cm^2/g$$
$$\rho = 7.874\, g/cm^3$$
$$\Delta E = (1.451\, MeV \cdot cm^2/g)(7.874\, g/cm^3)(1\, cm)$$
$$= 11.4\, MeV$$

- How much iron would stop a 318 MeV/c muon?

  Approximately 28 cm

Assignment

- We detect muons using plastic scintillator material (polymethylmethacrylate = acrylic).
  - How much energy is deposited when a minimum ionizing muon passes through 1 cm of acrylic scintillator?
- Students sometimes wonder whether aluminum foil could be used to shield us from cosmic rays.
  - Estimate the thickness of aluminum foil
  - How much energy is lost when a minimum ionizing muon passes through one thickness of aluminum foil?
- How much energy does a minimum ionizing muon lose when it passes through one floor of the physics building?
  - Assume one floor is 8 inches of concrete.
    - Convert inches to cm
    - Assume “building concrete” is the same as “shielding concrete”