Physics 56400

Introduction to Elementary Particle Physics I

Lecture 5

Fall 2019 Semester

Prof. Matthew Jones

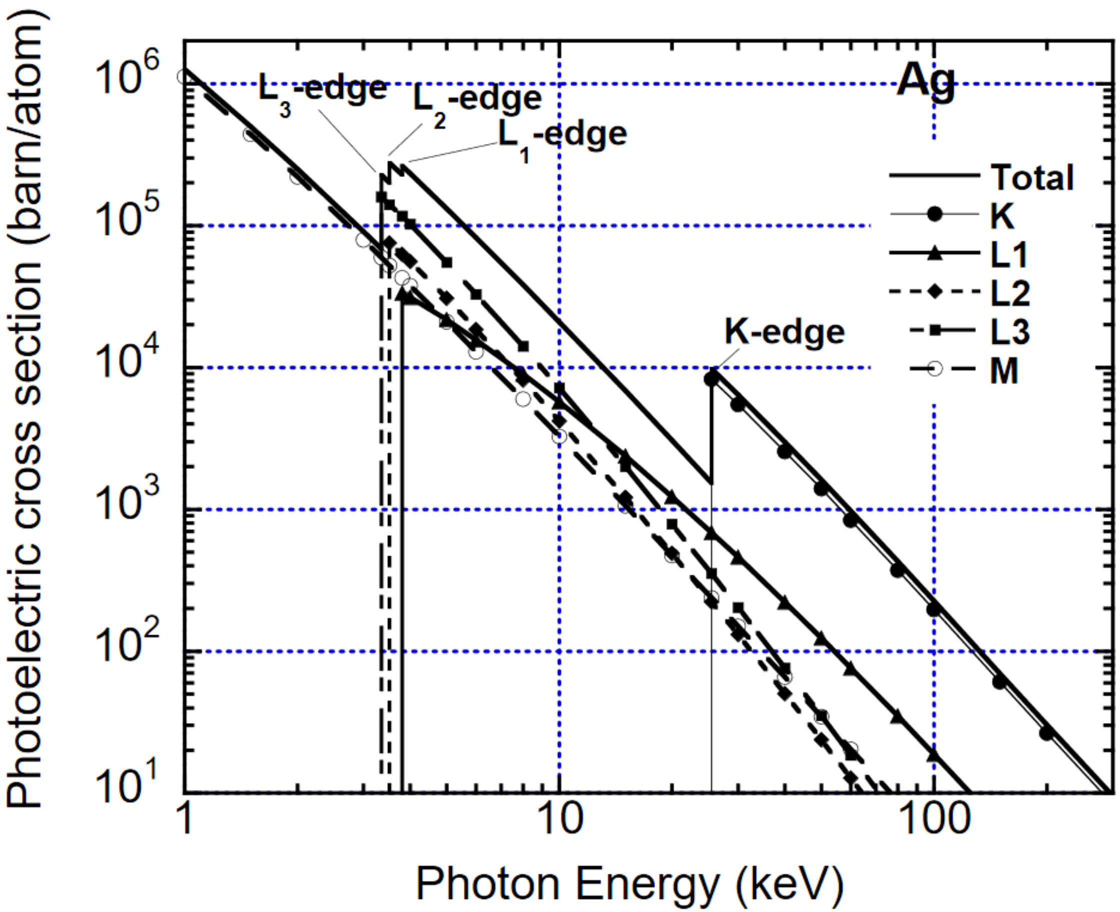
Interaction of Radiation with Matter

- Electrons and photons
  - Photoelectric effect
  - Compton scattering
  - Pair production
  - Bremsstrahlung
  - Synchrotron radiation
- Charged particles
  - Ionization
  - Cerenkov radiation
- Neutrons
  - Elastic scattering
  - Nuclear interactions
- Neutrinos
  - Weak interactions

Interaction of Photons with Matter

- Low-energy photons can excite atomic electrons
  - Non-ionized atoms can de-excite, emitting lower energy photons uniformly over all angles.
  - When an atom is ionized, the ejected electron has less energy than the photon because of the work function of the material.
  - Inner shell (K-shell) electrons are more tightly bound and are harder to ionize.

Photoelectric Effect



Low energy:

$$\sigma_{p.e.} \sim Z^4/E^3$$

High energy:

$$\sigma_{p.e.} \sim Z^5/E$$

Cross section falls rapidly with increasing energy.

This is the interaction between the photon and the atom as a whole. When the photon wavelength is small enough it no longer "sees" the whole atom at once.

Photoelectric Effect

After an electron has been removed from the atom, the system can return to its ground state in various ways:

- Fluorescence x-ray emission:
  - An outer-shell electron falls into the inner-shell vacancy
- Auger electron emission:
  - Excess energy from an outer-shell electron falling into the inner-shell vacancy ejects more outer-shell electrons
- Coster-Kronig process:
  - The inner-shell vacancy is filled by an electron, leaving another vacancy in a more outer shell

Compton Scattering

- When the wavelength of a photon is smaller than the size of an atom, it begins to see the individual electrons.
  - A photon with energy 10 keV has a wavelength of
    $$\lambda = \frac{hc}{E} = 2\pi \frac{\hbar c}{E} = 2\pi \; \frac{197 \text{ MeV} \cdot \text{fm}}{10 \text{ keV}} \sim 0.1 \text{ nm}$$
- Based on kinematic arguments alone, we saw that the energy of the scattered photon depended on the scattering angle:
  $$\frac{1}{E'} - \frac{1}{E} = \frac{1 - \cos\theta}{m_e}$$

Compton Scattering

- Klein-Nishina angular distribution per electron:

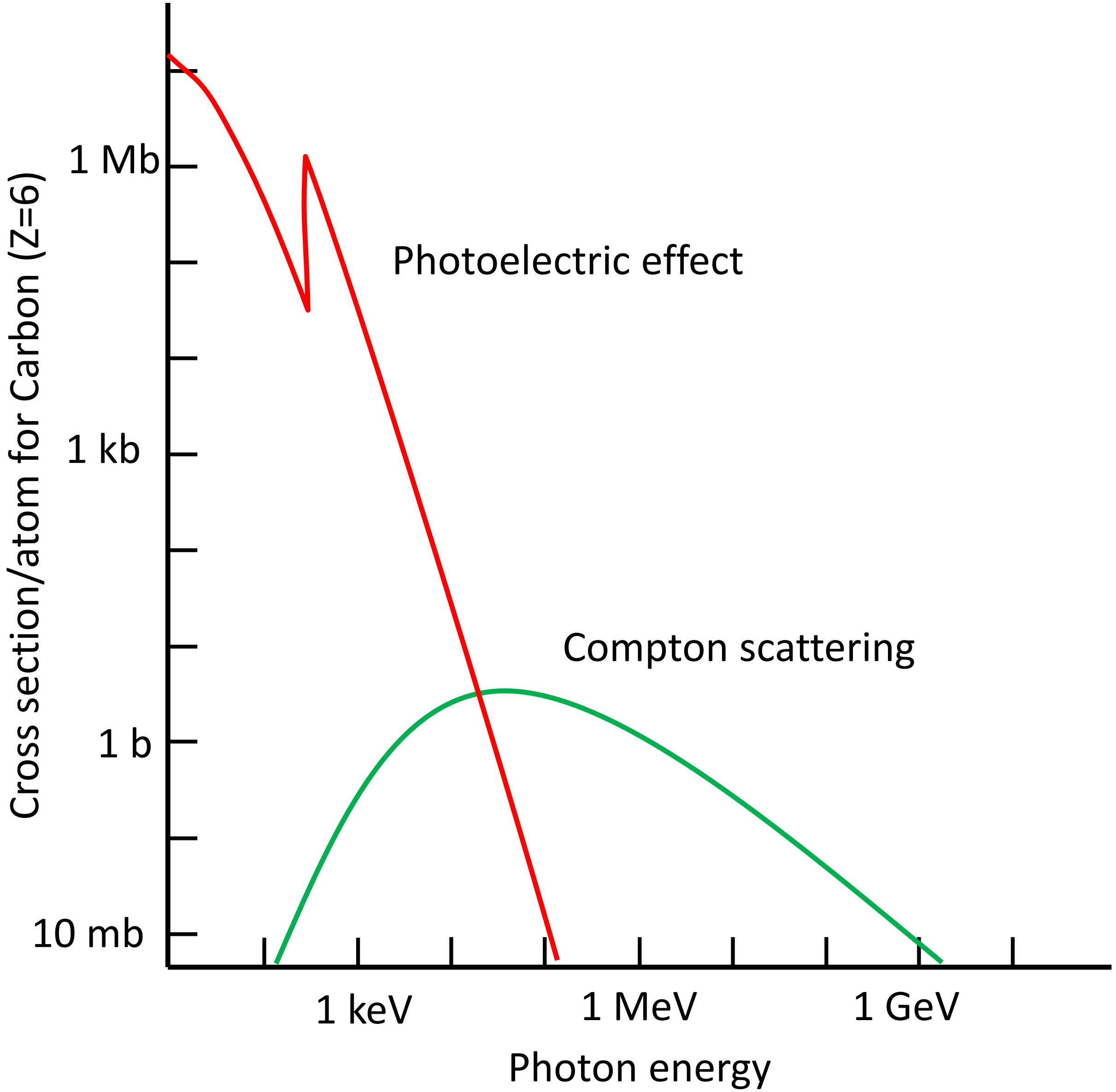
$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{1}{1+\epsilon(1-\cos\theta)}\right)^2\left(1+\cos^2\theta+\frac{\epsilon^2(1-\cos\theta)^2}{1+\epsilon(1-\cos\theta)}\right)$$

$$r_e = \frac{e^2}{m_e c^2} = 2.818\ \mathrm{fm}$$ (classical electron radius)

$$\epsilon = \frac{E}{m_e c^2}$$ (ratio of incident photon energy to electron mass)

- Cross section per atom is proportional to Z
- Modified at low energy due to binding energy of atomic electrons.

Compton Scattering



Pair Production

- When a photon has energy greater than about $2m_ec^2$, it can convert into an e^+e^- pair in the electric field of a nucleus.

$$\frac{d\sigma}{dx} = \frac{m}{X_0 N_A}\left(1 - \frac{4}{3}x(1-x)\right)$$

$$x = \frac{E_{e^-}}{E_\gamma}$$

- m is the atomic mass of the material (frequently denoted A).
- X_0 is the radiation length $[\mathrm{g \cdot cm^{-2}}]$ of the material.

$$\frac{1}{X_0} \sim \frac{Z^2}{m\, m_e^2}$$

- Pair production cross section is larger for high-Z materials.

Pair Production

- High-energy limit:

$$\sigma = \frac{7}{9}\frac{m}{X_0 N_A}$$

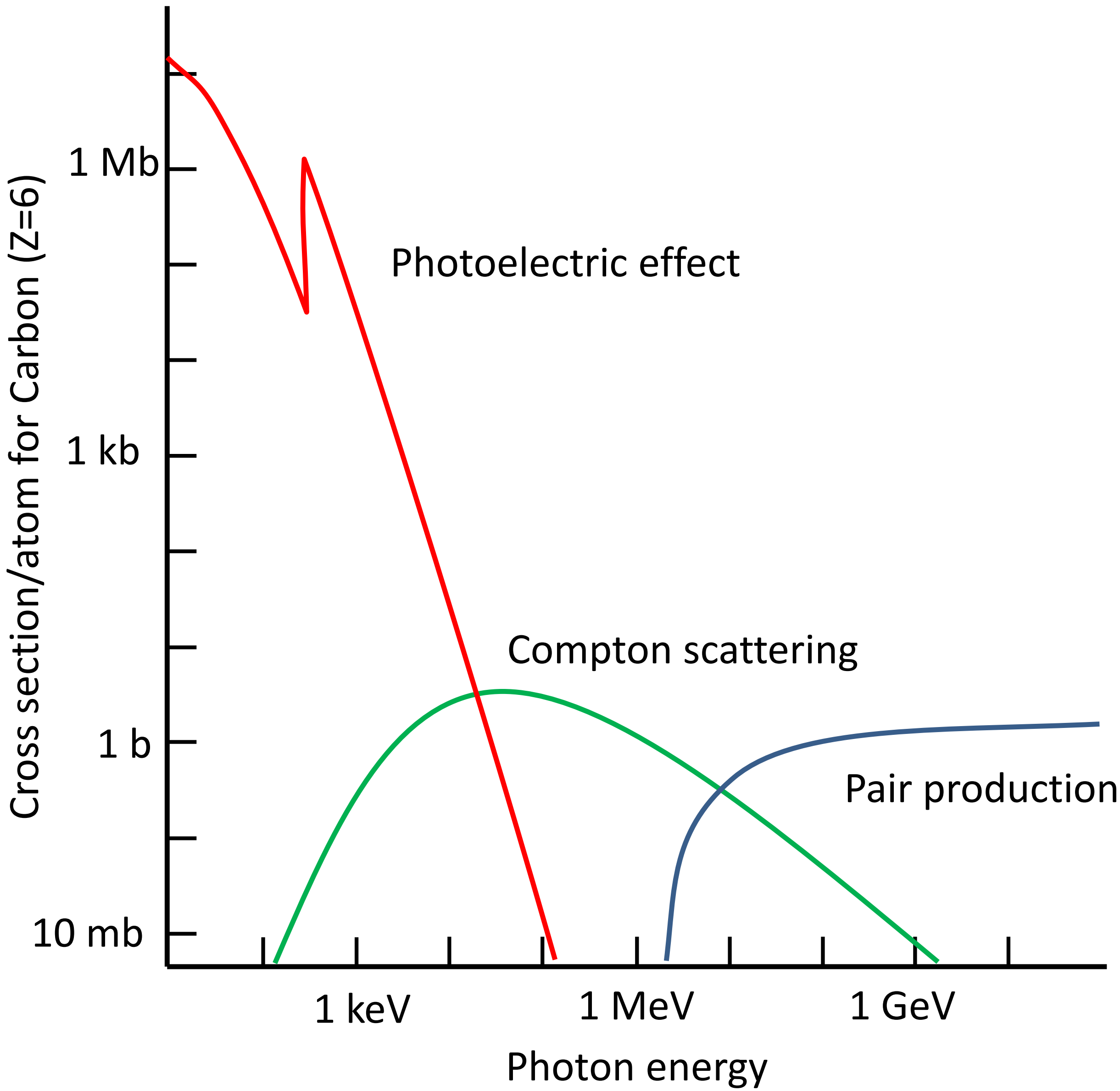
Atomic mass, m

6. Atomic and Nuclear Properties of Materials

Table 6.1 Abridged from `pdg.lbl.gov/AtomicNuclearProperties` by D.E. Groom (2017). See web pages for more detail about entries in this table and for several hundred others. Parentheses in the dE/dx and density columns indicate gases at 20° C and 1 atm. Boiling points are at 1 atm. Refractive indices n are evaluated at the sodium D line blend (589.2 nm); values ≫1 in brackets indicate $(n-1)\times 10^6$ for gases at 0° C and 1 atm.

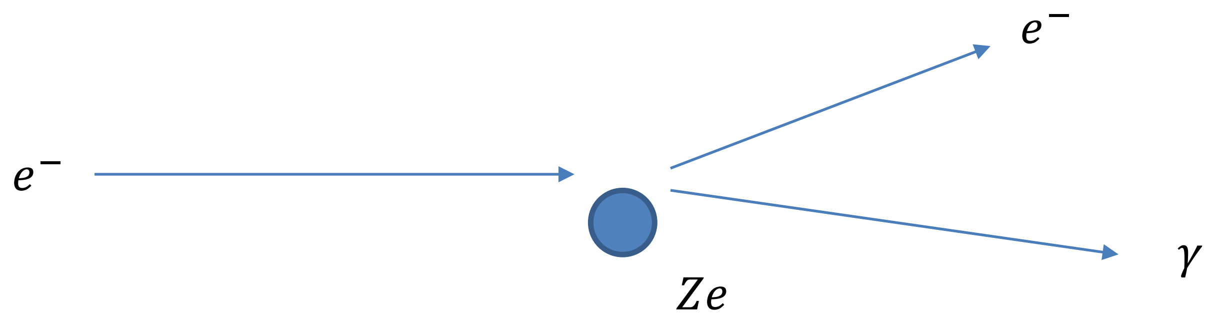
Material	Z	A	$\langle Z/A \rangle$	Nucl.coll. length λ_T {g cm^{-2}}	Nucl.inter length λ_I {g cm^{-2}}	Rad.len. X_0 {g cm^{-2}}	$dE/dx\vert_{min}$ { MeV g^{-1}cm^2}	Density {g cm^{-3}} ({g ℓ^{-1}})	Melting point (K)	Boiling point (K)	Refract. index @ Na D
H_2	1	1.008(7)	0.99212	42.8	52.0	63.05	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.014101764(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	6.94(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.0121831(5)	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			2.419
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210	Sublimes at 4098. K		
N_2	7	14.007(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	15.999(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	18.998403163(6)	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]
N	13	26.9815385(7)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Al	13	26.9815385(7)	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	72.630(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.	
Au	79	196.966569(5)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	1408.	4404.	

Photon Interactions with Matter



Electron interactions: Bremsstrahlung

- Accelerated charges radiate electromagnetic fields
- Bremsstrahlung: breaking radiation



$$\frac{d\sigma}{dE_e} = \frac{m}{X_0 N_A E_e}\left(\frac{4}{3} - \frac{4}{3}y + y^2\right)$$

$$y = \frac{E_\gamma}{E_e}$$

Electromagnetic Interactions

- Pair production, Compton scattering and bremsstrahlung all occur with similar characteristic length scales

$$N(x) = N_0 e^{-x\rho/X_0}$$

- The "radiation length" is usually scaled by the density

	$\rho\ [g \cdot cm^{-3}]$	$X_0\ [g \cdot cm^{-2}]$	$\frac{X_0}{\rho}\ [cm]$
Helium	**0.166 x 10^{-3}**	94.32	5682 **m**
Carbon	**2.21**	42.70	19.3
Lead	**11.35**	6.37	0.56

Synchrotron Radiation

- When an electron moves in a circle (for example, in a magnetic field) its velocity remains constant but its direction changes.
- This acceleration leads to the emission of photons.
- Radiated power (over all wavelengths):

$$P = \frac{e^2}{6\pi\epsilon_0 c^7 r^2} \frac{E^4 \beta^2}{m_e^4}$$

- Most important for high-energy electrons
- Limits the achievable energy of circular electron accelerators.

Ionization

- A charged particle with mass M will transfer energy to the electrons in the surrounding medium via its electric field.
- Maximum possible energy transfer:

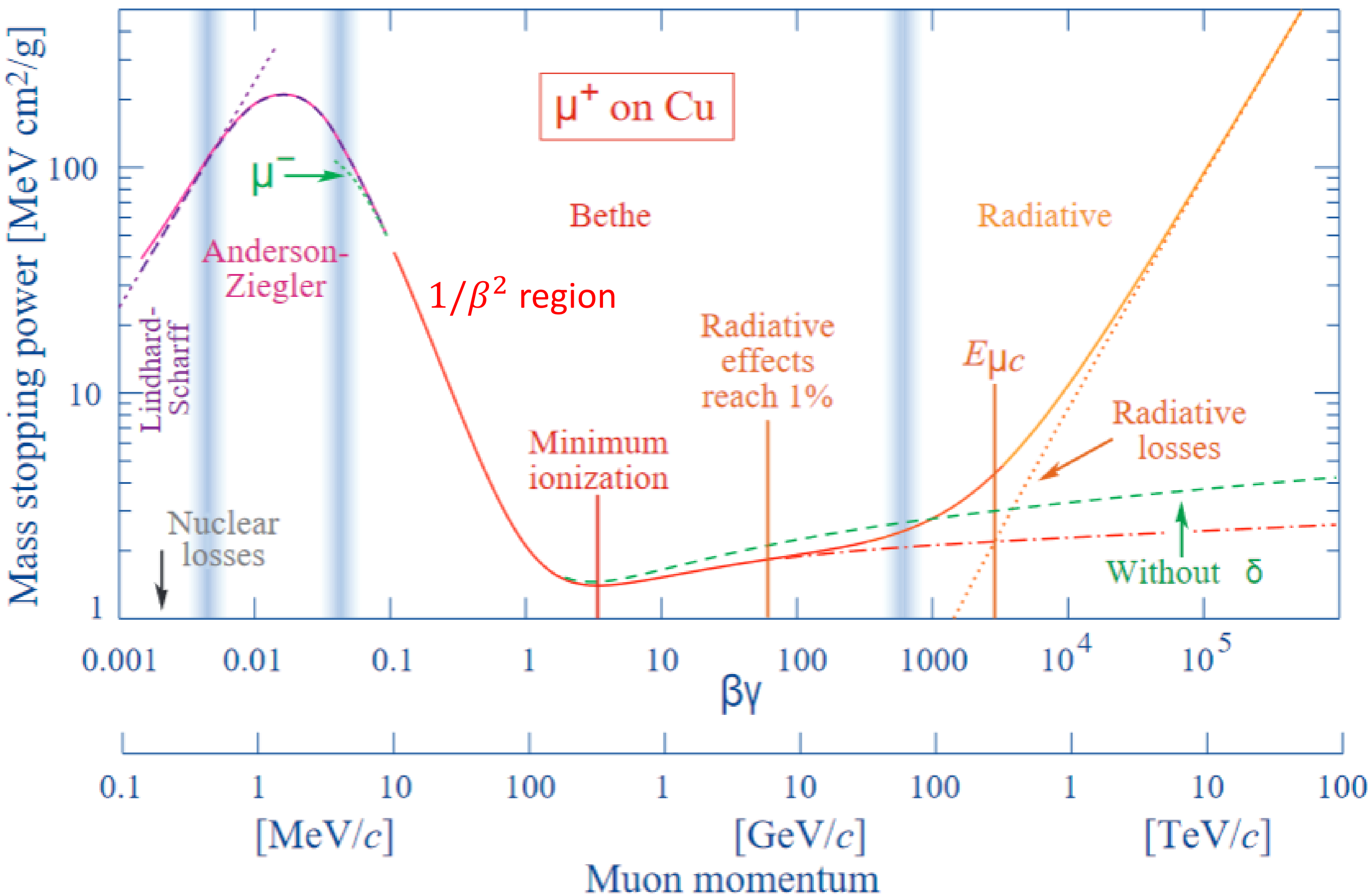
$$W_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

- Bethe equation:

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

  - $K = 0.307075 \ \mathrm{MeV} \cdot \mathrm{mol}^{-1} \cdot \mathrm{cm}^2$
  - I is the mean excitation energy (typically a few eV)
  - δ is called the "density effect correction"

Ionization



The curve is a function of $\beta\gamma$ – it is a universal shape for all particle types.

Ionization

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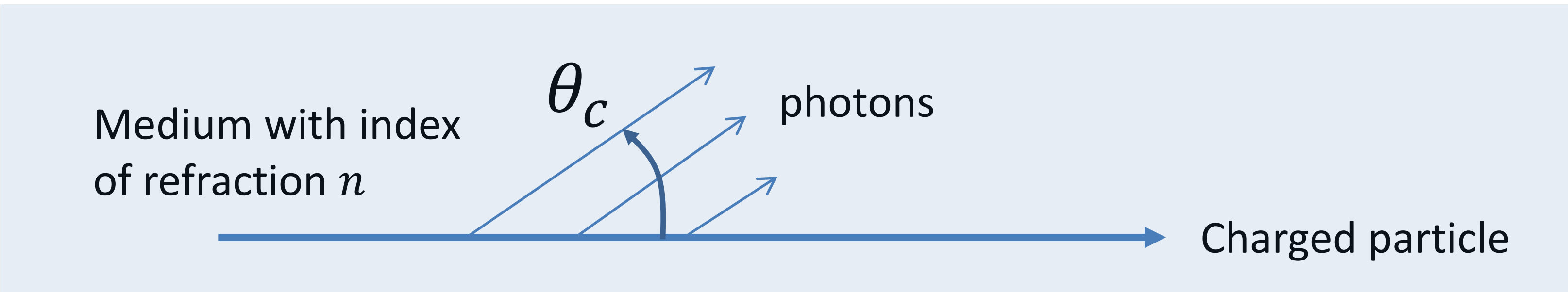
Cherenkov Radiation

- When a charged particle moves through a medium with a speed that is faster than the speed of light in the medium, it emits Cherenkov radiation



$$\cos\theta_c = \frac{1}{n\beta}$$

$$\frac{dN}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

- Not a significant energy loss mechanism, but a useful way to detect charged particles

Charged Particles

- Charged particles that interact primarily via ionization must move macroscopic distances through material before decaying.
- Typically, these include
  - Protons (stable)
  - Muons ($\tau = 2.2\ \mu\mathrm{s}$)
  - Charged pions, $\pi^{\pm}$ ($\tau = 26\ \mathrm{ns}$)
  - Charged kaons, $K^{\pm}$ ($\tau = 12.4\ \mathrm{ns}$)
  - Deuterons, tritons, α-particles and other nuclei

Neutral Particles

- Neutral particles that are composed of quarks are called hadrons
- Hadrons with relatively long lifetimes include
  - The neutron, n ($\tau = 880 \text{ s}$)
  - Neutral kaons, K_L^0 ($\tau = 52 \text{ ns}$) and K_S^0 ($\tau = 89 \text{ ps}$)
  - Neutral pions decay immediately to photons, $\pi^0 \to \gamma\gamma$ which subsequently interact electromagnetically
- Neutral particles can scatter elastically from nuclei, which could then interact as charged particles
- Neutral hadrons interact with nuclear material to produce secondary (charged and neutral) collision products (eg, charged and neutral pions).
- Nuclear interaction length, $\lambda_I = \rho\lambda$

$$N(x) = N_0 e^{-x\rho/\lambda_I}$$

- Nuclear collision length, λ_T.

Charged Hadrons

- Long-lived charged hadrons $(p, \pi^{\pm}, K^{\pm})$ will interact both by ionization and by nuclear interactions
- Characteristic length scales are different
  - Ionization is continuous
  - Mean free path is of order λ_I
- Example for carbon and lead:

	$\rho\ [g \cdot cm^{-3}]$	$\lambda_T [g \cdot cm^{-2}]$	$\frac{\lambda_T}{\rho}\ [cm]$	$\lambda_I [g \cdot cm^{-2}]$	$\frac{\lambda_I}{\rho}\ [cm]$
Carbon	**2.21**	59.2	26.8	85.8	38.8
Lead	**11.35**	114.1	10.1	199.6	17.6

Neutrinos

- Neutrinos are electrically neutral
  - They do not lose energy via ionization
  - They do not interact with other charged particles
- Neutrinos are not made of quarks
  - They do not interact strongly with nuclei
- They only interact rarely via weak interactions
  - Inverse beta decay
  - Elastic scattering
- These have extremely small cross sections
- Detecting neutrinos requires extremely large detectors and the interaction rate is usually quite low
- We do not try to *directly* identify neutrinos in collider experiments.

Examples of Neutrino Detectors