PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 56400

Introduction to Elementary Particle Physics I

Fall 2019 Semester

Prof. Matthew Jones

Essential Information

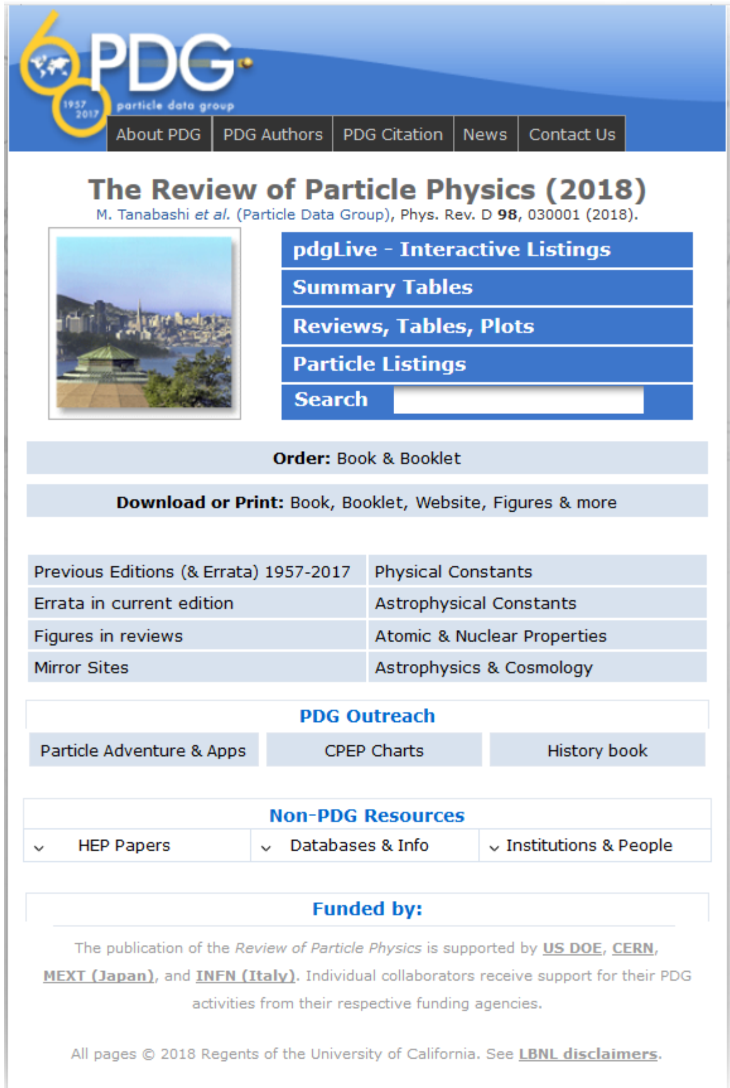
- Course web page, whereat can be found the syllabus: http://www.physics.purdue.edu/~mjones/phys56400
- Basic information:

Lecturer:	**Prof. Matthew Jones** *Office:* Room 378 Physics Building *Phone:* 49-62464 *E-mail:* jones105@purdue.edu *Office hours:* Any time really… try your luck (or by appointment).
Class:	Lecture: Tuesday and Thursday 10:30–11:45 PM, room PHYS 201.
Text:	Martin and Shaw, *Particle Physics*

GRADING:
Your course grade will be based on homework, exam scores and the final term paper, with the approximate weights:

Homework	30%
Midterm exam	30%
Final term paper	40%

Essential Information

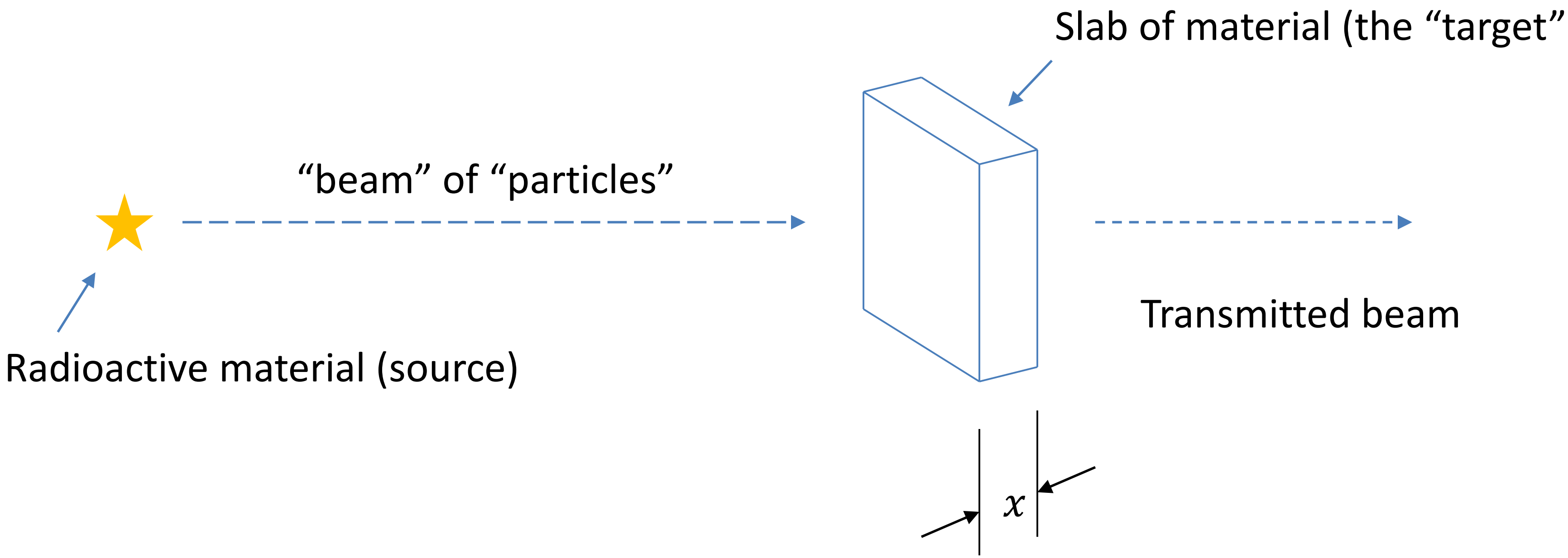


http://pdg.lbl.gov/

Order your free particle data booklet today!

Example Experiment

- Start by considering a very simple particle physics experiment:



What is the probability that a beam particle will interact in the target?

Example Experiment

- The probability that it interacts in a thin slice of target should be proportional to the thickness of the thin slice
- The probability that it interacts should be independent of where it is in the target

$$P(x) = \frac{dx}{\lambda}$$

- Number of interactions should be proportional to the number of incident beam particles at any point x:

$$dN = -N(x)\frac{dx}{\lambda}$$

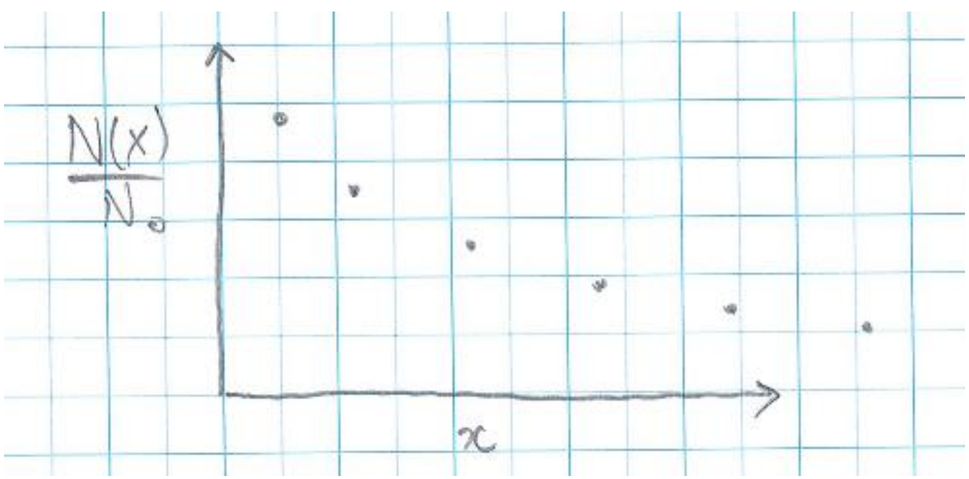
$$\frac{dN}{N} = -\frac{dx}{\lambda}$$

Example Experiment

- The solution to this equation is well known:

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

- The beam is exponentially attenuated by the target material.
- How can we measure λ?



Measure $N(x)/N_0$ for various thicknesses of target material.

Fit with an exponential or fit a straight line to $\log N(x)$ vs x.

- Slope will be $1/\lambda$.

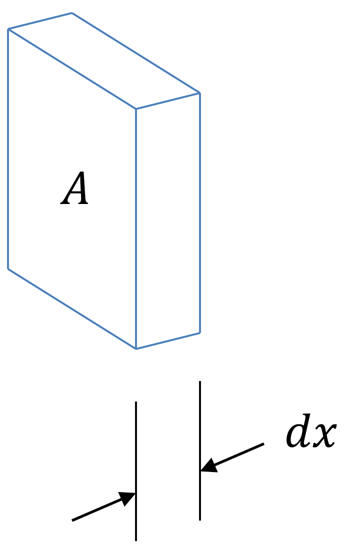
Example Experiment

- What properties of the target material determine the value of λ?
- We need to introduce a model for the interactions between the beam and target particles.
- We also need to clearly specify what we mean by “interaction”…
  - An interaction could be one that completely removes a particle from the beam
  - An interaction could also be one that scatters a particle at some angle
  - Is scattering at a vanishingly small angle still something we want to call an “interaction”?

Example Experiment

- Simple model:
  - *If a beam particle hits a target particle, it will simply disappear from the beam*
  - *Assume the beam particles are point-like and the target particles are spheres of radius* R.
- How many target particles per unit area in a thin slice?

Volume of target: $V = A\,dx$
Density of target: ρ (mass per unit volume)
Atomic mass of target particles: m (eg, g/mole)
Avagadro's number: N_A (particles per mole)



$$N_T = N_A \frac{\rho}{m} V = N_A \frac{\rho}{m} A\,dx$$

Example Experiment

- The probability of interacting in a thin slice of target is the same as the fraction of the area A that is obscured by the target particles

$$P = \frac{N_T\ \pi R^2}{A} = \frac{N_A \rho}{m} \cdot \pi R^2 dx$$

- But this is just the same as

$$P(x) = \frac{dx}{\lambda}$$

- Therefore,

$$\lambda = \frac{m}{N_A \rho \cdot \pi R^2}$$

- In practice, it is common to normalize λ by dividing by the target density and call it the “interaction length”:

$$\lambda_I = \lambda\ \rho$$

Note that the units are g/cm^2!

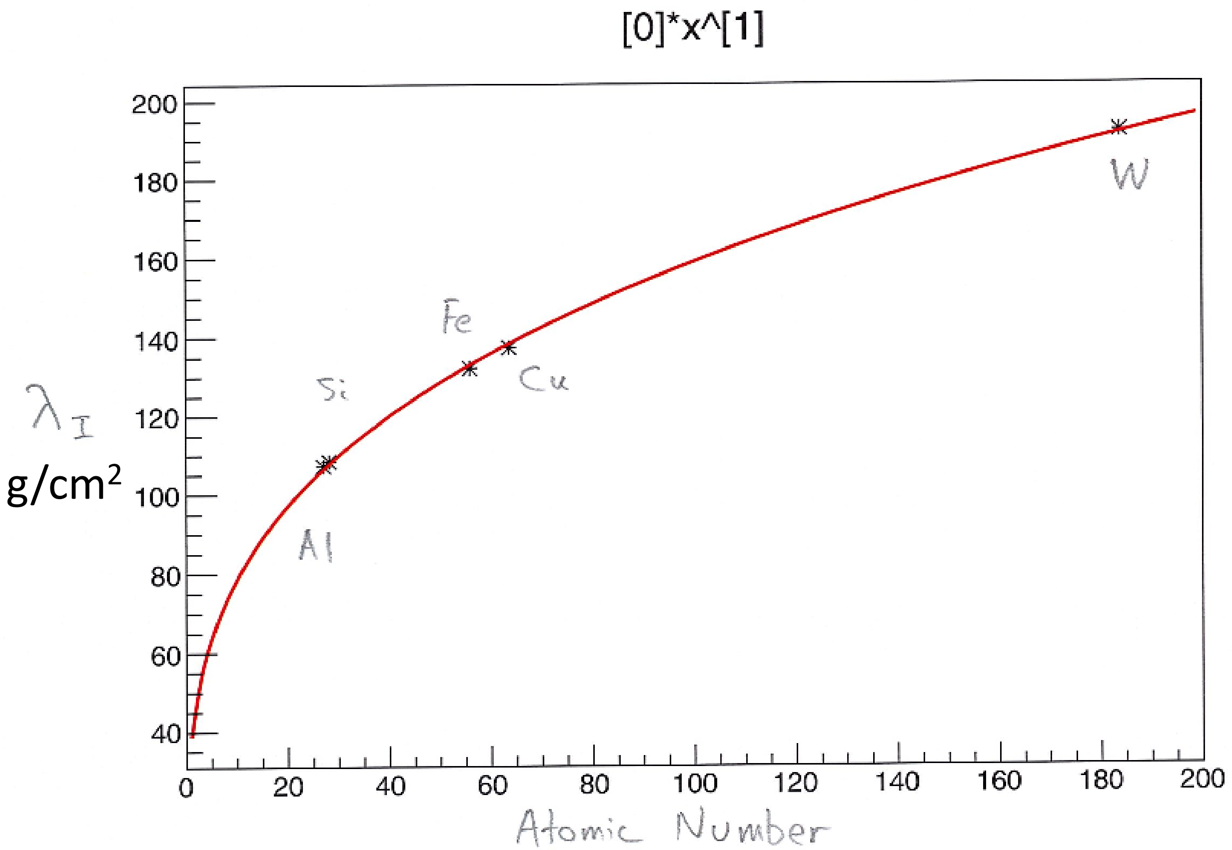
Example Experiment

- Does this make sense?
- A simple nuclear model assumes a uniform nuclear mass density.
  - Mass of a target particle is proportional to the atomic number (number of protons+neutrons), A
  - Volume of a target particle is also proportional to the atomic number, A
  - Radius is proportional to $\sqrt[3]{A}$

$$\lambda_I \propto \frac{m}{R^2} \sim A^{1/3}$$

- Can we use this model to estimate the size of a nucleon?

Example Experiment



Nuclear interaction lengths obtained from the table in the Particle Data Book.

$$\lambda_I = kA^{\alpha}$$

$$k = 39 \text{ g/cm}^2$$

$$\alpha = 0.31$$

The exponent is very close to 1/3 which suggests that nuclei might actually behave in this way…

Example Experiment

- Radius of a nucleon:

$$R = \sqrt{\frac{m}{\pi \, N_A \, \lambda_I}}$$

- Consider an iron target:
  - $m = 55.845 \text{ g/mol}$
  - $\lambda_I = 132.1 \text{ g/cm}^2$ (look it up in the Particle Data Book)
  - $N_A = 6.022 \times 10^{23} \text{ /mol}$

$$R = 4.73 \times 10^{-13} \text{ cm} = 4.73 \text{ fm}$$

Example Experiment

- What cross sectional area is obscured by a single nucleus?

$$\sigma = \pi R^2$$
$$= 1.49 \times 10^{-29}\ \mathrm{m}^2$$
$$= 0.149\ \mathrm{barn}$$

- Cross sections in particle physics are frequently expressed in barns…

$$1\ \mathrm{barn} = 10^{-24}\ \mathrm{cm}^2 = 10^{-28}\ \mathrm{m}^2$$

- The origin of the term has great local historical significance!

Cross Section

- How is the “cross section” related to the nuclear interaction length?
- Probability of interacting in a target of area A and thickness Δx with density ρ is

$$P = \frac{N_A \rho A \Delta x}{m} \cdot \frac{\sigma}{A} = \frac{\Delta x}{\lambda}$$

- What is the rate of interactions?

$$R = v\, \mu \frac{N_A \rho}{m}\, \Delta x \cdot \sigma$$

  - v is the velocity of the beam particles (eg, cm/s)
  - μ is the linear density of beam particles (eg, particles/cm)

Cross Section

- Cross sections should be thought of in terms of probability
- For example,

"What is the probability that an 800 MeV proton hits an aluminum nucleus and makes an Na-22 atom?"

- The cross section for Na-22 production from aluminum at 800 MeV is

$$\sigma = 15.0 \text{ mbarn}$$

- The fraction of the area covered by this cross section is

$$\frac{N_A \rho A \Delta x}{m} \cdot \frac{\sigma}{A} = \frac{N_A \rho \, \sigma \, \Delta x}{m}$$

- This is the probability that an 800 MeV proton, shot randomly at the aluminum, will make an Na-22 atom.

Cross Section

- The cross section for making Be-7 is lower:

$$\sigma = 6.8 \text{ mbarn}$$

- This just means that it is only about half as likely to produce Be-7 as it is to produce Na-22.
- Lots of other isotopes could be produced and they would have their own cross sections.
- So, it is useful to think of the cross section as an “area” of a target nucleus, but it really is more closely related to probability.

Luminosity

- We try to distinguish the contributions from the experiment and the fundamental interaction:

$$R = \mathcal{L}\,\sigma$$

- The luminosity has dimensions $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$
- The luminosity is a property of the beam and the target
  - It can be calculated using detailed measurements of the beam properties, but with limited precision
  - It is often measured using a well understood physics process which has a relatively large cross section
- The cross section depends on the physics that governs the interactions between beam and target particles

Example

- In 2017, instantaneous luminosity of the LHC was
$$\mathcal{L} = 2.06 \ \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$
- The cross section for producing a Higgs boson is about
$$\sigma_H \sim 50\ \mathrm{pb} = 50 \times 10^{-12} \times 10^{-24}\ \mathrm{cm}^2$$
- Higgs production rate:
$$R_H = 1\ \mathrm{s}^{-1}$$
- Inelastic proton cross section:
$$\sigma_{inel} \sim 70\ \mathrm{mb} = 70 \ \times 10^{-27}\ \mathrm{cm}^2$$
- Rate of inelastic collisions:
$$R_{inel} = 1.44 \ \times 10^{9}\ \mathrm{s}^{-1}$$
- One estimate of the instantaneous luminosity is from
$$\mathcal{L} = \frac{R_{inel}^{measured}}{\sigma_{inel}^{theory}}$$