Introduction to Elementary Particle Physics

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Elementary Particle Physics

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Scattering

Part I: Introduction

Reference:

B. Povh et al, Particles and Nuclei, 6th Edition, Springer Verlag, 2008

Scattering: General observations about scattering processes

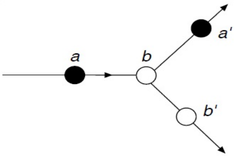
Scattering experiments are used

- to study the details of the interactions between different particles
- to obtain information about the internal structure of atomic nuclei and their constituents

In general

- In the reaction $a + b \to c + d$, a is the **projectile** and b is the **target**
- c and d are the **products** of the reaction
- We use detectors to determine
  - the rate of the reactions
  - the energy and mass of the reaction products
  - the relative angle to the beam direction

Elastic Scattering: $a + b \to a' + b'$



- Same particles are presented before and after the scattering
- They are identical up to their momenta and energies

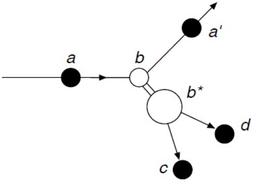
$$\begin{aligned} E_a + E_b &= E_{a'} + E_{b'} \\ \mathbf{p}_a + \mathbf{p}_b &= \mathbf{p}_{a'} + \mathbf{p}_{b'} \end{aligned}$$

Moreover

$$E_{kin}^{before} = E_{kin}^{after} \longrightarrow m_a + m_b = m_{a'} + m_{b'}$$

Inelastic Scattering: $a + b \to a' + b^\star, \qquad b^\star \to c + d$

$$E_{kin}^{before} > E_{kin}^{after} \longrightarrow \sum_i m_i^{before} < \sum_i m_i^{after}$$

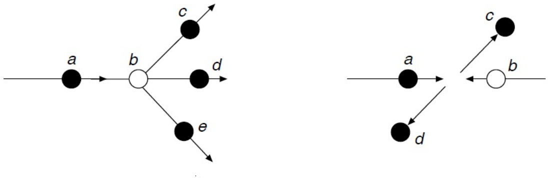


- In inelastic reactions, part of the kinetic energy transferred from *a* to *b* excites it into $b^\star$
- The excited state will afterwards return to the ground state by emitting a light particle (e.g. a photon or a π meson) or it may decay into two or more different particles

Inelastic Scattering

- **Inclusive measurement:** A measurement of a reaction in which only the scattered particle a' is observed and the other reaction products are not is called an inclusive measurement
- **Exclusive measurement:** If all reaction products are detected, we speak of an exclusive measurement

Inelastic Scattering



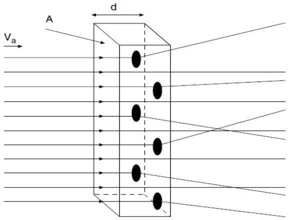
- In some processes the beam particles (*a*) may completely disappear in the reaction.
- Its total energy then goes into the excitation of the target or into the production of new particles.

Such inelastic reactions represent the basis of nuclear and particle **spectroscopy**

Geometric reaction cross-section

Projectile

- Point-like particles $\rightarrow a$
- Monoenergetic beam of a with velocity $\rightarrow v_a$
- Number of beam particles $\rightarrow N_a$
- Particle density $\rightarrow n_a$
- Beam particle rate $\rightarrow \dot{N}_a$



Beam cross-sectional area $\rightarrow A$

Target

- Thickness of the target $\rightarrow d$
- Number of scattering center (b) $\rightarrow N_b = n_b A d$
- Particle density $\rightarrow n_b$
- Cross-sectional area of each target particle $\rightarrow \sigma_b$ (to be determined)

Geometric reaction cross-section

We assume:

- After the collision the beam particle is removed from the beam
- We do not distinguish between elastic and inelastic scattering

Then

The area presented by a single scattering center to the incoming projectile a

is called the ***geometric reaction cross-section***

- Flux Φ_a:

$$\Phi_a = \frac{\dot{N}_a}{A} = n_a v_a$$

- Total number of target particles with the beam area

$$N_b = n_b A d$$

- Total reaction rate

$$\dot{N} = \Phi_a N_b \sigma_b$$

Geometric reaction cross-section

If we assume a homogeneous constant beam (e.g. neutrons from a reactor)

$$\begin{aligned}\sigma_b &= \frac{\dot{N}}{\Phi_a N_b} \\ &= \frac{\text{\# of reactions per unit time}}{\text{\# of beam particles per unit time per unit area} \times \text{\# scattering centers}}\end{aligned}$$

In high energy physics experiments, since the beam is generally not homogeneous but the area density of the scattering centers is homogeneous, we use

$$\sigma_b = \frac{\text{\# of reactions per unit time}}{\text{\# of beam particles per unit time} \times \text{\# scattering centers per unit area}}$$

Total cross-section

So far we have neglected

- Energy dependence
- Shape, strength and range of the interaction potential (e.g. neutrinos feel only the weak interaction, electrons feel the electromagnetic interaction, and we have $\sigma_\nu \ll \sigma_e$)

But, we nevertheless use the former definition

$$\sigma_{total} = \frac{\text{\# of reactions per unit time}}{\text{\# of beam particles per unit time} \times \text{\# scattering centers per unit area}}$$

$$\sigma_{total} = \sigma_{elastic} + \sigma_{inelastic}$$

Its unit: 1 barn $= 1\text{b} = 10^{-28} m^2$

Typical cross-sections

$$\sigma_{pp}(10\text{GeV}) \approx 40\text{mb}$$

$$\sigma_{\nu p}(10\text{GeV}) \approx 70\text{fb}$$

Luminosity

$$\mathcal{L} \equiv \Phi_a N_b = \frac{\dot{N}_a}{A} N_b = n_a v_a N_b = \dot{N}_a n_b d$$

$[\mathcal{L}]$=(Area $\times$ time)$^{-1}$

Another definition for luminosity in a storage ring

$$\mathcal{L} = \frac{N_a N_b j v / U}{A}$$

- Number of particle packets $\rightarrow j$
- Velocity of N_a or N_b particles (in two opposite directions) $\rightarrow v$
- Circumference of the ring $\rightarrow U$
- Beam cross-section at the collision point $\rightarrow A$

  Assuming a Gaussian distribution of the beam particles around the beam center with horizontal and vertical standard deviations σ_x and σ_y

$$A = 4\pi\sigma_x\sigma_y$$

- Typical beam diameter $\lesssim 10^{-4} m$

Integrated luminosity

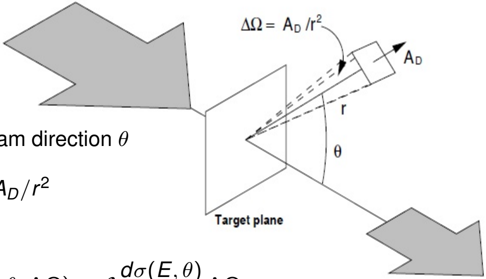
$$\int \mathcal{L} dt, \qquad \left[\int \mathcal{L} dt\right] = (\text{Area}\times\text{time})^{-1} \times \text{ time} = \text{Area}^{-1} = \text{barn}^{-1}$$

- The number of reactions which can be observed in a given reaction time

$$\begin{aligned} &= \text{Integrated luminosity} \times \text{the cross-section} \\ &= 100 \text{ pb}^{-1} \times 1 \text{ nb} = 10^{2+12-9} = 10^5 \text{reactions} \end{aligned}$$

Differential cross-section

- Detector area A_D
- Distance r
- Angle with respect to the beam direction θ
- Covered solid angle $\Delta\Omega = A_D/r^2$



The rate of the reaction

$$\dot{N}(E, \theta, \Delta\Omega) = \mathcal{L}\frac{d\sigma(E, \theta)}{d\Omega}\Delta\Omega$$

Double differential cross-section

$$\sigma_{tot}(E) = \int_0^E \int_{4\pi} \frac{d^2\sigma(E', \theta)}{dE' d\Omega} d\Omega dE'$$

E' is the energy of the scattered particles