FUNDAMENTALS OF ELEMENTARY PARTICLE PHYSICS

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: at rest. Compare this with the
0-GeV protons.[1]
electrons.
pproximately 1.7 MeV/g-cm^{-2} in
erage, 37 eV to produce an ion
n pairs are produced per centi-
eric pressure.
angle due to multiple coulomb
aversing 10 cm of liquid propane
g/cm^2). Compare this with the
is bent if it travels 10 cm in a
Discuss the implications of this
m resolution in a propane bubble
se conditions. Repeat for liquid
$_0$ = 58 g/cm^2).
diator for a threshold Cerenkov
e to 800 MeV/c pions but not to
GeV/c pions but not to 8 GeV/c

pically have dimensions ~1 m.
ing beams of μ^+, π^+, K^+, Λ^0, and π^0
stances of about 1 m. In particu-
entum for which the mean free
h of the above particles.

given in the text are kinetic, rather than

CHAPTER 3

discussion of strong interactions

There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out.

From Sir Isaac Newton,
"Opticks," Dover, New York, 1952

3-1 INTRODUCTION

The strong interaction is most familiar as the force between nucleons responsible for nuclear binding. Generally speaking, mesons, nucleons, and hyperons interact among themselves through strong interactions. Collectively, as stated in Chap. 1, such particles are called hadrons. As a rule, if a reaction satisfies the conservation laws appropriate to the strong interactions, it is likely to occur with appreciable probability. For example, at very high energies, rates for the reactions

$$p + p \to n + p + \pi^+$$
$$p + p \to p + p + \pi^0$$
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$$\cdots$$

are of the same order of magnitude. Final states containing strange particles are somewhat less likely, but still appear with appreciable probability.

Unfortunately no satisfactory theory of strong interactions has yet been advanced. There is nothing equivalent to the combination of quantum mechanics and electromagnetic theory (*quantum electrodynamics*), which has proved so successful in atomic physics and, in principle at least, seems capable of "explaining" all atomic physics. The difficulty in the theory of the strong interactions seems basically due to the strength of the interaction itself. As a result approximations, such as perturbation theory in quantum mechanics, break down. Furthermore, because of a phenomenon known as *virtual dissociation*, all the hadrons are strongly coupled to each other. Thus for a time $\Delta t \sim \hbar/\Delta E$ (where ΔE is the apparent energy viola-

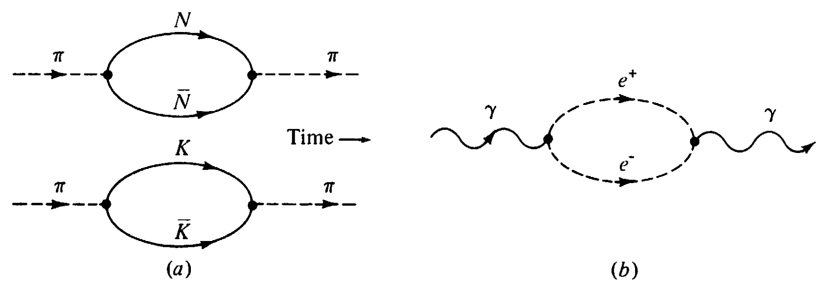

Figure 3-1 (*a*) The virtual dissociation of a pion into a nucleon-antinucleon or K-$\bar{K}$ pair. (*b*) The dissociation of a photon into an e^+-e^- pair.

tion) allowed by the uncertainty principle, the π meson can be thought to exist as a nucleon-antinucleon pair or a K-$\bar{K}$ pair (Fig. 3-1*a*). The photon can likewise dissociate into an electron-positron pair through virtual electromagnetic interactions (Fig. 3-1*b*), but the probability of this dissociation is much lower than for those occurring through virtual strong interactions, because electromagnetic interactions are inherently weaker. Thus virtual electromagnetic processes can often be neglected, and even when it is necessary to take them into account, there exist suitable calculational techniques.

Because of such virtual processes the hadrons are all closely coupled to each other and, in a sense, every problem in strong interactions is a many-body problem. Feynman has described the nuclear force as "almost as complicated as it can be." It depends on velocity and spin orientation as well as position and isotopic spin. Virtual strong interactions are also a problem in treating the weak decays of hadrons since, for example, a K meson can be thought of as a virtual $\bar{\Lambda}^0$-nucleon pair. This has hampered the development of a complete theory of the weak interactions, which otherwise would be amenable to approximation schemes of the type used for electromagnetic interactions.

The bulk of the experimental data on strong interactions has been obtained by studying the scattering of one particle on another, for example,

$$p + p \to ?$$
$$\pi + p \to ?$$

It is possible to make fairly intense beams of $\pi^\pm$, K^0, $K^\pm$, n, p, and $\bar{p}$ for such studies. The most accessible target particles are protons (in the form of a liquid-hydrogen target). Scattering from neutrons can be studied somewhat less directly through

$$p + d \rightarrow ?$$
$$\pi + d \rightarrow ?$$

Since the deuteron is a loosely bound n-p system, in many situations the neutron can be considered a free neutron with corrections made to account for the effects of the proton nearby.

In general it is not possible to study systems like the π-π system directly in scattering experiments, but some information can be gleaned indirectly (Sec. 3-7).

3-2 DEFINITION OF A CROSS SECTION

The probability of a certain reaction can be expressed in terms of a *cross section*. If we imagine a beam of particles passing through a thickness dx of a target, the fraction of particles that interact because of collisions can be written

$$\frac{dI}{I} = -\sigma N\, dx \tag{3-1}$$

where I is the beam flux in appropriate units (e.g., total particles or particles per second), and N is the number of target nuclei per cubic centimeter in the target. The cross section σ is a proportionality constant with dimensions of area. Common units are

$$1 \text{ barn (b)} = 10^{-24}\text{ cm}^2 \qquad 1\text{ mb} = 10^{-27}\text{ cm}^2$$

The cross section σ can be thought of as the effective area of a nucleus (Fig. 3-2). This might be very different from the geometric area. We can define various types of cross sections. For example,

Total cross section σ_T. The cross section for all processes which scatter or otherwise remove particles from the beam

Elastic cross section σ_{el}. The cross section for elastic scattering, for example, $p + p \rightarrow p + p$

Inelastic cross section σ_{inel}. The cross section for all processes other than elastic scattering, $\sigma_{inel} = \sigma_T - \sigma_{el}$

We can also define a differential cross section $d\sigma/d\Omega$ by the equation[1]

$$\frac{\Delta I}{I} = \left(\frac{d\sigma}{d\Omega}\,\Delta\Omega\right) Nx \tag{3-2}$$

Here x is the target thickness, and $\Delta I/I$ is the fraction of the incident beam scattered into a certain solid angle $\Delta\Omega$ (Fig. 3-3). Generally $d\sigma/d\Omega$ will be a function of angle and incident energy. Unless otherwise specified $d\sigma/d\Omega$ will refer to the cross section in the c.m.s. It is often convenient to define the differential cross section in such a way that it is relativistically invariant. This can be done by defining the differential cross section in terms of the invariant four-momentum transfer t, where t is the square of the difference between the final and

[1] We can define a differential cross section for elastic or inelastic scattering, but unless otherwise specified we refer to the differential cross section for *elastic* scattering.

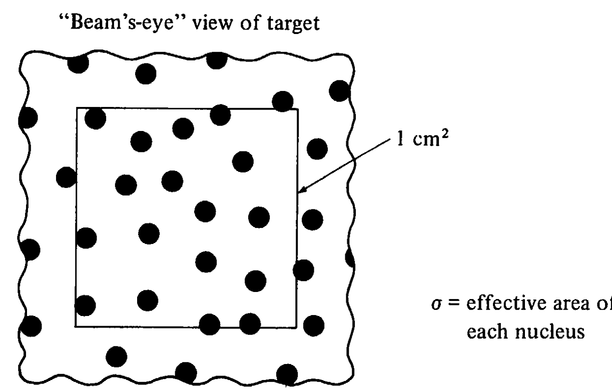

Figure 3-2 A "beam's-eye" view of a target. The shaded circles represent the effective area of each nucleus. If a beam particle strikes the shaded area, it is assumed to have interacted. The fraction of the beam that interacts, dI/I, is therefore the ratio of the shaded area to the total area. In the 1-cm² area there are $N\,dx$ targets, each of area σ, so that $-dI/I = \sigma N\,dx/(1\text{ cm}^2)$.

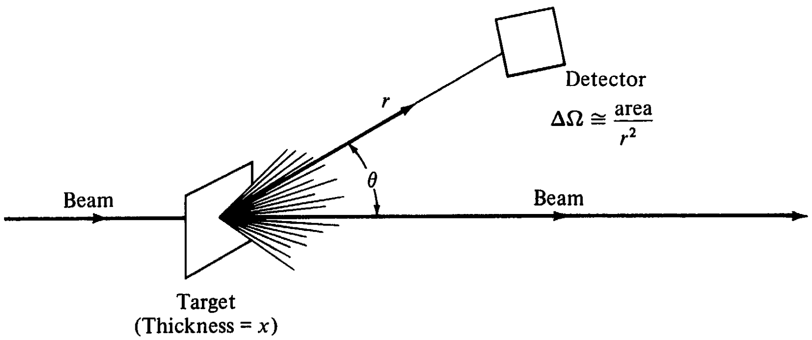

Figure 3-3 Basic arrangement for a differential cross-section measurement. The beam is incident on a thin target. The detector, which subtends a solid angle $\Delta\Omega$ (assumed small), detects particles coming off at an angle θ.

initial four-momentum of the incident particle.[1] For elastic scattering, $t = -2p^{*2}(1 - \cos\theta_{\text{c.m.}})$, where p^* is the momentum of either particle in the c.m.s., and $\theta_{\text{c.m.}}$ the c.m.s. angle. The differential cross section $d\sigma/d|t|$ is then related to the cross section in the c.m.s., $d\sigma/d\Omega$, by

$$\frac{d\sigma}{d|t|} = \frac{\pi}{p^{*2}} \frac{d\sigma}{d\Omega} \tag{3-3}$$

3-3 THE NUCLEON-NUCLEON SYSTEM

The nucleon-nucleon (N-N) system has been studied very extensively. Its great importance lies in the fact that the properties of this system determine those of the nucleus. Much can therefore be learned about the N-N system by studying the nucleus. However this is the province of nuclear physics, and we shall restrict ourselves to the elementary N-N system.

[1] See Appendix B for a summary of relativistic formulas. Often q^2 is used for the invariant four-momentum squared, instead of t. There is also some inconsistency in the sign conventions used. As usually defined, t is negative for elastic scattering. In Sec. 5-1 we use q^2 for the absolute value of t to conform with common usage in electron-scattering experiments. An expression for q^2 is developed there in terms of the kinetic energy of the target particle after the scattering.

REVIEW OF EXPERIMENTAL DATA

We first review some of the basic experimental data. Figure 3-4 shows the behavior of the total cross section σ_T, the elastic cross section σ_{el}, and the inelastic cross section σ_{inel} for p-p scattering. Below the threshold for single-pion production $\sigma_{\text{el}} = \sigma_T$. [Note that a geometric cross section of 50 mb corresponds to a radius of 1.25×10^{-13} cm $\equiv$ 1.25 fermi (fm).[1]]

Cross sections for n-p scattering are shown in Fig. 3-5. The inelastic and elastic cross sections for n-p scattering are rather poorly

[1] A convenient unit of length in elementary particle physics is the *fermi*, where 1 fm $\equiv 10^{-13}$ cm. This corresponds roughly to the charge radius of the proton ($\approx$0.7 fm) or the Compton wavelength of the pion ($\approx$1.4 fm).

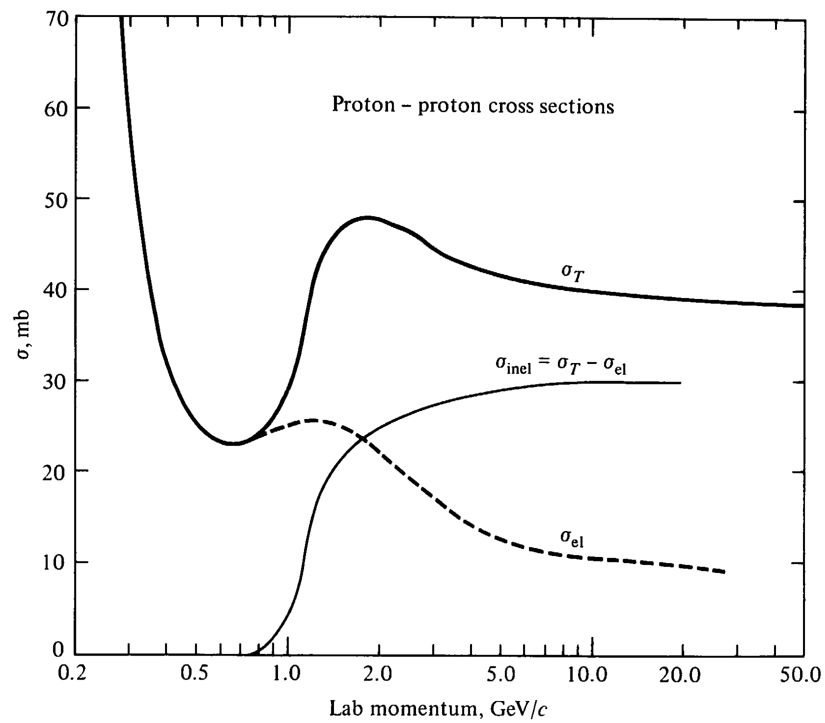

Figure 3-4 Total, elastic, and inelastic cross sections for p-p scattering versus momentum. *(Data taken from a compilation by the Particle Data Group, Lawrence Radiation Laboratory Rep. UCRL-20,000 NN, August, 1970.)*

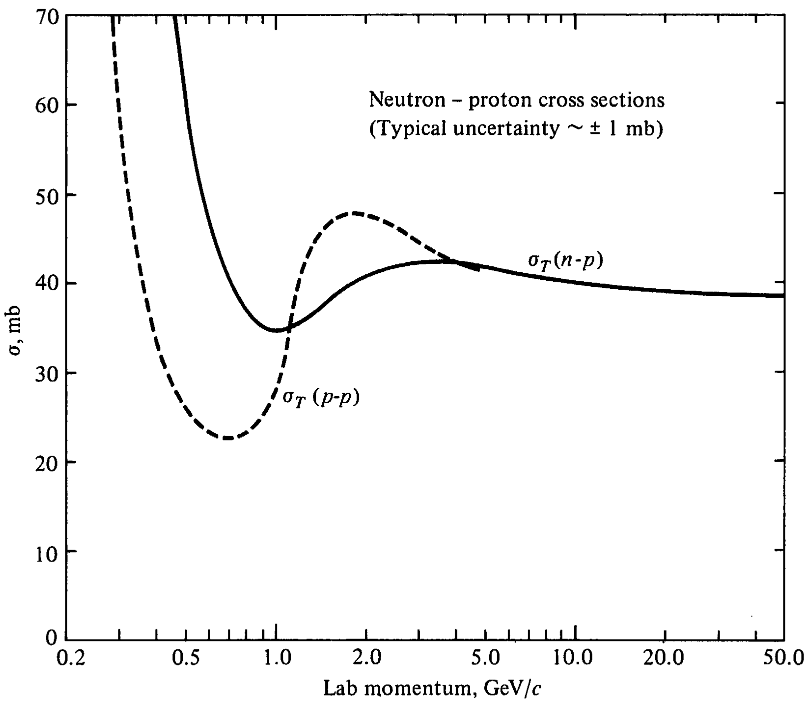

Figure 3-5 Neutron-proton total cross section versus momentum. The dashed line shows the p-p total cross section for comparison.

known and are not given. A common feature of total cross sections for all interactions is that at very high energies they become almost energy independent.

Another basic piece of experimental information is the differential cross section $d\sigma/d\Omega$ for elastic scattering.

If we consider a p-p collision in the c.m.s., it is clear from the symmetry of the initial state that all experimental quantities (for example, $d\sigma/d\Omega$) must be symmetrical about 90° in the c.m.s. Below approximately 500 MeV (kinetic energy in the laboratory system) the p-p differential cross section is almost independent of angle, but rises at small angles as a result of the long-range coulomb interaction between protons (Fig. 3-6).

At higher energies, as inelastic scattering becomes important, the differential cross section becomes more and more peaked near the

forward direction (Fig. 3-7). This forward peak is often called the *diffraction peak.* It is basically a wave phenomenon, and is completely analogous to the diffraction of light around a spherical obstacle. The angular width of the diffraction peak is $\sim\lambda/R$, where R is the radius of the obstacle (just as it is in the more familiar case of a circular aperture such as a telescope).

The differential cross section for n-p scattering (Fig. 3-8) is generally similar to that for p-p. However since there is no longer symmetry about 90° in the c.m.s., we need to plot the cross section from 0 to 180°. At low energies the cross section is roughly symmetrical about 90°. At higher energies the diffraction peak becomes prominent at small angles. At high energies there is also a small,

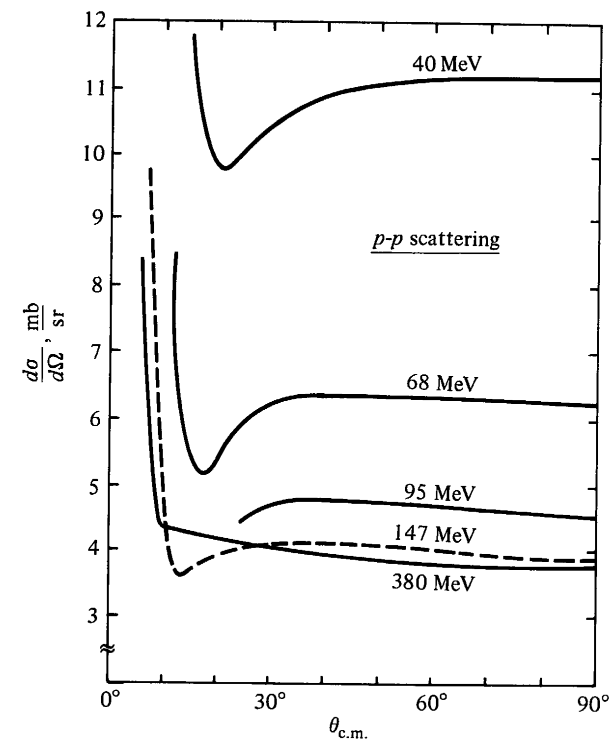

Figure 3-6 Typical behavior of the differential cross section for elastic p-p scattering as a function of c.m.s. angle at low energies.

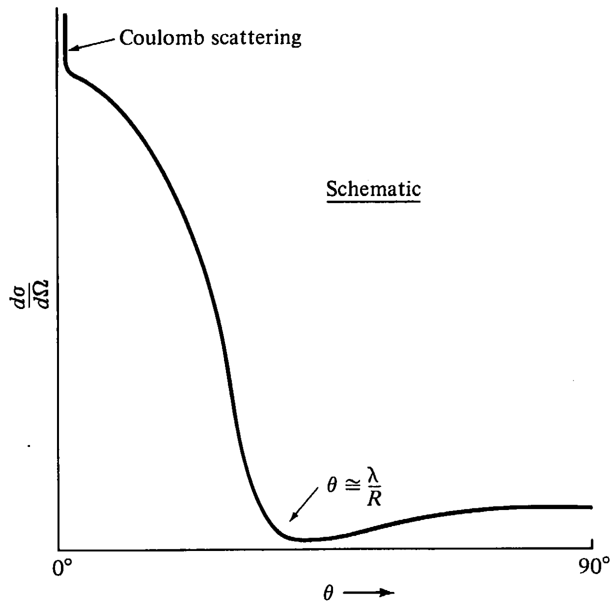

Figure 3-7 Behavior of the differential cross section at high energies (schematic). Most of the scattering is at angles $\lesssim\lambda/R$, where $\lambda = h/p$, and R is the radius of the target ($\sim$1 fm for protons).

very sharp peak in the cross section near 180° (see the 1-GeV curve in Fig. 3-8). This peak is considerably narrower than the forward peak. In the *n-p* system, 180° scattering in the c.m.s. corresponds to a head-on collision; the target particle after the collision has the same velocity and angle the incident particle had before the collision. It is just as though the neutron and proton had exchanged identities by the transfer of one unit of positive charge from the proton to the neutron. For this reason *n-p* scattering near 180° is referred to as *charge-exchange* scattering.

APPLICATION OF ISOTOPIC SPIN

A variety of evidence from nuclear physics suggests that the forces between nucleons are charge independent if allowances are made for

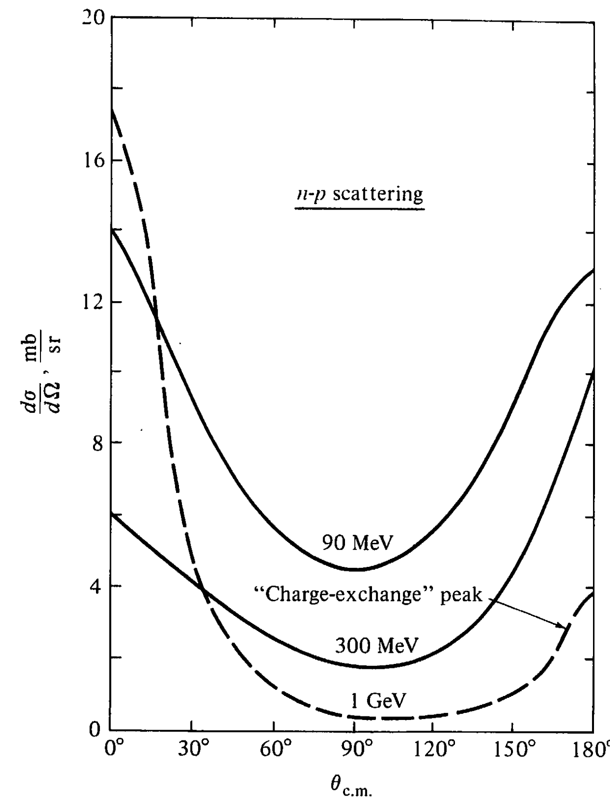

Figure 3-8 Typical behavior of the differential cross section for elastic *n-p* scattering.

coulomb effects (see, for example, E. G. Segrè, "Nuclei and Particles," sec. 10-4). This concept has been generalized in terms of isotopic spin to include similar regularities observed in other systems, such as the π-N system. As discussed in Sec. 1-8, the strong interactions depend only on the magnitude of the total isospin **T** of a system and not on its orientation in isospin space. In particular they do not depend on T_3, which is related to the charge by Eq. (1-1),

$$T_3 = \frac{Q}{e} - \frac{B}{2} - \frac{S}{2}$$

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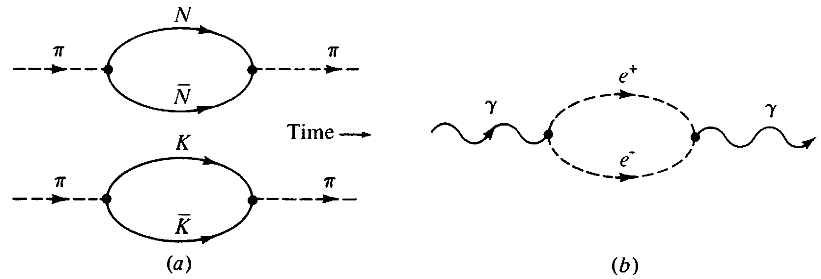

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