CHAPTER - 2

DEEP INELASTIC SCATTERING
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2.1: Scattering Phenomena

Scattering is a general physical process where some forms of radiation, such as light, sound, or moving particles, are forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which they pass. The first scattering experiments were performed by Hans Geiger (1882-1945) and Ernest Marsden (1889-1970), under the guidance of Ernest Rutherford (1871-1937) and serve as the foundation for the nuclear model of the atom [1,2]. These experiments verified that the nuclear charge is a multiple of ‘e’, the electron charge, specifically, Ze and that it is concentrated near the center of the atom. This was determined by observing the angular distribution of the scattered particles.

Experimental technology has advanced greatly since Rutherford’s time, but the principles behind the experiments are still the same: particles are scattered off a target, detected after the interaction and their energy and scattering angle are measured. Scattering experiments are an important tool of nuclear and particle physics. They are used both to
study details of the interactions between different particles and to obtain information about the internal structure of atomic nuclei and their constituents. In a typical scattering experiment, the object to be studied (the target) is bombarded with a beam of particles with well-defined energy. Occasionally, a reaction of the form between the projectile and

\[ a + b \rightarrow c + d \]

the target occurs. Here, \( a \) and \( b \) denote the beam and target particles, and \( c \) and \( d \) denote the products of the reaction. In inelastic reactions, the number of the reaction products may be larger than two. The rate, the energies and masses of the reaction products and their angles relative to the beam direction may be determined with suitable systems of detectors.

It is nowadays possible to produce beams of a broad variety of particles (electrons, protons, neutrons, heavy ions …). Solid, liquid or gaseous targets may be used as scattering material or, in storage ring experiments, another beam of particles may serve as the target. Figure 2.1 shows some scattering processes. One can distinguish between elastic and inelastic scattering reactions. In an elastic process (figure 2.1a)

\[ a + b \rightarrow c' + d', \]

the same particles are presented both before and after the scattering. The target \( b \) remains in its ground state, absorbing merely the recoil momentum and hence changing its kinetic energy. The apostrophe
indicates that the particles in the initial and in the final state are identical up to momentum and energy. The scattering angle and the energy of the particle $a'$ and the production angle and energy of $b'$ are unambiguously correlated. In inelastic reactions (figure 2.1b)

$$a + b \to a' + b^* \quad \& \quad b^* \to c + d$$

part of the kinetic energy transferred from $a$ to the target $b$ excites it into a higher energy state $b^*$. The excited state will afterwards return to the ground state by emitting a light particle or it may decay into two or more different particles.

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. If all reaction products are detected, we speak of an exclusive measurement. When allowed by the laws of conservation of lepton and baryon number, the beam particle may completely disappear in the reaction as shown in figures (2.1c) and (2.1d).

2.2: Deep inelastic scattering (DIS)

It is the name given to a process used to probe the insides of hadrons (particularly the baryons, such as protons and neutrons), using electrons, muons and neutrinos. It provided the first convincing evidence of the reality of quarks. It is a relatively new process, first attempted in
the 1960s and 1970s. It is an extension of Rutherford scattering to much higher energies of the scattering particle and thus to much smaller resolution of the components of the nuclei.

In the early stages of DIS experiments, electrons were used since they were easier to produce and easier to accelerate. But at high energies, electrons pose a problem because they radiate a large amount of energy. The highest energies obtained at that time were 12 GeV at Cornell and 26 GeV at Stanford Linear Accelerator Center (SLAC). Muon offered itself as a good alternative candidate. Protons were accelerated to very high energies more economically than electrons and they produced pions which subsequently decayed into muons. The second generation of muon beams at about 300 GeV with improved quality and intensity were available both at CERN and Fermi Lab [3]. The DIS experiments showed that the nucleon consists of point particles called partons.

Considering the inclusive scattering of a high-energy lepton, with initial energy (four momentum) $E(k)$, final energy $E'(k')$ and scattering angle $\theta$, from a hadronic target of mass $M$ and initial four momentum $p$, and space-like four-momentum transferred to the target as $q$, then for an unpolarized target, the laboratory differential cross section for electromagnetic scattering is
\[
\frac{d^2 \sigma}{dE'd\Omega} = 4\alpha^2 (E')^2 \frac{F_2}{q^4} \left( -\frac{2}{v} \cos^2 \theta \frac{F_1}{2} + 2 \frac{F_1}{M} \sin^2 \theta \frac{1}{2} \right)
\] (2.1)

The quantities \(F_1(x,Q^2)\) and \(F_2(x,Q^2)\) occurring in the above equation are called structure functions of the nucleon. The deep inelastic lepton-nucleon scattering can be considered as the absorption of virtual photon by the nucleon and hence the two structure functions \(F_1(x,Q^2)\) and \(F_2(x,Q^2)\) are related to the photo-absorption cross sections for transverse photons (helicity +1 or -1) and longitudinal photons (helicity 0). Since the photoabsorption has these two independent cross sections \(\sigma_T\) and \(\sigma_L\), two independent structure functions \(F_1\) and \(F_2\) are present in electron or muon inelastic cross section. All of the information about the structure of the target is now contained in the structure functions \(F_1\) and \(F_2\). The dimensional structure functions \(W_1(Q^2,v)\) and \(W_2(Q^2,v)\) are usually replaced by two dimensionless structure functions:

\[
F_1(x,Q^2) = M c^2 W_1(Q^2,v)
\] (2.2)

\[
F_2(x,Q^2) = v W_2(Q^2,v)
\] (2.3)

Here \(v = E - E'\) is the photon energy in the laboratory frame.

The structure functions \(F_1\) and \(F_2\) and the virtual photon absorption cross sections \(\sigma_T\) and \(\sigma_L\) are connected by
\[ F_1 = \frac{2Mv - Q^2}{8\pi^2\alpha} \sigma_T \]  
(2.4)

and

\[ F_2 = \frac{2Mv - Q^2}{8\pi^2\alpha} \frac{\nu}{M} \frac{Q^2}{Q^2 + \nu^2} (\sigma_T + \sigma_L) \]  
(2.5)

These can depend on at most two variables. Here \( \alpha \) is fine structure constant. These variables are chosen to be Lorentz invariant quantities \( Q^2 (= -q^2 > 0) \) and Bjorken \( x(= -q^2/2p.q = Q^2/2Mv) \). In terms of these new variables, the differential cross section takes the form:

\[
\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2(E')^2}{xQ^4} \frac{E'}{E} (F_2 \cos^2 \theta \frac{\nu}{2} + 2\frac{\nu}{M} F_1 \sin^2 \theta \frac{\nu}{2}) 
\]  
(2.6)

In terms of the variable \( y=\frac{\nu}{E} \) and \( F_A^2 \) which is structure function of nucleus divided by atomic mass number \( A \), the above equation is also given by

\[
\frac{d^2\sigma^A}{dx dQ^2} = \frac{4\pi\alpha^2A}{Q^4} [(1 - y - \frac{M x y}{Q^2})\frac{F_A^2(x, Q^2)}{x} + y^2F_1^A(x, Q^2)] 
\]  
(2.7)

One can also say that \( F_A^2 \) is structure function of a bound nucleon. Because the DIS cross sections at large \( Q^2 \) are small, earlier DIS experiments have used heavy nuclei to increase statistics by a factor \( A \), where \( A \) is an atomic weight of the target. This has been motivated by a fact that in DIS reactions a momentum transfer to the bound nucleon is of the order \( k \sim \sqrt{Q^2} \sim 1-10 \) GeV, i.e. three orders of magnitude larger than
nucleon binding. So, for DIS one can assume that nucleons in nuclei are free. Possible violation of this assumption one could expect at very small \( x \ll 0.1 \) or at very large \( x > 0.7 \), where effects of nucleon (anti)shadowing and Fermi motion can play role, respectively. It was believed that in the kinematic region of \( 0.1 < x < 0.7 \), the inelastic structure function per nucleon \( F_2^A \) of atomic weight \( A \) was simply related to the inelastic structure functions \( F_2^p \) and \( F_2^n \) of a free proton and neutron by

\[
A F_2^A (x, Q^2) = Z F_2^p (x, Q^2) + (A - Z) F_2^n (x, Q^2)
\]  

At small \( x \) or \( Q^2 \), shadowing [4] was expected to decrease the structure functions of nuclei, due to either the virtual photon having a hadronic component or overlapping of nucleons due to relativistic contraction. For \( x > 0.7 \), the motion of nucleons within the nucleus (Fermi smearing), convoluted with the sharply decreasing value of \( F_2^p \) and \( F_2^n \) with increasing \( x \), will effectively increase the nuclear structure function relative to that of the nucleon structure function [5].

Early inelastic lepton scattering experiments using nuclear targets searched for shadowing [6,7] in the region of \( x < 0.2 \) and \( Q^2 < 1.6 \text{GeV}^2 \), where the quark-parton model is not expected to hold and where shadowing was expected to be important. Shadowing in electroproduction at \( Q^2 \sim 1 \text{GeV}^2 \) was found to be significantly smaller than in
photoproduction. Since shadowing was expected to rapidly disappear with increasing $Q^2$, further investigations on the $A$ dependence of the structure function for larger values of $x$ and $Q^2$ were not undertaken and equation (8) was assumed to hold. Later, high $Q^2$ muon and neutrino scattering experiments were designed to use nuclear targets because such targets were easier to construct than hydrogen or deuterium targets with the required number of scattering centers. However, it was implicitly assumed that, aside from Fermi motion corrections, such experiments measure the structure functions of free nucleons. For $A=2Z$, $F_2^A = \frac{A}{2} F_2^D$

where $F_2^D = (F_2^p + F_2^n)$. The ratio $F_2^A/F_2^D$ is expected to be close to unity.

Deep inelastic lepton-hadron scattering has played a seminal role in the development of our present understanding of the sub-structure of elementary particles. The discovery of Bjorken scaling in the late nineteen-sixties provided the critical impetus for the idea that elementary particles contain almost point like constituents and for the subsequent invention of the Parton Model. DIS continued to play an essential role in the long period of consolidation that followed, in the gradual linking of partons and quarks, in the discovery of the existence of missing constituents, later identified as gluons, and in the wonderful confluence of all the different parts of the picture into a coherent dynamical theory of
quarks and gluons - Quantumchromodynamics (QCD). Then the emphasis has shifted to the detailed study of the \(x\)-dependence of the parton distribution functions and to the study of their \(Q^2\)-evolution, probably the most direct test of the perturbative aspects of QCD.

Polarized DIS, involving the collision of a longitudinally polarized lepton beam on a polarized target (either longitudinally or transversely polarized) provides a different, complementary and equally important insight into the structure of the nucleon. Whereas ordinary DIS probes simply the number density of partons with a fraction \(x\) of the momentum of the parent hadron, polarized DIS can partly answer the more sophisticated question as to the number density of partons with given \(x\) and given spin polarization, in a hadron of definite polarization, either along or transverse to the motion of the hadron. Since the discovery of the EMC effect, rapid progress has been made in measurements of the spin averaged EMC effect. On the other hand, there has been no experimental information on the spin dependence of the EMC effect. This spin dependent EMC effect emphasizes the quark polarization degrees of freedom within a nucleus, due to the spin-dependence of the coupling between the quarks and the strong field inside the nucleus.
REFERENCES


Figure 2.1: Scattering processes

Scattering processes: (a) elastic scattering; (b) inelastic scattering – production of an excited state which then decays into two particles; (c) inelastic production of new particles; (d) reaction of colliding beams.
CHAPTER - 3

MODELS OF THE NUCLEON