Experiments on Nucleon Structure with Neutrino and Charged Lepton Beams

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Abstract. Lepton scattering is the most basic tool to investigate the nucleon structure. QCD studies of the nucleon structure are an important subject. QCD is a part of Standard Model of particle physics but still requires careful tests both experimentally and theoretically. The quark-gluon structure of the proton and neutron has been explored by a series of deep inelastic scattering experiments with lepton beams. Neutrino scattering, with the charged current and the neutral current, provides a unique possibility to study anti-quark, strangeness, and spin structure. The role of neutrino scattering, when combined with the existing and upcoming data from electron and muon scattering, is described.

1. Introduction

The neutrino scattering and charged lepton scattering have very complemetary features: the neutrino scattering is a process with weak interaction:

$$\nu + N \rightarrow \mu + X, \text{or} \tag{1}$$

$$\nu + N \rightarrow \nu + X \tag{2}$$

In the first process the intermediate vector boson W is exchanged between the beam and the target while in the second process Z is exchanged.

The charged lepton scattering, on the contrary, is an electromagnetic process and the scattering takes place in proportion with electric charge squared of the target, namely u, d, s... quarks:

$$\mathrm{e}(\mu) + N \rightarrow \mathrm{e}(\mu) + X \tag{3}$$

In this process a virtual photon is exchanged.

The goal is to determine the structure functions and to extract the quark distribution functions $u(x), d(x), s(x), \bar{u}(x), \bar{d}(x), \bar{s}(x)$, along with the gluon distribution function $G(x)$. Those are functions of Bjorken x and also depend weakly on Q^2.

The spin dependent quark and gluon distrubution functions, $\Delta u(x), \Delta G(x)$ etc., are the next step to be studied with neutrino beam as well. The neutrino beam is 100% polarized and is suited for studies of the spin structure of the nucleon.

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2. Deep inelastic scattering

The deep inelastic scattering is a kinematic region where the spacial resolution of the scattering process is sufficiently high so that the quarks in the nucleon can be regarded as a target rather than the nucleon itself. The invariant mass of all the hadrons in the final state is a good measure and usually $W > 4$ GeV is required. The typical beam energy is 30 GeV and above. Q^2 is above 1 GeV^2.

2.1. Status of the charged lepton scattering

Following SLAC experiment in 1960's and 1970's, EMC, NMC and BCDMS at CERN, FNAL experiments, a series of SLAC experiments, H1 and ZEUS at DESY reached a high precision in the measurements of the structure functions. NMC's discovery of the violation of Gottfried sum indicated that quarks in the sea are flavour dependent:$\bar{d}(x) > \bar{u}(x)$[1].

Spin of the nucleon is an important subject. The EMC's discovery in 1988[2] that quark spin contribution to the nucleon spin 1/2 is very small opened a new field of nucleon structure studies and attracted many experimentalists and theoretists. Over 500 experimentalists are working on this subject at the moment at various laboratories in the world using different techniques. HERMES at DESY, SMC and COMPASS at CERN, experiments at SLAC, TJLAB and RHIC are the examples. This 'nucleon spin problem' has motivated revisions of QCD models.

Spin dependent structure functions, to the leading twist level, are $g_1(x)$ and $h_1(x)$. The former is the helicity distribution while the latter is the transversity distribution. $h_1(x)$ can be measured with a target polarized transversely to the beam. There has been a progress towards $h_1(x)$ measurement by HERMES at DESY[3]

Other important progress is the measurement of exclusive process such as Deeply Virtual Compton Scattering[4] and exclusive meson productions[5]. With the theoretical framework proposed as 'generalized parton distribution (also called skewed or off-forward parton distribution)'[6] the contribution of the total angular momentum of the quarks J will be extracted. This is the only window at the moment to access the angular momentum contribution to the nucleon spin. In the framework of generalized parton distribution one can combine the data on nucleon form factors, data from deep inelastic scattering, and data from exclusive processes.

3. Physics with neutrino scattering at Neutrino Factory

Comparing to the pioneering experiments of neutrino scattering which were done in the past, a large technical step forward is expected with the neutrino factory. Firstly, because of the high beam intensity the hydrogen target can be used instead of nuclear targets for the first time. Secondly, polarized hydrogen and deuteron targets can be used to investigate nucleon spin.

The specific feature of the neutrino scattering is the selectivity in the charged current interaction. When the neutrino beam is used, μ^- appears in the final state because of lepton number conservation. Therefore, only a negative charged quark can interact, changing itself to a positive charged quark. With the antineutrino beam, the situation is opposite. This selectivity helps us to decompose the structure function into the distribution function of each quark.

3.1. Unpolarized Structure Functions

An interesting quantity to determine is the gluon contribution to the linear momentum of the nucleon:

$$\int xG(x)dx \tag{4}$$

This is obtained by integrating the quark contributions to the linear momentum:

$$\int x(u(x) + d(x) + s(x) + \bar{u}(x) + \bar{d}(x) + \bar{s}(x))dx \tag{5}$$

as the sum of equations (4) and (5) should be 1. At the moment equation (5) is known to be about 0.5 but the precision is not high. The fraction attributed to the gluon is the evidence that gluon explicitely plays a major role as a nucleon constituent. The precise determination of equation (5) provides a strong constraint to the gluon distribution in the nucleon.

3.2. Polarized Structure Functions

The polarized parton distributions, in particular the helicity distributions $\Delta u(x), \Delta d(x), \Delta s(x), \Delta\bar{u}(x), \Delta\bar{d}(x), \Delta\bar{s}(x), \Delta G(x)$ have been determined with the recent charged lepton scattering experiments. However, the charge selectivity and left-handedness of neutrino scattering further help us to improve the precision. The roles of spin of u, d, and s quarks in the sea are not sufficiently explored up to now. Neutrino experiments make desicive contributions to this problem.

Systematic analyses comparing with data from charged lepton scattering and from polarized proton collisions at RHIC are important.

3.3. Detector

The beam energy is around 30 GeV, thus the detector of HERMES experiment can be considered as an model[7]. It was built for electron scattering but has a good hadron identification capability, which will be the key of the experiments at Neutrino Factory.

4. Summary

The neutrino scattering experiments are discussed based on the achievements of lepton scattering experiments up to now. The specific features of the neutrino scattering, due to its weak interaction properties and selectivity, will make important contributions to the QCD studies of the nucleon structure.

References

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