March 18, 2013
Tokai, KEK

3 Dimensional Parton Structure of the Nucleon

T.-A. Shibata

Tokyo Institute of Technology

List of Contents

1. Introduction
2. Form Factors, Photon Absorption, Structure Functions
3. Partons
4. Mass of Quarks
5. Transverse Structure of the Nucleon
6. Summary

1. Introduction

What are you measuring (studying) ?

What are you measuring (studying) for ?

In the past:

Phase shift analysis of hadron scattering

A complete set of polarization measurements

Impact on the study of the nuclear force

2. Form Factors, Photon Absorption, Structure Functions

Form Factors

Elastic scattering, electron scattering

Deviation from the scattering off a point -like target

$G_E(Q^2)$ Electric Form Factor

→ Mean radius of electric charge distribution

$G_M(Q^2)$ Magnetic Form Factor

→ Mean radius of electric current distribution

Absorption Cross Section of Real Photon: $\sigma_{abs}(E_\gamma)$

Hadron Production with a Real Photon Beam

$\mathbf{Q^2 = 0}$ No Spatial Resolution

Absorption Cross Section of Real Photon with spin 1/2or 3/2 state

Deep Inelastic Scattering

Elastic Scattering ⟺ Inelastic Scattering

Absorption of a Virtual Photon — Absorption of a Virtual Photon

Scattering Angle — Scattering Angle

Energy after Scattering

⟹ x, Q^2

Deep Inelastic Scattering > Resonance Region

x, Q^2, W

Structure Functions

Factorization

-- Factorization of hard process and soft (long range) process

It is not a theorem. It has to be proven in each process.

$$F_1(x, Q^2), \quad F_2(x, Q^2),$$

What is the physical meaning of Q^2?

Not spatial resolution

What is the physical picture of Bjorken x?

Bjorken scaling

Bjorken X is Lorentz Invariant Quantity $$x = \frac{Q^2}{2P \bullet q}$$

$$\mathbf{x} = \frac{Q^2}{2M\nu}$$ Fixed target experiment, in Lab frame

Bjorken X is the momentum fraction of the parton in Breit frame

$$E_{\gamma^*} = 0$$

The momentum fraction stays the same in different frames only if the partons are massless.

Helicity Structure Functions

$$g_1(x, Q^2), \qquad g_2(x, Q^2),$$

Absorption of a Virtual Photon

Cross Section Difference between spin 1/2 and 3/2 States

Can your experiment determine Bjorken x event by event?

In case of HERMES, Yes in most cases.
No in some specific cases.

Why is the event-by-event Bjorken x determination important ?

1st moment is important

$$\int_0^1 F_1(x,Q^2)$$

nth moment

$$\int_0^1 x^{n-1} F_1(x,Q^2)$$

Violation of Gottfried Sum Rule: NMC

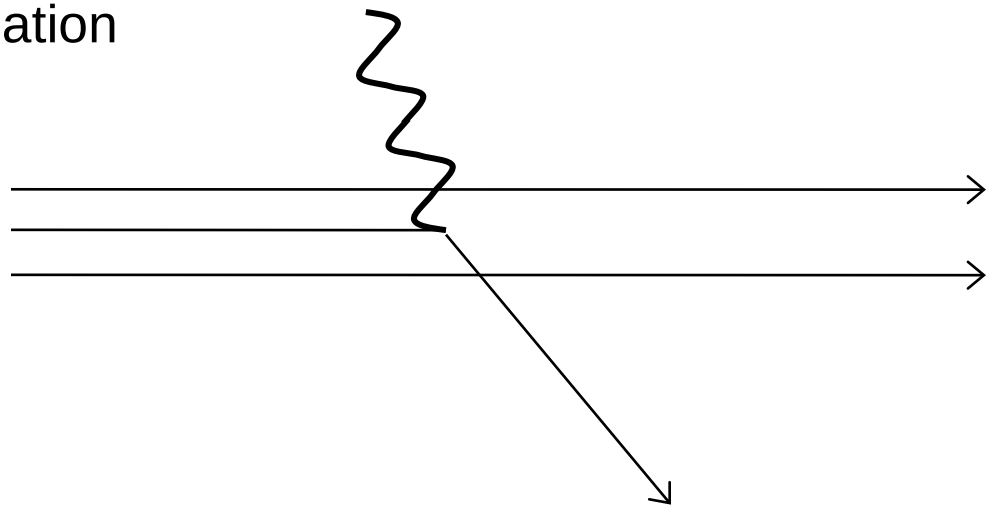
$$\int_0^1 g_1(x,Q^2)$$

Analysis of Quark Spin Contribution to the Nucleon Spin

3. Partons

Impulse approximation

Incoherent sum



Partons are quarks and gluons

Parton distribution functions $\mathbf{q(x,Q^2)}$, $\mathbf{g(x,Q^2)}$

Asymptotic Freedom

Running Coupling Constant α_s

$$\alpha_s \to 0 \quad \text{as} \quad Q^2 \to \infty$$

Perturbative QCD

QCD Evolution -- DGLAP Evolution Equation

What is the applicable Q^2 Region?
In particular, at low Q^2

Color Confinement of Quarks

4. Mass of Quarks

Massless Quarks requirement from Gauge symmetry

Interaction with Higgs field

u, d Quarks --- several MeV, current mass, PDG

However, the nucleon mass is about 940 MeV.

The constituent quark mass is about 300 MeV.

98% of quark mass is due to **the strong interaction**.

Why does it appear in the scattering?

Partons are massless. They are on the light cone

5. Transverse Structure of the Nucleon

Measure azimuthal angle ϕ , not only the scattering angle θ

Hadron measurement in coincidence

$h_1(x, Q^2)$ Transversity Structure Function

Quark Spin in transversely polarized nucleon

Sivers Function

Orbital motion of quarks in transversely polarized nucleon

Boer-Mulders Function

Orbital motion and spin of quarks in unpolarized nucleon

HERMES, among others, answered some of These Questions

Quark Spin Contribution to the Nucleon Spin (2007)

Phys. Rev. D 75 (2007) 012007 33 ± 4 %

Collins Asymmetry (2005) Phys. Rev. Lett. 94 (2005) 012002

Sivers Asymmetry (2009) Phys. Rev. Lett. 94 (2005) 012002,
Phys. Rev. Lett. 103 (2009)152002

Deeply Virtual Compton Scattering (2001)
and Exclusive Hadron Productions

Phys. Rev. Lett. 87 (2001) 182001

Boer-Mulders Function (2013)

Phys. Rev. D 87 (2013) 012010

6. Summary

-- Perturbative QCD, Factorization and Structure Functions are rigid framework for the study of nucleon structure.

-- Parton picture is powerful for the study of the longitudinal structure of the nucleon.

-- Transverse spin and transverse motion are also key elements for the structure of the nucleon.

-- Some questions on the transverse structure of the nucleon have been answered while many are waiting to be resolved.