“An investigation of the spin structure of the proton in deep inelastic scattering of polarised muons on polarised protons”

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Nuclear Physics B328 (1989) 1-35

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1. Introduction

The proton is not elementary particle. It has internal structure. It basically consists of 3 quarks.

- spin of the proton $1/2$
- spin of the quark $1/2$

How is the spin structure of proton?

If two quarks have spin in up direction, and a quark has in down direction, the total spin is $1/2$.

It is important to check whether this picture is correct.
2. Polarized deep inelastic scattering

The muon scatters off a quark exchanging the virtual photon. When the muon is polarized, the virtual photon is also polarized.

muon spin : $\frac{1}{2}$
spin of the virtual photon : 1

The quark can absorb the virtual photon if the quark spin flips. So the quark spin must be antiparallel to the spin of the virtual photon.

Asymmetry is defined as follows:

$$A = \frac{d\sigma_{\uparrow\downarrow} - d\sigma_{\uparrow\uparrow}}{d\sigma_{\uparrow\downarrow} + d\sigma_{\uparrow\uparrow}}$$
Bjorken $x$

$$x = \frac{Q^2}{2 \, M \nu} \quad (0 < x < 1)$$

$x$ has no dimension.

$x$ means the ratio of quark momentum to proton momentum.

$$A = \frac{D \, g_1}{F_1} \quad \rightarrow \quad g_1 = \frac{A \, F_1}{D} \quad \rightarrow \quad \int_0^1 g_1^p \, dx$$

$D$ : depolarization factor

$F_1$ : spin independent structure function

$g_1$ : spin dependence of distribution of quark momentum in proton

in quark-parton model

\[
\int_0^1 g_1^p \, dx = \frac{1}{2} \left( \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right) = \frac{1}{12} \left[ (\Delta u - \Delta d) + \frac{1}{3} (\Delta u + \Delta d - 2 \Delta s) + \frac{4}{3} (\Delta u + \Delta d + \Delta s) \right]
\]

\[
a_3 = 1.254 \pm 0.006 \quad a_8 = 0.397 \pm 0.020
\]

This value can be extracted.

\[
\langle S_z \rangle_{\text{quarks}} = \frac{1}{2} (\Delta u + \Delta d + \Delta s) = \frac{1}{2} \sqrt{\frac{3}{2}} \, a_0
\]
3. EMC experiment

The experiment was carried out at CERN, Geneva.

- **Muon beam**: polarized positive muons
- **Muons**
  - **Energy**: 100, 120, 200 GeV

- **Proton beam**: 450 GeV
- **Pion beam**: 110, 130, 210 GeV

- **Muon beam polarization**: typically 0.79±0.06
EMC experiment

target:
two cells
(parallel, antiparallel)
free protons in the NH$_3$
polarization ~77%
magnetic spectrometer
lead glass
iron absorber
muon detector

mu

momentum analyzed scattered muon forward hadrons
measure $\gamma$
absorb $\gamma$, hadrons

0 5m
4. Result

The horizontal axis is Bjorken scale in logarithmic scale. The dashed curve is the value based on a quark-parton model.

\[
x = 0.1 \sim 0.7 : \text{SLAC (1970's)}
\]

\[
x = 0.01 \sim 0.7 : \text{EMC (1989)}
\]

\[
x \text{ coverage was extended.}
\]
Quark spin contribution to the proton spin is only $(12\pm9\pm14)\%$. 

$$\int_0^1 g_1^p\,dx = 0.126 \pm 0.010 \pm 0.015$$

The horizontal axis is Bjorken scale in logarithmic scale.

$$\langle S_z \rangle_{\text{quarks}} = \frac{1}{2} \sqrt{\frac{3}{2}} a_0$$

$$= +0.060 \pm 0.047 \pm 0.069$$
5. Summary

- The proton basically consists of 3 quarks.
- It is important to study the contribution of the quark spin to the proton spin.
- Polarized deep inelastic scattering was carried out by EMC.
  - beam: polarized (~80%) positive muon 100, 120, 200GeV
  - target: polarized (~77%) proton
- The contribution of the quark spin to the proton spin was found to be small: $(12 \pm 9 \pm 14)\%$

There must be something else which contribute to the proton spin; gluon spin, orbital angular momentum of quarks and gluons, · · · ·.
Related experiments are being carried out at COMPASS-CERN, SLAC, HERMES-DESY, Belle-KEKB, RHIC-spin-BNL, J-lab etc.