EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PPE/92-45

March 13th, 1992

Deep Inelastic Scattering of Polarized Muons

Rüdiger Voss

CERN, Geneva, Switzerland

Abstract

An introduction is given to the physics of deep inelastic scattering with polarized muon beams on polarized nuclear targets. Earlier results on this subject are reviewed and an outlook is given on current and future experiments in this field.

Invited Talk at the Workshop on "The Future of Muon Physics"
Universität Heidelberg, 7-10 May 1991

Deep inelastic scattering of polarized muons

Rüdiger Voss

CERN, PPE Division, CH-1211 Geneva 23, Switzerland

Abstract. An introduction is given to the physics of deep inelastic scattering with polarized muon beams on polarized nuclear targets. Earlier results on this subject are reviewed and an outlook is given on current and future experiments in this field.

1 Introduction

The physics of deep inelastic scattering with polarized high energy electron and muon beams is presently experiencing a Renaissance, following the seminal results obtained by the European Muon Collaboration (EMC) at CERN on the spin structure function of the proton. The EMC result has raised a number of questions about the understanding of the dynamics of the nucleon spin at the parton level which have not been answered so far and will require more experimental information to be resolved theoretically, including data on the spin structure of the neutron which is totally unknown today. This paper tries to give an introduction to the phenomenology and the experimental techniques of spin physics with high energy polarized muon beams, with emphasis on the SMC experiment currently underway at CERN.

This discussion is limited to the experimental study of spin-dependent structure functions. The equally rich topic of electroweak physics with polarized muon beams is not touched upon here [1]. The subject of unpolarized deep inelastic muon scattering has been reviewed at this conference by D. Geesaman [2].

2 Polarized high energy muon beams

Two high energy muon beams are presently in operation at the CERN SPS and at the Fermilab Tevatron. Muons are produced by the decay of high energy pions and kaons in flight and the designs of both beams follow similar principles. So far, only the SPS muon beam [3,4] has been used in the past – and will be used in the

future – for experiments which exploit the polarization properties of such beams.

2.1 Layout of the CERN SPS muon beam

A schematic layout of this beam is shown in Fig. 1. A beam of secondary hadrons – mostly pions and kaons – is produced by the 450 GeV proton beam extracted from the SPS and impinging on a primary production target. Downstream of this target, the beam can be subdivided into four functional sections:

1. *Momentum selection of parent hadrons.* A series of 6 quadrupoles collects charged kaons and pions and focuses them onto a vertical bending magnet which selects the central value of the parent hadron momentum in a momentum band $\Delta p/p$ up to 10%. Five more quadrupoles provide for an optimal matching to the second section of the beam.

2. *The decay channel.* This channel is designed to transport both the hadron beam over its entire phase space, and the decay muons over the entire kinematically allowed momentum band ($p_\pi \gtrsim p_\mu \gtrsim 0.57p_\pi$). This design allows to freely choose the μ/π momentum ratio and thus the polarization of the beam (see below). It is achieved with a regular lattice of alternately focussing and defocussing quadrupoles (FODO array) of 60° phase advance per cell, a structure more commonly found in storage rings. With a decay length of about 500 m, 10% of the parent hadrons decay into muons at 100 GeV beam energy.

3. *The hadron absorber.* The muon beam is focused by a set of quadrupoles onto a beryllium absorber of 9.9 m maximum length to remove the remaining hadrons. This absorber is subdivided into 9 elements which can be moved individually into the beam to obtain the desired compromise between multiple scattering and hadron contamination. The effect of multiple scattering on the beam size is minimized by locating the absorber in a

Fig. 1. Layout of the CERN SPS muon beam M2. F and D indicate focussing and defocussing quadrupoles, respectively; EPB is the extracted proton beam, and the CMH (CMV) are horizontal (vertical) magnetic collimators (scrapers). Note that the horizontal and vertical scales are strongly different.

focus of the beam. With all absorber elements in place, the π contamination is less than 10^{-6} .

4. *The muon transport system.* The absorber elements are installed inside the gap of a vertical bending magnet which selects the final μ momentum band of about $\pm 3\%$. The muon beam is transported from the underground absorber section to the experimental area by a FODO structure similar to the decay section. This section provides the necessary drift space to clean the beam from halo muons which originate mainly from π decays not captured in the acceptance of the decay channel. This halo is eliminated with a system of 2 horizontal and 5 vertical magnetic collimators (scrapers). A last vertical bending magnet serves to deflect the beam back into the horizontal direction before it is focussed onto the experiment. This magnet is instrumented with a system of fast scintillator hodoscopes and serves as a spectrometer magnet to measure the momentum of individual muons triggering the experiment.

The SPS muon beam is capable of producing intensities of several $10^8 \mu$ per accelerator pulse of about 2 sec length, with a repetition rate of 14.4 sec. In practice, the beam intensity is limited by the proton intensity

available at the primary production target and by the rate capabilities of the experiments. Recent experiments have operated at typical intensities of a few $10^7 \mu$ /pulse.

The beam was first commissioned in 1978 and operated until 1989 without significant modifications, mostly at beam energies between 100 and 280 GeV. The muon transport system has recently been modified to make the beam dispersion-free in the experimental area. This beam is better adapted to the needs of the NA47 experiment discussed below, allowing for small beam spot sizes of about 2 cm FWHM at all critical locations in the experiment. The price to pay for this improvement was a reduction of the maximum muon energy to 225 GeV/c.

2.2 Kinematics of beam polarization

High energy muon beams originating from $\pi(K)$ decays are naturally polarized due to parity violation. In the decay $\pi(K) \rightarrow \mu\nu_\mu$, the muon and the neutrino are fully polarized in the center-of-mass system, giving positive (negative) helicity to the positive (negative) muon. Lorentz boosting changes the longitudinal polarization

of the massive muons which in the laboratory system depends on the ratio of muon to hadron energy. If both hadron and muon beams were monochromatic, the longitudinal polarization of the muons would be given by [5,6]

$$P_L = \pm \frac{u - (m_\mu/m_{\pi,K})^2(1-u)}{u + (m_\mu/m_{\pi,K})^2(1-u)} \quad (1)$$

where the + (−) sign refers to negative (positive) muons, and where

$$u = \frac{E_\mu/E_{\pi,K} - (m_\mu/m_{\pi,K})^2}{1 - (m_\mu/m_{\pi,K})^2} = \cos^2 \frac{\theta^*}{2}, \quad (2)$$

where θ^* is the angle between muon and pion direction in the center-of-mass system.

In practice, hadron and muons are not monochromatic but the selection of both π and μ beams of limited phase space preserves a resulting net polarization of the muons arriving at the experimental target.

2.3 Beam polarization from Monte Carlo simulations

Monte Carlo programs exist [7] which simulate the phase space of parent hadrons and decay muons and model in detail their propagation through the beam transport system. These programs can be used to calculate the beam polarization in a straightforward way and the most reliable figures on the polarization of the CERN muon beam which are presently available come from Monte Carlo simulations. In practice, the accuracy of such calculations is limited to a few percent by effects which are poorly known and are difficult to simulate exactly, such as the exact shape of the secondary hadron spectrum, the kaon background to the pion spectrum, radiative energy losses of muons in the hadron absorber, and possible depolarizing effects in the beam optics. A reliable determination of the beam polarization to better than $\approx 5\%$ therefore calls for a good experimental measurement.

2.4 Polarization measurements from μ - e decay in flight

The standard technique to measure the polarization of a high energy muon beam also exploits parity violation and makes use of the fact that in the decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ the positron is preferentially emitted in the muon spin direction in the center-of-mass system, and in the opposite direction in the case of μ^- decay. The Lorentz boost will therefore yield a positron spectrum in the laboratory system which depends on the polarization of the muon beam [8,9],

$$\frac{dN}{dv} = N_0 \left[\frac{5}{3} - 3v^2 + \frac{4}{3}v^3 - P_L \left(\frac{1}{3} - 3v^2 + \frac{8}{3}v^3 \right) \right] \quad (3)$$

where $v = E_e/E_\mu$, $N_0 = 1.6 \cdot 10^{-4} l(m)/E(\text{GeV})$, and where l is the length of the decay space available to the muons (Fig. 2). The polarization is best measured

Fig. 2. Energy spectrum of positrons from muon decay, for longitudinal muon polarizations $P_L = -1, 0, +1$.

around $v = 0.75$ where the electron energies are high and the spectrum is most sensitive to the polarization.

Polarization measurements based on this technique are experimentally demanding. They require a two-stage spectrometer to measure both the muon and the electron energy; the muon spectrometer has to operate at high rates to compensate for the small decay rate, and the electron spectrometer usually has to withstand a strong background of electrons and positrons from other sources, mostly from radiative energy losses of muons. In an earlier measurement in the SPS beam, a leadglass calorimeter to measure the positron energy was placed close to the beam right downstream of the last vertical bending magnet which serves as spectrometer magnet to measure the muon momentum (see above) [10]. Within errors of $\approx 10\%$, these measurements were in agreement with the Monte Carlo simulations (Fig. 3).

An improved implementation of such a decay polarimeter has been designed for the SMC experiment which is described in Sect. 5.1 below.

2.5 Polarization measurements by Møller scattering

Measuring the cross section asymmetry of elastic scattering off polarized electrons is the standard technique to measure the polarization of high energy electron beams, where the polarized electron target is usually realized by a thin magnetized iron foil [11]. In order to apply the same technique to a muon beam, one has to use much thicker targets to compensate for the much lower beam intensity, and the dilution of the cross section asymmetry by background from radiative energy losses has to be carefully controlled. A practical implementation of this

Fig. 3. Polarization vs. muon energy for different combinations of pion/muon energy in the SPS muon beam. Circles show results of a Monte Carlo calculation and rhombs show the measurements of ref. [10]. The kinematic relation of eq. (1) is also shown for pions (dashed line) and kaons (solid line).

technique has been proposed in ref. [12] and will be tried in the SMC polarimeter from 1992 onwards.

3 Polarized lepton-nucleon scattering

A detailed account of the cross sections relevant for deep inelastic scattering of polarized leptons can be found in refs. [1, 13-15]. The following brief review is limited to the phenomenology of the scattering of longitudinally polarized electrons and muons. The scattering of transversely polarized beams is not discussed here.

3.1 The deep inelastic cross section

In the laboratory system, the scattering process is conveniently visualized in the two kinematic planes depicted in Fig. 4. The scattering plane is defined, as in the unpolarized case, by the momentum 3-vectors $\vec{k}$ and $\vec{k}'$ of the incoming and scattered lepton, respectively; θ is the scattering angle. The polarization plane is defined

Fig. 4. Kinematic planes of scattering of longitudinally polarized leptons.

by $\vec{k}$ and by the polarization vector $\vec{P}$ of the nucleon. The angle between $\vec{k}$ and $\vec{P}$ is often referred to as β ($0 \leq \beta \leq \pi$) and ϕ is the angle between the scattering and the polarization planes. The kinematics of inclusive scattering are completely described by two independent variables. One often uses the squared four-momentum transfer Q^2 and the energy transfer ν . Both are Lorentz invariants and are given in the laboratory system and in the high energy limit by

$$Q^2 = 4EE' \sin^2 \theta/2, \quad (4)$$

$$\nu = E - E', \quad (5)$$

where E and E' are the energies of the incident and the scattered muon in this system, respectively. Alternatively, the scaling variables x (Bjorken variable) and y may be used:

$$x = Q^2/2M\nu, \quad (6)$$

$$y = \nu/E, \quad (7)$$

where M is the nucleon mass.

The differential deep inelastic cross section for the process shown in Fig. 4 can be decomposed into an unpolarized piece σ_0 and a polarized piece $\Delta\sigma$,

$$\frac{d^3\sigma(\beta)}{dx dy d\phi} = \frac{d^3\sigma_0}{dx dy d\phi} - \frac{d^3\Delta\sigma(\beta)}{dx dy d\phi}, \quad (8)$$

where the unpolarized part has been discussed in ref. [2]. In the Born approximation, it is given by

$$\frac{d^3\sigma_0}{dx dy d\phi} = \frac{2\alpha^2}{Q^2 xy} \left[xy^2 F_1(x, Q^2) + \left(1 - y - \frac{Mxy}{2E}\right) F_2(x, Q^2) \right], \quad (9)$$

where F_1 and F_2 are the *structure functions* of the unpolarized nucleon. In the same approximation, the polarized piece is given by

$$\begin{aligned} \frac{d^3 \Delta\sigma(\beta)}{dx dy d\phi} = & \frac{2\alpha^2}{MExy} \left\{ \cos\beta \left[\left(1 - \frac{y}{2} - \frac{Mxy}{2E}\right) g_1(x, Q^2) - \right. \right. \\ & \left. \frac{Mx}{2E} g_2(x, Q^2) \right] - \\ & \left. \cos\phi \sin\beta \frac{\sqrt{Q^2}}{\nu} \left(1 - y - \frac{Mxy}{2E}\right)^{\frac{1}{2}} \right. \\ & \left. \left[\frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right] \right\}, \quad (10) \end{aligned}$$

where g_1 and g_2 are the so-called *spin structure functions* of the nucleon. They play a central role in the understanding of the spin structure of nucleons.

An inspection of eq. (10) reveals immediately how these two structure functions can be disentangled experimentally from the measured differential cross section. For $\sin\beta = 0$, i.e. target polarization (anti)parallel to the beam direction, one mainly measures g_1 since g_2 is strongly suppressed at high energies by the factor $Mx/2E$. For $\cos\beta = 0$, i.e. transverse target polarization, g_1 and g_2 contribute to the measured cross section with approximately equal weight. So far, only the case of longitudinal target polarization has been studied experimentally and no data exist on g_2 .

3.2 Structure functions in the Quark-Parton Model

In the so-called naive Quark-Parton Model (QPM) [16], deep inelastic scattering is described as *elastic* scattering of leptons on quasifree pointlike partons (quarks) inside the nucleon. The deep inelastic cross section (8) can then be computed as incoherent sum over the elastic cross section of these partons, provided a prescription is given for their kinematical distribution inside the target. This prescription is provided by the structure functions.

Most structure functions take a simple intuitive meaning in the QPM. This is especially true for the well-known unpolarized structure functions F_1 and F_2 which appear in eq. (9) and which can be written as simple linear combinations of probability densities of quarks, $q(x, Q^2)$. In the so-called scaling limit of non-interacting quarks, these quark distributions depend on the Bjorken variable x only:

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i(x) + \bar{q}_i(x)] \quad (11)$$

$$F_2(x) = x \sum_i e_i^2 [q_i(x) + \bar{q}_i(x)] \quad (12)$$

where the index i refers to all quark flavours participating in the scattering process, the $\bar{q}$ distribution describes the antiquarks in the nucleon, and the e_i are the quark charges in units of the elementary charge. The Bjorken variable also finds a simple, intuitive interpretation in the QPM: in the limit of very high energies, it is the

fraction of the total nucleon momentum p carried by the individual quark i on which the lepton is scattered, i.e. $x = p_i/p$.

From equations (11) and (12) one finds immediately the Callan-Gross relation

$$F_2(x) = 2xF_1(x). \quad (13)$$

Again, this relation holds in the high energy limit only and is violated at finite energies. This violation is characterized by the quantity

$$R(x, Q^2) = \frac{\left(1 + \frac{2Mx}{Ey}\right) F_2(x, Q^2) - 2xF_1(x, Q^2)}{2xF_1(x, Q^2)} \quad (14)$$

which can also be interpreted as the ratio of cross sections for longitudinally and transversely polarized virtual photons,

$$R = \frac{\sigma_L}{\sigma_T}. \quad (15)$$

The spin structure function g_1 also has a straightforward interpretation in the QPM:

$$g_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i^+(x) - q_i^-(x)], \quad (16)$$

where $q_i^+(x)$ ($q_i^-(x)$) is the density of quarks with helicity parallel (antiparallel) to the nucleon spin. This interpretation of $g_1(x)$ can be understood from the fact that a virtual photon with spin projection $+1$ can only be absorbed by a quark with spin projection $-1/2$, and vice versa.

The interpretation of the "transverse" spin structure function g_2 in the QPM is much less obvious and is presently the subject of much theoretical debate [17]. Wandzura and Wilczek [18] have shown that in Quantum Chromodynamics (QCD) it can be decomposed as

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2), \quad (17)$$

where the "trivial" piece g_2^{WW} is a "leading twist" (twist-2) contribution in the jargon of QCD, and is completely determined by $g_1(x, Q^2)$:

$$g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{dy}{y} g_1(y, Q^2). \quad (18)$$

The term $\bar{g}_2(x, Q^2)$ is a twist-3 contribution which seems to be best understood in an Operator Product Expansion (OPE) analysis in QCD, where it is sensitive to a quark-gluon correlation function in the nucleon and thus contains unique new physics. In Regge theory, g_2 is shown to fulfill, under certain conditions, the Burkhardt-Cottingham sum rule [19,17]

$$\int_0^1 dx g_2(x, Q^2) = 0. \quad (19)$$

3.3 Sum rules for spin structure functions

Just as for unpolarized structure functions, no theoretical predictions exist yet for the x dependence of their spin dependent counterparts, although such predictions are expected to emerge ultimately from non-perturbative QCD. Predictions do exist, however, in the form of sum rules related to polarized structure functions. The most general of these, and one of the most fundamental predictions of the QPM indeed, is the celebrated Bjorken sum rule [20]

$$\int_0^1 [g_1^p(x) - g_1^n(x)] dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right|, \quad (20)$$

where p and n denote the proton and the neutron, respectively, and where g_A and g_V are the axial and vector weak coupling constants of nuclear beta decay. In this form, the sum rule was derived by Bjorken from light cone algebra and from very general assumptions on the partonic structure of the weak and electromagnetic hadronic currents. Nowadays, the sum rule (20) can be rigorously derived in QCD in the limit $Q^2 \rightarrow \infty$. At finite values of Q^2 [21],

$$\int_0^1 [g_1^p(x, Q^2) - g_1^n(x, Q^2)] dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_s(Q^2)}{\pi} \right], \quad (21)$$

where α_s is the strong coupling constant.

Separate sum rules for the proton and the neutron were derived by Ellis and Jaffe for the proton and the neutron [22]. Ignoring QCD radiative corrections, they read

$$\int_0^1 g_1^p(x) dx = \frac{1}{12} \left| \frac{g_A}{g_V} \right| \left[+1 + \frac{5}{3} \frac{3F/D-1}{F/D+1} \right] \quad (22)$$

and

$$\int_0^1 g_1^n(x) dx = \frac{1}{12} \left| \frac{g_A}{g_V} \right| \left[-1 + \frac{5}{3} \frac{3F/D-1}{F/D+1} \right], \quad (23)$$

where F (D) are the antisymmetric (symmetric) weak $SU(3)$ couplings measurable in hyperon decays. These predictions are less fundamental than the Bjorken sum rule since they assume exact flavour $SU(3)$ symmetry of the baryon octet decays, and zero net polarization of the sea of strange quarks and heavier flavours.

No experimental data exist on g_1^n and the only sum rule which is tested experimentally until now is the Ellis-Jaffe prediction (22) for the proton. These data will be discussed in Sect. 4. below.

3.4 Cross section asymmetries

Since the polarized piece (10) gives, in general, only a small contribution to the cross section, it is customary to evaluate it from measurements of cross section asymmetries in which the unpolarized part (9) cancels. In the most simple case where both the beam and the target are longitudinally polarized (i.e. $\sin \beta = 0$), this asymmetry is

$$A = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \quad (24)$$

where $\sigma^{\uparrow\downarrow}$ and $\sigma^{\uparrow\uparrow}$ are the cross sections for opposite and equal spin directions, respectively. From equations (10)–(16), neglecting terms of order M/E , one finds

$$A = D[A_1 + \eta A_2], \quad (25)$$

where

$$A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\sum_i e_i^2 [q_i^+(x) - q_i^-(x)]}{\sum_i e_i^2 [q_i^+(x) + q_i^-(x)]}, \quad (26)$$

$$A_2(x) = \sqrt{\frac{2Mx}{Ey}} \frac{g_1(x) + g_2(x)}{F_1(x)}. \quad (27)$$

D is sometimes called the depolarization factor of the virtual photon and is given by

$$D = \frac{2y - y^2}{2(1-y)(1+R) + y^2}; \quad (28)$$

the factor η depends only on kinematic variables:

$$\eta = \frac{\sqrt{Q^2}}{E} \frac{2(1-y)}{y(2-y)}. \quad (29)$$

A_1 and A_2 can also be interpreted as virtual photon-nucleon asymmetries

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}, \quad (30)$$

$$A_2 = \frac{2\sigma_{TL}}{\sigma_{1/2} + \sigma_{3/2}}, \quad (31)$$

where $1/2$ and $3/2$ are the total spin projections in the direction of the virtual photon, and σ_{TL} is a cross section arising from the interference of amplitudes for longitudinal and transverse polarized virtual photons. The following bounds can be derived for A_1 and A_2 [23]:

$$|A_1| \leq 1, \quad |A_2| \leq R; \quad (32)$$

for this reason, A_2 is expected to give a small contribution to A and is usually ignored.

Finally, the experimentally measured counting rate asymmetry is related to the cross section asymmetry (24) by

$$A_{exp} = f_t P_t P_\mu A, \quad (33)$$

Fig. 5. The spin structure function $g_1^p(x)$ measured by the EMC Collaboration ("This experiment") and the SLAC-Yale Collaboration. The dashed curve is a phenomenological parametrisation.

where P_μ is the beam polarization, P_t the polarization of the target nucleons, and f_t the target dilution factor, i.e. the fraction of polarized nucleons in the target material.

4 The proton spin crisis

The most recent data on spin structure functions were presented in 1987 by the European Muon Collaboration (EMC) at CERN [24,25]. The EMC measurement of $g_1^p(x)$ was found to be in good agreement with earlier data from the SLAC-Yale collaboration [26-28] but covers a significantly larger kinematic range in the x variable (Fig. 5). These data therefore allowed the first significant test of the Ellis-Jaffe sum rule which is shown in Fig. 6.

Using the parametrisation of Fig. 5 to extrapolate the measured integral to $x = 0$, the result from the combined EMC and SLAC data is

$$\int_0^1 g_1^p(x) dx = 0.126 \pm 0.010 (\text{stat.}) \pm 0.015 (\text{syst.}).$$

The Ellis-Jaffe prediction, using the most recent data on F/D [29], is

$$\int_0^1 g_1^p(x) dx = 0.189 \pm 0.005,$$

i.e. there is a 3.5 standard deviation discrepancy between the Ellis-Jaffe prediction and the experimental data.

The quark contribution to the total spin of the proton is given by

$$\frac{1}{2} \Delta \Sigma = \frac{1}{2} (\Delta u + \Delta d + \Delta s) \quad (34)$$

Fig. 6. The integral $\int_{x_m}^1 g_1^p(x) dx$ as a function of the lower integration limit x_m . The prediction of the Ellis-Jaffe sum rule is also shown.

where heavier flavours have been neglected and where

$$\Delta q = \int_0^1 [q^+(x) + \bar{q}^+(x) + q^-(x) + \bar{q}^-(x)] \quad (35)$$

is, apart from a factor $1/2$, the contribution to the nucleon spin from an individual quark flavour. Using a generalization of the Ellis-Jaffe sum rule by Glück and Reya which includes QCD radiative corrections [30], assuming isospin invariance and the same experimental data on the $SU(3)$ couplings F and D , it can be shown that [25]

$$\frac{1}{2} \Delta \Sigma = 0.060 \pm 0.047 (\text{stat.}) \pm 0.069 (\text{syst.}),$$

i.e. the quark contribution to the total proton spin is compatible with zero within the experimental errors. The proton spin fulfills the sum rule

$$S_p = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \frac{1}{2} \Delta g + \langle L_z \rangle, \quad (36)$$

where Δg is the gluon equivalent of $\Delta \Sigma$ and $\langle L_z \rangle$ is the mean z component of the orbital angular momentum of the partons. Most of the proton spin must therefore be carried by gluons and/or parton orbital momentum. This surprising result has triggered intense theoretical efforts to explain the spin composition of the proton. The recent literature on this subject is too vast to be reviewed here [31].

5 New experiments on spin dependent structure functions

Following the unexpected result of the EMC experiment, several new experiments to study spin dependent structure functions have also been proposed, most of which share the following main goals:

Fig. 7. Schematic layout of the SMC spectrometer. The muon beam arrives from the left and impinges on a twin solid state target. Downstream of the target, one distinguishes the momentum measurement stage with the Forward Spectrometer Magnet (FSM), and the muon identification system downstream of the hadron absorber (ABS). The detectors to the left of the target are beam defining counters to measure the track of the incident muon, and veto counters to shield the experiment from halo muons.

1. New measurements of $g_1^p(x)$ for an improved test of the Ellis-Jaffe sum rule for the proton,
2. measurement of the neutron distribution $g_1^n(x)$ and test of the corresponding Ellis-Jaffe sum rule,
3. test of the Bjorken sum rule,
4. measurement of the "transverse" spin structure function $g_2(x)$.

The study of other related physical questions has also been proposed by several of these next generation experiments [32].

The direct successor of the EMC is the SMC experiment which has recently started to take data at CERN and uses the muon beam described above in Section 2.1. All other experiments which are presently proposed or in preparation use polarized electron beams.

5.1 The SMC experiment

The SMC (Spin Muon Collaboration) experiment [33] uses an upgraded configuration of the apparatus built for the earlier EMC experiments [24,25,34].

In this experiment polarized high-energy muons are scattered off two solid targets polarized in opposite directions. The target materials are deuterated and normal hydrocarbon glasses, doped with a small amount of paramagnetic metallo-organic substance EHBA-Cr(V) or its deuterated version. The glass matrix consists mainly of 1-butanol C_4H_9OH (95%) and water (5%), or their deuterated forms. The dilution factors for free hydrogen (deuterium) nuclei in these materials are $f_p = 0.13$ and $f_d = 0.23$.

The Dynamic Nuclear Polarization (DNP) [35] technique is used to obtain high nuclear polarizations in the targets. In this technique the paramagnetic electron spin system in the material is saturated slightly off-resonance (70 GHz); this produces dynamic cooling of the spin-spin interactions among the electrons by a factor around $\pm 1/400$. The nuclear spins are cooled to a temperature very close to that of the electron spin-spin interactions,

because no other thermal contact to the nuclear spin system is provided in the material. If the material is cooled to 500 mK by a $^3\text{He} - ^4\text{He}$ dilution refrigerator, nuclear spin temperatures around ± 2 mK can be obtained.

The target material is arranged inside a superconducting solenoid, with a 2.5 Tesla field of high homogeneity, in two cells so that each cell can be irradiated with microwave power from an independent source. The microwave frequencies are adjusted just below and just above the electron spin resonance line so that maximum positive and negative polarizations are obtained in the two target cells. In the present materials the proton polarizations of $\pm 85\%$ and deuteron polarizations of about $\pm 30\%$ have been obtained in the large target cells containing each about 500 g of solid target material.

The target is cooled with a powerful dilution refrigerator [36] so that the microwave losses of about 2 W in the material can be cooled at a helium temperature of 0.5 K. When the microwave power is turned off, the refrigerator cools the material to about 50 mK temperature, where the nuclear spin lattice relaxation becomes extremely slow, thus enabling the "freezing" of the target polarization. The polarization of such a frozen-spin target is insensitive to the magnetic field inhomogeneity, and reasonably slow relaxation is measured down to 0.5 Tesla field value. In this mode the target polarizations can be reversed by the rotation of the magnetic field, which is accomplished by exciting a dipole magnet superimposed on the solenoid, while ramping the solenoid current through zero value.

The target polarization is measured with $\pm 3\%$ relative accuracy by continuous wave NMR techniques using a series-resonant circuit and a Q-meter with real-part detector. The polarization can also be monitored continuously during frozen-spin operation in 0.5 T field.

During a first phase (1991/92), the SMC uses an improved version of the target set-up used which was originally built for the EMC experiment [37]. From 1993 onwards, a new target configuration will be used with longer target cells (60 cm instead of 36 cm each) in a bigger cryostat, a new solenoid with improved field homogeneity for higher polarization, and a more powerful refrigerator. In this configuration, a transverse dipole field can be superimposed to the solenoid field which is employed for fast polarization reversal by field rotation in frozen spin mode, or for transverse target polarization to measure g_2 . It is expected that a proton polarization above 80% and deuteron polarizations of up to 40% will be achieved with this target.

The muon spectrometer of the SMC experiment is an upgraded version of the well-known EMC apparatus (Fig. 7). A high precision measurement of the scattering angle and of the momentum of charged particles is provided by a large aperture dipole magnet ($\int B dl = 2.3 \text{ Tm}$) instrumented with multiwire proportional chambers and drift chambers. The momentum measurement stage is followed by a muon identification stage which consists of an iron absorber to remove the hadrons produced in the deep inelastic interaction, an array of large-surface streamer tubes and drift tubes to

measure the muon tracks behind the absorber, and two arrays of scintillator hodoscopes which provide the muon trigger of the experiment.

The muon spectrometer is followed by a beam polarimeter [33] which has been newly designed for the SMC experiment, following the principles outlined in Sect. 2.4 and 2.5 above. The muon energy is measured in the upstream magnetic spectrometer which is part of the beam transport system and was mentioned above in Sect. 2.1. The polarimeter provides a 30 m long decay space for the muons, the beginning of which is defined by an electromagnetic shower counter to suppress background from electromagnetic interactions in material exposed to the upstream beam. Decay electrons are identified and momentum analyzed by a simultaneous measurement of their momentum and energy in a magnetic spectrometer and in a lead-glass calorimeter. A magnetized iron target for polarization measurement with the Møller scattering method is presently under construction.

The SMC experiment will test the sum rules (21)–(23) to an accuracy of 10–20% which will be dominated by systematic errors. The main uncertainties are the measurement errors on the beam and target polarization and the uncertainty in the extrapolation of $g_1(x)$ to $x = 0$.

5.2 Electron beam experiments

Four experiments are presently under construction, or have been proposed, to study spin structure functions in polarized electron beams.

1. The SLAC E-142 experiment [38] will use an external polarized electron beam of 23 GeV from a GaAs source ($P_e \approx 40\%$) and a high-pressure (10 atm) polarized ^3He target of about 50% polarization. For a measurement of spin asymmetries, ^3He is effectively an almost pure neutron target since the proton spins are oriented antiparallel. The scattered electrons are detected in two point-focussing spectrometers under 4.5° and 7.5° with respect to the beam axis. The experiment has been approved and is scheduled to take data in the fall of 1992.
2. The SLAC E-143 experiment [39] uses the same spectrometer as E-142, but proposes a more advanced technology for the GaAs source and solid NH_3 and ND_3 targets polarized with the DNP method. The experiment has also been approved and is scheduled to take data in 1993.
3. The HERMES collaboration [40] proposes to use the high intensity internal electron beam of the HERA electron-proton storage ring at DESY, at an energy of 35 GeV. The target proposed for the HERMES experiment is a windowless storage cell fed with polarized hydrogen, deuterium, or ^3He gas. Scattered electrons are detected in a compact, large solid angle forward spectrometer. The experiment relies on sufficient longitudinal polarization of the HERA electron beam which is expected from the Sokolov-Ternov effect [41]. Transverse polarization arises naturally in electron storage

rings from synchrotron radiation and can become large when the machine is designed to minimize depolarizing effects. Transverse beam polarization can be transformed into longitudinal polarization with spin rotators. Final approval and scheduling of the HERMES experiment is subject to the experimental observation of sufficient transverse polarization ($\approx 50\%$) of the HERA electron beam; a polarization of $P_e = (8 \pm 1)\%$ has recently been observed [42].

4. The HELP collaboration [43] proposes to use the polarized internal 45 GeV beam of the LEP electron-positron storage ring at CERN. The proposal foresees a polarized jet gas target and a spectrometer which is very similar to the HERMES apparatus. The expected luminosity is, however, smaller than the one of HERMES by about two orders of magnitude due to the lower intensity of the LEP beams and the lower thickness of the jet target. The experiment is subject to similar uncertainties on the beam polarization as HERMES, and its prospects are unclear at present since its beam requirements are potentially incompatible with the physics program of the four large LEP detectors.

A more detailed comparison of most of the experiments discussed here can be found in ref. [32].

6 Conclusion

The EMC results on the spin structure function of the proton have resuscitated a major interest in the experimental and theoretical study of the internal spin structure of hadrons. A new generation of experiments, exploiting a large variety of different techniques for spectrometers and beam and target polarization, has recently started to collect data. In about five years from now our understanding of spin structure functions, which is scarce and incomplete today, should have substantially improved.

Acknowledgement. I wish to thank K. Jungmann and G. zu Putlitz for organizing a very stimulating meeting, and for their patience in waiting for a very late manuscript. L. Gatignon, T.O. Niinikoski and A. Staude have critically read the manuscript and contributed numerous clarifications. L. Gatignon also has kindly contributed Fig. 1 to this paper.

References

1. See e.g. T. Sloan, G. Smadja and R. Voss, Phys. Rep. 162 (1988) 45.
2. D. Geesaman, these proceedings.
3. R. Clift and N. Doble, Proposed design of a high-energy, high intensity muon beam for the SPS North Experimental Area, CERN/SPSC/74-12 (CERN/Lab. II/EA/74-2).
4. L. Gatignon, M2 Handbook, CERN, March 1991 (unpublished).
5. L.M. Lederman and M.J. Tannenbaum, Advances in Particle Physics, Vol. I, New York 1968, p. 11.
6. F.-L. Navarria, Rivista Nuovo Cimento 6 (1983) 1.
7. Ch. Iselin, HALO, CERN 74-17 (1974) (CERN Yellow Report).
8. F. Combley and E. Picasso, Phys. Rep. C14 (1974) 20.
9. S.V. Golovkin et al., Nucl. Instr. Meth. 138 (1976) 235.
10. D. Bollini et al., Nuovo Cimento 63A (1981) 441.
11. P.S. Cooper et al., Phys. Rev. Lett. 34 (1975) 1589.
12. P. Schüller, Proc. 8th Int. Symp. on High Energy Spin Physics, Minneapolis 1988.
13. T. Kamae, Y. Shimizu and M. Igarashi, eds., Report of the TRISTAN ep (ee) Working Group, University of Tokyo preprint UTPN-165 (UT-345) (1980).
14. N.S. Craigie et al., Phys. Rep. 99 (1983) 69.
15. V.W. Hughes and J. Kuti, Ann. Rev. Nucl. Part. Sci. 33 (1983) 611.
16. For an excellent introduction into the Quark-Parton Model, see: F. Halzen and A.D. Martin, Quarks and Leptons. New York, Chichester, Brisbane, Toronto, Singapore: John Wiley & Sons, 1984.
17. R.L. Jaffe, Comments Nucl. Part. Phys. 19 (1990) 239.
18. S. Wandzura and F. Wilczek, Phys. Lett. 72B (1977) 195.
19. H. Burkhardt and W.N. Cottingham, Ann. Phys. (N.Y.) 56 (1970) 453.
20. J.D. Bjorken, Phys. Rev. 148 (1966) 1467; Phys. Rev. D1 (1970) 465; ibid. D1 (1970) 1376.
21. J. Kodaira et al., Phys. Rev. D20 (1979) 627.
22. J. Ellis and R.L. Jaffe, Phys. Rev. D9 (1974) 1444; D10 (1974) 1669.
23. M.G. Doncel and E. de Rafael, Nuovo Cimento 4A (1971) 363; P. Gnädig and F. Niedermayer, Nucl. Phys. B55 (1973) 612.
24. EMC, J. Ashman et al., Phys. Lett. 206B (1988) 364.
25. EMC, J. Ashman et al., Nucl. Phys. B328 (1989) 1.
26. SLAC-Yale E80 Collaboration, M.J. Alguard et al., Phys. Rev. Lett. 37 (1976) 1261; ibid. 41 (1978) 70.
27. SLAC-Yale E180 Collaboration, G. Baum et al., Phys. Rev. Lett. 51 (1983) 1135.
28. SLAC-Yale Collaboration, G. Baum et al., Phys. Rev. Lett. 45 (1980) 2000.
29. M. Bourquin et al., Z. Phys. C21 (1983) 27.
30. M. Glück und E. Reya, Z. Phys. C39 (1988) 569.
31. For recent reviews see e.g.: H. Rollnik, Proc. 9th Int. Symp. on High Energy Spin Physics, Bonn 1990, K.-H. Althoff and W. Meyer, eds., p. 183; E. Reya, Dortmund preprint DO-TH 91/09.
32. K. Rith, Proc. 9th Int. Symp. on High Energy Spin Physics, Bonn 1990, K.-H. Althoff and W. Meyer, eds., p. 198.
33. The Spin Muon Collaboration (SMC), Measurement of the spin-dependent structure functions of the neutron and proton, CERN/SPSC 88-47 (SPSC/P242), 1988.
34. EMC, O.C. Allkofer et al., Nucl. Instr. Meth. 179 (1981) 445.
35. M. Borghini, Phys. Rev. Lett. 20 (1968) 419.
36. T.O. Niinikoski, Nucl. Instr. and Meth. 192 (1982) 151.
37. S.C. Brown et al., in Proc. Proc. 4th Workshop on Polarized Target Materials and Techniques, Bonn 1984, ed. W. Meyer, (Physikalisches Institut, Universität Bonn, Bonn 1984) p. 102.
38. R. Arnold et al., A proposal to measure the neutron spin dependent structure function, SLAC Proposal E-142, 1989.
39. E143 Collaboration, R. Arnold et al., Measurements of the Nucleon Spin structure at SLAC in End Station A.
40. The HERMES Collaboration, A Proposal to Measure the Spin-Dependent Structure Functions of the Neutron and the Proton at HERA, DESY-PRC 90/01, 1990.
41. A.A. Sokolov and I.M. Ternov, Sov. Phys. Dokl. 8 (1964) 1203.
42. R. Brinkmann, Status Report on HERA at the 50th Plenary ECFA Meeting, CERN, Geneva, December 1991.
43. G. Ballochi et al., CERN/LEPC 89-10 (LEPC/M 88), 1989.

This article was processed using Springer-Verlag T_EX Z. Physik C macro package 1991 and the AMS fonts, developed by the American Mathematical Society.