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Development on Dynamic Nuclear Polarized Targets

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Abstract

Our interest in understanding the spin content of the nucleon has left its marks on the recent development of the dynamic nuclear polarized (DNP) targets. This can be seen from the targets developed at CERN and SLAC for the measurement of the polarized spin structure functions in deep inelastic scattering. The results of the experiments indicated that less than 30% of the nucleon spin is carried by the quarks. This unpredicted small value initiated planning of new polarized target experiments to determine the gluon polarization on the nucleon using polarized real photons and polarized ^{6}LiD targets. In several facilities very intense polarized photon beams are available at a wide energy range. During the next few years these photon beams with DNP targets will be used to test the fundamental GDH sum rule. Other DNP target developments are also discussed.

1 Introduction

The development of the dynamic polarized nuclear (DNP) targets is strongly dictated by the large and complicated experiments with these targets. The effort has focused on the target technology and equipment that allow more precise experiments. This includes development of target materials that not only provide an accurate and high degree of polarization with low scattering backgrounds but also could handle high beam intensities that in many cases are required for the precision experiments.

In recent years, the question of the spin distribution of the nucleon among its constituents has received major attention. The simple presentation for the total nucleon spin of 1/2 is given by

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z, \tag{1}$$

where $\Delta\Sigma(= \Delta u + \Delta d + \Delta s + ...)$ determines the quark contributions, ΔG represents the gluon spin contribution, and L_z is the sum of the orbital angular momentum contributions coming from the quarks and gluons. During last decade, using the polarized deep inelastic scattering (PDIS) on polarized targets – mainly dynamic nuclear polarized (DNP) targets – the spin contribution on the nucleon carried by quarks has been extensively studied at CERN by the SMC collaboration [1] and at SLAC by E154 [2] using a polarized ^{3}He gas target, E143 [3,4], and E155 [5,6] with DNP targets. Before these experiments were possible, a major DNP target development has to have taken place. All the experiments to date, including the polarized internal gas target experiments at HERMES [7], have extracted the value of $\Delta\Sigma$ in the order of 0.3 [6]. A good discussion on the spin physics and polarized structure functions can be found in Ref. [8].

The PDIS experiments, up to date, do not distinguish spin distributions between the various polarized quarks. At present, there is also no direct measurements of ΔG and L_z available. Although, experiments that will attempt to measure ΔG are underway or planned.

2 Dynamic Nuclear Polarized Targets for Nuclear and Particle Physics Experiments

A dynamic nuclear polarized (DNP) target is a solid-state target where free nucleons of interest are polarized by the dynamic nuclear polarization (DNP) technique, that requires a low temperature, 1–0.3 K, and a high magnetic field, 2.5–7 T. A microwave range oscillating magnetic field is used to drive the dynamic nuclear polarization process *via* paramagnetic centers in the target material. A strength of the DNP target is that the target polarization can be reversed without changing any magnetic fields by changing only the microwave frequency. This polarization reversal does not cause any false asymmetry to the experiment. The nuclear polarization is monitored typically by using the CW nuclear magnetic resonance (NMR). The theory for the DNP process can be found from Refs [9,10]. A thorough review of the DNP targets is given by Crabb and Meyer [11] and references herein.

The development of DNP targets includes the development of suitable target materials that have a high degree of nucleon polarization, high density of polarizable free nucleons of interest and low density of bound nuclei i.e. a large dilution factor f, ratio between free and bound nucleons [12]. In a number of today's experiments, the target material has to function in a high intensity charged particle beam without the loss of polarization through radiation damage. In the latest targets paramagnetic centers for the DNP process were created by a charged particle irradiation [13]. To date, the most used tar-

get material is hydrogenous and deuterated ammonia. Also, chemically doped hydrocarbons like butanol are used in present targets [14,15].

The DNP process requires the temperature range of 0.3-1 K. These temperatures can be achieved with a ^{4}He or ^{3}He evaporator or with a dilution refrigerator. Commercially suitable ^{4}He and ^{3}He evaporators are available, but dilution refrigerators still have to be designed and constructed by DNP target groups. The main problem is to have a refrigerator with large enough cooling power to remove heat created by the microwave irradiation during the DNP process and in some cases, by an intense beam. Depending on the target material, magnetic field, and operating temperature, the heat load varies from 1–20 mW per gram of material. A more complicated mode of operation of a DNP target is a frozen-spin mode where the DNP process is turned off and the target is cooled to 50 mK or less. At these temperatures and at a 0.3 T holding field the polarization decay time constants of days have been achieved [16].

An uncertainty in the target polarization affects directly the overall uncertainty of an experiment. The measurement of the absolute value of target polarization using CW NMR is a technique that has been developed over the whole period that DNP targets have been in use. The NMR system for these experiments has been largely standardized and is well understood [17]. The systematic uncertainties in a polarization measurement in a proton (deuteron) target are typically in the range of 2 to 7%. This uncertainty consists of errors in the polarization calibration measurement about 1% (0.8%), in the temperature measurement during the polarization calibration about 1% (0.4%), and then the 1.2% (1.8%) systematic error in the NMR measurement of the enhanced signal [14]. In the latest DNP experiments, the target polarization uncertainty was a significant part in the overall experiment error, and, therefore, more development work is needed to reduce the target uncertainty [17].

3 Polarized Deep Inelastic Scattering Experiments with DNP Targets

The PDIS experiments of the spin structure function measurements used longitudinally (transversely) polarized DNP targets and longitudinally polarized muons at CERN and electrons at SLAC. The experiments measured the lepton-nucleon asymmetries

$$A_{\parallel} = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} = \frac{1}{f_{\mathrm{RC}}} \frac{C_{\mathrm{N}}}{f P_{\mathrm{b}} P_{\mathrm{t}}} \frac{(N_- - N_+)}{(N_- + N_+)} + A_{\mathrm{RC}}, \tag{2}$$

where the arrows indicate the beam and target polarizations, f_{RC} and A_{RC} take into account radiative corrections [6], C_N is a correction factor for the polarized nucleons other than the nucleons of interest, like ^{15}N in a NH_3 target, f is the dilution factor representing the fraction of events originating from polarized free hydrogen within the target, and $N_-(N_+)$ is the number of scattered electrons per incident beam charge for the negative (positive) beam helicity. Also, transverse spin asymmetry $A_\perp$ data has to be taken in order to determine the longitudinal spin structure functions [5]. $A_\perp$ corresponds to transverse nucleon spin orientation with respect to the beam direction. From measured $A_\parallel$ and $A_\perp$ the deep inelastic spin structure functions $g_1^{p,d}(x, Q^2)$ and $g_2^{p,d}(x, Q^2)$ were extracted from the proton and deuteron data in a wide range of the Bjorken x-space. The $g_1^n(x, Q^2)$ can be deduced from the proton and deuteron data. The Bjorken scaling variable is defined as a fraction of the nucleon momentum carried by the struck parton, $x = Q^2/2M\nu$, where $-Q^2$ is squared four momentum, M is the nucleon rest mass and ν is the energy of the virtual photon. The experiments were run at small x and high Q^2 so that pQCD could be applied reliably.

From the measured spin-dependent structure functions the net quark helicity $\Delta\Sigma$ in nucleon was obtained to be $\Delta\Sigma = 0.23\pm0.04\pm0.06$ at $Q^2 = 5$ $(GeV/c)^2$ [6]. This result can be compared to the Bjorken sum rule, a fundamental QCD prediction that connects the nucleon spin structure to the weak axial charge g_A [18];

$$\int\limits_0^1 [g_1^p(x, Q^2) - g_1^n(x, Q^2)]dx = \frac{1}{6}\frac{g_A}{g_V}C_{NS} = 0.171 \pm 0.006 \qquad (3)$$

at $Q^2 = 5$ $(GeV/c)^2$. The data from the neutron beta decay experiments provide the ratio of the weak axial coupling to the weak vector coupling constant $g_A/g_V = 1.2573 \pm 0.0028$. The constant C_{NS} represents the non-singlet QCD correction. The result validates the Bjorken sum rule in the experimental accuracy of 5–10%. The uncertainty is mainly due to the extrapolation to the unmeasured region of x.

Although, the precision spin structure function experiments at CERN and SLAC were run some time ago, they are briefly described here firstly, because they represent two different type of DNP targets, and secondly, because of their influence on the present development in the field.

The SMC experiment at CERN covered the kinematic range of $0.0008 < x <$ 0.7 and $0.2 < Q^2 < 100$ $(GeV/c)^2$ [1]. The experiment scattered longitudinally polarized 100 GeV/c and 190 GeV/c muons on the polarized DNP target that consisted of two cells that were polarized in opposite directions. The total length of the target was 1.5 m and the total volume was 2.5 liters. The

large target thickness was necessary to compensate for the small muon scattering cross sections. The target was operated at 0.05–0.5 K and 2.5 T field by the world's most powerful dilution refrigerator built by the collaboration [14,19]. Since the direction of the muon beam polarization could not be flipped – a normal approach to control systematic errors in a polarized asymmetry experiment – they instead rotated adiabatically the target polarization by a magnetic field system of 0.5 T at a temperature of less than 100 mK. The rotation operation required about 35 min [14]. Other polarized target experiments that will use target materials with long polarizing times are planning to adapt this target polarization rotation method to optimize their beam-on-target time. The SMC used NH_3, p-butanol and d-butanol as target materials. The experiment quoted typical proton and deuteron polarizations of ±94% and ±60%, respectively. Considerable attention was paid to the accuracies of the NMR polarization measurements and their analysis [20–23,14]. The target related systematic uncertainty for the both nucleons was 2 − 3% [14].

The SLAC spin structure function experiments with DNP targets E143 and E155 [3–6] had to take a different approach because of the energetic (30 − 50 GeV/c) and intense electron beam. An advantage of the SLAC beam was that the systematic errors of the experiments could be controlled by flipping the helicity state of the beam in every pulse at the rate of 120 Hz. On the other hand, the intense beam damaged rapidly the targets and, therefore, the targets had to be periodically annealed to restore the polarization. The targets typically were 2.5 cm in diameter and 3 cm long. The small size of the target made it possible to install two DNP targets and one background target to a single target ladder. This arrangement minimized the beam-off time used otherwise for a target annealing process or a target change. The target was cooled by a ^{4}He evaporator to 1 K and polarized in a 5 T magnetic field. This 1K/5T DNP target greatly simplified cryogenics and made the operation of the target system very reliable [24]. At present, a number of 1K/5T DNP targets are used in different experiments [24–28]. In the SLAC experiments NH_3 was used for the proton data and ND_3 and ^{6}LiD for the deuteron data [5]. This was the first use of ^{6}LiD in a high-energy electron beam. Polarizations of 55–90% and 20–40% were reported for proton and deuteron, respectively. The experiments covered the kinematic range of $0.014 < x < 0.9$ and $0.7 < Q^2 < 40$ (GeV/c)^2.

The feasibility of the polarized nuclear targets like ^{3}He or ^{6}LiD for the PDIS experiments has been discussed widely in the literature [29–33]. The experiments did not observe any differences in the neutron data when polarized ^{3}He, ND_3, or ^{6}LiD were used. The use of ^{6}LiD as a polarized target in spin structure experiments requires that the nuclear properties of both lithium and deuteron are understood and also the kinematic x dependence of the nucleon polarization. The ^{6}Li structure, to first order, is well described by the alpha+deuteron picture. Thus half of the nucleons in ^{6}LiD are polarized resulting the dilu-

tion factor of $f=0.50$ that can be compared to $f=0.16$ of ammonia. Lithium deuteride is also five times as radiation resistant as ND_3 [29].

For the design of a DNP target, it is useful to know the contributions of typical DNP target components such as windows, NMR coil, liquid helium, etc. to the experimental asymmetry of equation (2). For example, the SLAC NH_3 target contained in the detector acceptance about 13% free polarized protons, 66% ^{15}N (slightly polarized), 10% ^4He liquid, 6% Al, and 5% Cu-Ni (NMR coil) by weight [6]. These nuclei have an effect on the dilution factor that has a x dependence [6,14].

In addition to the SMC and SLAC experiments the spin structure functions have been measured by the HERMES experiment with polarized internal gas targets [7]. The world's data on the proton and the neutron g_1^p and g_1^n are shown in Ref. [6].

4   Towards Gluon Polarization Measurements

The PDIS experiments access only the quark spin distribution on the nucleon. To learn the gluon spin distribution, two new DNP target experiments, specifically designed for determining of the gluon spin density $\Delta g(x)$ within the nucleon, are under construction at CERN and SLAC. Both experiments, COMPASS at CERN [34] and E161 at SLAC [35], will measure the asymmetry of polarized photoproduction of charmed quarks from polarized targets. Photoproduction of open charm *via* the photon-gluon fusion process, $\vec{\gamma}g \rightarrow c\bar{c}$, will be tagged by decays of D mesons. Contributions from the quark distributions can be neglected in this process because there is no or only a small intrinsic charm quark content in the nucleon.

The experiments will measure the polarized photon-nucleon cross-section asymmetry

$$A^{\vec{\gamma}\vec{N}\rightarrow c\bar{c}}(k) = \frac{\Delta\sigma^{\vec{\gamma}\vec{N}\rightarrow c\bar{c}X}(k)}{\sigma^{\vec{\gamma}\vec{N}\rightarrow c\bar{c}X}(k)} = \frac{1}{P_tP_bf}\frac{N^{\uparrow\uparrow}-N^{\downarrow\uparrow}}{N^{\uparrow\uparrow}+N^{\downarrow\uparrow}}, \qquad (4)$$

where k is the photon energy, P_t is the target polarization, P_b is the photon beam polarization, and f is the target dilution factor.

In these experiments the quark content of the target is not important except that the target has to have as high an average polarization per nucleon as possible, therefore, both experiments are planning to use ^6LiD that has the best dilution factor, $f = 0.5$, compared to other practical DNP target materials. The polarization of ^6Li is measured to be equal to the deuteron polarization.

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But the polarizing times are long, up to 20–40 h, depending on the polarizing temperature and magnetic field. At 300 mK temperature and at a magnetic field of 6.5 T 70% ^{6}Li polarization has been measured [36,37]. Other studies have confirmed the polarizability of ^{6}LiD [38–40].

The experiments will detect open charm production through various D meson decays. The decay products have large production angles with respect to the incoming beam thus requiring a large polarized target magnet opening to match a large solid angle spectrometer.

The COMPASS experiment (common muon and proton apparatus for structure and spectroscopy) will determine the gluon polarization from the cross section asymmetry for polarized open charm muonproduction at $x = 0.09$. With the 160 GeV/c muon beam photons at the energy range of 35 to 85 GeV will be produced. The experiment is planning to use the SMC refrigerator and its 2.5 T solenoid magnet with two targets 3 cm in diameter and total 60 cm long. Depending on physics goals ^{6}LiD, d-butanol or NH$_3$ will be used. Apart from the gluon polarization measurement, COMPASS plans to study additionally at high Q^2 the transversity structure function h_1 [34,8], spin-flavour decomposition of the structure functions, and lambda polarization [34,41].

The E161 at SLAC will measure the gluon spin distribution within the nucleon using polarized open charm photoproduction. The 35–45 GeV photon beam will be produced by polarized 45–50 GeV/c electrons hitting an oriented diamond crystal. The experiment will cover the x-range of 0.1 to 0.5. E161 will use a horizontal dilution refrigerator [42,43] and a 6.5 T warm bore solenoid magnet to obtain a high degree of ^{6}Li polarization. The diameter of the ^{6}LiD target will be 1 cm and length 8 cm.

5 Test of the GDH sum rule

The Gerasimov-Drell-Hearn (GDH) sum rule [44] is one of the most fundamental relations in hadronic physics. A high precision measurement of the sum rule will test physics beyond standard model. The GDH sum rule relates the difference in the total hadronic photo-absorption cross section for left- ($\sigma_{\rm L}^{\lambda N}$) and right-handed ($\sigma_{\rm R}^{\lambda N}$) circularly polarized photons interacting with longitudinally polarized nucleons to the nucleon's anomalous magnetic moment κ_N;

$$\int_{k_\pi}^{\infty} \frac{{\rm d}k}{k} \Delta\sigma^{\gamma N}(k) = \frac{2\pi^2\alpha\kappa_N^2}{M^2}, \tag{5}$$

were k is the photon energy, $\Delta\sigma^{\gamma N}(k) = \sigma_{\mathrm{L}}^{\gamma N}(k) - \sigma_{\mathrm{R}}^{\gamma N}(k)$, the threshold energy $k_\pi = 0.15$ GeV is needed to produce at least one pion, α is the electromagnetic coupling constant, and M is the mass of the nucleon. $\mu_p = (1 + \kappa_p)\mu_{\mathrm{B}}$ and $\mu_n = \kappa_n\mu_{\mathrm{B}}$. From the experiment we have $\kappa_p = 1.79$ and $\kappa_n = -1.9$.

The experimental test of the integral is one of the major challenges for photoproduction experiments over the coming years. The prediction of the GDH sum rule is 204 μb for the proton, 232 μb for the neutron, and 219 μb (-15 μb) for the average isoscalar (isovector) combinations. The fundamental meaning of the sum rule is that any particle with a non-zero anomalous magnetic moment must have an excitation spectrum and internal structure.

A worldwide program with polarized targets is already underway to test the GDH sum rule at the large photon energy range. The first result is reported by the experiment at MAMI where the value of $226 \pm 5 \pm 12$ μb was obtained for the proton at the photon energy range of 200–800 MeV [45]. This experiment is now relocated to the Bonn electron accelerator facility ELSA where higher photon energies are available [46]. Most of the GDH experiments require a frozen-spin DNP target that has to allow the detection of emitted particles in a very large angular acceptance [16,47].

The following list indicates facilities and the available photon energy range in GeV for GDH experiments: SLAC; E159 ($4 < E_\gamma < 45$) [48], ELSA ($0.14 < E_\gamma < 3$), JLab ($E_\gamma \to 4$), SPring-8 ($1.5 < E_\gamma < 3.5$), GRAAL ($0.5 < E_\gamma < 1.5$; with HD target) [49], LEGS ($E_\gamma \to 0.47$) [50], and HIγS ($0.002 < E_\gamma < 0.225$) [47].

6 Other DNP Target Developments

6.1 DNP target experiments at the Thomas Jefferson National Accelerator Facility (JLab)

Since the start of the JLab polarized target program in 1998, experiments have been run in Hall C with the University of Virgina 1K/5T target and in Hall B with the JLab 1K/5T polarized target [28] specifically designed for experiments with the CLAS spectrometer. The JLab polarized target program consists of polarized structure function measurements on the proton and deuteron at the wide x range including the nucleon resonance region, a precision measurement of $G_{\mathrm{e}}^{\mathrm{n}}$ on polarized ND_3, tests of the GDH sum rule, and a study of the helicity structure of single pion electroproduction.

The results from the measurements of the analyzing power A_N in proton-proton elastic scattering from 24–28 GeV/c at the PS at CERN [51] and at AGS at BNL [52] indicate that A_N increases as a function of momentum transfer squared, $p_\perp^2$. This behavior is not explained by pQCD. In order to measure A_N at higher proton energies, the updated University of Michigan 1K/5T polarized target system will be transported to IHEP, Protvino, for use in the SPIN@U-70 experiment [27].

6.3 Low-energy $N - N$ polarization experiments

The Triangle Universities Nuclear Laboratory TUNL continues to produce precise data on low energy spin-dependent $N - N$ interactions. The latest experiment measured the $N - N$ tensor force from the $\vec{n} - \vec{p}$ scattering [53,15]. The group is in process to convert their target system to a dilution refrigerator based target. Furthermore, they are building a frozen-spin deuteron target for the GDH experiment at the HIγS Facility at the Duke Free-Electron Laser Laboratory (DFELL) [47].

6.4 Other DNP target developments

6.4.1 New type of DNP targets

The production of highly polarized protons in a low magnetic field and at high temperatures had been a DNP target dream for a long time. Protons in a crystal of naphthalene or p-terphenyl doped with pentacene have been polarized to 32% and 18%, respectively, at liquid nitrogen temperature and in a magnetic field of 0.3 T by means of microwave-induced optical nuclear polarization (MIONP) [54]. A MIONP proton target is under development at RIKEN for experiments with radio-isotope beams [55].

At PSI the protons in an organic scintillator doped with TEMPO, were polarized to 80% [56]. The scintillating DNP target material offers new possibilities to perform high precision polarization experiments, allowing the particle detection in coincidence and thus an improvement in the S/N ratio.

The DNP proton targets have been used to polarize low-energy neutron beams since 1964 [57,58,26]. A polarized proton target is the most efficient way to filter the spin of epithermal neutrons (see Ref. [59]).

In recent years, polarized low-energy neutron scattering on DNP targets has been used to study structures of proteins and other biological molecules [60,61].

7 Discussion

A complete description of the spin structure of the nucleon requires the determination of three structure functions: the momentum distribution $f_1(x, Q^2)$, the longitudinal helicity distribution $g_1(x, Q^2)$, and the transverse helicity distribution $h_1(x, Q^2)$. The gluons contribute to $g_1(x, Q^2)$ but not to $h_1(x, Q^2)$. Using the DNP targets the quark part of the longitudinal helicity distribution functions have been determined and the experiments under construction, COMPASS at CERN and E161 at SLAC, will determine the gluon spin distribution. In addition, COMPASS will also attempt to measure $h_1(x, Q^2)$. After the preliminary HERMES gluon polarization result, it seems that we need also to measure the orbital angular momentum, L_z, part of the nucleon spin. Unfortunately, there is, not yet a good experiment to measure it.

The DNP targets will be needed to continue the measurement of the quark flavour distributions on the nucleon spin and their x dependence. Some of these measurements will take place at JLab.

The big task of the coming years will be the precision test of the GDH sum rule. This will require construction of frozen-spin DNP proton and deuteron targets.

In the few years we will see interesting results with some surprises from the experiments with DNP targets but before that we have to overcome some challenges.

References

[1] B. Adeva *et al.*, Phys. Lett. **B 412** (1997) 414; D. Adams *et al.*, Phys. Rev. D. **56** (1997) 5330; B. Adeva *et al.*, Phys. Lett. **B 420** (1998) 180; B. Adeva *et al.*, Phys. Rev. D **60** (1999) 2004; B. Adeva *et al.*, Phys. Rev. D **58** (1998) 112001; B. Adeva *et al.*, Phys. Rev. D **58** (1998) 112002.

[2] K. Abe *et al.*, Phys. Rev. Lett. **79** (1996) 6620.

[3] K. Abe *et al.*, Phys. Rev. Lett. **74** (1995) 346.

[4] K. Abe *et al.*, Phys. Rev. Lett. **75** (1995) 25; K. Abe *et al.*, Phys. Rev. Lett. **76** (1996) 587; K. Abe *et al.*, Phys. Rev. Lett. **78** (1997) 815; K. Abe *et al.*, Phys. Rev. D **58** (1998) 112003.

[5] P. L. Anthony *et al.*, Phys. Lett. B **458** (1999) 529; P. L. Anthony *et al.*, Phys. Lett. B **458** (1999) 536; P. L. Anthony *et al.*, Phys. Lett. B **463** (1999) 339.

[6] P. L. Anthony *et al.*, Phys. Lett. B **493** (2000) 19.

[7] K. Ackerstaff *et al.*, Phys. Lett. B **404** (1997) 383; A. Airapetian *et al.*, Phys. Lett. B **442** (1998) 484.

[8] B. Lampe and E. Reya, Phys. Rep. **332** (2000) 1.

[9] A. Abragam and M. Goldman, Rep. Prog. Phys. **41** (1978) 395.

[10] A. Abragam and M. Goldman, *Nuclear Magnetism: Order and Disorder* (Oxford University Press, Oxford, 1982).

[11] D. G. Crabb and W. Meyer, Ann. Rev. Nucl. Part. Sci. **47** (1997) 67.

[12] St. Goertz *et al.*, in these proceedings.

[13] D. G. Crabb *et al.*, Phys. Rev. Lett. **64** (1990) 2627; W. Meyer *et al.*, Nucl. Instr. and Meth. A **215** (1983) 65.

[14] D. Adams *et al.*, Nucl. Instr. and Meth. A **437** (1999) 23.

[15] D. Markoff *et al.*, In these proceedings.

[16] Ch. Bradtke *et al.*, Nucl. Instr. and Meth. A **436** (1999) 430.

[17] G. R. Court *et al.*, In these proceedings; G. R. Court *et al.*, Nucl. Instr. and Meth. A **177** (1980) 218.

[18] J. D. Bjorken, Phys. Rev. D **1** (1970) 1376.

[19] J. Kyynäräinen, Nucl. Instr. and Meth. A **356** (1995) 47.

[20] C. M. Dulya, Nucl. Instr. and Meth. A **356** (1995) 88.

[21] D. Krämer, Nucl. Instr. and Meth. A **356** (1995) 79.

[22] T. Niinikoski, Nucl. Instr. and Meth. A **356** (1995) 62.

[23] Y. Semertzidis, Nucl. Instr. and Meth. A **356** (1995) 83.

[24] D. G. Crabb *et al.*, Nucl. Instr. and Meth. A **356** (1995) 9.

[25] D. G. Crabb *et al.*, Phys. Rev. Lett. **64** (1990) 2627.

[26] S. I. Penttilä *et al.*, Proc. 11th Int. Symp. on High-Energy Spin Phys., (AIP Conf. Proc. **343**, 1995) p. 532.

[27] D. G. Crabb *et al.*, in these proceedings.

[28] M. Anghinolfi, Proc. Int. Workshop on Polarized Sources and Targets, eds. A. Gute *et al.*, Erlangen 1999 p. 442.

[29] S. Bültmann *et al.*, Nucl. Instr. and Meth. **A 425** (1999) 23.

[30] N. W. Schellingerhout *et al.*, Phys. Rev. C **41** (1993) 2714.

[31] F. M. Steffens *et al.*, Phys. Lett. **B 447** (1999) 233.

[32] O. A. Rondon, Phys. Rev. D **60** (1999) 035201.

[33] V. Guzey, Phys. Rev. D **64** (2000) 045201.

[34] The COMPASS Collaboration, COMPASS proposal, CERN/SPSLC 96-14, SPSC/P297 (Geneva, 1996); CERN/SPLC 96-30 (Geneva, 1996).

[35] The E161 Collaboration, SLAC-PROPOSAL-E161, (September 2000).

[36] A. Abragam *et al.*, J. Physique-Letts. **41** (1980) L-309.

[37] V. Bouffard *et al.*, J. Physique **41** (1980) 1447.

[38] B. van den Brandt *et al.*, Proc. 9th Int. Symp. on High Energy Spin Phys., eds. W. Meyer, E. Steffens, and W. Thiel (Springer-Verlag Berlin Heidelberg, 1991), Vol. 2, p. 320.

[39] G. Durand *et al.*, Proc. Int. Symp. on High Energy Spin Phys., Nagoya, Japan 1992, eds. T. Hasegawa *et al.*, p. 355.

[40] S. Goertz *et al.*, Nucl. Inst. and Meth. **A 356** (1995) 20.

[41] R. L. Jaffe, Phys. Rev. D **54** (1996) R6581.

[42] T. O. Niinikoski and J.-M. Rieubland, Proc. 9th Int. Cryo. Eng. Conf. (Butterworth, Guildford, 1982) p. 580.

[43] C. V. Gaulard *et al.*, Phys. Rev. C **60** (1999) 024604.

[44] S. D. Drell and A. C. Hearn, Phys. Rev. Lett. **16** (1966) 908; S. B. Gerasimov, Yad. Fiz. **2** (1966) 598; S. J. Brodsky and J. R. Primack, Ann. Phys. **52** (1969) 315.

[45] J. Ahrens *et al.*, Phys. Rev. Lett **87** (2001) 022003.

[46] G. Reicherz, in these proceedings.

[47] D. G. Haase *et al.*, In these proceedings.

[48] The E159 Collaboration, SLAC-PROPOSAL-E159, (September 2000).

[49] M. Bassan *et al.*, in these proceedings.

[50] M. M. Lowry *et al.*, in these proceedings.

[51] J. Antille *et al.*, Nucl. Phys. **B 185** (1981) 1.

[52] D. G. Crabb *et al.*, Phys. Rev. Lett. **65** (1990) 3241.

[53] J. R. Walston *et al.*, Phys. Rev. C **63** (2000) 014004.

[54] M. Iinuma *et al.*, Phys. Rev. Lett. **84** (2000) 171.

[55] T. Wakui *et al.*, in these proceedings.

[56] B. van den Brandt *et al.*, Nucl. Instr. and Meth. **A 446** (2000) 592.

[57] D. Draghicescu *et al.*, Phys. Lett. **12** (1964) 334.

[58] S. Ishimoto *et al.*, Japanese J. Appl. Phys. **25** (1986) L246.

[59] O. Zimmer, in these proceedings; W. M. Snow *et al.*, in these proceedings; A. Gorzel *et al.*, in these proceedings; T. R. Gentile *et al.*, in these proceedings.

[60] H. B. Stuhrmann *et al.*, Nucl. Instr. and Meth. **A 356** (1995) 124.

[61] B. van den Brandt *et al.*, in these proceedings.