Spectator tagging in electron deuteron scattering and the measurement of the Bjorken Sum Rule

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Abstract: The tagging of spectator nucleons in polarised and unpolarised electron deuteron scattering offers the possibility to measure proton and neutron structure functions separately in the same nuclear environment. In contrast to fixed target experiments, the spectator in collider mode has large momentum and is therefore rather easy to measure. In a polarised deuteron beam proton and neutron are both polarised. Tagging offers the ideal figure of merit, superior to any subtraction method of H, D and ^{3}He beams. As the proton and neutron asymmetries are measured simultaneously in one experiment many systematic uncertainties cancel and provide optimal conditions to measure the Bjorken Sum Rule. From the machine point of view, the acceleration of polarised deuterons compared to protons has both advantages and difficulties. It is not clear if deuteron polarisation can be handled at high beam energies. It might turn out that a common solution to the luminosity and polarisation problems is to significantly reduce the HERA deuteron energy.

1 Physics Motivation

HERA is a tool to investigate the structure of the nucleon. For a complete picture of the nucleon the scattering off protons alone is not sufficient, a neutron target is required. In unpolarised fixed target experiments, the neutron structure functions are derived from the difference of deuterium and hydrogen scattering processes. Nuclear effects in the deuteron are small. For nuclei with higher atomic mass nuclear effects become larger. They are known as the nuclear EMC effect.

In polarised DIS in a similar fashion the difference of the deuterium and hydrogen spin asymmetries are used to derive the neutron spin structure functions. The spins of proton and neutron in a vector polarised deuteron are aligned parallel. However, there is an approximately 5% D-state probability in the deuteron wave function which has to be taken into account in the derivation of the neutron spin structure function. In polarised DIS there is an alternative possibility to derive the neutron spin structure by using a ^{3}He target. The ^{3}He nucleus contains two anti-aligned proton spins. The ^{3}He spin asymmetry is directly related to the neutron spin. This is strictly true only for the S-state of the ^{3}He wave function. With about 10% probability the nucleus is in the S'- or D-state. In these states the spin asymmetry is dominated by the proton spin. In principle a 'spin-nuclear' EMC effect, i.e. the modification of the spin distributions of quarks in nuclear matter, may add some uncertainty to the measurement.

Spectator tagging in deuteron scattering offers a unique experimental approach to measure differences of the proton and neutron scattering, i.e. to measure non-singlet distribution functions. Spectator tagging means that the nucleon which is not involved in the DIS scattering process is identified in the detector, so that for every DIS event on deuteron it is experimentally known if it happened in the proton or the neutron. This method cannot or can only very poorly be applied to fixed target experiments as the momentum of the spectator in the rest frame of the deuteron is defined by its nuclear Fermi momentum, i.e. it is in the 100 MeV range.

The situation is completely different in a collider experiment. The spectator is boosted to half of the beam energy and can in principle be easily detected. For an 820 GeV deuteron beam the spectator proton has a momentum of 410 GeV and is separated from the electron and deuteron beams by the first dipole field as shown in figure 1. The 410 GeV neutron spectator is not bent and can be detected in a neutron calorimeter downstream the interaction point.

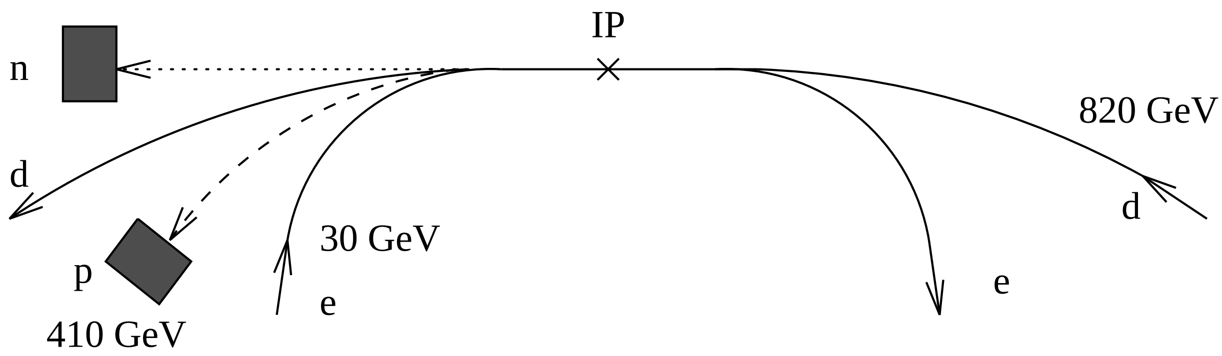

Figure 1: *The spectator nucleon in electron deuteron scattering at HERA can be detected in coincidence with the deep inelastic event. The proton and neutron tagging offers the possibility to measure proton and neutron spin structure functions simultaneously without switching targets.*

Tagging a polarised deuteron beam allows the measurement of the fundamental Bjorken Sum Rule in one nuclear environment and in one single experiment without switching targets. It has been pointed out that a precision measurement of the QCD corrections involved in the Bjorken Sum Rule allows a determination of the QCD coupling constant $\alpha_s(Q^2)$ [1]. The verification of the running of α_s with Q^2 and the comparison with results from jet physics would be fundamental tests of the standard model.

The spectator tagging method can be extended by measuring the angle and momentum of the spectator and correlating it to the kinematics of the DIS process. This way semi-inclusive (spin-)structure functions can be obtained which contain information about the nuclear structure of the deuteron. By comparing the results with the known structure functions of the free proton, nuclear corrections can be tested and possible new nuclear effects can be measured.

2 Experimental Aspects

The most striking advantage of the spectator tagging in polarised deuteron scattering is the high figure of merit which can be obtained. Assuming the Ellis-Jaffe Sum Rule for proton and neutron and the Bjorken Sum Rule should be measured in the experiment. The precision which can be obtained is compared for the following three scenarios: deuteron tagging (I), p/d subtraction (II) and p/^{3}He subtraction (III). The maximal achievable polarisation and luminosity may be different for the different beams but due to lack of better knowledge it is assumed that the polarisation is identical and that the luminosity $\mathcal{L}_c$ (in units of charge/cm^2/s) is (1 : 0.5 : 0.5) for the proton compared to the deuteron and ^{3}He beam. The nucleonic luminosity $\mathcal{L}_n$ (in units of nucleons/cm^2/s) which is relevant for the number of DIS events is then (1 : 1 : 0.67). In order to have the same statistical error on the neutron as on the proton asymmetry the following data taking times are required approximately:

deuteron tagging (I): 2 time units deuteron beam with half of the data protons and neutrons.

p/d subtraction (II): 3 time units proton beam, 6 units deuteron beam. The error on the neutron asymmetry is derived according to $\delta A_1^n \approx \sqrt{(2\delta A_1^d)^2 + (\delta A_1^p)^2}$.

p/^{3}He subtraction (III): 1 time unit proton beam and $3^2/0.67 = 13.5$ time units on ^{3}He. The factor 3^2 comes from the dilution of the neutron asymmetry by the two unpolarised protons in ^{3}He.

To conclude: the time required for the same statistical precision on the spin asymmetries for proton and neutron is (1 : 4.5 : 7.25) for the scenario (I : II : III). Statistically, the deuteron tagging method is clearly favoured.

Assuming 100% tagging efficiency the advantages of deuteron tagging in systematics are obvious:

- proton and neutron are measured in one experiment, without changing targets, with identical luminosity, with identical beam polarisations, with identical acceptance and efficiency for the registration of the DIS event.
- the CMS energy of the electron nucleon system are the same for proton and neutron in case of deuteron tagging. It is important to mention that that is not the case for the p/d or p/^{3}He subtraction methods if the beam energies are the same for the p, d and ^{3}He beams. Each nucleon carries only a fraction of the beam energy, i.e. the nucleon in ^{3}He carries only a third of the energy compared to the nucleon in the proton beam. This leads to completely different energies and angles of the DIS event in the lab frame for a given x and Q^2. On the other hand, if one wants to keep the lab kinematics identical, the beam energies of the p, d and ^{3}He beams have to be different and therefore the polarisation, the luminosity and the luminosity measurement will be very different, leading possibly to large systematic errors in the subtraction methods (II) and (III).
- The nuclear environment of proton and neutron are identical in the tagging method (III). Therefore some of the nuclear effects will cancel in the ratio of the proton and neutron cross sections and asymmetries. The remaining nuclear effect can be determined by the comparison with the results from the free proton. If the tagging detectors have the possibility to measure the momentum and angle of the spectator, nuclear effects can be checked by selecting special kinematics, e.g. spectators at rest in the deuteron rest system or spectators at the tails of the nuclear momentum distributions.

All the above considerations assume that the DIS scattering occurs incoherently on one of the two nucleons of the deuteron and that the tagging efficiency is 100%. Both assumptions are certainly not strictly true. The incoherent scattering on nucleons does not necessarily apply at very low x and to diffractive events. This is however a generic feature of the scattering process and is also present in the subtraction methods (II) and (III). It is not necessary a limitation but can be regarded as a possibility to learn about nuclear structure especially if the momentum of the spectator is measured. Additionally, diffractive events can be identified by a rapidity gap in the hadronic final state.

The tagging efficiency has physics and technical limitations. In first order, tagging inefficiencies cancel when the spin asymmetry is formed, as long as the tagging efficiency is spin independent. However the asymmetry may be diluted by other processes. The physics limitations come from the fact that charge exchange and diffractive processes may dilute a clean DIS tagging. Detailed Monte-Carlo corrections are needed to take these processes into account. Technical limitations come from the restrictions in space due to machine elements, from particle background and from the beam divergence. The scattering angle of the spectator is below 0.2 mrad for a typical Fermi-momentum of 100 MeV/c. Due to the divergence of the beam at the interaction point the angular distribution is smeared. This limits the possibility to precisely determine the transverse Fermi momentum of the spectator. The longitudinal momentum of the Fermi motion is boosted with the γ factor of the beam. This makes is rather easy to measure. A ± 100 MeV/c longitudinal motion translates to a spectator energy of 410 ± 41 GeV. The precision with which the spectator momentum can be determined depends on the energy spread of the machine ($\sim 1\%$) and the resolution of the spectator detector.

The design of the neutron spectator detector is rather simple, it just requires a neutron calorimeter downstream the interaction point with the possibility to identify neutrons compared to charged particles and photons. The calorimeter has to be able to handle background from photoproduction. The design of the proton detector is more complicated. The protons are bent by the first separation fields of the off-axis HERA quadrupoles. In the current beam lattice the spectators with large transverse Fermi momentum are bent by the quadrupole components and cannot be properly separated. The existing proton detectors of ZEUS and H1 have an insufficient acceptance for the spectators. A clean separation of the proton spectators from the deuteron beam requires a special design of the interaction region. The optimal solution would be a dipole separation without quadrupole components. This dipole field could be part of the spin rotator and would be used as spectrometer magnet for the momentum measurement of the proton spectator at the same time.

3 Machine Aspects

The injection and acceleration of polarised protons and the maintenance of polarisation at HERA energies is regarded as a very difficult task which is currently being studied in detail. The task to produce longitudinally polarised deuterons at HERA is certainly very different. If it is easier or more difficult is hard to predict as there is not much experimental and theoretical experience with polarised deuterons. The reason why it is so different is due to the small gyromagnetic anomaly of the deuteron $(g_d-2)/2 = -0.14$ compared to the proton $(g_p-2)/2 = 1.79$. This leads to the effect that the number of depolarising resonances, which are the main difficulty in the proton polarisation, is reduced by a factor of 25. The deuteron spin tune at 820 GeV is only $\nu_s = 62$ for the deuteron compared to $\nu_s = 1600$ for the proton. The spin tune of the deuteron beam is similar to the spin tune of electrons at 27.5 GeV ($\nu_s = 62.5$) which have been successfully polarised at HERA.

The main difficulty of a polarised deuteron beam is the manipulation of the spin. A spin rotator or a Siberian snake requires much stronger magnetic fields for deuterons than for protons, again due to the small gyro-magnetic anomaly. As the spin tune of the deuteron and the electron beam are similar, the geometry of the rotator bump could be similar too as it is only determined by the spin tune of the beam and not by its energy. Therefore a design like the HERA-e mini-spin rotators would allow to rotate the deuteron spins by 90° if the warm coils would be replaced by strong superconducting magnets.

Due to the smallness of the spin tune, it might be that a deuteron beam would not require Siberian snakes, however this has to be studied in detail.

4 Conclusions

The tagging of proton and neutron spectators in unpolarised and polarised electron deuteron scattering offers unique possibilities to study the difference of DIS cross sections and asymmetries in proton and neutron. The tagging offers a statistical figure of merit which is superior by a factor of about 5...7 for the measurement of the proton and neutron Ellis-Jaffe and Bjorken Sum Rules. The experimental conditions are ideal in the sense that proton and neutron can be measured in the same nuclear environment with identical experimental conditions. The main concern is the question how efficient the tagging is and whether it is possible to maintain high deuteron polarisation at HERA. First experiences were obtained at the KEK-PS where polarised deuteron beams have been successfully accelerated in a storage ring up to an energy of 10.2 GeV.

Concerning the aim to measure the Bjorken Sum Rule and the spin structure functions at small x ($x < 0.01$) with high precision, in principle the high energies at HERA are not needed. If it would be possible to collide the polarised HERA electrons at 27.5 GeV with polarised deuterons at 10...40 GeV, the center of mass energy would be large enough to cover the relevant kinematic range ($s = 1100...4400$ GeV^2). The energy would also be still high enough for gluon spin studies using jet and charm production. At these energies also deuteron polarisation is a much smaller problem and electron cooling of the stored deuterons and/or continuous injection of deuterons into the storage ring would possibly allow for low emittance and high luminosity. As the DIS cross section increases at lower energy, a much higher statistical precision could be obtained.

Acknowledgments

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References

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