CHAPTER 1

Introduction

One of the early ideas to describe the atom internal structure were given by W. Prout already in 1815 in an anonymously published paper [1]. The author has shown that, within experimental uncertainties, the atomic weights of various compounds are multiples of the hydrogen atom weight. This observation lead him to the hypothesis that the hydrogen atom is the only truly fundamental object, which he called protyle. Later on, once more precise measurements got available this hypothesis was disproved (existence of isotopes).

Almost a century later E. Rutherford in 1911 discovered the existence of atomic nuclei [2] – the discovery which started the modern understanding of the atom structure. In experiments made in 1917 (and reported in 1919) he also managed to observe the hydrogen nucleus as a product of bombarding ordinary nitrogen-14 with alpha particles. Influenced by the earlier hypothesis of W. Prout, E. Rutherford assumed that the hydrogen nucleus is present in all other nuclei and called it proton. With the later discovery of the neutron by J. Chadwick [3] the modern structure of the atom was fully established. At that time both protons and neutrons were considered as fundamental objects. However, with the increasing energy of scattering experiments many new particle types were produced. The emerging particle "ZOO" in late 50's and beginning of 60's put a question mark on which are the really fundamental objects of matter.

The model of the internal nucleon structure by M. Gell-Mann [4] and G. Zweig [5] from 1964 predicted that a nucleon is composed of 3 quarks. These are point-like fermions with spin $1/2$ and fractional electric charge ($\pm 1/3, \pm 2/3$). At the time of the model introduction only 3 quark types were needed—up, down and strange. The proton and neutron were built exclusively from up and down quarks, uud and ddu, respectively. As the nucleon itself is a fermion with a spin $1/2$, it was not too difficult to explain how the spin of the proton is built out of three $1/2$ fermions. Moreover, such a simple model quite accurately predicted the anomalous magnetic moment of the nucleon, a quantity directly related to the quark orientation inside the nucleon, see *e.g.* [6]. The only problem of this model was the fact that the predicted particles with fractional electric charge were not found in any experiment. Citing the Nobel prize winner J.I. Friedman [7], "To many physicists this was not surprising. Fractional charges were considered to be a really strange and unacceptable concept, and the general point of view in 1966 was that quarks were most likely just mathematical representations – useful but not real".

Even when the first evidences of point-like objects in the nucleon were reported by SLAC [8, 9], the existence of quarks was not fully recognised by the whole particle physics community until the 4th quark predicted by the theory [10], the charm quark, was discovered in 1974 in the observation of the J/Ψ meson in e^+e^- annihilation [11, 12].

With the onset of the Parton Model by R. Feynman [13], and later of the Quark Parton Model [14], in addition to the three aforementioned quarks now called the valence quarks, also sea quark and antiquark pairs were considered, as well as electrically neutral partons with spin 1 (bosons), later called gluons. Experimental evidence of the gluons existence was obtained in 1979 in DESY [15]. However, even with these complications it was assumed that only quarks carry the spin of the proton.

In the same year of the J/Ψ discovery, an experiment at SLAC for the first time scattered a polarised beam on a polarised target. From the obtained results one could conclude that, within the large statistical uncertainties, indeed as expected quarks could explain the spin of the nucleon [16, 17]. As in addition the (closely related) anomalous magnetic moments of baryons were well described by the simplest Quark Parton Model, for the next almost 15 years the study of the internal spin structure of the nucleon was not considered a top priority.

For the vast majority of the community the EMC experiment, in which polarised muons were interacting with a polarised target, was supposed to just confirm the earlier SLAC measurements and the expectation from the Ellis–Jaffe sum rule [19]. Needless to say, the EMC result [20] came as a true surprise, the fraction of the proton spin carried by quarks, $\Delta\Sigma$, was measured to be $\Delta\Sigma = 0.12 \pm 0.10 \pm 0.14$, instead of 1. Even if relativistic corrections were later considered, see *e.g.* [21], the expected value of $\Delta\Sigma \approx 0.6$ was far away from the actual measurement. The importance of this discovery was clearly recognised by the physics community, the two EMC papers having in total 3406 citations as on 15 March 2016. The EMC experiment had a significant Polish contribution by B. Badełek, J. Ciborowski, J. Gajewski, J.P. Nassalski, E. Rondio, L. Ropelewski and A. Sandacz. The EMC discovery started the so called "spin crisis". For the next two decades it shaped the way the field of spin measurements evolved. The next generation of experiments performed at CERN (SMC) [22], DESY (HERMES) [23] and at JLAB [24–26] confirmed the EMC observation that the quarks can explain only a small fraction of the nucleon spin.

In a more general case the spin of the nucleon can be carried by the helicity of quarks, $\Delta\Sigma$, the helicity of gluons ΔG, as well as by the orbital angular momenta of quarks and gluons L_{q} and L_{g}, respectively. In the so-called Jaffe–Manohar scheme this can be written as

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{\mathrm{q}} + L_{\mathrm{g}}. \tag{1.1}$$

Observe that this definition is not gauge invariant. It holds only in the so-called light-cone gauge. However, this decomposition still plays an important role, as many of the experimental results concerning lepton-nucleon scattering are interpreted in the light-cone gauge. The proper gauge invariant definition of the nucleon spin is given by the Ji sum rule [27].

At the end of the 90's there were several reasons why the community decided to go after a measurement of ΔG. From early unpolarised deep inelastic scattering measurements it was known that quarks carry only about 50% of the proton momentum (in the infinite momentum frame) [6]. The rest was postulated and later proved to be carried by gluons. Thus, gluons were a natural candidate to solve yet another "crisis". Moreover, due to the so-called axial anomaly [28, 29], in case the gluon polarisation is large ($\Delta G \approx 2$–3), quarks could still carry a large fraction of the nucleon spin as predicted by simple models. Observe however that such a large gluons polarisation would have to be compensated by quark and gluon orbital momenta. This fact is hard to reconcile with the simple QPM, where three quarks in the nucleon are supposed to be in the lowest orbital momentum state. There was also one additional argument in favour of ΔG measurements, namely, at that time there was no physical observable known which could be linked with the orbital momenta of quarks and/or gluons in the nucleon.

Therefore, it was only natural that experiments like HERMES and SMC put the gluon polarisation measurement in their agenda. Several experiments were planned, where the gluon polarisation in the nucleon was considered as a flagship measurement in COMPASS at CERN, STAR and PHENIX at RHIC.

Since then almost 30 years have passed but the "spin puzzle" persists. Originally the COMPASS golden channel of analysis was the observation of the decay products of the D^0 meson, $D^0 \to K\pi$. In the COMPASS kinematics the observation of a D^0 meson is a signature of the so-called photon-gluon fusion process, which is sensitive to the gluon polarization in the nucleon. In the COMPASS proposal this channel was discussed in detail using Monte-Carlo techniques. However, when the measurement was performed it turned out that the background was vastly underestimated, and some of the crucial efficiencies related to the spectrometer were overestimated. As a result the precision of the gluon polarisation measurement was worse by a factor of about four compared to the proposal expectations. This strongly motivated the search for more efficient methods of gluon polarisation estimation. One of such new analysis methods was developed by the author and it is described in this monograph.

The method is successful as it leads to the best estimate of the gluon polarisation in the nucleon from all direct measurements performed so far. At the same time the method is rather complex, and so far poorly documented[1], which is unfortunate as the idea and the method itself can be used in other experiments. Taking this into account the author decided to include more details concerning the method and its application in the data analysis than a reader would expect in this type of monograph.

The organisation of the monograph is the following. In the next chapter the formalism describing deep inelastic scattering is given, as well as ideas concerning direct and indirect methods of ΔG extraction. The results concerning the gluon helicity in the nucleon obtained in previous measurements are presented in Chapter 3. In Chapter 4 the COMPASS spectrometer is described. Chapter 5 describes the proposed method of $\Delta g/g$ extraction which is based on analysis of data with a hadron observed in the final state. The details concerning data selection are described in Chapter 6, while Monte-Carlo models, parametrised by Neural Network, which are needed to relate experimental observables with the gluon polarisation are described in Chapter 7. In Chapter 8 the details concerning the study of systematic uncertainties are presented. In Chapter 9 the obtained results of the gluon polarisation in the nucleon are given, including a comparison with previous measurements as well as with the extraction from global QCD fits. The summary and outlook is presented in Chapter 10. Throughout the monograph natural units are assumed in which $\hbar = c = 1$. Observe that some figures are not intellectual property of the author, therefore it may happen that the aforementioned convention is not fulfilled.

It should be stressed that in recent years large activities were started in order to understand the three-dimensional picture of the nucleon by studying Transverse Momentum Dependent Parton Distribution functions and the Generalised Parton Distribution functions. Presently, these functions can be linked in a model dependent way to the orbital momenta of quarks and gluons. These very important steps forward in understanding the multidimensional structure of the nucleon are beyond the scope of this monograph. For a recent review of the spin physics of the nucleon see *e.g.* [31].

[1] Soon there will be a COMPASS paper published [30], of which I am the corresponding author. The complexity of the analysis was one of the reasons why it was done by a team of post-docs, but as a result there is no Ph.D. thesis on the subject.