Measurement of single-spin azimuthal asymmetries on a longitudinally polarised deuterium target

Today we know that all ordinary matter is composed of electrons and nuclei, and nuclei are formed from protons and neutrons. But they are not the smallest elementary objects we can find in nature, they are in fact composite structures. We know that the familiar proton and neutron are actually enigmatic composite objects made out of point-like partons: quarks, anti-quarks and gluons. All properties of the proton we know today, like its electrical charge, its mass and its “internal rotation”, the so called “spin”, originate from the properties of the quarks and the gluons inside the proton. To describe the composition of a proton from quarks and gluons we can use distribution functions. We can imagine these functions like microscopic maps of the proton, which show the density of the quarks and gluons inside a proton and the spin of them.

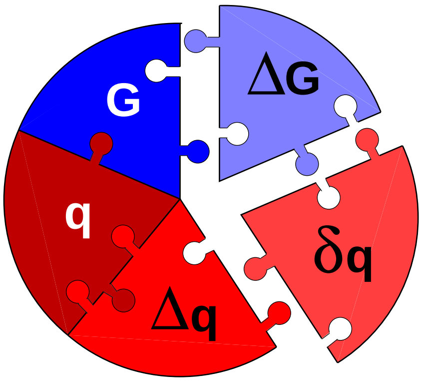

Figure 1: Picture illustrating the knowledge of the Proton structure. The missing pieces are ΔG and δq.

For gluons, there are two distribution functions, the gluon density distribution G and the gluon spin distribution ΔG. For quarks, there exist three distribution functions, the quark density q, the longitudinal spin distribution Δq and the transverse spin distribution δq, which is also just called “transversity”. In contrast to the one spin density for the gluons, we can find two different spin densities for quarks. The difference between them is the orientation of the spin axis, which we may imagine like the axis around which the quarks are rotating like little gyroscopes. The longitudinal spin density Δq describes the spin of quarks which have a spin axis oriented along the direction of motion of the proton, the transversity is used for quarks with a spin axis orthogonal to it.

If one has measured all five distribution functions shown in figure 1, one has obtained a complete picture of the composition of the proton. Up to now, only three of the five components of this “proton puzzle” have been measured by particle physicists. These are the quark and gluon densities q and G and the longitudinal spin distribution of the quarks Δq. The other two functions ΔG and δq are not yet known. In this article results of the HERMES experiment are shown, which may help to come closer to an understanding of one of the two unknown functions, the transversity δq.

To obtain information about the tiny structures inside of the proton, one needs a "microscope" with a very high resolution. Since the diameter of the proton (about 1.5 fm) is much smaller than the wavelength of visible light, we need electromagnetic radiation of a very short wavelength.

Radiation with such a short wavelength can be produced when we scatter electrons with very high energies (27 billions of electonvolts) on protons. Quantum mechanically, we describe this *deep-inelastic* scattering by the exchange of a virtual photon γ^* between the electron and the proton. The photon is called virtual in this case, since it has a mass (unlike ordinary photons, which are massless) and can exist only for a very short time. The virtual photon might be thought of classically as having a very short wavelength: it scatters from a single point-like, electrically charged quark inside the proton and kicks it out, thereby destroying the proton and producing other particles from the debris.

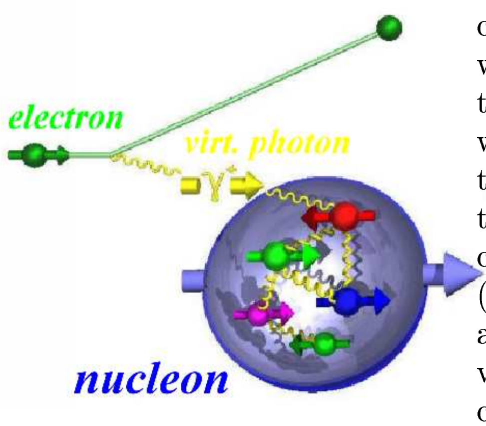

Figure 2: Picture illustrating deep inelastic scattering.

The most promising way to measure the transversity is supposed to be deep-inelastic scattering with a transversely polarised target. In this measurement, the transversity distribution function appears in combination with another function, a fragmentation function, which describes the fragmentation of the transversely polarised quark into the particles which are formed in the scattering. Up to now, we have measured with a longitudinally polarised target only.

To describe the exact measurement we have done, we should have a look to the geometry of a deep inelastic scattering process: In the picture on the right we can see the electron, our short wavelength "microscopic" virtual photon which hits the nucleon and one outgoing particle, which was produced in the scattering. It can be one of particles π^+, π^0, π^- or K^+, which together are also called mesons. The incoming and the outgoing electron define a plane - the lepton scattering plane.

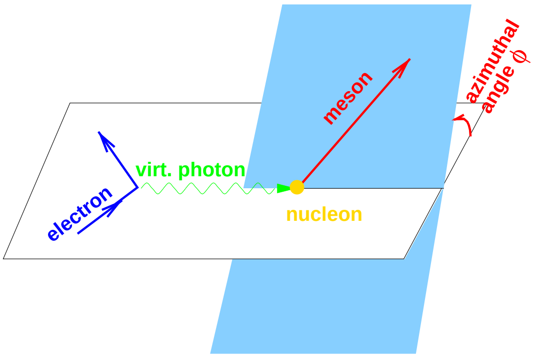

Figure 3: Picture illustrating the geometry of the scattering.

Let‘s imagine that this plane is the surface of your desktop, then the electron the virtual photon and the nucleon are moving along the surface of your desk. Only one particle is moving out of this plane, the produced meson, and is flying towards you. The angle, under which it is coming out of the plane, we call the azimuthal angle ϕ. And this angle we can measure with the detectors in our experiment.

What we have measured is the following: how the azimuthal angles of the outgoing mesons change if we invert the spin direction of the nucleon. For both longitudinal spin directions of our nucleons we have counted how many mesons are flying away in which direction. And from these numbers, let us call them $N^{\leftarrow}$ for the one spin direction of the nucleon and $N^{\rightarrow}$ for the other one we have calculated a *single spin asymmetry*. Let us call it A:

$$A(\phi) = \frac{1}{|P|}\frac{N^{\rightarrow}(\phi) - N^{\leftarrow}(\phi)}{N^{\rightarrow}(\phi) + N^{\leftarrow}(\phi)}$$

In this formula, P is the polarisation of our target, the ϕ's are there to remind us that we are looking at the direction of the outgoing mesons. If the direction of the mesons would not change if we invert the spin of our nucleons, the numbers $N^{\rightarrow}$ and $N^{\leftarrow}$ would be equal and since we subtract them in our formula from each other, the single spin asymmetry would be zero.

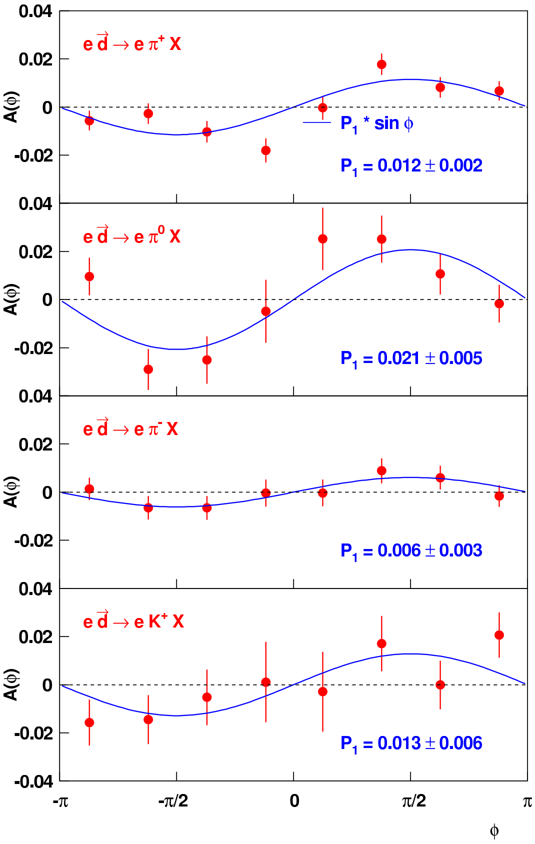

Figure 4: Picture depenence of the asymmetry on the azimuthal angle ϕ.

But look what we have measured. The asymmetry shows a pronounced dependence of ϕ! As you can see in the figure the ϕ-dependence of the asymmetry is rather well described by the simple function $P_1 \sin\phi$, with a positive amplitude P_1. We call this amplitude *analysing power*, it is just the $\sin\phi$ moment of the asymmetry. The measurement you can see in the picture on the left are taken with a deuteron as a target nucleus. A deuteron is a nucleus which contains only two nucleons, one proton and one neutron. So the result we obtained is the superposition of the scattering on protons and neutrons. Theoretical physicists have done calculations for this scattering process and made some predictions for the analysing power when they put in some models for the transversity distribution of the quarks. The results of these calculations do indeed agree nicely with our measurement. Unfortunately we are not yet ready to calculate the transversity directly from our measurements. One reason is the longitudinal target polarisation of our deuteron target. In the case of a longitudinally polarised target there may be other so called chiral odd distribution functions which can contribute to the measured asymmetry as well. That‘s why we have already started with measurements with a transversely polarised proton target, from which we will be able to directly determine the unknown transversity distribution and we hope we soon can help solving the “nucleon spin puzzle”.