Nuclear effects in semi-inclusive deep-inelastic scattering off 84Kr and other nuclei
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Chapter 3

The HERMES experiment

In order to perform at HERA measurements of nucleon spin structure, the HERMES experiment was designed and built. The HERMES detector is located at one of the four experimental halls of the HERA electron-proton collider at DESY, as illustrated in Fig. 3.1. At HERA a polarized 27.5 GeV electron/positron beam and an unpolarized proton beam (920 GeV) are available. The proton beam passes unused through the HERMES detector. Instead a fixed polarized target is introduced into the electron/positron beam. Many different measurements can be carried out at HERMES on various properties of the nucleon related and unrelated to spin, such as the flavor asymmetry of the sea quarks [45], the exclusive vector-meson lepton production [46] and hadronization in nuclei [47]. For this purpose data are collected with polarized and unpolarized gaseous targets including $^1\text{H}$, $^2\text{H}$, $^3\text{He}$, $^4\text{He}$, $^{14}\text{N}$, $^{20}\text{Ne}$ and $^{84}\text{Kr}$. Because the physics analyses presented in this thesis are based on data obtained with unpolarized targets, no details are given on the polarized target or beam polarization techniques in the following sections. Details on the equipment needed for the polarized measurements can be found in [48, 49, 50]. In this chapter a brief description is given of the (unpolarized) target set-up at HERMES (sect. 3.1), and a more general description of the detector is presented. Some details are given on the techniques used to identify scattered and produced particles in deep-inelastic lepton scattering.
3.1 The target

The HERMES target consists of an open ended storage cell [51] internal to the HERA positron ring. Using an Unpolarized Gas Feed System (UGFS) it is possible to deliver $^1$H, $^2$H, $^4$He, $^{14}$N, $^{20}$Ne or $^{84}$Kr gases with total areal densities between $10^{15}$ and $10^{16}$ nucl/cm$^2$ to the storage cell. The pressure in the UGFS is regulated via a diaphragm and a termo-valve in order to supply a constant density to the cell. The flow rate through the diaphragm can be measured with two barometers, by the pressure dependence of the diaphragm conductance. From the flow rate the target density for each gas can be evaluated given the cell conductance. Unfortunately this method gives an uncertainty on the absolute value of the target density of about 20%, mostly due to the uncertainty on the diaphragm and the cell conductances [52].

3.2 The spectrometer

The HERMES spectrometer is designed to perform asymmetry measurements in inclusive Deep-Inelastic Scattering with high precision. In addition, hadronic products of the scattering processes can be reconstructed over a wide kinematic range, opening the possibility to carry out semi-inclusive measurements as well.

The HERMES spectrometer is a standard forward angle detector, symmetric about a central, horizontal shielding plate in the magnet. Both HERA beam pipes pass through the detector in the gap between the top and bottom part. A diagram of the spectrometer is shown in Fig. 3.2. The front tracking chambers are used to determine the polar ($\theta$) and the azimuthal ($\phi$) scat-
tering angles. The combination of the trajectories reconstructed by the chambers before and behind the magnet give the particle's momentum. In addition, three proportional chambers in the magnet help to merge front and back tracks and make it possible to track low momentum particles that do not reach the rear section of the spectrometer. Particles with scattering angles within ±170 mrad in the horizontal direction and between +(-)40 and +(-)140 mrad in the vertical direction are accepted. Together these boundaries lead to a polar angular acceptance of 40 < θ < 220 mrad.

3.2.1 Tracking

The first detector shown in Fig. 3.2, right after the target cell, with the name Lambda Wheels (LW) is the newly installed silicon detector. The LW are operational since 2001 but have not been used for measurements so far due to an extended period without beam at HERA which started in Sept. 2000. More information on this new detector is given in the next chapter. After the LW in the drawing are shown the detectors of the front tracking system. The combined information from the micro-strip gas counters (VC1/2), drift vertex chambers (DVC) and front drift chambers (FC1/2) provide the reconstruction of the vertex position in the target, and the definition of the scattering angle\(^1\). The part of the track reconstructed in the back drift chambers (BC1/2 and BC3/4) add the information of the magnetic deflection to obtain the particle momentum. The back chambers also identify the hit in the particle identification detectors (PID) which can be associated with a particular track. The orientation of the wires of all tracking detectors is either vertical or tilted by 30° left or right. Like the rest of the spectrometer the tracking system is symmetric about the beam plane.

Momentum and angular resolution for positrons is limited by Bremsstrahlung and multiple scattering in the material of the target cell walls, as well as of the first tracking detectors. The momentum resolution is 0.7-1.25% over the entire kinematic range of the experiment, while the scattering angle resolution is better then 0.6 mrad [48].

3.2.2 Particle identification

The particle identification (PID) system at HERMES consists of four components and was designed to identify the DIS positron (or electron) with high efficiency and low hadron contamination.

**Threshold and Ring Imaging Čerenkov detector**

The Čerenkov detector is used for the separation of leptons from hadrons and for pion identification in the momentum range between 4 and 14 GeV. Electromagnetic radiation (Čerenkov

\(^1\)In practice most analyses presented in this thesis are based on using either the FC1/2 alone, or a combination of VC1/2 and FC1/2.
light) is emitted when a particle traverses a medium with a velocity larger than the speed of light in that medium, \( v > \frac{c}{n} \) with \( n \) the refraction index of the medium. The existing threshold Čerenkov detector was replaced in 1998 by a dual radiator Ring Imaging Čerenkov (RICH) to provide particle identification for pions, kaons and protons in the momentum range from 2 to 15 GeV [53]. The detector uses two radiators, a wall of silica aerogel tiles at the entrance of the detector, followed by a volume filled with \( C_4F_{10} \), a heavy fluorocarbon gas. The photon detector consists of 1934 photomultiplier tubes (PMT) located above (below) the active volume for the top (bottom) part of the detector. The Čerenkov light cones are imaged onto the PMT by a spherical mirror array located at the rear of the radiator box. In Fig. 3.3 a schematic drawing of the main components of the (upper half of the) RICH are shown. Different Čerenkov angles are produced in the aerogel and the heavy gas depending on the index of refraction as \( \cos \theta_c = \frac{c}{nv} \). Moreover, the size of the angle has a different mo-

**Figure 3.2:** Side view of the HERMES spectrometer. Both axes give the actual distance in meters with respect to the HERMES interaction point.
mentum dependence for pions, kaons and protons, as is shown in Fig. 3.4. These differences allow the identification of the different particle types with an efficiency of 98% for pions, 87% for kaons and 92% (82%) for protons (antiprotons).²

**Transition Radiation Detector**

The purpose of the *Transition Radiation Detector* (TRD) is to provide a pion rejection factor of at least 100 for electrons or positrons. The efficiency above 5 GeV for electron/positron detection is above 90%. Transition radiation is emitted when a charged particle crosses the boundary of materials with different dielectric constants. At 5 GeV the energy loss ($dE/dx$) of a pion in the detector is approximately 11 keV, while an electron deposits about twice as much energy due to transition radiation and the relativistic rise in $dE/dx$.

The detector consists of 2 halves of 6 sandwich modules alternating radiator material and X-ray detectors. The signal from the TRD is obtained by the combination of 5 out of 6 modules, where the one which received the largest signal is rejected. This method is called the *truncated-mean average*, and is meant to reduce proton-hadron signal overlap.

²The RICH efficiencies reported here are evaluated in the specific case of the analysis presented in chapter 6.
3.2. The spectrometer

Figure 3.4: The Čerenkov angle $\theta$ versus hadron momentum for the aerogel (upper band) and $C_4F_{10}$ gas radiators (lower band). The data shown are based on a Monte Carlo simulation.

Figure 3.5: Analogue signals from the four Particle Identification Detectors in HERMES. The Monte Carlo results of the separated signals of hadrons and DIS positrons are shown for each of the four detectors. In this simulation the threshold Čerenkov detector is used rather than the RICH which was installed in 1998.
Pre-shower and Calorimeter

A lead glass calorimeter and a pre-shower hodoscope are used in the first level trigger to identify scattered positrons or electrons based on the difference between electromagnetic and hadronic shower in a localized energy region ($\geq 3.5$ GeV for un polarized targets). The calorimeter is also used to measure the energy of the scattered leptons, and photons from radiative decay of $\pi^0$ and $\eta$ mesons. The energy resolution of the calorimeter is parameterized as [54]

$$\frac{\sigma(E)}{E_{\text{calo}}} = \frac{5.1 \pm 1.1}{\sqrt{\text{E}[\text{GeV}]}} + (2.0 \pm 0.5)[\%].$$  \hspace{1cm} (3.1)

The depth of each of the $9 \times 9 \times 50 \text{ cm}^3$ glass blocks corresponds to 18 radiation lengths. The electrons therefore will lose all their energy in the calorimeter while the hadrons will deposit only a fraction of their energy. The ratio $E/p$ can be used to distinguish electrons from hadrons, where $E$ is the deposited energy in the calorimeter and $p$ the momentum determined by the spectrometer.

The pre-shower detector consists of a $1.1 \text{ cm} \text{ Pb}$ layer in front of the hodoscope denoted by H2 in the diagram. The passive radiator initiates electro-magnetic showers that deposit more energy for leptons in the scintillator than other minimum ionizing particles (hadrons). While pions deposit only 2 MeV, positrons are distinguished by a broad distribution with a mean deposited energy of about 20-40 MeV. The pre-shower resolution adds to the calorimeter once resulting in the total energy resolution given by [54]

$$\frac{\sigma(E)}{E} = \left( \frac{\sigma(E)}{E}_{\text{calo}} \right) + \frac{10.0 \pm 2.0}{E[\text{GeV}]} [\%].$$  \hspace{1cm} (3.2)

Particle identification scheme

In order to discuss the overall particle identification properties of the HERMES spectrometer, the results of a Monte Carlo simulation of the yield of each PID detector for hadrons and leptons separately are given in Fig. 3.5. The signals from the four detectors are usually combined using a likelihood method, which allows to convert the observed signal strengths into true probabilities for hadron or lepton identification using Bayes’ theorem:

$$P^i = \frac{\Phi^i \mathcal{L}^i}{\sum_j \Phi^j \mathcal{L}^j},$$  \hspace{1cm} (3.3)

where $\Phi^i$ is the flux of particles of type $i$ which is (generally) a function of momentum and scattering angle, and $\mathcal{L}^i$ is the likelihood for observing a particle of type $i$ for which the amplitude of the signal in a given detector is taken. The PID function which is used in practical data analyses, is evaluated according to:

$$\text{PID} = \log_{10} \frac{P^e}{P^h} = \log_{10} \frac{\mathcal{L}^e}{\mathcal{L}^h} + \log_{10} \frac{\Phi^e}{\Phi^h},$$  \hspace{1cm} (3.4)
where $P^{e(h)}$ is the probability that the reconstructed particle is a lepton(hadron), and $P^{e} + P^{h} = 1$. For the ratio of likelihoods $\frac{L^{e}}{L^{h}}$ the signals from the various PID detectors are combined as follows [55]:

$$\log_{10} \frac{L^{e}}{L^{h}} = \log_{10} \frac{L_{\text{Cal}}^{e} \cdot L_{\text{Pre}}^{e} \cdot L_{\text{Cer}}^{e}}{L_{\text{Cal}}^{h} \cdot L_{\text{Pre}}^{h} \cdot L_{\text{Cer}}^{h}} + \log_{10} \frac{L_{\text{TRD}}^{e}}{L_{\text{TRD}}^{h}}$$

(3.5)

where PID$_{3}$ indicates the sum of the 3 likelihoods of Čerenkov, Pre-shower and Calorimeter and PID$_{5}$ the sum of the 5 likelihoods of the TRD modules according to the truncated-mean method. In the analysis performed after the year 1998 the Čerenkov likelihood is removed from the PID scheme and a new function called PID$_{2}$ is defined containing only the calorimeter and pre-shower information, while the RICH information is analyzed separately as explained in the next subsection. In order to be able to select well defined regions of the yield of all PID detectors the electron efficiency $\epsilon$ and hadron contamination $h$ can be calculated from the probability functions defined in Eq. (3.3) as follows:

$$\epsilon = \frac{\int_{-\infty}^{\infty} d\text{PID} \; P^{e} \; N}{\int_{-\infty}^{\infty} d\text{PID} \; P^{e} \; N}$$

(3.6)

$$h = \frac{\int_{-\infty}^{\infty} d\text{PID} \; P^{h} \; N}{\int_{-\infty}^{\infty} d\text{PID} \; N}$$

(3.7)

where the integrals are evaluated using only the PID variables implicitly defined in Eq. (3.5), and $N$ is the number of particles at a given PID value. With this method it has been found that electrons and positrons can be identified with an efficiency of more than 98% and a hadron contamination of less than 1%.

**RICH particle identification**

The RICH PID combines the information from the reconstructed angles and the unknown threshold behavior of the response of both radiators, the aerogel and the $C_{4}F_{10}$ gas. Two methods are used to combine all this information into a particle identification response: Inverse Ray Tracing (IRT) and Direct Ray Tracing (DRT) [53]. For the purpose of the present analysis only the IRT method is applied, which is further described in Ref. [56].

For each hit in the PMTs one aerogel Čerenkov angle and one gas Čerenkov angle is reconstructed. The average angles resulting from the IRT method are compared to the simulated curves of Fig. 3.4 at the measured momentum with a likelihood analysis to obtain the probability that a given hadron produced the track. The likelihood algorithm defines for a known particle flux $\Phi_{t}$, a set of probabilities $P_{t}$ for a true particle of type $t$ to be identified as a
particle of type \( i \) (i.e. \( \pi, K, p \), or \( X \)) if the average angle reconstructed with the IRT method is \( < \theta > \). This set of identification probabilities is a \( 4 \times 3 \) matrix since it includes also the probability that a particle of type \( t \) is not identified by the RICH (type \( X \), or unknown):

\[
P(\pi, K, p) = \begin{bmatrix}
P_\pi^\pi & P_\pi^K & P_\pi^p \\
P_K^\pi & P_K^K & P_K^p \\
P_p^\pi & P_p^K & P_p^p \\
P_X^\pi & P_X^K & P_X^p \\
\end{bmatrix}.
\] (3.8)

However, what is needed in an analysis in order to extract the information of the true particle type is the complementary matrix of true type probabilities \( Q_i^t \) that a particle is identified as type \( i \) if it is truly of type \( t \):

\[
Q(\pi, K, p) = \begin{bmatrix}
Q_\pi^\pi & Q_\pi^K & Q_\pi^p & Q_X^X \\
Q_K^\pi & Q_K^K & Q_K^p & Q_K^X \\
Q_p^\pi & Q_p^K & Q_p^p & Q_p^X \\
Q_X^\pi & Q_X^K & Q_X^p & Q_X^X \\
\end{bmatrix}.
\] (3.9)

The diagonal terms of the left \( 3 \times 3 \) matrix are the purities for a certain data sample, the off-diagonal terms are the contaminations. The columns of the \( P \) and the \( Q \) matrices are normalized to unity. The relation between the \( P \) and the \( Q \) matrices is given by the Bayes’ theorem:

\[
Q_i^t = \frac{P_i^t \cdot \Phi_t}{\sum_s P_s^t \cdot \Phi_s},
\] (3.10)

where \( \Phi_t \) is the relative flux of hadrons of type \( t = \pi, K, p \) and \( i \) is the identified type \( (i = \pi, K, p, X) \). For each kinematic interval in momentum of the data sample in which the fluxes are calculated, the relation between the vectors of the numbers of true \( \bar{N} \) and identified \( \bar{I} \) particles is given by:

\[
\bar{N} = Q \cdot \bar{I}
\] (3.11)

or in terms of a matrix product,

\[
[N_\pi, N_K, N_p] = \begin{bmatrix}
Q_\pi^\pi & Q_\pi^K & Q_\pi^p & Q_X^X \\
Q_K^\pi & Q_K^K & Q_K^p & Q_K^X \\
Q_p^\pi & Q_p^K & Q_p^p & Q_p^X \\
\end{bmatrix} \cdot \begin{bmatrix}
I_\pi \\
I_K \\
I_p \\
I_X \\
\end{bmatrix}.
\] (3.12)

Eq. (3.12) is applied to the data in chapter 6 to identify pions, kaons and protons. Currently the \( P \) matrices used for the HERMES RICH detector are binned in momentum and also in track multiplicity to account for events with overlapping rings. While the \( P \) matrices are only dependent on the detector response, the \( Q \) matrices combine the performance of the detector to the relative particle fluxes of a data sample and therefore are analysis dependent. \( Q \) matrices are binned in momentum, track multiplicity and particle charge, to account for differences in the fluxes of opposite charges.
3.2.3 The luminosity monitor

A measurement of the integrated luminosity recorded during a certain time period is needed as a relative normalization factor to compare cross sections from different data sets, i.e. different spin states or different target gases. The luminosity accounts for differences in target thickness, beam intensity and beam position. The measurement is based on elastic scattering of beam positrons from atomic target gas electrons (Bhabha scattering). However, it should be noted that the named process $e^+e^- \rightarrow e^+e^-$ is indistinguishable from processes involving the annihilation of an electron and positron into two photon pairs $e^+e^- \rightarrow \gamma\gamma$ because the luminosity monitor cannot separate electrons from photons. The coincidences of scattered particles are detected in two arrays of $3 \times 4$ calorimeter blocks placed at $z = 7.2$ m from the center of the target and positioned at 3 cm left and right from the center of the beam pipe during standard data taking. During injection and dumping of the beam the luminosity detector is moved to a larger distance. The hit distribution in the calorimeters is shown in Fig. 3.6. Coincident pairs are selected requiring two signals with energy above 5 GeV in both the left and right calorimeter. An average rate of about 150 Hz provides a statistical accuracy of the luminosity measurement of 1% for every 100 s. It is noted that due to geometry and calibration differences care should be taken when data from different years are normalized by means of the luminosity monitor (see section 5.2.4).

Figure 3.6: Hit distribution in the calorimeter blocks of the luminosity monitor. The zero position in x and y indicates the center of the beam pipe
3.3 Data acquisition

3.3.1 Trigger

The HERMES first level trigger consists of discriminated signals from the hodoscopes plus a column-wise summed calorimeter signal and, in the years before 1998, the Čerenkov counter signal. The decision to initiate digitization and readout of an event is made within about 400 ns. In this way various triggers are constructed such as one for DIS events, photo-produced hadrons, etc.

The DIS trigger is the one most relevant for the analyses presented in this thesis. It requires a hit in each of the three hodoscopes H0, H1 and H2, plus energy deposition in one of the calorimeter columns above threshold. As a clock to synchronize the trigger the HERA electron bunch timing is taken. The calorimeter threshold for unpolarized data taking is set to 3.5 GeV, which equals a cut at $y < 0.87$. Such a setting suppresses the charged hadronic background by a factor of more than 10 in the trigger. The pre-shower threshold is set below the level of minimum ionizing particle to suppress hadronic showers depositing enough energy. The requirement of a signal in the hodoscope H1 ensures a complete track behind the spectrometer magnet and helps to suppress neutral particle background. A time window set around the HERA clock signal works efficiently to suppress the background from protons coming from the HERA proton ring passing through the detector in the opposite direction.

3.3.2 Data acquisition system

The HERMES Data AcQuisition system (DAQ) consists of two separated parts, the front-end electronics located in a trailer close to the experimental area and the online workstation cluster. The connection between the two is realized with optical fibers. The maximum DAQ throughput is 1.5 Mbyte/s. Raw events are collected online and separated in runs, of about 450 Mbyte recorded data. During the time needed for the digitization and readout of the detector, no new trigger can be accepted, leading to a trigger dead time. For each trigger a dead time fraction $\delta_i$ is defined as:

$$\delta_i = 1 - \frac{T_{\text{acc}}^i}{T_{\text{gen}}^i},$$

(3.13)

where $T_{\text{acc}}^i$ and $T_{\text{gen}}^i$ are the number of accepted and generated triggers of type $i$ respectively. The dead time fraction is dependent on the trigger rate. For each trigger a value of $\delta_i$ is given every 10 seconds, the period of time (chosen arbitrarily) referred to as a burst. Data are normally analyzed which have $\delta_i$ above 0.5, but a typical value for the dead time is higher (i.e. for the DIS trigger dead time around 0.9).