Quark fragmentation to $\pi^{\pm}$, π^{0}, $K^{\pm}$, p and $\bar{p}$ in the nuclear environment

When an electron (or its anti-particle, the positron) of sufficiently high energy is incident on a target, it interacts via the exchange of a virtual photon with one of the constituents of the nucleons: the quarks. After the quark has absorbed the photon, it has high energy, and begins to depart the target nucleon. However, it is a unique feature of the interaction between quarks, the "strong force", that it is not possible for a quark to exist in isolation. We can imagine that as a quark leaves a nucleon, a string is stretched between it and the remaining quarks. As the string is stretched, it stores some of the kinetic energy of the struck quark. When the energy content of the string exceeds a certain threshold, the string breaks, creating a new quark (q) and anti-quark ($\bar{q}$) at the new ends of the string fragments. Some of the energy stored in the string appears as the (small) masses of the new quarks. The quark from the $q\bar{q}$ pair combines with the remaining quarks, while the antiquark combines with the outgoing quark, resulting in the formation of a pion, in this case. This process, also known as the fragmentation of quarks into hadrons, can be described by fragmentation functions $D_f^h(z)$, denoting the probability that a quark of flavor f produces a hadron of type h carrying a fraction z of the energy of the struck quark.

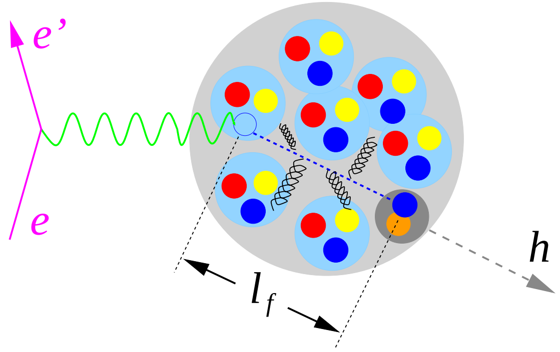

Figure 1: Pictorial view of hadron formation in the electron scattering. A quark in one of the nucleons in the nucleus is hit, resulting in the formation of hadrons

Experimental information on the hadronization process can be obtained by embedding the formation process in an atomic nucleus, which acts as an ensemble of targets as depicted in Fig. 1. The observed hadron yield is reduced by the interaction of the struck quark and of the formed hadron inside the nucleus. Specifically, quark propagation in the nuclear environment involves processes like multiple interactions with the surrounding medium resulting in energy loss of the quark. If the final hadron is formed inside the nucleus, the hadron can also interact with the nucleons via the relevant hadron-nucleon interaction cross section, causing a further reduction of the hadron yield.

The quark and hadron interactions are discriminated according to the time $\tau_f = l_f/c$ of the hadron formation which may occur inside or outside the nucleus. Hence the ratio of the number of hadrons per electron scattered (this quantity is called multiplicity) produced on a heavy nucleus of mass number A to that on deuterium (D) can provide information on the space-time development of the hadronization process as well as on the in-medium modification of the fragmentation functions $D_f^h(z)$.

In order to optimize the influence of the nuclear environment on the hadronization process it is important that the energy ν transferred from the incident beam to the target is not larger than about 30 GeV. In this case the length-scales involved in the hadronization process (which can be estimated as hc/ν) are of the same order of the nuclear size. In this respect the energy domain covered by HERMES is well suited as ν ranges from 7 to 23 GeV.

Recently HERMES reported on the multiplicity of charged hadrons and identified π^+ and π^- from nitrogen relative to that from deuterium. A significant difference was found between the multiplicity ratio of positive and negative hadrons, while the multiplicity ratio for identified pions was found to be the same for both charges. Thus this difference must be caused by other hadrons, such as protons, antiprotons and kaons. This unexpected result was attributed to the protons contributing to the positive hadron sample, since their fraction is four time larger than the antiproton fraction in the negative hadron sample. As the multiplicity ratio for positive hadrons was higher compared to the ratio for negative hadrons, this implies that the protons should be less attenuated in the nuclear medium. In order to clarify this issue, additional measurements with identification of other hadron species have been performed at HERMES.

In this paper the multiplicities measured on krypton relative to that of deuterium are presented which includes for the first time data for various identified hadrons: charged and neutral pions ($\pi^\pm$, π^0), charged kaons ($K^\pm$), protons and antiprotons (p, $\bar{p}$).

The complete particle identification in HERMES, achieved with the installation of the RICH detector in 1998, allows the information for different hadron types to be fully disentangled. This is shown in Fig. 2 where the multiplicity ratios R_M^h between Kr and D nuclei are presented as function of z (the fraction of the energy of the struck quark carried by the hadron) for the first time for various identified hadrons. The multiplicity ratios for π^+ and π^- are seen to be in agreement with what was already found on ^{14}N shown in the upper panel of Fig. 2. In addition, the multiplicity ratio for neutral pions is found to be consistent with that for charged pions. Also the medium effects on K^- production are similar to the pion case. Quite interesting is the difference between K^+ and K^-. An even larger difference is observed between p and $\overline{p}$. In particular the multiplicity ratio for the proton is strongly different in the low-z region, which contains contributions from both the target fragmentation hadrons and hadrons decelerated in nuclear re-scattering.

The different results for different hadrons may reveal differences in the modification of q and $\overline{q}$ fragmentation functions $D_f^h(z)$, thus leading to a more significant difference between the multiplicity ratio of protons and antiprotons than between those of pions and kaons.

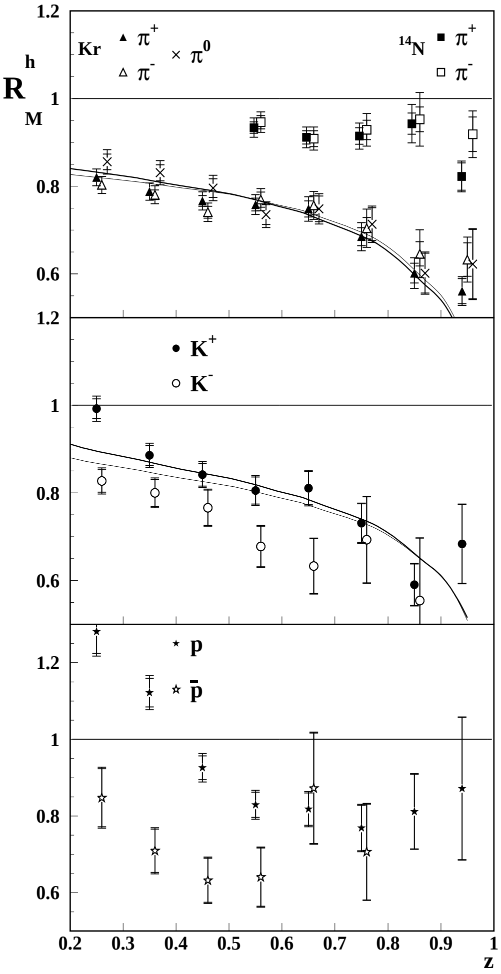

Figure 2: HERMES multiplicity ratio Kr/D for various identified hadrons as a function of z. The multiplicity ratio N/D for identified charged pions is also shown. The thick (thin) solid lines represents recent theoretical calculation for positive (negative) charge states.

The observed differences in the multiplicity ratios may also suggest different formation times of p and $\bar{p}$ compared to the one of π and K, due to the fact that protons and antiprotons are formed by three quarks instead of two quarks like pions and kaons. Also the different hadron-nucleon interaction cross sections for various hadrons can play a role: while this cross section is similar for positive and negative pions, it is larger for negative kaons as compared to positive kaons, and even larger for antiprotons than protons, in qualitative agreement with the trend shown by the data.

An interesting insight for the mass number dependence of the nuclear attenuation (defined as 1-R^h_M) comes from the comparison between the krypton and nitrogen data for charged pions. The experimental data are found to be consistent with the $A^{2/3}$-dependence predicted by theoretical models containing a so-far untested prediction, i.e. the energy loss of a quark traversing a length L of nuclear matter is proportional to L^2 (or equivalently to $A^{2/3}$). Data on more nuclei are needed to enable systematic studies of the A-dependence of nuclear attenuation effects.