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HADRONIZATION PROCESS IN DEEP INELASTIC SCATTERING AT HERMES

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The influence of the nuclear medium on lepto-production of hadrons was studied in the HERMES experiment at DESY in semi-inclusive deep-inelastic scattering of 27.6 GeV and 12 GeV positrons off deuterium, and off light and heavy targets. The differential multiplicity for nuclei relative to that of deuterium has been measured for the first time for various identified hadrons (π^+, π^-, π^0, K^+, K^-, p and $\bar{p}$) as a function of the virtual photon energy ν, the fraction z of this energy transferred to the hadron, and the hadron transverse momentum squared p_t^2.

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1. Introduction

The inclusive deep-inelastic-scattering (DIS) of high energy leptons on free nucleons has been used from late 60s to measure the partonic distributions and, by using nuclear targets, to study the medium modification to these distributions. These modifications were found to be large and were explained by invoking medium effects at both hadronic and partonic levels (see Ref. [1] for a review). Semi-inclusive DIS (SIDIS) of high energy leptons on free nucleons can be used to study another fundamental property of the quarks, the fragmentation function. This function can also be modified by the nuclear medium and this modification can be revealed by performing SIDIS measurements on nuclear targets.

2. Fragmentation functions and multiplicities

The SIDIS diagram and the relevant variables for this process are shown in Fig. 1. The SIDIS process can be factorized in a parton distribution function q_f, which is function of the Bjorken scaling variable $x = Q^2/(2M\nu)$, a hard scattering

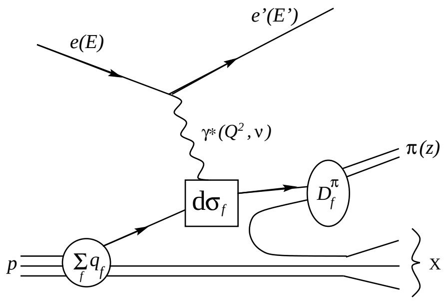

Fig. 1. Diagram of deep inelastic scattering on proton with the exchange of a virtual photon of 4-momentum Q^2 and energy $\nu = E - E'$. In inclusive DIS, only the scattered lepton e′ is detected. In semi-inclusive DIS, also the leading hadron (π in this case), which is formed from the fragmentation of the struck quark, is detected with a fractional energy z with respect to ν. The target fragments X are not observed in semi-inclusive DIS.

cross section $\mathrm{d}\sigma_\mathrm{f}$ calculable in QCD, and a parton fragmentation function D_f^h. The fragmentation function $D_\mathrm{f}^\mathrm{h}(z)$ represents the probability for a quark of flavour f to fragment into a specific hadron h carrying a fraction $z = E_\mathrm{h}/\nu$ of the energy of the struck quark. In analogy with the parton distribution functions, the fragmentation functions depend on a scaling variable z.

In the quark parton model (QPM) description of SIDIS, the fragmentation functions are multiplied by the parton distributions, and experimental hadron multiplicities M^h are determined by normalizing the SIDIS yield N^h to the DIS rate N_DIS:

$$M^\mathrm{h} = \frac{1}{N_\mathrm{DIS}} \frac{\mathrm{d}N^\mathrm{h}(x,z)}{\mathrm{d}z} = \frac{\sum_\mathrm{f} e_\mathrm{f}^2 q_\mathrm{f}(x) D_\mathrm{f}^\mathrm{h}(z)}{\sum_\mathrm{f} e_\mathrm{f}^2 q_\mathrm{f}(x)}$$

Within the QPM and under the u-quark dominance assumption, the pion multiplicities are almost equivalent to the pion fragmentation functions. In QCD, the relation between fragmentation functions and multiplicities is more complicated since both the leading order (LO) and the next to leading order (NLO) terms of the cross section are convoluted with parton distributions and with the hadron fragmentation functions [2]. Nevertheless, it has been shown [3] that, once integrating over a broad range of x, the SIDIS multiplicities are in good agreement with the NLO-QCD evolution of fragmentation functions determined from e^+e^- measurements at LEP. This result suggests the validity of the factorization assumption for the SIDIS process, as shown in Fig. 1, and of the approximation of fragmentation functions with multiplicities.

3. Hadronization in the nuclear medium

The study of the medium modification of fragmentation functions can be performed by SIDIS measurements on nuclear targets. As illustrated in Fig. 2, the

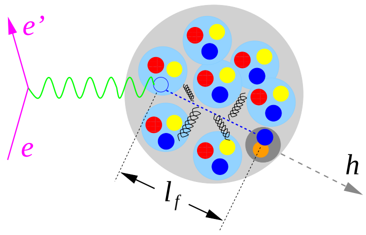

Fig. 2. Pictorial view of SIDIS in nuclei. The observed hadron yield is reduced by the interaction of the struck quark and of the formed hadron inside the nucleus.

nucleus acts as an ensemble of targets which reduce the multiplicity of fast hadrons due to both partonic and hadronic interactions. The partonic and hadronic effects are discriminated according to the time $\tau_{\rm h}$=$l_{\rm h}/c$ of the hadron formation which may occur inside or outside the nucleus. The hadron formation times, which are basic ingredients also in hadron-nucleus and in heavy-ion reactions, are currently not well determined [4].

The experimental results for semi-inclusive deep-inelastic scattering on nuclei are usually presented in terms of the hadron multiplicity ratio $R_{\rm M}^{\rm h}$, which represents the ratio of the number of hadrons of type h produced per deep-inelastic scattering event on a nuclear target of mass A to that from a deuterium target. The ratio $R_{\rm M}^{\rm h}$ depends on the leptonic variables ν and Q^2, and on the hadronic variables z and $p_{\rm t}^2$, where $p_{\rm t}$ is the hadron momentum component transverse to the virtual photon direction. After the first measurements performed at SLAC [5] and CERN [6], the recent results from HERMES [7, 8] provided a new strong boost of interest in this field [9].

HERMES is an experiment at DESY [10] which is mainly devoted to the study of the spin structure of the nucleon by using a polarized positron (or electron) beam and polarized internal gas targets. In addition, some HERMES runs have been performed with unpolarized nuclear gas targets (D, ^{4}He, N, Ne, Kr) with densities up to $\sim 10^{16}$ nucl/cm^2, allowing the extension of the physics program to the study of several nuclear effects both with an incident beam of 27.5 GeV and 12 GeV [11].

In the HERMES spectrometer, both the scattered positrons and the produced hadrons are detected and identified within an angular acceptance of $\pm$ 170 mrad horizontally and $\pm$ (40-140) mrad vertically. This system provided positron identification with an average efficiency of 99 % and an hadron contamination of less than 1 %. The charged hadron type identification is performed by the dual-radiator RICH detector, which was installed in 1998 replacing the previous threshold Čerenkov gas detector; the identification of neutral pions is accomplished using the electromagnetic calorimeter. The large acceptance and the complete particle identification make HERMES well suited for performing semi-inclusive measurements. To minimize the fraction of hadrons produced in the target fragmentation and to ensure the factorization of the SIDIS process, only fast hadrons with $z > 0.2$ are considered in the extraction of the hadron multiplicity.

In the left panel of Fig. 3, the 27 GeV data for the fast hadron multiplicity ratios, as function of ν for N and Kr, are shown in comparison with data from earlier experiments. As it is seen, the HERMES kinematics is well suited to study quark propagation and hadronization, and the results indicate an increase of the multiplicity ratio (thus a decrease of the medium effect) with ν, in agreement with the higher-energy EMC data. The discrepancy with SLAC is partially due to the EMC effect, not considered in the SLAC data which were normalized to the luminosities instead of to the DIS cross sections. In the right panel of Fig. 3, the 12 GeV and the 27 GeV data for positive and negative hadrons are presented, showing for the first time a difference in $R_{\rm M}^{\rm h}$ of positive and negative hadrons.

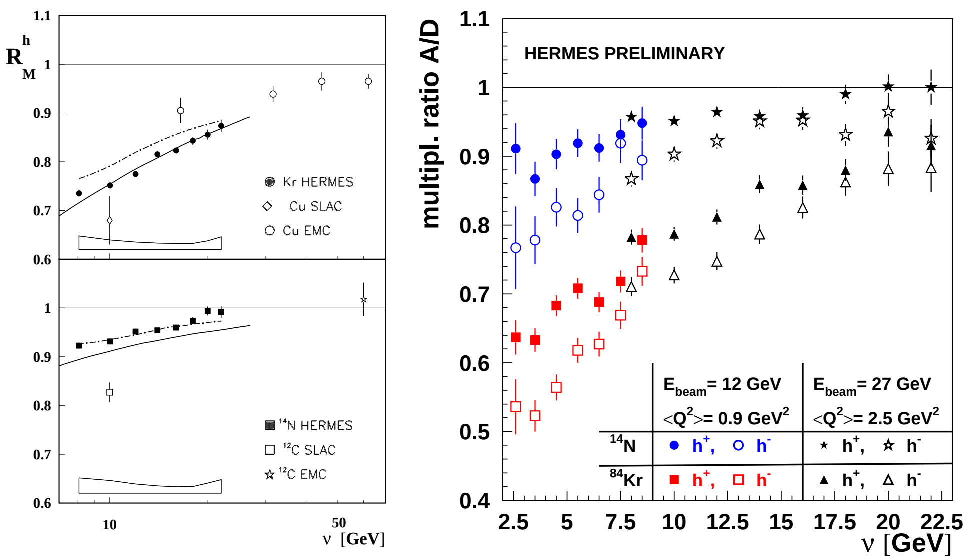

Fig. 3. Multiplicity ratios as a function of ν for hadrons with $z > 0.2$ for HERMES, SLAC and EMC (left panel). The solid curves are calculations from Ref. [16] and the dot-dashed curves are calculations from Ref. [12]. Multiplicity ratios for positive and negative hadrons at 12 GeV *and 27* GeV *beam energy (right panel).*

The complete particle identification in HERMES allows to fully disentangle the information for different hadron types. For the first time, the multiplicity ratios were studied for identified neutral and charged pions, kaons, protons and antiprotons, as shown in Fig. 4. The ν-dependences of $R_{\rm M}^{\rm h}$ and the corresponding z-dependences are shown in the right part and in the left part of Fig. 4, respectively. As it is seen, the medium effects for charged and neutral pions are similar. Also the medium effects on $\rm K^-$ production are similar to the pion case. Quite interesting is the difference between $\rm K^+$ and $\rm K^-$ and especially between p and $\overline{p}$. In particular the effect for the proton is strongly different at low-z, where a contamination from the target fragmentation can contribute.

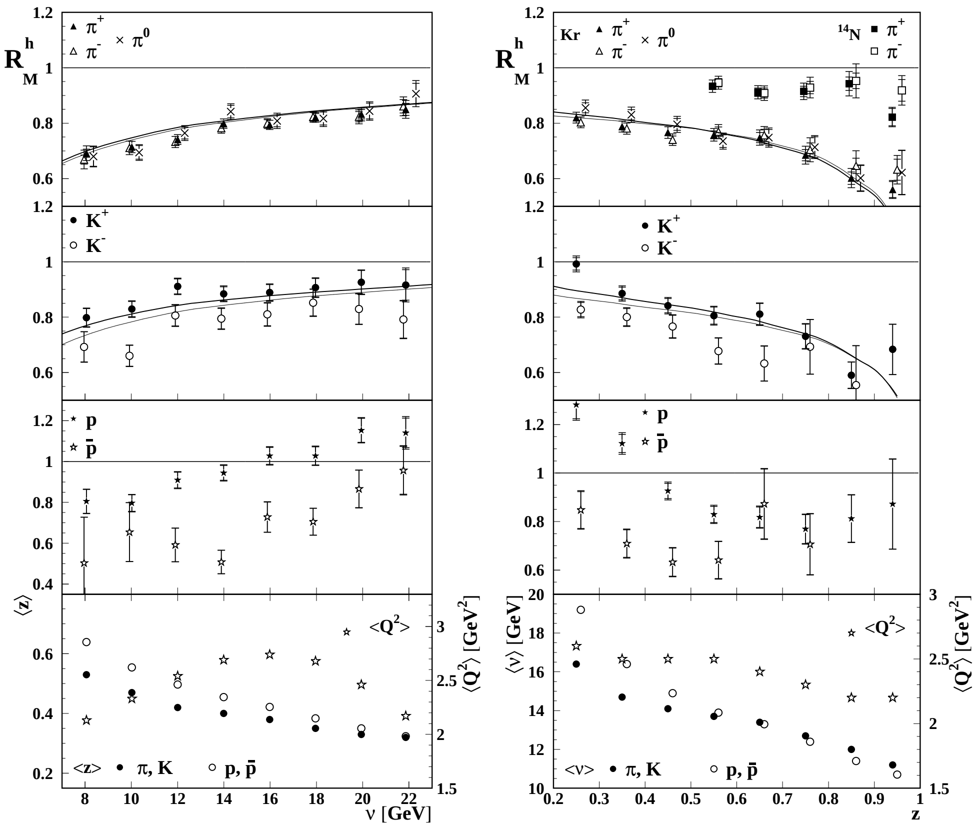

Fig. 4. HERMES multiplicity ratio for Kr *for different charged hadrons as a function of ν (left panel) and z (right panel). In the lower panels, the relevant average kinematic variables are presented for each ν- or z-bin. The thick (thin) solid curves represent the calculations of Ref. [16] for positive (negative) charge states.*

The attenuation ratios for identified hadron has been recently measured also for ^{4}He and ^{20}Ne. The preliminary results presented in Fig. 5 for pions, kaons, protons and antiprotons clearly show the different attenuation ratios for different hadrons in all studied nuclei.

The observed differences may reveal different modification of q and $\overline{q}$ fragmentation functions [12], thus leading to a more significant difference between the multiplicity ratio of protons and antiprotons than between those of mesons. The experimental results can also be interpreted in terms of different formation times of baryons and mesons [13], or in terms of different hadron-nucleon interaction cross sections [14]. 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.

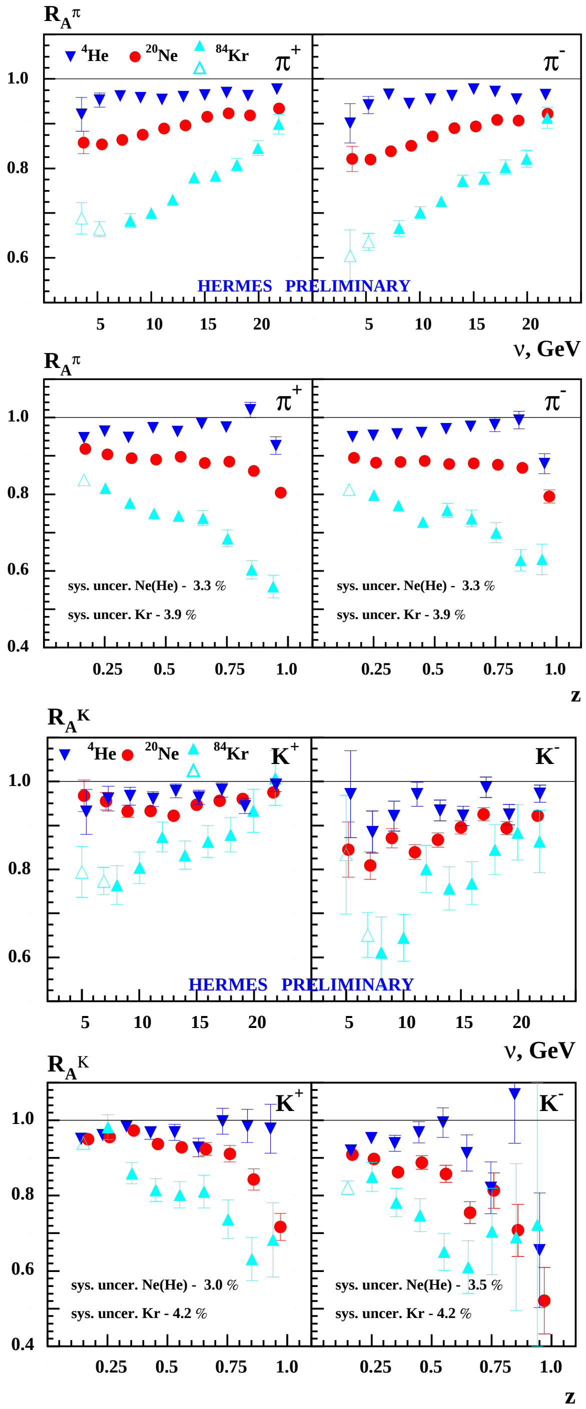

Fig. 5. HERMES multiplicity ratios for ^{4}He, ^{20}Ne *and* Kr *for identified charged pions, kaons (at left) protons and antiprotons (at right) as a function of* ν *and* z*.*

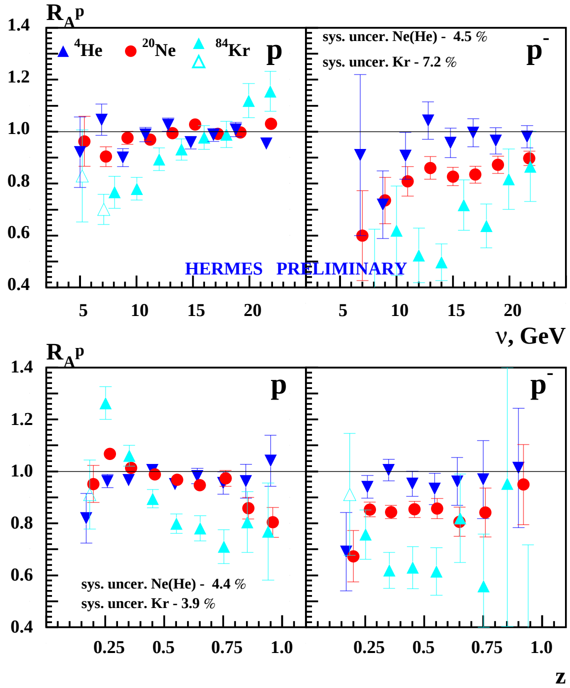

Fig. 5 (continued). HERMES multiplicity ratios for ^{4}He, ^{20}Ne *and* Kr *for identified charged pions, kaons (at left) protons and antiprotons (at right) as a function of* ν *and* z.

4. *Modification of the* $p_{\rm t}$ *distribution*

The scattering of quark and gluon increases the transverse momentum $k_{\rm t}$ of the struck quark compared to its intrinsic value and, as consequence, the transverse momentum $p_{\rm t}$ of the leading hadron. This effect is known as the Cronin effect [18] and has previously been observed in many hadronic reactions like in pA collisions or in high-energy heavy-ion collisions performed at CERN SPS [19], as shown in the left panel of Fig. 6.

A nuclear enhancement at high $p_{\rm t}^2$ is also observed in the HERMES data shown in the right panel of Fig. 6. In this plot, the EMC [6] data on Cu, which cover a different ν-range $10 < \nu < 80$ GeV, are also displayed. The data for $p_{\rm t}^2 < 0.7$ GeV^2 show the attenuation previously discussed, while the data for $p_{\rm t}^2 \geq 0.7$ GeV^2 reflect the $p_{\rm t}$ broadening ascribed to multiple scattering effects. This effect is similar to the one reported for proton-nucleus and nucleus-nucleus collisions but is smaller in magnitude. The enhancement is also predicted to occur at a $p_{\rm t}$-scale of about $1-2$ GeV [20, 21], in agreement with the semi-inclusive deep-inelastic scattering data shown in Fig. 6. The HERMES data may help to interpret the new relativistic heavy-ion results from SPS [22] and RHIC [23], which show a weaker $p_{\rm t}$ enhancement than expected from the original Cronin effect.

The $p_{\rm t}$ broadening in SIDIS is predicted [24] to depend on the multiparton correlation functions inside a nucleus and to be proportional to the nuclear radius. Therefore, it will be important to measure the p_{t} broadening on several nuclei and for different hadron types.

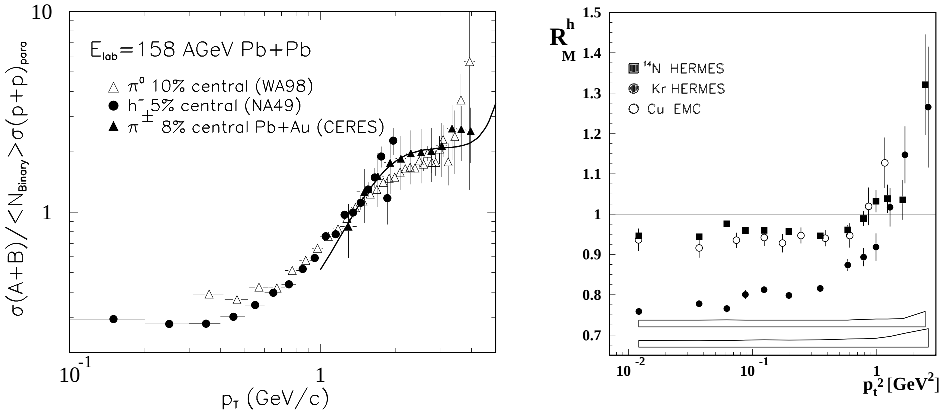

Fig. 6. p_{t}-dependence of of nuclear modification factor in heavy ion reactions (left) and of the nuclear multiplicity ratio in SIDIS (right). The curve is a calculation which considers multiple parton scattering process in the framework of the Glauber formalism.

5. *Recent theoretical predictions*

The hadronization process in the nuclear medium is traditionally described in the framework of the phenomenological string models and final-state interactions of the produced hadrons with the surrounding medium. Alternatively, in-medium modifications of the quark fragmentation functions have been recently proposed.

In Ref. [12], the modification of quark fragmentation functions and their QCD evolution are described in the framework of multiple parton scattering. No subsequent interaction of the produced hadrons in the nuclear medium has been included, which is at variance with the description of the hadronization process in terms of both parton and hadron interactions. As a consequence of the partonic energy loss $\mathrm{d}E/\mathrm{d}x$ due to the induced gluon radiation, the fragmentation function in the nucleus $D^{\mathrm{A}}(z, Q^2)$ is modified compared to the one in deuterium $D^{\mathrm{D}}(z, Q^2)$. In Fig. 3, the predictions for $D^{\mathrm{A}}(z, Q^2)/D^{\mathrm{D}}(z, Q^2)$ are compared to the HERMES data for charged hadrons. In the framework of this calculation, for a cold and static system like the nucleus, the quark energy loss involved in SIDIS reaction has been determined. The extracted energy loss is $\mathrm{d}E/\mathrm{d}x \approx 0.5$ GeV/fm for a quark with $E = 10$ GeV in an Au nucleus. Including the effect of the expansion, an increase of the gluon density of a factor ~ 15 has been derived for the initial hot stage of $\mathrm{Au} + \mathrm{Au}$ collisions at RHIC at $\sqrt{s}$=130 GeV.

A theoretical description of the HERMES data in terms of in-medium distribution of the parton energy loss has been recently given in Ref. [15]. In this model, the mean energy loss has been fixed by fitting the Drell–Yan data and the corresponding modified fragmentation function computed. The calculation quite well reproduce the HERMES data, and the derived energy loss per unit length $\mathrm{d}E/\mathrm{d}x = 0.62$ GeV/fm is close to the result of Ref. [12].

In Ref. [17], the combined effect of the fragmentation-function modification due to the induced gluon radiation and of the hadron interaction inside the nucleus has been calculated. The contribution due to the interaction of the pre-formed hadron in the nuclear medium was found dominant compared to the one due to the induced gluon radiation.

Also in Ref. [16], the nuclear absorption of the pre-formed hadrons is seen to significantly affect the hadron production on heavy nuclei in the kinematic region of the HERMES experiment. In this work, the modification of quark fragmentation functions is considered in terms of Q^2-rescaling model, originally developed to interpret the EMC effect in the nuclear structure functions, and of absorption of the produced hadrons. The model predictions are shown in Fig. 4 where the charge- and flavour-separated theoretical multiplicities are compared with the data. A nice description for the $\pi^{\pm}$ and K^{+} data is obtained. For the K^{-} data, the slope of the prediction resembles that of the data, but less attenuation is predicted than observed. The discrepancy between theory and data has been suggested [16] to point to a different formation mechanism for the negative kaons, as they do not contain any valence quarks which dominate in the HERMES kinematics.

Finally, in Ref. [4] the HERMES data are described in terms of FSI of the produced hadrons without invoking any changes in the fragmentation function due to gluon radiation. The results are very sensitive to the pre-hadron interaction during the formation time, in agreement with the results of Refs. [17] and [16], that could also be interpreted as an in medium change of the fragmentation function.

In order to clearly disentangle between parton energy loss effect and hadron interaction in the nuclear medium, theoretical modeling of hadronization from p_{t}-dependence and from flavour-dependence of the fragmentation function for several nuclei will be probably necessary.

6. *Conclusions*

The recent and precise HERMES results in SIDIS on light and heavy nuclei have shown a significant nuclear attenuation for fast hadrons which can be interpreted as a in-medium modification of the parton fragmentation function. For the first time, different medium effects have been observed for different hadron types. In particular, while the effect for the pion does not depend on the charge, a sizable difference has been observed between K^{+} and K^{-} and between p and $\overline{p}$. The hadron multiplicity is observed to be enhanced at high p_{t} in the nuclear medium, showing evidence of the Cronin effect in DIS.

The SIDIS results are shown to provide information on the parton energy loss, on the p_{t}-broadening and on the characteristic time-distance scales of hadronization. These are basic ingredients for other hadronic reactions and in particular for the heavy-ion interactions at high energies, which are currently studied to provide hints for the quark gluon plasma formation.

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PROCES HADRONIZACIJE U DUBOKO-NEELASTIČNOM RASPRŠENJU U EKSPERIMENTU HERMES

Proučavamo utjecaj nuklearne tvari na leptonsku tvorbu hadrona u mjerenju HERMES u DESYu poluinkluzivnim duboko-neelastičnim raspršenjem pozitrona energije 27.6 GeV i 12 GeV u deuteriju, te lakim i teškim metama. Načinili smo prva mjerenja omjera diferencijalne višestrukosti za jezgre u odnosu prema deuteriju za više utvrđenih hadrona (π^+, π^-, π^0, K^+, K^-, p and $\bar{p}$) u ovisnosti o virtualnoj energiji fotona ν, dijela te energije z predane hadronu i kvadrata poprečnog impulsa p_t^2.