Double-hadron leptoproduction in the nuclear medium

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The first measurements of double-hadron production in deep-inelastic scattering within the nuclear medium were made with the HERMES spectrometer at HERA using a 27.6 GeV positron beam. By comparing data for deuterium, nitrogen, krypton and xenon nuclei, the influence of the nuclear medium on the ratio of double-hadron to single-hadron yields was investigated. Nuclear effects on the additional hadron are clearly observed, but with little or no difference among nitrogen, krypton or xenon, and with smaller magnitude than effects seen on previously measured single-hadron multiplicities. The data are compared with models based on partonic energy loss or pre-hadronic scattering, and with a model based on a purely absorptive treatment of the final state interactions. Thus, the double-hadron ratio provides an additional tool for studying modifications of hadronization in nuclear matter.

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Hadron production from a free nucleon in deep-inelastic scattering is generally described by fragmentation functions that contain non-perturbative information about parton hadronization. These functions are expected to be different for nuclear targets because of several possible effects: energy loss of the propagating quarks, rescattering during the pre-hadronic formation process or interactions of the final-state hadrons within the nucleus.

Despite recent accurate experimental data from single-hadron lepton production and relativistic heavy-ion collisions, the underlying mechanisms in theoretical models for hadronization in the nuclear medium differ greatly. In-medium modification of the quark fragmentation function has been described in terms of rescattering of gluons and quarks, and of energy loss due to induced gluon radiation. Alternatively, colorless pre-hadron rescattering in the medium has been suggested with additional effects due to $Q^2$ rescaling. Older interpretations based on hadronic final-state interactions require a hadron formation length smaller than the nuclear size, which is unlikely for struck quarks boosted to energies larger than a few GeV. Although models based on some of these ideas are already in conflict with data, clearly other types of data are needed to further distinguish among these interpretations.

Double-hadron lepton production offers an additional way to study hadronization. If partonic energy loss of the struck quark were the only mechanism involved, it would be naively expected that the attenuation effect does not depend strongly on the number of hadrons involved, and the double-hadron to single-hadron ratio for a nuclear target should be only slightly dependent on the mass number $A$. On the contrary, if final hadron absorption were the dominant process, the requirement of an additional slower sub-leading hadron that is more strongly absorbed would suppress the two-hadron yield from heavier nuclei, so that this ratio should decrease with $A$.

Data from STAR on hadron pair production as a function of azimuthal angle showed that for a fixed value of the trigger hadron’s transverse momentum, the production of opposite-side hadron pairs is completely suppressed for central Au+Au collisions due to the final-state interactions with the dense medium generated in such collisions. On the other hand, the same-side pairs exhibit jet-like correlations that are similar to $p+p$ and $p+d$ collisions. These results were used in Ref. to advocate the picture that jet fragmentation occurs outside the dense medium. In this model it has been shown that if hadron absorption or rescattering were responsible for the observed hadron suppression, it would likely destroy the jet structure, and in particular the correlations between leading and sub-leading hadrons within the jet cone. However, the heavy-ion data cannot exclude hadronic absorption effects completely.

In this paper the first measurement of double-hadron lepton production on nitrogen, krypton and xenon relative to deuterium is presented. All charged hadrons and $\pi^0$ mesons are considered.

Semi-inclusive deep-inelastic scattering data are presented in terms of the ratio

$$R_{2h}(z_2) = \frac{(dN^{z_1>0.5}(z_2)/dz_2)_A}{(dN^{z_1>0.5}(z_2)/dz_2)_D},$$

in which $z = E_h/\nu$ is the fractional hadronic energy, $E_h$ is the hadron energy and $\nu$ is the virtual photon energy, all of which are evaluated in the target rest frame. The values $z_1$ and $z_2$ correspond to the leading (largest $z$) and sub-leading (second largest $z$) hadrons, respectively. The quantity $dN^{z_1>0.5}$ is the number of events with at least two detected hadrons in a bin of width $d_z$ at $z_2$ with $z_1 > 0.5$. The quantity $N^{z_1>0.5}$ is the number of events with at least one detected hadron with $z_1 > 0.5$. The label $A(D)$ indicates that the term is calculated for a nuclear (deuterium) target.

The measurement was performed with the HERMES spectrometer using the 27.6 GeV positron beam stored in the HERA ring at DESY. The spectrometer consists of two identical halves located above and below the positron beam pipe. The scattered positrons and the produced hadrons were detected simultaneously within an angular acceptance of $\pm 170$ mrad horizontally, and $\pm (40 - 140)$ mrad vertically.

The nuclear targets, which were internal to the positron storage ring, consisted of polarized or unpolarized deuterium, or unpolarized high-density nitrogen.
krypton or xenon gas injected into a 40 cm long open-ended tubular storage cell. Target areal densities up to $1.4 \times 10^{16}$ nucleons/cm$^2$ were obtained for unpolarized gas corresponding to luminosities up to $3 \times 10^{33}$ nucleons/(cm$^2$ s).

The positron trigger was formed by a coincidence between the signals from three scintillator hodoscope planes, and a lead glass calorimeter where a minimum energy deposit of 3.5 GeV (1.4 GeV) for unpolarized (polarized) target runs was required. The scattered positrons were identified using a transition-radiation detector, a scintillator pre-shower counter, and an electromagnetic calorimeter. Scattered positrons were selected by imposing constraints on the squared four-momentum of the virtual photon $Q^2 > 1$ GeV$^2$, on the invariant mass of the photon-nucleon system $W = \sqrt{2M\nu + M^2 - Q^2} > 2$ GeV where $M$ is the nucleon mass, and on the energy fraction of the virtual photon $y = \nu/E < 0.85$ where $E$ is the beam energy. The constraints on $W$ and $y$ are applied to exclude nucleon resonance excitations and to limit the magnitude of the radiative corrections, respectively. In addition the requirement $\nu > 7$ GeV was imposed to limit the kinematical correlations between $\nu$ and $z$.

Charged hadrons (i.e. $\pi$, $K$ and $p$ without distinction) were reconstructed for momenta above 1.4 GeV. The electromagnetic calorimeter [19] provided neutral pion identification through the detection of neutral clusters originating from two-photon decay. Each of the two clusters was required to have an energy $E_\pi \geq 0.8$ GeV. The $\pi^0$ mesons were selected by requiring that the reconstructed invariant mass was within two standard deviations of the center of the $\pi^0$ mass peak.

The leading hadron was selected with $z_1 > 0.5$. In this case, it is expected to contain the struck current quark with high probability. No explicit constraint was applied to $z_2$. Both $z_1$ and $z_2$ were calculated assuming that all hadrons have the mass of the pion.

Using the code of Ref. [20], radiative corrections to $R_{2h}$ were found to be negligible in the whole kinematic range. This is because there is no elastic or quasi-elastic tail in semi-inclusive events, and the inelastic corrections largely cancel in the measured ratio.

Two methods of double-hadron event selection were used. Selection I contains only the combinations of hadron charges (leading-subleading) $++$, $-+$, $+0$, $0+$, $-0$, $0-$. This suppresses the contributions from $\rho^0 \rightarrow \pi^+\pi^-$ decay because the $-+$ and $++$ combinations are missing. Moreover, in the Lund string model, the exclusion of the opposite-charge combinations enhances the rank-1 (leading) plus rank-3 (sub-leading) combination [21]. The higher the particle rank, the more likely it is formed deep inside the nucleus, and the corresponding hadron absorption should be larger. Selection II contains all particle charge combinations. Here, the sub-leading hadron is mainly of rank-2 and the contribution from $\rho^0$ decay is larger. In both Selections I and II the relative yield from exclusive $\rho^0$ production in $N_{z_2} > 0.5$ is small and was evaluated by Monte Carlo calculation to be on the order of 12% for the deuterium target.

![Graph showing the ratio $R_{2h}$ as a function of $z_2$ for $^{14}$N (squares), Kr (circles) and Xe (triangles) with $z_1 > 0.5$. Only Selection I was considered. The systematical uncertainty is 2% for all the targets and is independent of $z_2$. In the upper panel the curves (solid for $^{14}$N, dashed for Kr, dotted for Xe) are calculated within a BUU transport model [18]. In the bottom panel the same data are shown with calculations that assume only absorption for the three nuclei (same line types as in the upper plot) [18].](image)

Fig. 1 shows the double ratio $R_{2h}$ as a function of $z_2$ for Selection I only. The kinematic variables are in the range $\langle \nu \rangle = 16$ GeV and $\langle Q^2 \rangle = 2.1$ to 2.6 GeV$^2$ as $z_2$ goes from 0.09 to 0.44. The averages over $z_2$ are $\langle \nu \rangle = 17.7$ GeV and $\langle Q^2 \rangle = 2.4$ GeV$^2$.

The ratio $R_{2h}$ is generally below unity with no significant difference between the three nuclei. These data clearly show that the nuclear effect in the double-hadron ratio is much smaller than for the single-hadron attenuation measured under the same kinematic conditions [10–12]. For $z_2 < 0.1$, where $R_{2h}$ rises towards and possibly above 1, the slow hadrons originate largely from target fragmentation [10, 12]. Also for $z_2 > 0.4$, where the two hadrons have similar energy, $R_{2h}$ seems to rise towards
The systematic uncertainty is 4% (3%) for xenon and krypton as for nitrogen above $z_2$ = 0.1, which is not supported by the data.

FIG. 2: The ratio $R_{2h}$ as a function of $z_2$ for $^{14}$N (squares), Kr (circles) and Xe (triangles) with $z_1 > 0.5$ for Selection II. The data are presented. The ratio of double- to single-hadron yields $R_{2h}$ calculated for all hadron charge combinations (Selection II). Inclusion of the $\omega$ and $\rho^0$ production, $R_{2h}$ was extracted for all hadron pairs except those with invariant mass near the $\rho^0$. This has no noticeable effect on $R_{2h}$. Therefore, the final data are presented over the full invariant mass range. The effect of only the exclusive $\rho^0$ production is even smaller since it contributes only 5% of the total yield. The contamination from exclusive production of $\rho^\pm$ and $\omega$ mesons is completely negligible, being suppressed by more than one order of magnitude with respect to the $\rho^0$ contribution.

The curves in Fig. 2 represent the model \[16, 17\] in which modifications of the fragmentation functions arise from parton energy loss. Contrary to naive expectations, this model predicts a significant $A$-dependence, in conflict with the data.

Table II provides a quantitative comparison between the data and theoretical predictions for $R_{2h}$ integrated over $z_2$.

The total systematic uncertainty on $R_{2h}$ is 4% (3%) for xenon and krypton (nitrogen) and is nearly independent of $z_2$. The main contribution to the systematic uncertainty comes from the decay of exclusively produced $\rho^0$ mesons. However, for the double-hadron multiplicities $dN_{2h}$/$dA$/$dz_2$ the $\rho^0$ contribution has a negligible effect. The $\rho^0$ contribution to $N_{2h}$/$dA$/$dz_2$ was estimated in analogy with Ref.\[2, 3\] to be about 2% (3%) for light (heavy) nuclei. The only other contributing factor is the uncertainty in the overall efficiency of 2%. The geometric acceptance for semi-inclusive hadron production was verified to be the same for both the nuclear and deuterium targets by studying the multiplicity ratio as a function of the hadron polar angle. This ratio is constant within experimental error.

In conclusion, the first measurement of double-hadron production on deuterium, nitrogen, krypton and xenon is presented. The ratio of double- to single-hadron yields from nuclear targets compared to deuterium are similar for atomic mass numbers $A$ = 14, 84 and 131, as a function of the relative energy of the sub-leading hadron. This is at variance with the single-hadron attenuation data, which depend strongly on $A$. The data do not support naive expectations for pre-hadronic and hadronic final-state interactions that are purely absorptive. Models that interpret modifications to fragmentation as being due to pre-hadronic scattering or partonic energy loss are also inconsistent with the data. In fact the latter predict an even larger $A$-dependence, while the data show little. Like the jet correlation measurements in heavy-ion collisions, the double-hadron observables in semi-inclusive deep inelastic scattering provide new information for differentiating between models of hadronization in nuclei that are indistinguishable in single-hadron measurements.

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TABLE I: Averaged values of $R_{2h}$ for $z_1 > 0.5$.

|          | $z_2 < 0.5$ | $0.1 < z_2 < 0.5$ | $0.1 < z_2 < 0.5$ | $0.1 < z_2 < 0.5$ | $0.1 < z_2 < 0.5$ |
|----------|-------------|-------------------|-------------------|-------------------|-------------------|
|          |             | Model [10]        | Model Abs. [10]   | Model [16, 17]    |                   |
| $^4$He/D| Selection I | 0.946 ± 0.017 ± 0.019 | 0.941 ± 0.018 ± 0.019 | 0.931 | 0.907 | - |
| $^4$He/D| Selection II| 0.975 ± 0.009 ± 0.029 | 0.972 ± 0.010 ± 0.029 | - | - | 0.965 |
| Kr/D    | Selection I | 0.929 ± 0.015 ± 0.019 | 0.917 ± 0.016 ± 0.018 | 0.835 | 0.796 | - |
| Kr/D    | Selection II| 0.902 ± 0.008 ± 0.036 | 0.892 ± 0.008 ± 0.036 | - | - | 0.879 |
| Xe/D    | Selection I | 0.936 ± 0.023 ± 0.019 | 0.915 ± 0.024 ± 0.018 | 0.815 | 0.773 | - |
| Xe/D    | Selection II| 0.936 ± 0.012 ± 0.037 | 0.925 ± 0.013 ± 0.037 | - | - | 0.800 |

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