Hadron Formation in Deep-Inelastic Positron Scattering in a Nuclear Environment

Existing knowledge about the amount of time that is needed to form a pion or a proton in high-energy physics reactions is extremely limited. However, it would be very interesting to obtain experimental information on this so-called formation time and its dependence on the type of particle involved. The formation time of hadrons (the generic name of particles such as pions and protons) represents fundamentally new knowledge of composite systems of quarks and gluons. Moreover, quantitative information on the hadron formation time is needed for the interpretation of relativistic heavy ion collisions, set up to search for a new form of matter, i.e. the quark-gluon plasma.

A simple estimate of the formation time of a hadron can be obtained in the framework of the color-string model, i.e. it is assumed that the time needed to form a hadron consisting of two quarks is roughly equal to the amount of time it takes to stretch a string which has a string constant $\kappa \approx 1$ GeV/fm. The rationale behind this model is the fact that the potential due to the strong interaction between two quarks increases linearly with distance just as for a string. In this framework the formation length is estimated to be $l_f \propto E/\kappa$, where E is the energy available to the two quarks. In a high-energy reaction the energy E is roughly equal to the amount of energy ν that is transferred from the incident beam to the target. Typically, ν (or E) amounts to many GeV's, corresponding to a formation length of many fm's. As the quarks inside the proton are known to propagate with a sizable fraction of the speed of light (c), the formation time will be on the order of 10^{-23} seconds.

Experimental information on the hadron formation time can be obtained by embedding the formation process in an atomic nucleus, as depicted in Fig. 1. In the atomic nucleus the produced hadron will reinteract with the surrounding nucleons, and as a result the amount

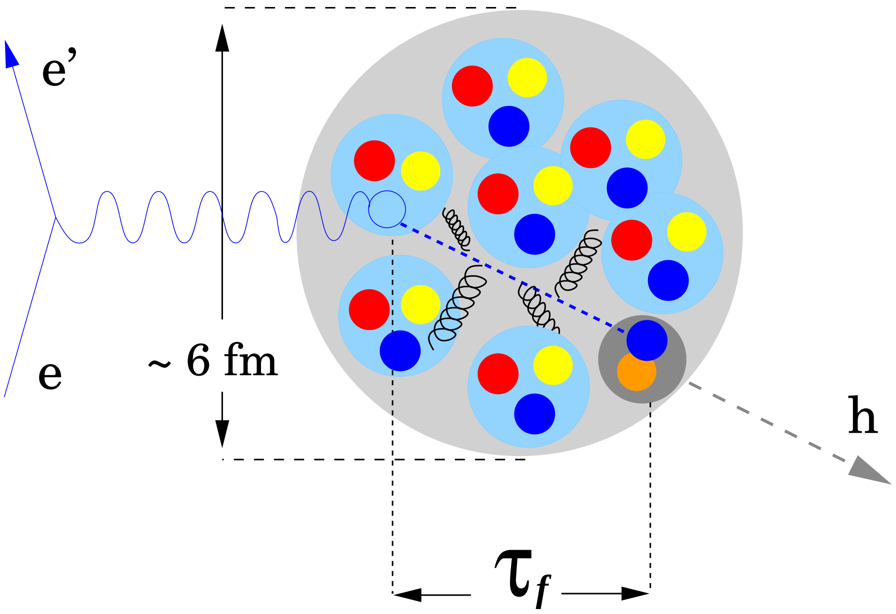

Figure 1: *Schematic picture of hadron formation electron scattering. A quark in one of the nucleons in the atomic nucleus of* ^{14}N *is hit, resulting in the formation of hadrons. Due to rescattering in the nucleus the number of hadrons observed will be reduced.*

of hadrons observed in the experiment will be less. The reduction of the observed number of hadrons will be larger if the hadron is formed sooner. Hence, the ratio of the number of hadrons produced on a heavy nucleus A to that on deuterium (D) is a direct measure of the formation time t_f^h.

In order to optimize the influence of the nuclear environment on the hadronization process it is important that the energy transfer ν is not much larger than 30 GeV. Otherwise, the formation length gets much larger than the nuclear diameter (of about 6 fm for ^{14}N), and the effect of the nuclear medium will be negligible. (This argument implicitly assumes that the interaction between the struck quark and the surrounding medium is very small, for which indeed experimental evidence has been obtained.) In this respect the energy domain covered by HERMES is ideal, i.e. ν ranges from 7 to 23 GeV.

The results of the experiment are displayed in figure 2. On the right hand side the ratio of hadrons produced on ^{14}N and ^{2}H (normalized against the number of deep-inelastic scattering events in each case), is plotted as a function of the fraction z of the energy transfer ν carried by the observed hadron. The data show a surprising decrease with z. Qualitatively this implies that fast hadrons have a relatively short formation time, leading to a relatively strong reduction of the ratio. Only the so-called gluon-bremsstrahlung model (solid line) and a parameterization of the data assuming $t_f^h = c_h(1-z)\nu$ (dotted) are able to describe the z-dependence of the data properly. Older calculations in which it is assumed that t_f^h is proportional to z (other curves) are in disagreement with the data.

In the left-hand side of figure 2 the ratio of hadrons produced on ^{14}N and ^{2}H is plotted versus the energy transfer ν for positive and negative hadrons (top panel), and positive and negative pions (bottom panel). The data are described using the same parameterization of the formation time quoted above, i.e. assuming that $t_f^h \propto (1-z)\nu$. From such parameterizations it can be derived that it takes between 0.2 and 8 times 10^{-23} seconds (depending on z and ν) to form a negative or positive pion. For negative hadrons the same values are found, but for positive

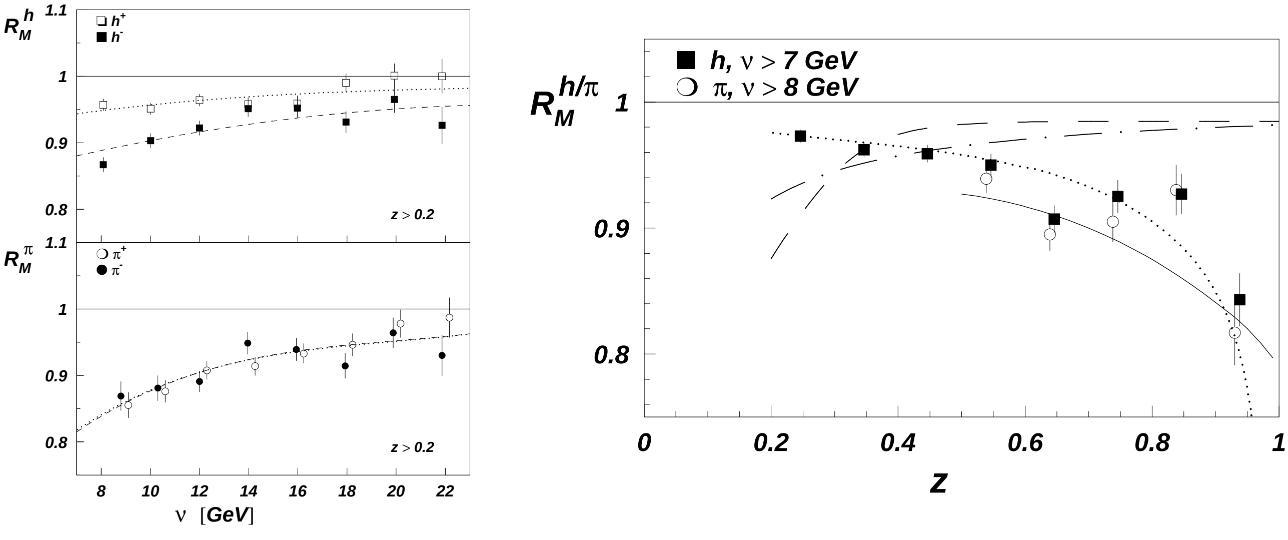

Figure 2: *The ratio of hadrons produced on ^{14}N and ^{2}D normalized to the number of scattered leptons. On the left-hand side the ratio is plotted versus the energy transfer ν for positive and negative hadrons (top panel), and positive and negative pions (bottom panel). On the right-hand side the same ratio is plotted versus the fractional energy z carried by the hadron.*

hadrons a much larger value is found. This can be understood from figure 2 (upper panel left), where it is seen that the positive hadrons are much less attenuated than negative hadrons. Less attenuation implies that less rescattering of the formed hadrons has occurred, which means that the positive hadrons — on average — were formed later. As positive and negative pions have similar formation times, this unexpected result must be attributed to the protons contributing to the positive hadron sample, which presumably have a much longer formation time.