Partonic Energy Loss and the Drell-Yan Process

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Abstract

We examine the current status of the extraction of the rate of partonic energy loss in nuclei from $A$ dependent data. The advantages and difficulties of using the Drell-Yan process to measure the energy loss of a parton traversing a cold nuclear medium are discussed. The prospects of using relatively low energy proton beams for a definitive measurement of partonic energy loss are presented.
Characterizing the energy loss of partons in nuclear matter has been a matter of considerable theoretical [1–8] and phenomenological [3–5,8–13] interest over the past few years. In spite of this activity there is no agreed to value for partonic $dE/dx$ (GeV/fm) in either cold or hot nuclear matter, though there is general agreement that the rate of energy loss in the latter exceeds that of the former.

Much of the problem stems from the inability to directly measure this energy loss, and the lack of a common agreement of the processes and mechanisms to be included in specifying the energy loss. The purpose of this communication is to briefly present the current status of the problem, present a clear idea of quark energy loss in the nuclear medium, and delineate an experimental program capable of determining the parameters to adequately characterize quark energy loss in cold nuclei. We do not deal with the issue of energy loss in relativistic heavy ion collisions (hot nuclear matter), because the complexity of these reactions makes quantitative extraction of partonic energy loss highly uncertain with present knowledge. We will further adhere to the conventional assumption that the rate of energy loss is independent of parton momentum at sufficiently high energies [1–5], though this assumption has been questioned [14].

Table I demonstrates the lack of agreement among the extracted values for quark energy loss that exist at the present time. Admittedly, much of the difficulty may be matters of definition. There is variability in the implicit definitions of what is included in the energy loss and the correct path length over which the energy loss takes place. To reduce some of the confusion in Table I, an average path length is employed using the conventional value, $\langle L \rangle = 3/4 \ (1.2 \ A^{1/3})$ fm. There are more elaborate treatments [8,11] of the nuclear path length that yield appreciably shorter path lengths and hence higher rates of energy loss.

Doubtless some of the discrepancies in Table I would be reduced if consistent definitions, analysis and proper attention to systematic errors were applied. The nuclear dependence of fragmentation appears to us to be too uncertain at the present time to permit a reliable extraction of partonic energy loss. The $A$ dependence of the $p_T$ broadening of the $p−A$ Drell-Yan (D-Y) yield may be an excellent measure of the incident quark energy loss due to gluon
radiation but the small value observed for the broadening indicates that non-perturbative physics is involved [15,16]. The above procedures will not take account of the significant energy loss (\(\sim 1\ \text{GeV/fm}\)) due to the color confining interaction which is operative even in vacuum. The same criticism may be levied against any direct comparison of jet energy loss in lepton-nucleus to lepton-proton DIS.

We believe that the best measure of the quark energy loss in cold nuclear matter is the nuclear dependence of the \(p - A\) D-Y cross section. Viewed in the infinite momentum frame the energy loss of the incident quark is terminated within the nuclear medium by the \(q - \bar{q}\) annihilation process. This approach has been taken by refs. [8,10–12] shown in Table I. The extracted energy losses are seen to be discrepant and are discussed below. First, for illustrative purposes a simple description of how nuclear energy loss affects the measured D-Y yield is presented. The \(p - A\), leading-order D-Y cross section per nucleon is given by

\[
\frac{d\sigma_{p^-A}^\text{DY}}{dx_1dx_2} = \frac{4\pi\alpha_{\text{em}}^2}{9s} x_1x_2 \sum_i e_i^2 [q_i^p(x_1)q_i^A(x_2) + \bar{q}_i^p(x_1)q_i^A(x_2)].
\]

(1)

The fractional momenta \(x_1\) and \(x_2\) of the partons of flavor \(i\) in the beam and target respectively are determined from the mass of the lepton pair, \(M^2 = sx_1x_2\), combined with the c.m. longitudinal momentum \((p_l)\) of the pair \(x_1 - x_2 = 2p_l/\sqrt{s}\). For large \(x_1\) \((x_1 > 0.5)\) and for an interval in \(x_2\) where \(\bar{q}^A(x_2)/\bar{q}^D(x_2) \sim 1\), which occurs for \(0.1 < x_2 < 0.3\) as shown in [15], the ratio of the D-Y yields from nucleus \(A\) to that from deuterium can be expressed as

\[
\left(\frac{d\sigma_{p^-A}^\text{DY}}{dx_1dx_2}\right)/\left(\frac{d\sigma_{p^-D}^\text{DY}}{dx_1dx_2}\right) \sim \frac{q_i^p(x_1^A)}{q_i^D(x_1^D)} \sim \frac{(1 - x_1^A)^3}{(1 - x_1^D)^3}.
\]

(2)

The cubic dependence on \((1 - x_1)\) comes from quark counting rules which are approximately correct as \(x_1 \rightarrow 1\). The energy of the incident quark is equal to \(E_p x_1\). Assuming that the incident quark experiences an energy loss per unit length, \(\alpha\), in nuclear matter, and that there is no such energy loss in deuterium, then

\[
x_1^D = x_1^p, \quad x_1^A = x_1^p + \alpha \frac{\langle L \rangle_A}{E_p},
\]

(3)

where \(\langle L \rangle_A\) is the average path length of the incident quark in the nucleus \(A\). Because of
the energy loss, $x_1^A$ must originate from larger values of $x_1^p$ than is the case for deuterium. Eq. 2 can then be expressed to lowest order in $\langle L\rangle_A/E_p$ as

$$\frac{d\sigma_{DY}^{p-A}}{dx_1dx_2} - \frac{d\sigma_{DY}^{p-D}}{dx_1dx_2} \sim \frac{(1 - x_1^p - \alpha \langle L \rangle_A/E_p)^3}{(1 - x_1^p)^3} \sim 1 - \frac{3\alpha \langle L \rangle_A}{E_p(1 - x_1^p)}.$$  

(4)

Eq. 4 shows that the effects of partonic energy loss are the largest at lower proton energies and at larger $x_1$. Under readily achievable conditions with $A = 200$, $E_p = 120$ GeV and $x_1 = 0.7$, Eq. 4 yields 0.78 for $\alpha = 0.5$ GeV/fm, a readily measurable suppression due to partonic energy loss. Of course, for a more quantitative analysis the approximations used in this paragraph should not be employed. The features presented in Eq. 4 remain when measured parton distributions are employed.

Why then, is there such difficulty in extracting a reliable value for nuclear partonic energy loss? First, there has not been experimental activity focused on elaborating partonic energy loss. The available data come from a variety of sources [10,15,18] that focused on other aspects of nuclear dependence in the D-Y process. There is the additional serious problem of separating the effects of shadowing from those of energy loss. We recall that nuclear shadowing effect was observed in Deep Inelastic Scattering for $x$ less than $\sim 0.07$. This effect is interpreted in the infinite momentum frame as a reduction of parton density at small $x$ due to recombination of quarks and gluons from different nucleons. In the target frame, nuclear shadowing occurs when the coherence length, $L_c \approx 1/(2m_N x_2)$, grows larger than the average distance between nucleons. Both the energy loss and the shadowing effects lead to an $A$-dependent reduction of the D-Y cross section. In principle, they are readily separable as shadowing reduces the yield at small values of $x_2$ while the effects of energy loss are expected to be most pronounced for large values of $x_1$. However, the acceptance of typical fixed-target detectors are biased to favor small values of $x_2$ in conjunction with large values of $x_1$. References [8,10,11] in Table I represent different analyses of the nuclear dependence of $E_p = 800$ GeV, $p-A$ D-Y yield. Reference [10] used $A$-dependent data from FNAL E866 which had had a large fraction of its data at $x_2 < 0.05$ and thus required careful attention to nuclear shadowing. The shadowing corrections employed a phenomenological
shadowing scheme due to Eskola et al. [19] which had determined the shadowing of sea quarks using the FNAL E772 data with no account of the effects of parton energy loss. Such an analysis naturally produces the small energy loss shown in Table I.

References [8,11] analyzed data from FNAL E772 [15] and FNAL E866. They utilized a very different reference frame and prescription for calculating shadowing than used in [10]. Specifically, the nuclear rest frame was employed so the lepton pair originates from a heavy photon bremsstrahlunged off the incident fast charged quark. This description has appreciably less shadowing and consequently requires greater parton energy loss to account for the reduced D-Y yield with increasing \( A \). Reference [8] has a complete description of this analysis procedure and demonstrates that it correctly accounts for shadowing in DIS. The energy loss per unit length reported in [8,11] is more than twice as large as that shown in Table I because in [8,11] the parton’s path length, \( \langle L \rangle_A = 184 \) in Tungsten is only 2.1 fm. This rather short parton path length is due to the requirement in [8,11] that the incident proton needs to travel a certain distance (mean-free-path \( \sim 2.5 \) fm) before an interaction can liberate the high-\( x \) parton. The results shown in Table I use the commonly defined parton path length to make the results more comparable. In [8,10,11], the incident proton energy is high (\( E_p = 800 \) GeV) so that fractional energy loss is small, making the extracted energy loss strongly dependent on the applied shadowing corrections.

The strongest evidence for a small rate of parton energy loss would appear to come from the nuclear dependence of \( \pi^- - N \) D-Y production. Two experiments, one at 225 GeV/c [17] and one at 150 GeV/c [18] reveal little in the way of nuclear dependence. An analysis [12] of the data from [18] is shown in Table I. The value obtained, \(-dE/dx = 0.20 \pm 0.15 \) GeV/fm, is in serious disagreement with [8,11]. Apart from explanations involving the low statistics of [18] and incomplete knowledge of the pion’s parton distribution, the difference might lie with a smaller \( \langle L \rangle_A \) for partons from the pion. The \( \pi-N \) cross section is only 60% that of N-N resulting in a longer nuclear mean-free-path for the pion and a corresponding shorter \( \langle L \rangle_A \) for the partons.

Thus, due to the multiplicity of significant physical effects and the sparse database
available, there is not yet a reliable value for the partonic energy loss in cold nuclei. To remedy this situation we propose a focused set of $p-A$, D-Y measurements at $E_p \sim 100$ GeV. The lower energy enhances the effects of energy loss, accesses a region of $x_2$ where shadowing is negligible, and using a proton beam allows the accumulation of adequate statistics in a reasonable time. The use of several targets of differing $A$ will be necessary in order to extract the effects of the appropriate parton path length, as well as the relative contributions of linear and quadratic dependence of the energy loss on path length.

To assess this issue more quantitatively we have examined the projected sensitivity for D-Y experiments using parton distributions fit to the world data and have incorporated nuclear effects in addition to parton energy loss. In particular, we consider using the proton beams from both the 120 GeV Fermilab Main Ring Injector and the future 50 GeV Japan Hadron Facility. Fig. 1 shows how parton energy loss would affect the $(p+W)/(p+d)$ per nucleon D-Y yields at these beam energies. In this calculation, we use the kinematic acceptance of a dimuon spectrometer proposed for Fermilab Experiment 906 [20] and a similar spectrometer considered [21] at the Japan Hadron Facility. Only D-Y muon pairs with $M > 4.2$ GeV are used to avoid contamination from charmonium decays. The coverages in $x_2$ are $0.1 < x_2 < 0.35$ and $0.2 < x_2 < 0.5$, respectively, for beam energies of 120 GeV and 50 GeV, well outside the small-$x_2$ region of nuclear shadowing. The parton distribution functions are taken from [22] and their modifications in the nuclear medium are from [19]. Leading-order D-Y formula given in Eq. 1 was used in this calculation. The effect of the next-to-leading order diagrams is to introduce an overall normalization factor which is expected to cancel in the D-Y cross section ratios. The average path length in nucleus was taken as $3/4 (1.2 A^{1/3})$. The various curves in Fig. 1 correspond to a partonic energy loss, $-dE/dx$, of 0.0, 0.1, 0.25 and 0.5 GeV/fm, respectively. As expected, these curves clearly demonstrate the great sensitivity of the D-Y cross section ratios to partonic energy loss when the incident proton energy is as low as shown in these examples. The projected statistical errors for a 60-day run on each target are also shown in Fig. 1. A partonic energy loss as small as 0.1 GeV/fm is seen to be readily measurable.
$A$-dependent D-Y data can further determine whether the energy loss is linear or quadratic with the path length. This is illustrated in Fig. 2 where D-Y cross section ratios are shown as a function of $A$. The solid circles correspond to a linear energy loss of 0.25 GeV/fm. The open squares correspond to the case where the energy loss is proportional to the path length squared and matched to give the same energy loss when $A = 184$ (Tungsten target). Fig. 2 shows that one can easily distinguish between $L$ and $L^2$ dependence of the energy loss even when it is as small as 0.25 GeV/fm.

Thus it appears that many of the presently confusing issues of partonic energy loss can be resolved via focused measurement of the p-A dependence of the Drell-Yan cross section. A comparison of the yields from several nuclear targets relative to that from deuterium should determine the amount of energy loss and the appropriate path length, thereby firmly establishing the rate of energy loss. In addition to solving an interesting problem in its own right, these measurements will have a direct impact on nuclear shadowing and on the interpretation of many hard scattering processes in nuclei.
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TABLE I. List of some published rates of parton energy loss in nuclear matter.

| Reference | $-dE/dx$ (GeV/fm) | Data and Analysis Employed |
|-----------|------------------|-----------------------------|
| [9]       | < 0.02           | $Pb - Pb$ jet quenching at SPS |
| [4]       | $\approx 2.8$    | $p_T$ broadening of $p - A$ jets |
| [3]       | $\approx 0.4$    | $p_T$ broadening of $p - A$ D-Y yield |
| [7]       | $\approx 1.2$    | Nuclear modification of $e - A$ fragmentation functions |
| [13]      | $\approx 0.5$    | Nuclear modification of $e - A$ fragmentation functions |
| [10]      | < 0.44           | Nuclear dependence of 800 GeV $p - A$ D-Y cross sections |
| [8]       | $1.12 \pm 0.15 \pm 0.21$ | Nuclear dependence of 800 GeV $p - A$ D-Y cross sections |
| [11]      | $0.95 \pm 0.21 \pm 0.21$ | Nuclear dependence of 800 GeV $p - A$ D-Y cross sections |
| [12]      | $0.20 \pm 0.15$  | Nuclear dependence of 150 GeV $\pi - A$ D-Y cross sections |
FIG. 1. Calculated \( (p + W)/(p + d) \) D-Y ratios at 50 GeV and 120 GeV proton beam energies. The solid, dashed, dotted, and dash-dotted curves correspond to a linear partonic energy loss rate of 0.0, 0.1, 0.25, 0.5 GeV/fm, respectively. Also shown in the figure are the expected statistical errors for \( (p + W)/(p + d) \) ratios in a 60-day run for \( p + W \) and \( p + d \) each.
FIG. 2. Calculated D-Y \((p + A)/(p + d)\) ratios with different assumption of the path-length dependence of partonic energy loss. Solid circles correspond to a linear partonic energy loss rate of 0.25 GeV/fm. The open squares correspond to a quadratic path-length dependence of the partonic energy loss. The statistical errors were calculated assuming a 60-day run for each target.