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Form 836 (7/06)

The First Precise Determination of Quark Energy Loss in Nuclei

Ivan Vitev (P-25 & T-16), Ming Liu (P-25), Patrick McGaughey (P-25) and Benwei Zhang (T-16)

The rate of energy loss of the basic building blocks of the proton, quarks and gluons, in nuclear matter is unknown and constitutes the largest gap in our current understanding of the fundamental nuclear interactions at relativistic energies. As a consequence, it also hampers the quantitative determination of the properties of the new state of matter created in relativistic heavy ion collisions, the quark-gluon plasma.

To bridge this gap, we propose a joint theoretical and experimental project that will provide the first precise determination of quark energy loss in nuclei. We will develop field-theoretic models, Feynman diagram-based resummation techniques and computational tools to reliably calculate the stopping power of cold nuclear matter. A unique opportunity exists today to perform this benchmark measurement at the Fermilab E906 experiment via an active proton-nucleus program. We will build a new muon identification system for E906 to achieve the world's best sensitivity to quark energy loss effects. Theoretically justified numerical simulations will guide the optimization of this detector design. This landmark measurement will establish the shortest radiation lengths ever observed in nature. The successful completion of our project is critical for the accurate modeling and reliable interpretation of the data from current and future heavy ion experiments. This research will help keep LANL at the forefront of contemporary nuclear science at high energies.

The First Precise Determination of Quark Energy Loss in Nuclei

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Ivan Vitev (PI, T-16), Ming Liu (Co-PI, P-25), Patrick McGaughey (P-25), Ben-Wei Zhang (T-16)

Project Goals

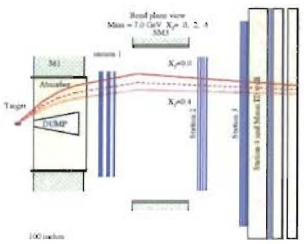
The energy loss of the basic building blocks of the proton, quarks and gluons, in nuclear matter is unknown and constitutes the largest gap in our understanding of fundamental nuclear interactions at relativistic energies. To bridge this gap, we will carry out a joint theoretical and experimental project that will provide the first precise determination of quark energy loss in nuclei.

- *We will develop field-theoretic models, analysis techniques, and computational tools to reliably calculate the stopping power of cold nuclear matter*
- *We will develop simulation software packages to incorporate these new theoretical results based on CERNLIB/PDFLIB/ROOT/PYTHIA and study dimuon production in p+A collisions at a beam energy 120 GeV*
- *We will construct a new muon identification detector based on the technology developed by the P-25 Muon Radiography team. We will prepare its installation at experiment E906 at Fermilab or at JPARC*
- *If installation is possible within the timeframe of the project, we will analyze theoretically and experimentally the Drell-Yan dimuon data and extract the energy loss of quarks in nuclei and the stopping poser of matter*

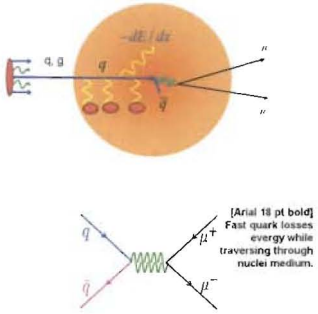
We anticipate that the experimental and theoretical advances in the field if cold nuclear matter energy loss that this project will bring may lead to the discovery of the shortest radiation length (a fundamental characteristic of the strength of particle-matter interactions) ever measured in Nature.

Methods

The enegy loss of fast quark moving through nuclei mediun can be measured via the so called Drell_Yan process where the incoming fast quark form the projectile annihilates with an anti-quark from the target and produced high energy di-muon pair. Such energy loss effect will show up in a difference of the produced dimuon energy spectra from the simple proton+proton (p+p) and proton+heavy nucleus (p+A) collisions. By comparing the experimental data and theoretical model calculations, we can derive the fast quek energy loss in the heavy nuclei A.

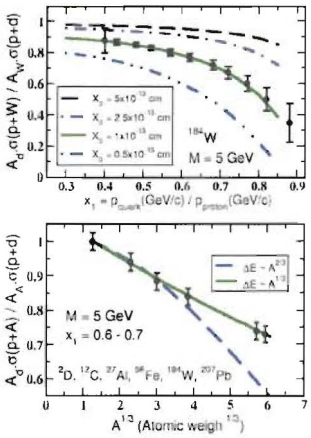


Bend plan view of the Fermilab fixed target experiment E906 setup.



We propose to measure Drell-Yan dimuons with the approved E906 experiment at Fermilab with a 120 GeV high luminosity proton beam and nuclear targets such as ^{1}H (^{2}D), ^{27}Al and heavy nuclei like ^{184}W. By systematically studying dimuon production as a function of nuclear mass number and momentum fraction x_1, we will directly determine the quark energy loss in cold nuclear matter. To achieve the maximum experimental sensitivity to quark energy loss effects, we will perform detailed simulations to optimize the beam luminosity, target

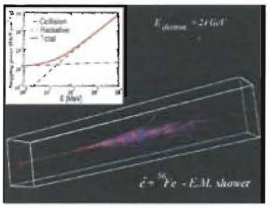
The top plot in the Figure shows the experimental statistical sensitivity at a dimuon mass of 5 GeV to different quark radiation lengths in nuclear matter with the expected beam luminosity on tungsten (W) and deuterium (d) targets. We anticipate that the radiation length can be measured with 20% accuracy. The bottom plot shows the nuclear mass dependence of the ratio of the Drell-Yan yields, normalized to the deuterium reference, and clearly demonstrates that the measurement can distinguish between the two leading theoretical models for the path length dependence of quark energy loss at the 5σ level.



Plots show the expected statistical sensitivity for the Drell-Yan yields of heavy / light targets. Top and bottom plots illustrate the ability to pinpoint the radiation length and nuclear size dependence of the quark energy loss, respectively.

Background & Significance

Precise theoretical and experimental determination of the stopping power of materials of electrons was one of the great early successes of the classical and quantum theories of electr-magnetic interactions. Today, its practical applications range from medical imaging to national security applications, such as proton and muon radiography. In contrast, very little is known about the stopping power of nuclear matter for strongly interacting particles, such as quarks. It is widely recognized in the nuclear and particle physics communities that progress in this area is urgently needed. It will have immediate impact on our understanding of the fundamental forces in nature and the interpretation of the data coming from the current and future heavy ion experiments (areas of basic research where the US has made large strategic investments).



Electro-magnetic shower induced by 24 GeV electron incident on an Iron target. Insert shows the dominance of radiative contributions to the stopping power at high energies, verified to a few % accuracy.

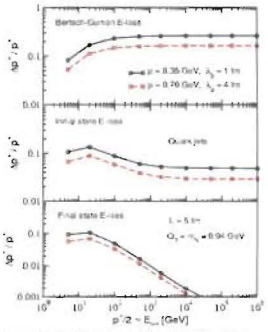
Schematic representation of the Fermilab fixed target experiment

This project embraces the unique opportunity to make the first precise determination of quark energy loss in large nuclei using as a platform upcoming experiments at the Fermilab and JPARC facilities in the US and Japan, respectively. It is based on a synergy of:

- Novel theoretical techniques (first ever calculation of initial-state energy loss) and precision heavy ion phenomenology
- Improvements in detector technology (design and deployment of readout electronics)
- Development of software simulation packages (optimization of the experimental setup for the breakthrough measurements).

Results & Discussion

- *Theory:* We used a formal recurrence relation approach to multiple parton scattering to find the complete solution to the problem of medium-induced gluon emission from partons propagating in cold nuclear matter. The differential bremsstrahlung spectrum, where Landau-Pomeranchuk-Migdal destructive interference effects are fully accounted for, is calculated for three different cases, see Figure:
  - A generalization of the incoherentBertsch-Gunion solution for asymptotic on-shell jets
  - Initial-state energy loss of incoming jets that undergo hard scattering
  - Final-state energy loss of jets that emerge out of a hard scatter



Plots show comparison between the Bertsch-Gunion, Initial-state and final-state energy loss for a typical large nucleus (Au, Pb)

- *Hardware (muon ID):* Final data taking and analysis were completed from the large muon tracker at LANSCE, whose detector elements will be re-used to construct the E906 muon identifier. A position resolution of 300 microns was obtained with a muon detection efficiency over 99%. The tracker was then disassembled and placed into storage, ready for shipment to FNAL.
- *Simulation:* We have developed a new event generator simulation package for fixed target p+p and p+n based on PYTHIA and ROOT libraries from CERN. We have analyzed 100M simulated Drell-Yan events at beam energy of 120 GeV to study the kinematic distributions of the muon pairs produced in the Drell-Yan process. Initial studies shows that we can clearly identify the Drell-Yan signal from other backgrounds (charm decays) in the dimuon channel, and there is a clear correlation between high mass dimuon rapidity and the initial quark's momentum (or the x_1 parameter), which is critical for the proposed quark energy loss study.

Conclusion & Future Plans

We plan to imple

[1] I. Vitev, Phys. Rev. C75: 064906, 2007.
[2] I. Vitev, J. Phys. G. in press (arXiv:0806.0003 [hep-ph]).

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