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Antiquark Distributions in the Proton

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Abstract

This is the final report of a three-year Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The study of quark and antiquark distributions in the nucleon has been a major endeavor in nuclear and particle physics. Results from a recent deep-inelastic scattering experiment suggest the surprising possibility that the up and down antiquark distributions in the proton are not symmetric. A sensitive and direct determination of the antiquark distributions in the proton can be made by comparing the Drell-Yan cross sections on hydrogen versus deuterium targets. We have proposed a new experiment (E866) at Fermilab to carry out such measurements. E866 has been taking data since September 1996. Preliminary results show that the apparatus is working very well. We anticipate having seven months of beam in 1997, which would allow us to achieve the sensitivities for a definitive measurement of flavor symmetry of sea quarks in the proton.

1. Background and Research Objectives

Since the discovery of parton substructures in the nucleon from Deep-Inelastic Scattering (DIS) experiments, the study of quark and gluon structures in nucleons and nuclei has been a major endeavor in particle and nuclear physics. The interest in this subject is demonstrated by the construction of large accelerators, such as HERA and RHIC, whose main goal is to probe quark and gluon structures in hadronic matter.

Despite the huge amount of theoretical and experimental effort, our current knowledge on the parton structures in nucleons and nuclei is still far from complete. This situation is

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clearly reflected in the several surprises discovered in recent DIS experiments. The first surprise was the famous "EMC effect," which showed that quark structure functions in nuclei are different from those in the nucleon. Another unexpected result came from a measurement of the proton spin-dependent structure function, indicating that only a small fraction of the proton spin is carried by the quarks. More recently, an experiment to measure the "Gottfried sum rule" revealed yet another surprise, suggesting that the $\bar{u}$ and $\bar{d}$ antiquark distributions in the proton are not symmetric. The goal of this LDRD project was to carry out a Fermilab experiment designed to measure accurately the ratio of $\bar{d}$ over $\bar{u}$ distributions in the proton.

The New Muon Collaboration (NMC) at CERN reported their measurement of the muon DIS on hydrogen and deuterium targets. The NMC data showed an apparent violation of the Gottfried sum rule, indicating that the $\bar{d}$ and $\bar{u}$ distributions in the proton are different. The NMC results attracted much attention since it has been taken for granted that the $\bar{u}$ and $\bar{d}$ have identical distributions in the nucleon. However, the $\bar{d}/\bar{u}$ symmetry in the proton is neither required by fundamental principles nor verified by previous experiments. In fact, based on the idea of the Pauli-exclusion principle, Field and Feynman suggested some time ago the possibility that $\bar{d}$ can be enhanced over $\bar{u}$ in the proton. More recently, a number of authors have also argued that the presence of virtual pions in the proton can lead to an excess of $\bar{d}$ over $\bar{u}$.

A very sensitive measurement of the antiquark distribution can be made with the Drell-Yan process using a proton beam. This point was clearly demonstrated in our previous Fermilab experiment (E772), which compared the antiquark distributions in heavy nuclei with those in deuterium. In fact, the E772 data on the ratio of tungsten over isoscalar targets already exclude some theoretical models that predict large $\bar{d}/\bar{u}$ asymmetry. Nevertheless, to obtain a much more sensitive measurement of the $\bar{d}(x)/\bar{u}(x)$ ratio, and to reduce the complication caused by the nuclear effect, it is best to compare the Drell-Yan cross sections on hydrogen versus deuterium targets. This consideration led to the submission of a Fermilab proposal (E866, Spokesman: G. T. Garvey; Deputy Spokesman: J. C. Peng), which was approved by the FNAL program advisory committee in December 1992. The LANL group has taken a leading role in proposing this experiment. In late 1994, P. L. McGaughey became the spokesman of E866.

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2. Importance to LANL's Science and Technology Base and National R&D Needs

The investigators in this LDRD project have successfully carried out many research programs in medium and high energy physics programs at LAMPF, AGS, FNAL, and CERN in recent years. Some highlights of their accomplishments are (1) development of polarization transfer techniques for inelastic scattering and charge-exchange reactions, (2) development of the NTOF polarimeter, (3) first study of (π, η) reactions at LAMPF, (4) experiments at AGS to establish the (π^+, K^+) reaction as a major new tool for hypernuclear spectroscopy, (5) double-charge-exchange experiments at LAMPF, (6) successful completion of Fermilab experiment E772, and (7) successful completion of Fermilab experiment E789. The spectrometer used by the LANL group for experiments E772 and E789 is being used in the E866 experiment. The LANL group has become one of the most experienced groups in operating this system and analyzing the data obtained with it. The LANL group takes major responsibilities in operating the spectrometer, maintaining and upgrading the data acquisition system, and developing the analysis software.

The E866 experiment will be performed with an energetic proton beam (800 GeV), together with a high-resolution, high-rate magnetic spectrometer. The expected statistical accuracy and the range of coverage in x (fraction of nucleon momentum carried by the antiquark) are unmatched by experiments at other facilities. The E866 experiment addresses a fundamental issue in nuclear and particle physics concerning the internal structure of the proton. Participation in E866 further strengthens LANL's increasingly important role in high-energy nuclear physics. The techniques and physics goals of E866 are also closely related to other ongoing LANL projects, such as the PHENIX experiment at RHIC.

3. Scientific Approach and Accomplishments

The major apparatus utilized in E866 is the E605/E772/E789 spectrometer, shown in Figure 1. This spectrometer was designed to detect a pair of oppositely charged particles with excellent mass resolution and high rate capability. A 15-meter-long magnet, located downstream of the target, bends the charged particles through its upper and lower apertures. A Ring Imaging Cherenkov (RICH) detector can be used to identify pions, kaons, and protons. Electrons are identified by the electron calorimeter. The trajectories and momenta of charged particles are measured by three 'stations' of scintillator hodoscopes and drift chambers. Detectors placed downstream of the calorimeters and hadron absorbers provide clear identification of muons.

In preparation for E866, several major tasks have been carried out. They include:

- (1) A cryogenic target system for liquid hydrogen and deuterium was built. This system is equipped with drive mechanism and controls so that the targets can be alternated during the experiment. Any drift in the beam or detector performance would largely cancel out and have minimal effects on the measurement of $\sigma(p+d)/\sigma(p+p)$ ratios.
- (2) A new magnet, SM0, was installed near the cryogenic target. The extra bending power in SM0 allows us to reach certain kinematic regions more effectively. The magnetic fields from the combined SM0 and SM12 magnets were subsequently mapped out in details.
- (3) To optimize the spectrometer acceptance, the drift chambers at station 1 were replaced by larger chambers built at LANL.
- (4) Additional upgrade of the data acquisition system, both to replace unreliable components and to provide a large increase in on-line monitoring facilities and real-time analysis power.
- (5) Implementation of diverse instrumentation for measuring/monitoring beam, target, trigger, and acquisition system parameters so as to achieve a 2% normalization accuracy.
- (6) Additional enhancements to off-line analysis facilities.

Following a longer-than-expected collider run, Fermilab finally switched to fixed-target run around July 1996. After some initial checking and debugging, the E866 experiment became fully operational and started to take physics data in September 1996. As of November 1996, E866 has already collected a large amount of data. Figure 2 shows the dimuon mass spectrum from an analysis of approximately 1/3 of the E866 data. The J/Ψ , Υ , and Drell-Yan continuum are clearly visible in the spectrum. Preliminary analysis has shown that the $\sigma(p+d)/\sigma(p+p)$ ratio indeed favors a $\bar{u}/\bar{d}$ asymmetric quark sea.

In addition to the dimuons produced in the liquid hydrogen and deuterium targets, a large number of dimuons produced in the beam dump were also detected in E866. Since almost all the proton beam interacts in the beam dump, the dimuon yield from the beam dump is large. A very interesting outcome of this, not envisaged in the original E866 proposal, is that the beam dump data are sensitive to regions of very small cross sections. Some of the most interesting questions in dimuon production can be best answered by such data.

The schedule for the current fixed-target run calls for seven months of beam during 1997 (January 15 to August 15). This offers an excellent opportunity for E866 to obtain additional data during 1997. The additional running could improve on the statistical accuracy of the $\bar{u}/\bar{d}$ measurement, and it could also allow E866 to address several important issues in Drell-Yan and quarkonium physics.

The additional E866 measurements can be grouped into three categories as follows (the main physics issues addressed in each category are also listed):

a. Additional Measurements on the LH₂ and LD₂ Targets

- Improved statistics on the $\bar{u}/\bar{d}$ measurements, especially at the large x_2 region.
- Q^2 dependence of the $\bar{u}/\bar{d}$ ratios.
- Absolute Drell-Yan cross sections of $p + p$ and $p + d$.

b. Dedicated Beam-Dump Measurements

- Decay angular distributions (θ and ϕ) for J/Ψ and Drell-Yan events at large x_F .
- Polarization of J/Ψ at large P_t or large x_F to test the color-octet model for quarkonium production.
- Drell-Yan and J/Ψ cross sections at very large P_t ($P_t \sim 10$ GeV/c). Possible relation between high P_t Drell-Yan and direct-photon production.
- Υ cross sections at large x_F and test of intrinsic charm/beauty in the proton.

c. High Resolution and High Statistics Nuclear-Dependence Measurements

- A-dependence of J/Ψ , Ψ' , Υ , Υ' , Υ'' .
- Study of low-mass dimuons and shadowing effects at low x_2 .
- A-dependence of J/Ψ production at negative x_F .

We expect that our request of E866 run extension will be approved by Fermilab. We also anticipate that a large quantity of data, covering a very broad range of physics topics, will be collected in E866. The first physics result should be ready for publication in a year. During the duration of this LDRD project, we have also studied the possibility of using quarkonium production and W/Z vector boson production as additional means to measure the $\bar{u}/\bar{d}$ asymmetry. These studies have resulted in journal publications.

In summary, experiment E866 is now running successfully at Fermilab. The goal of this LDRD project has been achieved. The opportunity to run E866 beyond the originally requested duration should bring many more interesting physics results. These results are expected to have a major impact in high-energy nuclear and particle physics.

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FNAL E866 (NUSEA)

Figure 2: Preliminary dimuon mass spectra from E866. The upper and lower figure corresponds to data from liquid deuterium and hydrogen target, respectively.