PHYSICS DIVISION TECHNOLOGY REVIEW

The NuSea Experiment—Measuring the Asymmetry of the Nucleonic Sea

Researchers in a collaboration led by Los Alamos are measuring the proton's excess of anti–down quarks relative to anti–up quarks. Their results are providing new information that is crucial to understanding the intricacies of the proton's internal structure.

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Since the 1960s, researchers have conducted a number of high-energy-physics experiments to probe the structure of the proton, the positively charged particle that is a building block of all atomic nuclei. The results of these studies have shown that a proton is composed of three valence (core) quarks—two up quarks and a down quark (*uud*)—held together by gluons. Surrounding the valence quarks is an indistinct sea of quark-antiquark pairs, primarily consisting of up (u), anti–up ($\bar{u}$), down (d), and anti–down ($\bar{d}$) quarks. The quark-antiquark pairs are believed to originate from processes such as gluon splitting or virtual-pion production (see Fig. 1).

Until the early 1990s, the scientific community had assumed that there were equal numbers of $\bar{u}$ and $\bar{d}$ quarks in this "nucleonic sea," a condition known as flavor symmetry. In 1991, however, the New Muon Collaboration (NMC) at the European Center for Particle Physics found evidence for a considerable excess of $\bar{d}$ relative to $\bar{u}$ in the nucleonic sea.

In an effort to better understand this surprising result, Los Alamos is leading a collaboration of 11 US institutions in the NuSea Experiment (E866) at Fermi National Accelerator Laboratory. In this experiment, we are determining how the sea-antiquark ratio $\bar{d}/\bar{u}$ and the difference $\bar{d}-\bar{u}$ vary depending on the "momentum fraction," the fraction of a proton's momentum that the sea antiquarks carry.

Previous experiments, including the NMC experiment, either measured the integral of $\bar{d}-\bar{u}$ over all momentum fractions or measured $\bar{d}/\bar{u}$ at only a single momentum fraction. In E866, however, we are determining individual values of $\bar{d}/\bar{u}$ and $\bar{d}-\bar{u}$ over a wide range of momentum fractions extending from 0.020 to 0.345.

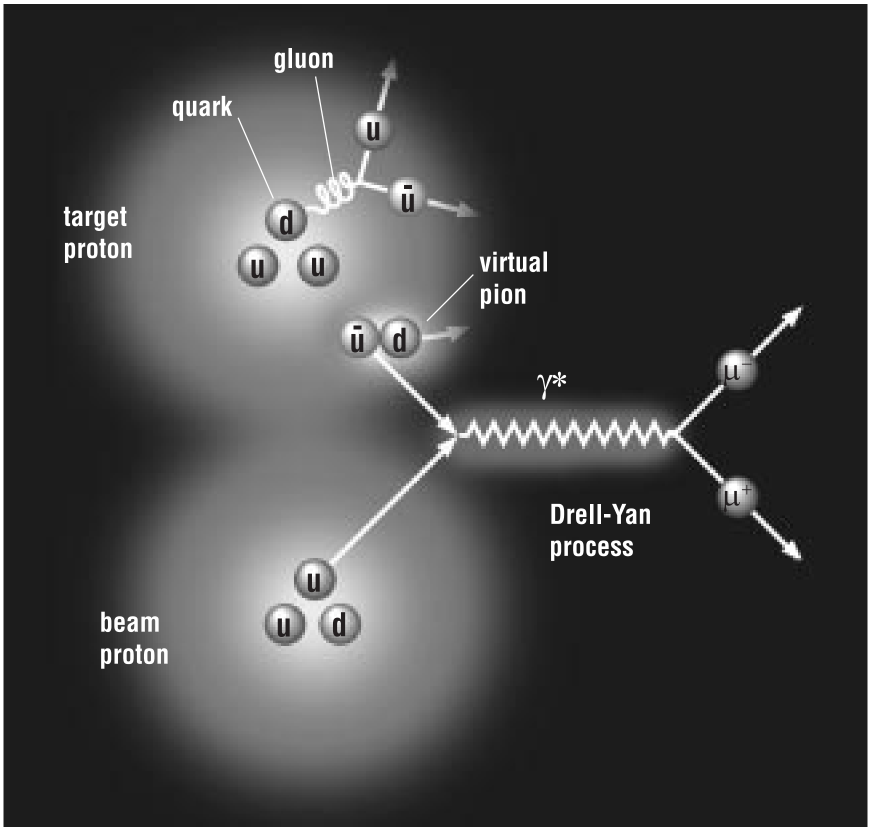

Fig. 1. A proton consists of three valence quarks (uud) held together by gluons and surrounded by a sea of quark-antiquark pairs that originate from gluon splitting (a symmetric process generating nearly equal numbers of $\bar{d}$ and $\bar{u}$) or virtual-pion production (an asymmetric process generating an excess of $\bar{d}$ relative to $\bar{u}$). Examples of these two processes are shown. We can determine $\bar{d}/\bar{u}$ by measuring the properties of the muon pairs produced in the Drell-Yan process (middle of figure), which occurs when a quark in a proton beam strikes a sea antiquark in a target.

To determine $\bar{d}/\bar{u}$ and $\bar{d}-\bar{u}$, we produce proton-proton ($p + p$) or proton-deuterium ($p + d$) collisions by aiming an 800-GeV proton beam at target flasks containing either liquid hydrogen or liquid deuterium. Each hydrogen atom contains a proton, and each deuterium atom contains both a proton and a neutron. The neutron's quark and antiquark content is the inverse of the proton's; wherever the proton has a u (or $\bar{u}$) quark, the neutron has a d (or $\bar{d}$) quark, and vice versa.

When a quark from a proton in the beam strikes a sea antiquark in a target nucleus, the quark-antiquark pair annihilate and form a virtual photon (γ*), which can then decay into a pair of oppositely charged muons (μ^+ and μ^-). Production of a pair of muons in this way is known as the Drell-Yan process (see Fig. 1).

In our experiment, these muons enter a pair spectrometer, where their paths are bent and tracked by a series of magnets, scintillator hodoscopes, and drift chambers. From the muon tracks, we can reconstruct the mass and momenta of the virtual photon that created the muon pair. These data provide information both on the Drell-Yan cross sections—i.e., the probabilities—for $p + p$ and $p + d$ collisions and on the momentum fraction of the quark in the proton or neutron that was hit. From these cross sections, we can calculate $\bar{d}/\bar{u}$ and $\bar{d}-\bar{u}$ at different momentum fractions.

Over a period of 6 months, we have recorded over 330,000 Drell-Yan events. The results of $\bar{d}/\bar{u}$ from approximately 140,000 of these events are represented in Fig. 2. In this figure, our data are compared with the results from the NA51 experiment, which measured $\bar{d}/\bar{u}$ at a single momentum fraction of 0.18, and with results from an empirical fit to previous data, or "parameterization," known as CTEQ4M. Within the statistical uncertainty, our results are consistent with the NA51 measurement at 0.18. They also agree well with the CTEQ4M results for momentum fractions below about 0.2 and confirm that there are more $\bar{d}$ than $\bar{u}$ quarks in this range. At higher momentum fractions, however, our data fall considerably below the CTEQ4M curve, a discrepancy that indicates the need to reevaluate the empirical fit. Our calculated value of $\bar{d}-\bar{u}$ integrated over all the momentum fractions in our experimental range was slightly lower than the results from the NMC experiment and from the CTEQ4M predictions.

The results of our experiment raise two fundamental questions: why is there an excess of $\bar{d}$ in the nucleonic sea at all, and why does the ratio $\bar{d}/\bar{u}$ first increase and then decrease? Researchers have previously suggested several models to explain asymmetric processes that would create an excess of $\bar{d}$ relative to $\bar{u}$ quarks. The model that best explains the excess is the pion-cloud model, which assumes that protons can produce pions, some of which contain more $\bar{d}$ than $\bar{u}$ quarks. The variation of $\bar{d}/\bar{u}$ over the range of momentum fractions implies that in different momentum-fraction regions, asymmetric processes (such as virtual-pion production) dominate to different extents over symmetric processes (such as gluon splitting), which produce approximately equal numbers of $\bar{u}$ and $\bar{d}$ quarks.

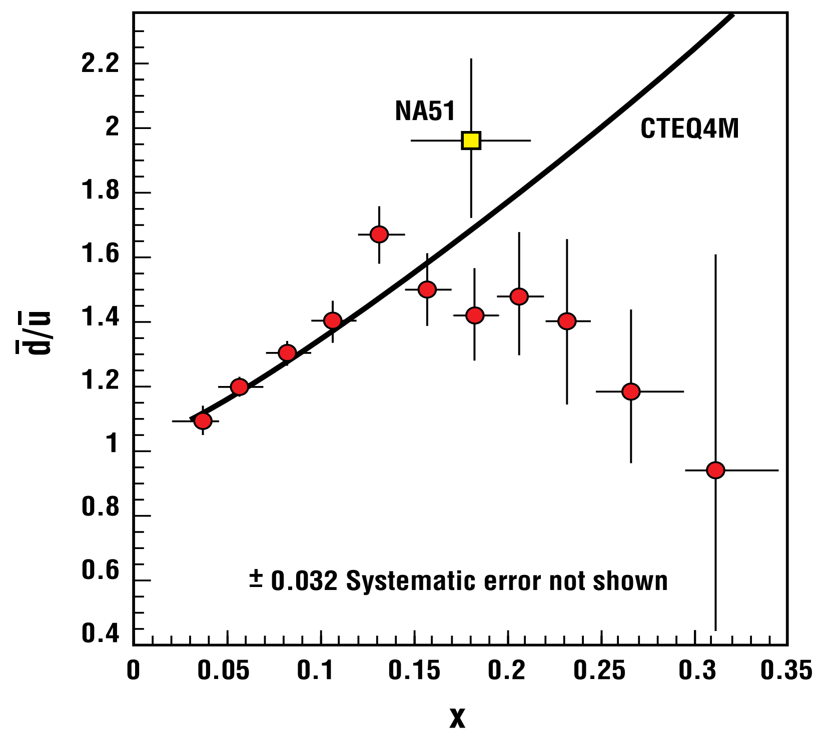

Fig. 2. The ratio $\bar{d}/\bar{u}$ in the proton plotted as a function of the momentum fraction (x) of a target quark (red circles). Also shown are the CTEQ4M parameterization (black curve) and the experimental result from the NA51 experiment (yellow square).

We continue to analyze the remainder of the data from E866, and we expect that the additional data will reduce the uncertainties in our measurements. The results from this experiment are an important contribution to basic science: our determinations of $\bar{d}/\bar{u}$ and $\bar{d}-\bar{u}$ are already being incorporated into theoretical models and may therefore help scientists solve the mysteries that still surround the complex interactions of the particles and forces inside the proton.

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