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Measurement of Light-antiquark Flavor Asymmetry by Drell–Yan Experiment SeaQuest at Fermilab

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The amounts of $\bar{d}$ and $\bar{u}$ in the proton were expected to be the same based on the flavor independence of gluon splitting. However, muon deep inelastic scattering experiment NMC at CERN found that the amount of $\bar{d}$ is larger than $\bar{u}$ in the proton. Bjorken x dependence of the sea quark flavor asymmetry can be studied in Drell–Yan experiments. The E866 experiment at Fermilab showed that $\bar{d}(x)/\bar{u}(x) > 1.0$ at $0.015 < x < 0.20$. SeaQuest at Fermilab measures the light-antiquark flavor asymmetry $\bar{d}/\bar{u}$ precisely in a large x range ($0.15 < x < 0.45$) including the unrevealed region in E866. It uses a 120 GeV proton beam extracted from Fermilab Main Injector colliding with liquid hydrogen and deuterium targets to measure the Drell–Yan process. The light-antiquark flavor asymmetry $\bar{d}(x)/\bar{u}(x)$ is derived from the cross section ratio of proton-deuteron to proton-proton Drell–Yan processes. SeaQuest released the preliminary result in 2016. The analyses toward final results are in progress.

KEYWORDS: nucleon structure, parton distribution functions, Drell–Yan process, QCD

1. Introduction

According to QCD, the coupling constant of strong interaction is independent of the quark flavor. Since the masses of d and u quarks are almost the same, the probabilities of gluon splitting into $d\bar{d}$ and into $u\bar{u}$ are expected to be the same in the proton. It means that the amounts of $\bar{d}$ and $\bar{u}$ in the proton were also expected to be the same.

One of the ways to confirm if they are symmetric or not is to measure the Gottfried sum. The Gottfried sum (S_G) is defined as follows:

$$S_G = \int_0^1 dx \left[F_2^p(x) - F_2^n(x)\right]/x = \frac{1}{3} + \frac{2}{3}\int_0^1 dx \left[\bar{u}(x) - \bar{d}(x)\right], \quad (1)$$

where x is Bjorken x, which is the momentum fraction of the parton to the proton, F_2^p and F_2^n are the structure functions of the proton and the neutron, respectively, and $\bar{u}$ and $\bar{d}$ are the parton distribution functions. Here, the isospin symmetry of proton and neutron is assumed. If $\bar{d}$ and $\bar{u}$ are symmetric, the second term of Eq. (1) vanishes and the Gottfried sum becomes 1/3 (Gottfried sum rule [1]). The NMC experiment at CERN measured the Gottfried sum via muon deep inelastic scattering [2]:

$$S_G = 0.235 \pm 0.026, \quad (2)$$

which is significantly less than 1/3. It means that the amount of $\bar{d}$ is more than that of $\bar{u}$ in the proton.

The Bjorken x dependence of $\bar{d}(x)/\bar{u}(x)$ was measured by the NA51 experiment at CERN ($x = 0.18$) and the E866 experiment at Fermilab ($0.015 < x < 0.35$) [3,4]. They found that $\bar{d}/\bar{u}$ is basically larger than 1.0 and a +70% asymmetry of $\bar{d}/\bar{u}$ at $x \sim 0.2$ at most. This tendency can be expressed by some theoretical models, such as meson-cloud model [5], statistical model [6], and so on. However, the E866 experiment shows $\bar{d}/\bar{u} < 1.0$ at $x \sim 0.3$, although it is consistent with 1.0 due to the large statistical uncertainty. No theories can reproduce this phenomenon at this moment. Therefore it is quite important to determine $\bar{d}/\bar{u}$ precisely at higher x region in order to understand the proton structure and to give an idea which model reproduces the actual proton structure.

2. SeaQuest Experiment

The SeaQuest experiment is performed at Fermi National Accelerator Laboratory (Fermilab) in the US. It aims at measuring $\bar{d}/\bar{u}$ precisely at higher x region ($0.15 < x < 0.45$) via the Drell–Yan process in proton-proton and proton-deuteron. Other physics motivations are the nuclear dependence, the angular distribution of the Drell–Yan dimuon, and the dark photon search.

The Drell–Yan process is a reaction where an antiquark in a hadron and a quark in another hadron annihilate and then decay into a lepton pair via a virtual photon in a high energy hadron-hadron scattering ($q + \bar{q} \rightarrow \gamma^* \rightarrow l + \bar{l}$) [7]. The differential cross section of the proton-proton Drell–Yan process at leading order is described as

$$\frac{d^2\sigma}{dx_{\mathrm{target}}dx_{\mathrm{beam}}} = \frac{4\pi\alpha^2}{9x_{\mathrm{target}}x_{\mathrm{beam}}}\frac{1}{s}\sum_{i=u,d,s,...} e_i^2\left[q_i(x_{\mathrm{beam}})\bar{q}_i(x_{\mathrm{target}}) + \bar{q}_i(x_{\mathrm{beam}})q_i(x_{\mathrm{target}})\right]. \quad (3)$$

In the SeaQuest acceptance ($x_{\mathrm{beam}} \gg x_{\mathrm{target}}$), the last term of Eq. (3) vanishes because the PDFs of antiquarks at large x are small. Thus the antiquarks in target protons are accessible via the Drell–Yan process in forward detection. The SeaQuest experiment measures the muons in the final state.

Figure 1 shows the SeaQuest spectrometer. The 120 GeV proton beam provided by Fermi Main

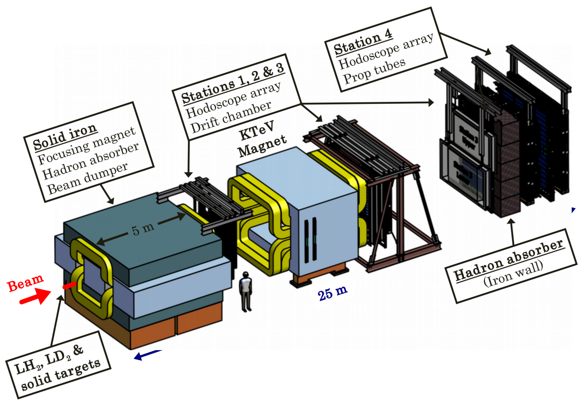


Fig. 1. SeaQuest spectrometer.

Injector comes from the left-hand side of the figure. It collides with the targets: liquid hydrogen (LH_2) and liquid deuterium (LD_2) for $\bar{d}/\bar{u}$, and solid targets (iron, carbon, tungsten) for nuclear dependence. An empty flask which is the same as the container of the liquid targets is also placed for the background subtraction. The spectrometer has four tracking stations. Each of them consists of hodoscope arrays and drift chambers or proportional tubes. There are two magnets placed: a focusing magnet is located between targets and St. 1 which is for focusing the proper muons to the detectors, and KTeV Magnet is located between St. 1 and St. 2 which is for the muon momentum determination. The focusing magnet also works as hadron absorber for dumping the incident proton beam. Another absorber is located between St. 3 and St. 4 and is for the muon identification.

Figure 2 shows the invariant mass spectrum of the reconstructed dimuons. The black points are

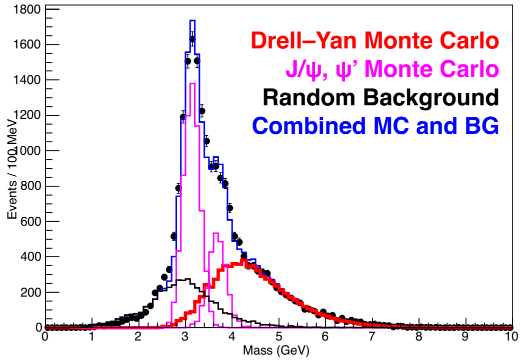


Fig. 2. Mass spectrum of reconstructed dimuons. Black points are the real data, which are fitted with Drell–Yan dimuons (red line), J/ψ and ψ' (magenta lines) estimated with Monte-Carlo simulation and the random background (black line) estimated with real data. Blue line is the sum of these four components.

the experimental data, and they are fitted with four components: the Drell–Yan dimuons from the Monte-Carlo simulation (red line), the J/ψ and ψ' dimuons from the Monte-Carlo simulation (magenta lines), and the random background estimated with real data by event mixing method (black line). The data are well fitted with the sum of the four components (blue line). It means that the detectors and dimuon reconstruction tools work as expected. In the data analysis, dimuons with their mass > 4.2 GeV are used because the Drell–Yan dimuons are dominant in that region.

3. Data Analysis

The light-antiquark flavor asymmetry $\bar{d}/\bar{u}$ is approximately proportional to the cross section ratio of the proton-deuteron to proton-proton Drell–Yan process. Therefore, the cross section ratio is extracted first and then is converted into $\bar{d}/\bar{u}$.

The formula to extract the cross section ratio is described as

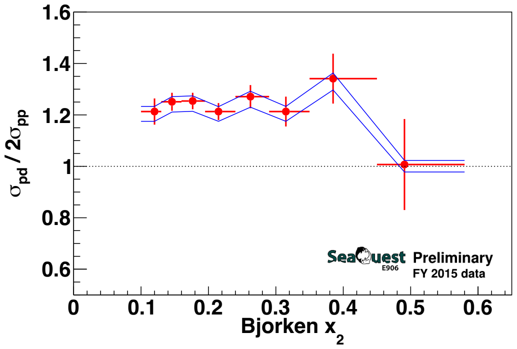
$$\frac{\sigma_{pd}}{2\sigma_{pp}} = \frac{1}{2}\left(\frac{N_D \cdot C_D}{P_D}\right) \Bigg/ \left(\frac{N_H \cdot C_H}{P_H}\right), \tag{4}$$

where the subscripts (D and H) denote the hydrogen and deuterium targets, respectively, N is the number of the reconstructed dimuons, C is the correction factor of the background and the reconstruction efficiency, P is the normalization factor for the number of nucleons in the beam and the target. Then the cross section ratio is converted into $\bar{d}/\bar{u}$ using the CT10LO PDF [8] and Eq. (3).

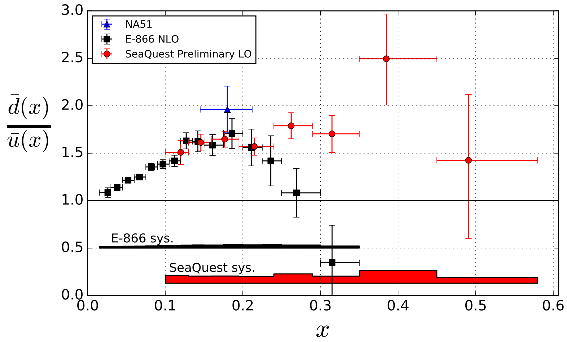
Figure 3 shows the results of the cross section ratio (a) and $\bar{d}/\bar{u}$ drawn with NA51 and E866 experiments results (b). The cross section ratio and $\bar{d}/\bar{u}$ were extracted in $0.1 < x < 0.58$. The systematical uncertainty arises from 1) the contamination of H in LD_2, 2) the random background, 3) the hit-rate dependence of the reconstruction efficiency, and 4) the uncertainty of the PDF set, which was used in the conversion from the cross section ratio to $\bar{d}/\bar{u}$. The nuclear corrections for deuterium have not yet been applied.

The values of $\bar{d}/\bar{u}$ in $0.1 < x < 0.45$ are larger than 1.0, and it is consistent with 1.0 in $0.45 < x < 0.58$. We also obtained the tendency that $\bar{d}$ is dominated which is shown by the NMC experiment.

In $0.1 < x < 0.24$, $\bar{d}/\bar{u}$ results are well consistent with the results of the NA51 and the E866 experiments. On the other hand, the results of SeaQuest are larger than those of E866 in $0.24 < x$. The differences of Q^2 and the PDF sets have already been investigated, and are not found the causes of this discrepancy.



(a) Cross section ratio. Blue lines show the systematical uncertainty.



(b) $\bar{d}/\bar{u}$.

Fig. 3. The results of (a) cross section ratio and (b) $\bar{d}/\bar{u}$.

4. Toward the Final Results

In current analysis method, there are two difficulties to resolve: the estimation for the rate-dependence effects of the reconstruction efficiency and of the random background. Here, the rate corresponds to the beam rate (the beam intensity). As we observe several difficulties in estimating them based on the simulation, we are testing a new method based on real data, so-called "extrapolation method".

The cross section ratio is first evaluated as a function of the rate. And then it is fitted with a function to extrapolate to the zero-rate. The intercept would be the "correct"cross section ratio, which has been effectively corrected for all rate effects.

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