mined. The NA51 collaboration at CERN carried out the first dedicated dimuon production experiment to study the flavor structure of the nucleon sea. Using a 450 GeV proton beam, NA51 obtained \( \frac{\bar{d}}{d} = 0.51 \pm 0.04 \) (stat) \( \pm 0.05 \) (sys) at \( x = 0.18 \) and \( \langle M_{\mu\mu} \rangle = 5.22 \) GeV. This important result established the asymmetry of the quark sea at a single value of \( x \). What remained to be done was to map out the \( x \)-dependence of this asymmetry.

At Fermilab, a DY experiment (E866/NuSea) aimed at a higher statistical accuracy with a much wider kinematic coverage than the NA51 experiment has been completed. \(^{22}\) The DY cross section ratio per nucleon for \( p + d \) to that for \( p + p \) is shown in Fig. 1. At positive \( x_F \), this ratio is given as

\[
\frac{\sigma_{DY}(p + d)}{2\sigma_{DY}(p + p)} \simeq (1 + \bar{d}(x_2)/\bar{u}(x_2))/2.
\]

Figure 1 shows that the DY cross section per nucleon for \( p + d \) clearly exceeds \( p + p \), and it indicates an excess of \( \bar{d} \) with respect to \( \bar{u} \) over an appreciable range in \( x_2 \). In contrast, the \( \sigma(p + d)/2\sigma(p + p) \) ratios for J/\( \Psi \) and \( \Upsilon \) production, also shown in Fig. 1, are very close to unity. This reflects the dominance of gluon-gluon fusion process for quarkonium production and the expectation that the gluon distributions in the proton and in the neutron are identical.

The Drell-Yan cross section ratios from E866 were analysed to obtain \( \bar{d} - \bar{u} \) over the region \( 0.02 < x < 0.345 \) as shown in Fig. 2. The HERMES collaboration has reported a semi-inclusive DIS measurement of charged pions from hydrogen and deuterium targets. \(^{23}\) Based on the differences between charged-pion yields from the two targets, \( \bar{d} - \bar{u} \) is determined in the kinematic range, \( 0.02 < x < 0.3 \) and 1 GeV\(^2\)/c\(^2\) \( < Q^2 < 10 \) GeV\(^2\)/c\(^2\). The HERMES results are consistent with the E866 results obtained at significantly higher \( Q^2 \).

Table 1. Values of the integral \( \int_0^1 [\bar{d}(x) - \bar{u}(x)] dx \) determined from the DIS, semi-inclusive DIS, and Drell-Yan experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \langle Q^2 \rangle ) (GeV(^2)/c(^2))</th>
<th>( \int_0^1 [\bar{d}(x) - \bar{u}(x)] dx )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMC/DIS</td>
<td>4.0</td>
<td>0.147 \pm 0.030</td>
</tr>
<tr>
<td>HERMES/SIDIS</td>
<td>2.3</td>
<td>0.16 \pm 0.03</td>
</tr>
<tr>
<td>FNAL E866/DY</td>
<td>54.0</td>
<td>0.118 \pm 0.012</td>
</tr>
</tbody>
</table>

In Fig. 2, the comparison of the measured \( \bar{d}(x) - \bar{u}(x) \) at \( Q^2 = 54 \) GeV\(^2\)/c\(^2\) to predictions of several models of the nucleon sea. The solid and short-dashed curves show pion-cloud calculations. \(^{24}\) The dotted curve is a chiral quark model calculation, \(^{25}\) while the dot-dash curve shows the chiral quark-soliton calculation. \(^{26}\) The long-dash curve shows the instanton model prediction. \(^{27}\)

Many theoretical models, including meson cloud model, chiral-quark model, Pauli-blocking model, instanton model, chiral-quark soliton model, and statistical model, have been proposed to explain the \( \bar{d} - \bar{u} \) asymmetry. For details of these various models, we refer to several recent review articles. \(^{28}\) As shown in Fig. 1, these models can describe the \( \bar{d} - \bar{u} \) data very well. However, they all have difficulties explaining the \( \bar{d} - \bar{u} \) data at large \( x \) (\( x > 0.2 \)). \(^{29}\) Thus, it would be very important to extend the DY measurements to larger \( x \) regimes. The new 120 GeV Fermilab Main Injector (FMI) and the proposed 50 GeV Japanese Hadron Facility (JHF) present opportunities for extending the \( \bar{d} - \bar{u} \) measurement to larger \( x \) (0.25 < \( x < 0.7 \)). Figure 3 shows the expected statistical accuracy for \( \sigma(p + d)/2\sigma(p + p) \) at JHF \(^{30}\) compared with
the data from E866 and a proposed measurement using the 120 GeV proton beam at the FMI. A definitive measurement of the $d/\bar{u}$ over the region $0.25 < x < 0.7$ could indeed be obtained at FMI and JHF.

To disentangle the $d/\bar{u}$ asymmetry from the possible charge-symmetry violation effect, one could consider $W$ boson production in $p + p$ collision at RHIC. An interesting quantity to be measured is the ratio of the $p + p \rightarrow W^+ + x$ and $p + p \rightarrow W^- + x$ cross sections. It can be shown that this ratio is very sensitive to $d/\bar{u}$. An important feature of the $W$ production asymmetry in $p + p$ collision is that it is completely free from the assumption of charge symmetry. Figure 4 shows the predictions for $p + p$ collision at $\sqrt{s} = 5.000$ GeV. The dashed curve corresponds to the $d/\bar{u}$ symmetric MRS S0' structure functions, while the solid and dotted curves are for the $d/\bar{u}$ asymmetric structure function MRST and MRS(R2), respectively. Figure 4 clearly shows that $W$ asymmetry measurements at RHIC could provide an independent determination of $d/\bar{u}$.

Models in which virtual mesons are admitted as degrees of freedom have implications that extend beyond the $d,\bar{u}$ flavor asymmetry addressed above. They create hidden strangeness in the nucleon via such virtual processes as $p \rightarrow A + K^+, \Sigma + K$, etc. Such processes are of considerable interest as they imply different $s$ and $\bar{s}$ parton distributions in the nucleon, a feature not found in gluonic production of $s\bar{s}$ pairs. This subject has received a fair amount of attention in the literature, but experiments have yet to clearly identify such a difference. Thus in contrast to the $d,\bar{u}$ flavor asymmetry, to date there is no positive experimental evidence for $s\bar{s}$ contributions to the nucleon from virtual meson-baryon states.

A difference between the $s$ and $\bar{s}$ distribution can be made manifest by direct measurement of the $s$ and $\bar{s}$ parton distribution functions in DIS neutrino scattering, or in the measurement of the $q^2$ dependence of the strange quark contribution ($F_{2s}(q^2)$) to the proton charge form factor. Measurement of these form factors allows extraction of the strangeness contribution to the nucleon's charge and magnetic moment and axial form factors. The portion of the charge form factor $F_{2s}(q^2)$ due to strangeness clearly is zero at $q^2 = 0$, but if the $s$ and $\bar{s}$ distributions are different the form factor becomes non-zero at finite $q^2$. These “strange” form factors can be measured in neutrino elastic scattering from the nucleon, or by selecting the parity-violating component of electron-nucleon elastic scattering, as is now being done at the Bates and Jefferson Laboratories.

### 3 Flavor structure of polarized nucleon sea

The flavor structure and the spin structure of the nucleon sea are closely connected. Many theoretical models originally proposed to explain the $d/\bar{u}$ flavor asymmetry also have specific implications for the spin structure of the nucleon sea. In the meson-cloud model, for example, a quark would undergo a spin flip upon an emission of a pseudoscalar meson ($u^\uparrow \rightarrow \pi^- (u\bar{d}, d\bar{u}) + u^\downarrow, \ u^\uparrow \rightarrow \pi^+ (u\bar{d}) + d^\downarrow$, etc.). The antiquarks ($\bar{u}, \bar{d}, \bar{s}$) are unpolarized ($\Delta \bar{u} = \Delta \bar{d} = \Delta \bar{s} = 0$) since they reside in spin-0 mesons. The strange quarks ($s$), on the other
hand, would have a negative polarization since the up valence quark in the proton are positively polarized and the $u^+ \to K^+ + s^+$ process would lead to an excess of $s^+$. By considering a vector meson ($\rho$) cloud, non-zero $\bar{u}, \bar{s}$ sea quark polarizations with $\Delta \bar{u} - \Delta \bar{s} > 0$ were predicted.

The Pauli-blocking model predicts that an excess of $q^\pi(q^\rho)$ valence quarks would inhibit the creation of a pair of $q^\pi(q^\rho)$ sea quarks. Since the polarization of the $u(d)$ quark valance quarks are positive (negative), this model predicts a positive (negative) polarization for the unpolarized $\bar{u}(\bar{d})$ sea ($\Delta \bar{u} > 0 > \Delta \bar{d}$).

In the instanton model, the quark sea can result from a scattering of a valence quark off a nonperturbative vacuum fluctuation of the gluon field, instanton. The interaction induced by an instanton is given by the 't Hooft effective lagrangian which allows processes such as $u^\uparrow \to u^\downarrow d^\uparrow \bar{d}^\downarrow$, $\bar{u}^\downarrow \to d^\uparrow u^\downarrow \bar{d}^\downarrow$, etc. Since the flavor of the quark-antiquark produced in this process is different from the flavor of the initial valence quark, this model readily explains $\Delta \bar{d} < 0$. Furthermore, the correlation between the sea quark helicity and the valence quark helicity in the 't Hooft effective lagrangian (i.e. $u^\uparrow$ leads to a $\bar{d}^\downarrow$) naturally predicts a positively (negatively) polarized unpolarized $\bar{u}(\bar{d})$ sea. In particular, this model predicts a large $\Delta \bar{u}$, $\Delta \bar{d}$ flavor asymmetry, $\Delta \bar{u} > \Delta \bar{d}$, namely,

$$\int_{0}^{1} \Delta \bar{u}(x) - \Delta \bar{d}(x) dx \approx \int_{0}^{1} \bar{u}(x) - \bar{d}(x) dx.$$  

In the chiral-quark soliton model, the model is predicted by the large $N_c$ limit of QCD becomes an effective theory of mesons with the baryons appearing as solitons. Quarks are described by single particle wave functions which are solutions of the Dirac equation in the field of the background pions. In this model, the polarized isovector distributions $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ appears in leading-order ($N_c^0$) in a $1/N_c$ expansion, while the unpolarized isovector distributions $\bar{u}(x) - \bar{d}(x)$ appear in next-to-leading order ($N_c$). Therefore, this model predicts a large flavor asymmetry for the polarized sea $\Delta \bar{u}(x) - \Delta \bar{d}(x) > \bar{u}(x) - \bar{d}(x)$.

In the statistical approach, the nucleon is treated as a collection of massless quarks, antiquarks, and gluons in thermal equilibrium within a finite size volume. The momentum distributions for quarks and antiquarks follow a Fermi-Dirac distributions function characterized by a common temperature and a chemical potential $\mu$ which depends on the flavor and helicity of the quark. It can be shown that

$$\mu_{u^\pi} = -\mu_{\bar{d}^\pi}; \mu_{d^\pi} = -\mu_{\bar{u}^\pi}. \tag{3}$$

Eq. 3, together with the constraints of the valence quark sum rules and inputs from polarized DIS experiments, can readily lead to the prediction that $\Delta \bar{d} > 0$ and $\Delta \bar{u} > 0 > \Delta \bar{d}$.

Predictions of various model calculations for $I_\Delta$, the first moment of $\Delta \bar{u}(x) - \Delta \bar{d}(x)$, are listed in Table 2. While the model cloud model gives small negative values for $I_\Delta$, all other models predict a positive $I_\Delta$ with a magnitude comparable or greater than the corresponding integral for unpolarized sea (recall that $\int_{0}^{1} \bar{u}(x) - \bar{d}(x) dx \simeq 0.12$). Several model-cloud calculations for the direct contribution of $\rho$ meson cloud are in good agreement. However, the large $\pi - \rho$ interference effect reported in [9] was not confirmed in a more recent study [60]. It is worth noting that a recent work [61] on $\pi - \sigma$ interference predicts a large effect on $\Delta \bar{d} - \Delta \bar{u}$, and with a sign opposite to other meson model calculations.

If the flavor asymmetry of the polarized sea is indeed large as the predictions of many models shown in Table 2, it would imply that a significant fraction of the Bjorken sum, $\int_{0}^{1} |u^\pi(x)| |g^\rho(x)| dx$, comes from the flavor asymmetry of polarized nucleon sea.

Measurements of $\Delta \bar{u}(x)$ and $\Delta \bar{d}(x)$ are clearly of great current interest. The HERMES collaboration has reported their preliminary results on the extraction of $\Delta \bar{u}(x)$ and $\Delta \bar{d}(x)$ using polarized semi-inclusive DIS data [63]. A global analysis of inclusive spin asymmetries for $n^+$, $n^-$, $K^+$, and $K^-$ has been carried out for longitudinally polarized hydrogen and deuterium targets. As a result, $\Delta u(x)$, $\Delta d(x)$, $\Delta \bar{u}(x)$, $\Delta \bar{d}(x)$, $\Delta s(x) = \Delta \bar{u}(x) - \Delta \bar{d}(x)$ polarized quark densities were extracted for $0.03 < x < 0.7$ at $Q^2 = 2.5$ GeV$^2$. These very interesting preliminary results showed that $\Delta s$ has a trend of being positive, in disagreement with the predictions of theoretical models which attributed the violation of Ellis-Jaffe sum rule to a large negative polarization of the strange sea. Furthermore, the preliminary HERMES result does not support the prediction of a large positive $\Delta \bar{u} - \Delta \bar{d}$. Although the statistics are still limited, the
HEMES preliminary result shows that $\Delta \bar{u}_\perp$, $\Delta \bar{d}_\perp$, $\Delta \bar{u}_\parallel - \Delta \bar{d}_\parallel$ are all consistent with being zero.

Another promising technique for measuring sea-quark polarization is $W$-boson production at RHIC. The longitudinal single-spin asymmetry for $W$ production in polarized $p + p \rightarrow W^\pm + x$ can be written in leading order as

$$A_{L \perp}^{W^+} \approx -\frac{\Delta \bar{d}(x)}{\bar{u}(x)}, \quad A_{L \perp}^{W^-} \approx -\frac{\Delta \bar{u}(x)}{\bar{u}(x)} \quad (4)$$

at suitable kinematic regions. Therefore, $A_L$ gives a direct measure of sea-quark polarization. The RHIC $W$-production and the HERMES SIDIS measurements are complementary and complementary tools for determining polarized sea quark distributions.

4 Conclusion

The flavor asymmetry of the nuclear sea has been clearly established by recent DIS and Drell-Yan experiments. The $x$ dependence of $\bar{d}/\bar{u}$ indicates that a $\bar{d}/\bar{u}$ symmetric sea dominates at small ($x < 0.05$) and large $x$ ($x > 0.3$). But for $0.1 < x < 0.2$ a large and significant flavor non-symmetric contribution determines the sea distributions. The surprisingly large asymmetry between $\bar{u}$ and $\bar{d}$ is unexplained by perturbative QCD, and it strongly suggests the presence of virtual isovector mesons, mostly pions, in the nucleon sea. Additional clues on the origins of the flavor asymmetry will come from future studies including:

- Measurements of $\bar{d}/\bar{u}$ for $x > 0.25$.
- Measurements of $\Delta \bar{u}$ and $\Delta \bar{d}$ using semi-inclusive DIS, and $W$-production in polarized $p + p$ collision.
- Direct measurement of the meson cloud in DIS experiments tagging on forward-going nucleons. Interesting first measurements were performed recently at HERA.
- More precise measurements on the $s$ versus $\bar{s}$ distributions in the nucleon.

References

47. B. Dressler et al., hep-ph/0109287.