1. INTRODUCTION

Matrix elements of the light cone operator

\[ O(x) = \int [d^4 e^{i k \cdot x} \bar{\psi}(\frac{k - n}{2}) \mu \rho e^{-i g} \int \frac{1}{\lambda / 2} d x \cdot A(\alpha) \psi(\frac{\lambda}{2})] \]

and the tower of twist-two operators

\[ \mathcal{O}_q^{(\mu_1 \mu_2 \cdots \mu_n)} = \bar{\psi}_q \gamma^{(\mu_1} D^{\mu_2} \cdots D^{\mu_n)} \psi_q \]

provide a wealth of precise information about the quark and gluon structure of the nucleon. The diagonal nucleon matrix element \( \langle P|O(x)|P \rangle \) measures the light cone momentum distribution, \( q(x) \), and \( \langle P|\mathcal{O}_q^{(\mu_1 \mu_2 \cdots \mu_n)}|P \rangle \) specifies the \((n-1)^{th}\) moment of this distribution, \( \int dx x^{n-1} q(x) \). Off-diagonal matrix elements of \( O(x) \) measure the generalized parton distributions\(^1\) \( H(x, \xi, t) \) and \( E(x, \xi, t) \):

\[ \langle P'|O(x)|P \rangle = \langle \gamma \rangle H(x, \xi, t) + \frac{i \Delta^2}{2 m} \langle \sigma \rangle E(x, \xi, t), \]

where \( \Delta^\mu = P'^\mu - P^\mu \), \( t = \Delta^2 \), \( \xi = -n \cdot \Delta/2 \), and \( \langle \Gamma \rangle = U(P') U(P) \). Off-diagonal matrix elements of the twist-two operators \( \langle P'|\mathcal{O}_q^{(\mu_1 \mu_2 \cdots \mu_n)}|P \rangle \) yield moments of these generalized parton distributions, and this work considers the generalized form factors \( A_{n0}(t) \equiv \int dx x^{n-1} H(x, 0, t) \) and \( B_{n0}(t) \equiv \int dx x^{n-1} E(x, 0, t) \).

Two special cases are important for the present work. The zeroth moments correspond to the familiar electromagnetic form factors (weighted with appropriate quark charges), \( A_{10}(t) = F_1(t) \) and \( B_{10}(t) = F_2(t) \). The first moments yield the total quark angular momentum, \( J_q = \frac{1}{2} \{ A_{20}(0) + B_{20}(0) \} \). Combined with the angular momentum from the quark spin, \( \frac{1}{2} \Sigma = \frac{1}{2} \{ (1) \Delta u + (1) \Delta d \} \), this enables decomposition of the quark contribution to the nucleon spin.

Burkardt\(^2\) has shown that the generalized parton distribution \( H(x, 0, \Delta^2) \) is the Fourier transform of the impact parameter dependent
Figure 2. Generalized form factors \(A_{20}^{u+d}(t)\) and \(B_{20}^{u+d}(t)\), with dipole fits denoted by dashed curves.

\[
\langle P' |O(\mu_1 \mu_2) |P \rangle = \bar{P}(\mu_1) \gamma_\mu_2 \langle \gamma_\mu_3 \rangle A_{20}(t) + \frac{i}{2m} \bar{P}(\mu_1) \gamma_\mu_2 (\sigma_\mu_3) \Delta B_{20}(t) + \frac{1}{m} \Delta A_{20}(t)
\]

\[
\langle P' |O(\mu_1 \mu_2 \mu_3) |P \rangle = \bar{P}(\mu_1) \gamma_\mu_2 (\gamma_\mu_3) \Delta B_{30}(t) + \frac{i}{2m} \bar{P}(\mu_1) \gamma_\mu_2 (\sigma_\mu_3) \Delta \Delta B_{30}(t)
\]

where \(\bar{P}_\mu = (P_\mu + P'_\mu)/2\).

We calculated connected diagram contributions using \(\sim 200\) SESAM[4] full QCD configurations with Wilson fermions at \(\beta = 5.6\) on \(16^3 \times 32\) lattices at each of three quark masses, \(\kappa = 0.1570, 0.1565,\) and \(0.1560\), corresponding to pion masses defined by \(r_0\) of 744, 831, and 897 MeV respectively.

Figure 1 shows our result for the electromagnetic form factor ratio \(F_2/F_1\) divided by the next to leading order light cone wave function result\[5\] \(\log^2(Q^2/\Lambda^2)/Q^2\) with \(\Lambda = 0.3\) GeV. The \(Q^2\) dependence is in excellent agreement with the recent JLab data\[6\] plotted in Ref. [5], but the overall ratio is a factor of four too high in the heavy quark world in which \(m_\pi \sim 700-900\) MeV.

The total quark contribution to the nucleon spin is given by the extrapolation to \(t = 0\) of \(A_{20}^{u+d}(t)\) and \(B_{20}^{u+d}(t)\) shown in Figure 2. Since \(A_{20}^{u+d}(t)\) is calculated directly at \(t = 0\) and \(B_{20}^{u+d}(t)\) is well fit by a constant that is measured to be nearly zero with small errors, the connected con-
\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
$\kappa$ & 0.1570 & 0.1565 & 0.1560 \\
\hline
$\Delta \Sigma$ & 0.67±.04 & 0.73 ±.03 & 0.68 ±.02 \\
$2L_q$ & 0.06±.05 & -0.04 ±.04 & 0.00 ±.03 \\
$2J_q$ & 0.73±.04 & 0.69±.02 & 0.68 ±.03 \\
\hline
\end{tabular}
\caption{Fraction of nucleon spin arising from quark spin, $\Delta \Sigma$, quark orbital angular momentum, $2L_q$, and quark total angular momentum, $2J_q$.}
\end{table}

The contribution to the angular momentum is measured to within a few percent. Combined with the results of $\Sigma$ from reference [7], we obtain the connected diagram contributions to the decomposition of nucleon spin shown in Table 1. Similar results have been obtained in refs. [8,9]. To the extent that the disconnected diagrams do not change the qualitative behavior, we conclude that of the order of 70\% of the spin of the nucleon arises from the quark spin and a negligible fraction arises from the quark orbital angular momentum in a heavy pion world where $m_\pi \sim 700 - 900$ MeV. In the chiral limit, the quark spin contribution must decrease to $\sim 30\%$ to agree with experiment.

Figure 3 shows the generalized form factors $A_{n=1}^{u-d}(t), A_{n=2}^{u-d}(t),$ and $A_{n=3}^{u-d}(t)$ for $\kappa = 0.1560$ and 0.1570, corresponding to the lowest three moments of $H(x,0,t)$. As explained above, the decrease in slope with increasing moment is a clear manifestation of the decrease of the transverse size of the light cone wave function as $x \to 1$. Note that the error bands are sufficiently narrow that the dramatic change of slope is clearly determined, strongly ruling out a factorized Ansatz for the momentum transfer dependence of generalized form factors. Qualitatively similar behavior is obtained for the connected contributions to $A_{n=1}^{u-d}(t)$ and for the spin-dependent $A_{n=1}^{u-d}(t)$ [10].

REFERENCES

10. W. Schroers et al., these proceedings, [arXiv:hep-lat/0309065].