THE NUCLEON'S ANTIQUARK SEA: A VIRTUAL MESON CLOUD OR GLUONS?

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We study the possible contribution of the nucleon’s virtual meson cloud to the sea quark distribution as observed in deep inelastic lepton scattering. We adjust the meson-nucleon cut-offs to the large-\(x\) tails of the antiquark distributions, find qualitatively different behavior in the flavor singlet and non-singlet channels and study the scale dependence of our results. We demonstrate that, within convolution models, to reproduce the sea quark distribution the relevant pion momenta should be around 0.8 GeV.

1 The Nucleon’s Meson Cloud and Deep Inelastic Lepton Scattering

In this realm, the nucleon is pictured as being part of the time a bare core and part of the time a baryon with one meson "in the air",

\[
|N\rangle = \sqrt{Z} |N_0\rangle + \sum_M g_{MNB} |BM\rangle .
\]

The wave function renormalization factor, \(\sqrt{Z}\), only affects the core because physical (renormalized) and not bare couplings were used [1]. Thus, we keep the conventional value for the \(\pi NN\) coupling constant, which follows unambiguously from dispersion relations for the \(\pi N\) amplitude. In this point our approach differs from other prescriptions [2] where a renormalization of the \(\pi NN\) coupling constant has been introduced. The meson cloud contribution to the nucleon’s antiquark sea can be written as,

\[
x\bar{q}_M(x, Q^2) = \sum_{M,B} \alpha_{MB}^q \int_x^1 dy f_{MB}(y) y \bar{q}_M \left( \frac{x}{y}, Q^2 \right),
\]

where \(\alpha_{MB}^q\) are spin-flavor \(SU(6)\) Clebsch-Gordan factors, \(x\bar{q}_M(x, Q^2)\) is the meson’s valence antiquark distribution [3] fit to Drell-Yan pair production experiments and

\[
f_{MB}(y) = \frac{g_{MNB}^2}{16\pi^2} y \int_{-\infty}^{t_{\text{min}}} dt \frac{\mathcal{I}(t, m_N, m_B)}{(t - m_M^2)^2} F_{MNB}^2(t)
\]

is the meson’s light-cone distribution in the nucleon’s cloud. Here, \(t_{\text{min}} = m_N^2y - m_B^2y/(1-y)\) and

\[
\mathcal{I}(t, m_N, m_B) = \begin{cases} 
-t + (m_B - m_N)^2 & \text{for } B \in \mathbf{8} \\
\frac{(m_B + m_N)^2 - t}{(m_B - m_N)^2 - t} & \text{for } B \in \mathbf{10}.
\end{cases}
\]
The only unknown quantity in the above equations is the form factor, which governs the emission of an off-mass-shell meson, and we parametrize it in exponential form:

\[ F_{MNt}(t) = e^{(t-3^{-1})/\Lambda_{MN}^2}. \]  (5)

2 The Nucleon’s Antiquark Sea

We adjust the various cut-offs to the nucleon’s strange quark content, \( x\bar{s} \), and to the \( SU(3) \) and \( SU(2) \) flavor breaking components of the nucleon’s antiquark sea, \( x\bar{q}_8 = x(\bar{u} + \bar{d} - 2\bar{s}) \) and \( x\bar{q}_3 = x(\bar{d} - \bar{u}) \). This yields

\[ \Lambda_{\pi NN} \approx 1000 \text{ MeV} \]
\[ \Lambda_{\pi N\Delta} \approx 800 \text{ MeV} \]
\[ \Lambda_{KNY} \approx 1200 \text{ MeV} \]  (6)

at a scale of \( Q^2 = 1 \text{ GeV}^2 \). Corresponding results are depicted in Fig. 1.

![Fig. 1: The various components of the nucleon’s antiquark sea. The solid and dashed curves show the MRS(A) [4] and CTEQ3M [5] parametrizations, the dotted line refers to our meson cloud calculation and the data points are from the CCFR collaboration [6].](image)

The agreement in the flavor breaking channels extends to smaller \( x \)-values than those actually considered in our fits (0.3 ≤ \( x \) ≤ 0.5) and it remains satisfactory when the four-momentum transfer is increased. The situation is very different for the \( x\bar{s} \) component, which is predominantly flavor singlet. Here, we only find reasonable agreement with the large-\( x \) tail and the deviations between our fit and the data grow rapidly with increasing \( Q^2 \).
3 Discussion

The vertices in Eq. (6) are softer than what is used in most meson-exchange models of the \(NN\) interaction [7] and they are harder than those inferred from considerations of integrated quantities (sum rules) in DIS [8]. The fact that the \(\pi N\Delta\) vertex is considerably softer than the \(\pi NN\) vertex indicates significant \(SU(6)\) breaking in the \(N/\Delta\) system. A quantitative measure of the importance of the mesonic component is the "number of mesons in the air", which is \(n_\pi = 0.66\) and \(n_K = 0.10\).

In Fig. 2, we analyze which meson virtualities and loop momenta yield the dominant share to the convolution integral of Eq. (2). We find that, typically, the mesons are highly virtual, \(-t \approx 0.4\) GeV\(^2\), and the integrals are dominated by large pion momenta of the order of \(|k| \approx 0.8\) GeV. Thus, the periphery of the nucleon, where the notion of a pion cloud is well defined theoretically, gives an insignificant contribution to the quark sea within a nucleon.

![Fig. 2: The different relative contributions to the convolution integral of Eq. (2) for the \(N \rightarrow N\pi\) sub-process and for a typical \(x\)-value of \(x = 0.3\).](image)

If we evaluate the meson cloud contribution to the violation of the Gottfried sum rule,

\[
\int_0^1 dx \frac{F_{2}^{\mu}(x,Q^2) - F_{2}^{\mu n}(x,Q^2)}{x} = \frac{1}{3} - \frac{2}{3} \Delta_G = \frac{1}{3} - \frac{2}{3} \int_0^1 dx \left[ \bar{d}(x,Q^2) - \bar{u}(x,Q^2) \right],
\]

we find a value of \(\Delta_G = 0.17\) at \(Q^2 = 4\) GeV\(^2\). This agrees with the quantity given by the NMC collaboration of \(\Delta_G^{\text{exp}} = 0.148 \pm 0.039\) [9]. However, the dominant contribution to \(\Delta_G\) comes from the small-\(x\) region where the meson cloud convolution picture is questionable due to shadowing effects. It was argued in Ref. [10] that \(\Delta_G^{\text{exp}}\) could already be saturated by the region \(0 < x < 0.02\) through \(A_2\) Reggeon exchange. This indicates that the violation of the Gottfried sum rule is not necessarily a mesonic effect.

The description of the flavor non-singlet share of the nucleon’s antiquark distributions is quite satisfactory for \(x\)-values larger than about 0.2, and the quality of the agreement is independent on the scale \(Q^2\). This indicates that the evolution of the partonic distributions in the framework of pQCD and the convolution picture are compatible with each other in the non-singlet channels. The flavor singlet component, on the other hand, is quite poorly described through the mesonic cloud, even at a small scale of \(Q^2 = 1\) GeV\(^2\). We are, in fact, only able to attribute the large-\(x\) tail of the \(x\bar{s}\) distribution to the nucleon’s virtual meson cloud, and the deviations from the data-based parametrizations grow rapidly with increasing \(Q^2\). This indicates that, in the singlet channel, other degrees of freedom, most notably gluon splitting into \(q\bar{q}\) pairs, are relevant, even at moderate \(x\) and small values of the four-momentum transfer. This hints that it is not possible to attribute the entire sea quark distribution in the nucleon to its mesonic cloud.
In DIS at high energies, the virtual photon converts into a hadronic $q\bar{q}$ state at a distance $l \approx 1/2m_N x$ before the target. If this coherence length is larger than the dimension of the target, $l \geq 2 \langle r_T \rangle$, not the virtual photon is probing the target but this $q\bar{q}$ state and the naive impulse approximation picture is no longer applicable. As the relevant meson loop momenta are $|k| \approx 0.8$ GeV, significant distances are of the order of $\langle r_{MN} \rangle \approx 0.25$ fm and the shadowing condition is already satisfied at $x \leq 0.2$. This underlines our conclusion that at small $x$ the meson cloud picture is not adequate and different degrees of freedom are dominant.

4 Summary

We critically discussed the analysis of the contribution of the nucleon’s virtual meson cloud to DIS. The meson-nucleon cut-offs that we determine are softer than those employed in most effective $NN$ potentials. However, the meson loop momenta that are probed in DIS, $|k| \approx 0.8$ GeV, are very different from those relevant for low-energy nuclear physics phenomena. While the agreement of our calculations with the data-based parametrizations is satisfactory and scale independent in the flavor breaking channels, the flavor singlet component is quite poorly described in the convolution picture. This stresses the importance of gluonic degrees of freedom, even at such a low scale as $Q^2 = 1$ GeV$^2$. For further details see Ref. [11].

Acknowledgements

This work was supported in part by the Israel-USA Binational Science Foundation Grant No. 9200126, by the MINERVA Foundation of the Federal Republic of Germany, and by the U.S. Department of Energy under Contract No. DE-FG02-93ER40771.

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