Omega Meson Cloud and the Proton’s Light Anti-Quark Distributions

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Abstract

We use the meson cloud model of the nucleon to calculate distribution functions for $(\bar{d} - \bar{u})$ and $\bar{d}/\bar{u}$ in the proton. Including the effect of the omega meson cloud, with a coupling constant $g_\omega^2/4\pi \approx 8$, allows a reasonably good description of the data.

There has been considerable interest in the flavor dependence of the proton’s quark distributions. About ten years ago, the NMC measurement of the integral of the $(\bar{d} - \bar{u})$ provided convincing evidence for the flavor asymmetry of the sea \cite{1}. The meson cloud model and the Sullivan process were used to explain the momentum fraction distribution of $(\bar{d} - \bar{u})$. For reviews, see Refs. \cite{2, 3}. Interest in the light sea quark distributions was heightened by the recent measurement of the ratio $\bar{d}/\bar{u}$ by means of the Drell-Yan process \cite{4, 5}. Similar results for $(\bar{d} - \bar{u})$ were obtained by HERMES \cite{6}. In the context of previous work on the light antiquark asymmetry in the nucleon, a good description of the data was obtained for the $x$-dependence (momentum fraction) of $(\bar{d} - \bar{u})$, but not for the ratio of $\bar{d}/\bar{u}$ \cite{5}. The meson cloud models provide ratios that either increase monotonically with $x$ or turn back towards unity too slowly \cite{7}. Various explanations have been advanced for the discrepancy, e.g., effects of the $\Delta$ \cite{8-11}, and the influence of the Pauli exclusion principle \cite{11}, adjustment of parameters \cite{12}, but none of these changes provides a satisfactory description of the $\bar{d}/\bar{u}$ distribution function. The use of a soft $\pi N\Delta$ form factor enables a reasonable description of $(\bar{d} - \bar{u})$ \cite{5}, but then $\bar{d}/\bar{u}$ is too large. The importance of understanding the ratio $\bar{d}/\bar{u}$ was emphasized recently \cite{13}.

In this Letter we show that the inclusion of the $\omega$ meson along with pion cloud effects, provides a good description of the present data for both $(\bar{d} - \bar{u})$ and $\bar{d}/\bar{u}$. The importance of the $\omega$ in providing the repulsive short-range part of the nucleon-nucleon and consequently attractive nucleon-antinucleon force has been known for a long time. The Compton wavelength of this meson is small, but the large (almost puzzlingly large $g_\omega^2/4\pi \approx 20$) coupling constants universally used to describe the nucleon-nucleon scattering data cause the potential to be non-vanishing over a fairly large range. The $\omega$ meson also
may be very important in deep inelastic scattering from nuclei [14], so it is natural to consider its effects for a proton target.

We provide the usual formulae [2] for the effects of the meson cloud (generalized Sullivan process) in order to facilitate the reader’s understanding of what follows. The wave function of the proton is written in terms of Fock states with and without mesons

$$|p\rangle = \sqrt{Z} |p\rangle_{\text{bare}} + \sum_{MB} \int dy d^2k_\perp \phi_{BM}(y, k_\perp^2) |B(y, k_\perp)\rangle M(1 - y, -k_\perp)\rangle .$$

(1)

Here Z is a wavefunction renormalization constant, $\phi_{BM}(y, k_\perp^2)$ is the probability amplitude for finding a physical nucleon in a state consisting of a baryon, B with longitudinal momentum fraction y and meson M of momentum fraction (1-y) and squared transverse relative momentum $k_\perp^2$.

The quark distribution function $q(x)$ of a proton is given by

$$q(x) = q_{\text{bare}}(x) + \delta q(x) ,$$

(2)

with

$$\delta q(x) = \sum_{MB} \left( \int_x^1 f_{MB}(y)q_M(\frac{x}{y})\frac{dy}{y} + \int_x^1 f_{BM}(y)q_B(\frac{x}{y})\frac{dy}{y} \right) ,$$

(3)

$$f_{MB}(y) = f_{BM}(1 - y) ,$$

(4)

and

$$f_{BM}(y) = \int_0^\infty |\phi_{BM}(y, k_\perp^2)|^2 d^2k_\perp .$$

(5)

The cut-offs required in the model are taken from ref. [2]

$$G_M(t, u) = \exp \frac{t - m_M^2}{2\Lambda_M^2} \exp \frac{u - m_\Delta^2}{2\Lambda_M^2} ,$$

(6)

where $\Lambda_M$ is a cut-off parameter for each meson and t and u are the usual kinematical variables, expressed in terms of $k_\perp$ and y. Such a form is required to respect the identity (1) [2, 15]. The expressions for the splitting functions $f_{MB}(y)$ are those given by [2] as derived in Ref. [16]. We include specifically $\pi$, $\omega$, and $\eta$ mesons, but the latter is negligible. In the present paper, we omit the effects of the $\rho$ meson as well as those of the intermediate $\Delta$. The former increases ($\bar{d} - \bar{u}$), whereas the latter decreases it, so these effects tend to cancel. These effects have been included by previous authors, and do not provide a satisfactory description of the ratio $\bar{d}/\bar{u}$. The number of each type of meson, $n_M$, is obtained by integrating the square of $f_{MB}(y)$ over y. Then for us $Z = 1 - 3n_\pi - n_\omega$.

We need to discuss the functions $q_M(x)$ and $q_B(x)$ of our calculation. Those for the nucleon and pion are measured, but the quark distribution functions of the $\omega$ meson are unknown. The bag model suggests that the structure functions of the $\omega$, $\rho$ and $\pi$ mesons are the same. The near equality is more believable for the $\omega$ and $\rho$, than for that between
the vector and pseudoscalar mesons. However, it has been traditional to assume that the structure function of the $\rho$ and $\pi$ are the same. Thus we use

\[ xq_v(x) = 0.99x^{0.61}(1-x)^{1.02} \]

\[ xq_{sea}(x) = 0.2(1-x)^{5.0}, \]

for the valence and sea quark distributions of both the pion and omega mesons. The bare nucleon sea is parametrized as

\[ x\bar{Q}_{\text{bare}}(x) = 0.11(1-x)^{15.8} \]

\[ \bar{Q}_{\text{bare}} = u_{\text{sea}} = \bar{u}_{\text{sea}} = d_{\text{sea}} = \bar{d}_{\text{sea}} \]

The value of $\Lambda_\pi = (0.83 \pm 0.05)$ GeV is chosen to reproduce the range of allowed values of the integral $\int D \equiv \int_0^1 dx (\bar{d}(x) - \bar{u}(x)) = 0.100 \pm 0.018$ using the sum rule of Henley & Miller: $D = \frac{2}{3}n_\pi = 2n_{\omega}$. The parameter $\Lambda_\omega$ is expected to be larger than $\Lambda_\pi$, and we used the range: $1.3 \text{ GeV} < \Lambda_\omega < 1.8 \text{ GeV}$.

The results of our calculations for $\bar{d}(x) - \bar{u}(x)$ are shown in Fig. 1, and those for the ratio $\bar{d}(x)/\bar{u}(x)$ are shown in Fig. 2. The $\pi$-nucleon coupling constant is taken as $\frac{g_\pi^2}{4\pi} = 13.6$, the $\omega$-proton coupling constant is taken to be $\frac{g_\omega^2}{4\pi} = 8.1$. In Fig. 1 the solid line is for $\Lambda_\pi = 0.83$ GeV, for which $\int_0^1 (\bar{d}(x) - \bar{u}(x))dx = 1.0$. The dashed lines are for $\Lambda_\pi = 0.78$ GeV and $\Lambda_\pi = 0.88$ GeV, the range of values constrained by the experimental error of $\pm 0.18$ in $D$. The $\omega$ meson, like any other isoscalar meson, has no effect here, so that this curve is that from the pion alone. In Fig. 2 the solid curve shown is for $\Lambda_\omega = 1.5$ GeV. The dashed line shows the effect of leaving out the $\omega$ cloud contribution.

We have examined the effect of varying both $\Lambda_\omega$ and $g_\omega$ in the range $1.3 \text{ GeV} \leq \Lambda \leq 1.8 \text{ GeV}$ and $7 < \frac{g_\omega^2}{4\pi} < 20$. The larger values of $g_\omega$ are favored in fits to nucleon-nucleon scattering data using one-boson exchange potentials and the smaller ones from dispersion relation descriptions of forward nucleon-nucleon scattering. The larger values of $g_\omega$ and $\Lambda$ tend to give too small values of the ratio $\bar{d}/\bar{u}$, while decreasing $g_\omega$ or $\Lambda$ causes the maximum value of $\bar{d}/\bar{u}$ to be too large and to appear at too high a value of $x$.

The effects of $\eta$ mesons are not included in the curves shown in the figures. These provide only a 1 to 2% change in $\bar{d}/\bar{u}$ for phenomenologically viable coupling constants. Although we also examined the change of distribution function for the bare quarks suggested by, the effect is sufficiently small when added to that of the $\omega$ meson that we do not show it.

It is clear from the figures that a good description of the present data is provided by the inclusion of the $\omega$ meson with a reasonable coupling constant, and that therefore the meson cloud picture can be successful. As mentioned above there are a number of effects discussed in the literature, not included here, which contribute to the proton sea. In addition, one could include the effects of the $\sigma$ meson, which would also tend to suppress $\bar{d}/\bar{u}$. Including these effects is likely to improve the description of the data or modify the parameters describing the $\omega$-nucleon interaction.
The existence of better data would provide a severe test of the present model, and the prospects of such seem imminent \cite{21}. But it is fair to conclude that the use of the $\omega$ along with the previously suggested meson cloud effects does allow for a good description of the present data.

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Figure Captions

FIGURE 1. Comparison of our meson cloud model with data \[5\] for \((\bar{d} - \bar{u})\). The solid line is for \(\Lambda_\pi = 0.83\) GeV, for which \(D = \int_0^1 (\bar{d} - \bar{u}) dx = 1.0\). The dashed lines are for \(\Lambda_\pi = 0.78\) GeV and \(\Lambda_\pi = 0.88\) GeV, the range of values constrained by the experimental error of \(\pm 0.18\) in \(D\).

FIGURE 2. Comparison of our meson cloud model with data \[5\] for \(\bar{d}/\bar{u}\). The solid line (\(\Lambda_\pi = 0.83\)) is for \(\frac{\omega}{4\pi} = 8.1\) and \(\Lambda_\omega = 1.5\) GeV. The dashed line shows our result if the \(\omega\) cloud contribution is omitted.
