Flavor asymmetry of the nucleon sea in an unquenched quark model

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Abstract. We discuss the flavor asymmetry of the nucleon sea in an unquenched quark model for baryons in which the effects of quark-antiquark pairs ($u\bar{u}$, $d\bar{d}$ and $s\bar{s}$) are taken into account in an explicit form. It is shown that the inclusion of $q\bar{q}$ pairs leads to an excess of $\bar{d}$ over $\bar{u}$ quarks in the proton.

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1 Introduction

The flavor content of the nucleon sea provides an important test for models of nucleon structure. A flavor symmetric sea leads to the Gottfried sum rule $S_G = 1/3$ \cite{1}, whereas any deviation from this value is an indication of the $d/\bar{u}$ asymmetry of the nucleon sea. The first clear evidence of a violation of the Gottfried sum rule came from the New Muon Collaboration (NMC) \cite{2}, which was later confirmed by Drell-Yan experiments \cite{3} and a measurement of semi-inclusive deep-inelastic scattering \cite{4}. All experiments show evidence that there are more $\bar{d}$ quarks in the proton than there are $\bar{u}$ quarks. The experimental studies and theoretical ideas on the flavor asymmetric sea are summarized in several review articles \cite{5}.

In the constituent quark model (CQM), the proton is described in terms of a $uud$ valence-quark configuration. Therefore, the violation of the Gottfried sum rule implies the existence of higher Fock components (such as $uud - q\bar{q}$ configurations) in the proton wave function. Additional indications for the importance of multiquark components are provided by parity-violating electron scattering experiments, which have shown evidence for a nonvanishing strange quark contribution, albeit small, to the charge and magnetization distributions of the proton \cite{6}, and by CQM studies of baryon spectroscopy \cite{7}.

Theoretically, the role of $q\bar{q}$ configurations in the nucleon wave function was studied in an application to the electromagnetic form factors \cite{8}. Mesonic contributions to the spin and flavor structure of the nucleon are reviewed in \cite{5}. In another, CQM based, approach, the importance of $s\bar{s}$ pairs in the proton was studied in a flux-tube breaking model based on valence-quark plus glue dominance to which $s\bar{s}$ pairs are added in perturbation \cite{9}. The pair-creation mechanism is inserted at the quark level and the one-loop diagrams are calculated by summing over a complete set of intermediate baryon-meson states $BC$ (see Fig.\textsuperscript{1}). The pairs are created with the $^3P_0$ quantum numbers of the vacuum. For consistency with the OZI-rule and to retain the success of the CQM in hadron spectroscopy, it was found necessary to sum over a complete set of intermediate states, including both pseudoscalar and vector mesons, rather than just a few low-lying states \cite{9,10}.

In order to address the violation of the Gottfried sum rule, we have generalized the model of \cite{9} to include $u\bar{u}$ and $d\bar{d}$ loops as well. The formalism of the ensuing unquenched quark model is described in a separate contribution to these proceedings \cite{11}. The aim of this manuscript is to discuss an application to the flavor asymmetry of the nucleon sea.

2 Flavor asymmetry

The first clear evidence for the flavor asymmetry of the nucleon sea was provided by NMC at CERN \cite{2}. The flavor asymmetry is related to the Gottfried integral for the dif-
Table 1. Experimental values of the Gottfried integral

| Experiment | $\langle Q^2 \rangle$ | $x$ range | $S_G$ |
|------------|----------------------|-----------|-------|
| NMC        | 4                    | 0.004 < $x$ < 0.80 | 0.2281 ± 0.0065 |
| HERMES     | 2.3                  | 0.020 < $x$ < 0.30 | 0.23 ± 0.02 |
| E866/NuSea | 54                   | 0.015 < $x$ < 0.35 | 0.255 ± 0.008 |

ference of the proton and neutron electromagnetic structure functions

$$S_G = \int_0^1 dx \frac{F_p^p(x) - F_n^p(x)}{x}$$

$$= \frac{1}{3} - \frac{2}{3} \int_0^1 dx \left[ \bar{d}(x) - \bar{u}(x) \right].$$

Under the assumption of a flavor symmetric sea $\bar{d}(x) = \bar{u}(x)$ one obtains the Gottfried sum rule $S_G = 1/3$. The final NMC value is $0.2281 ± 0.0065$ at $Q^2 = 4$ (GeV/c)$^2$ for the Gottfried integral over the range $0.004 < x < 0.8$ [2], which implies a flavor asymmetric sea. The violation of the Gottfried sum rule has been confirmed by other experimental collaborations [3, 4]. Table 1 shows that the experimental values of the Gottfried integral are consistent with each other within the quoted uncertainties, even though the experiments were performed at very different scales, as reflected in the average $Q^2$ values. Theoretically, it was shown that in the framework of the cloudy bag model the coupling of the proton to the pion cloud provides a mechanism to produce a flavor asymmetry due to the dominance of $n\pi^+$ among the virtual configurations [12].

In the unquenched quark model, the flavor asymmetry can be calculated from the difference of the number of $\bar{d}$ and $\bar{u}$ sea quarks in the proton

$$N_{\bar{d}} - N_{\bar{u}} = \int_0^1 dx \left[ \bar{d}(x) - \bar{u}(x) \right].$$

Even in absence of explicit information on the (anti)quark distribution functions, the integrated value can be obtained directly from the left-hand side of Eq. (1). The effect of the quark-antiquark pairs on the Gottfried integral is a reduction of about one third with respect to the Gottfried sum rule, corresponding to an excess of $\bar{d}$ over $\bar{u}$ quarks in the proton which is in qualitative agreement with the NMC result. It is important to note that in this calculation the parameters were taken from the literature [9, 13], and that no attempt was made to optimize their values. Due to isospin symmetry, the neutron has a similar excess of $\bar{u}$ over $\bar{d}$ quarks.

3 Summary, conclusions and outlook

In this contribution, we discussed the importance of quark-antiquark pairs in baryon spectroscopy. The calculations were carried out in an unquenched quark model for baryons in which the contributions from $uu\bar{d}$, $d\bar{d}$ and $\bar{s}s$ loops are taken into account in a systematic way [11].

The model was applied to the flavor asymmetry of the nucleon sea. In a first, exploratory, calculation in which the parameters were taken from the literature [9, 13], it was shown that the inclusion of $qq$ pairs leads immediately to an excess of $\bar{d}$ over $\bar{u}$ quarks in the proton. We emphasize again that no attempt was made to optimize the parameters in the calculations.

In our opinion the first results for the flavor asymmetry (discussed here) and the proton spin (see [11]) are very promising and encouraging. We believe that the inclusion of the effects of quark-antiquark pairs in a general and consistent way, as suggested in [11] and in this contribution, may provide a major improvement to the constituent quark model, increasing considerably its range and applicability.

In future work, the unquenched quark model will be applied systematically to several problems in light baryon spectroscopy, such as the electromagnetic and strong couplings, the elastic and transition form factors of baryon resonances, their sea quark content and their flavor decomposition [14].

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