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Electroproduction of baryon–meson states and strangeness suppression

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ABSTRACT

We describe the electroproduction ratios of baryon–meson states from nucleon, inferring from the sea quarks in the nucleon using an extension of the quark model that takes into account the sea. As a result we provide, with no adjustable parameters, the predictions of ratios of exclusive meson–baryon final states: ΛK^+, $\Sigma^* K$, ΣK, $p\pi^0$, and $n\pi^+$. These predictions are in agreement with the new JLab experimental data showing that sea quarks play an important role in the electroproduction. We also predicted further ratios of exclusive reactions that can be measured and tested in future experiments. In particular, we suggested new experiments on deuterium and tritium. Such measurements can provide crucial tests of different predictions concerning the structure of nucleon and its sea quarks helping to solve an outstanding problem. Finally, we compute the so called strangeness suppression factor, λ_s, that is the suppression of strange quark–antiquark pairs compared to nonstrange pairs, and we found that our finding with this simple extension of the quark model is in good agreement with the results of JLab and CERN experiments.

1. Introduction

In particle physics, the exact hadronization process is unknown. To determine the structure of events at high and low energies a model for hadronization from first principles is needed but it is still missing. There have been many attempts at modeling $q\bar{q}$ creation within the quark model (QM) formalism arising from Micu's suggestion [1] that hadron decays proceed through $q\bar{q}$ pair production with vacuum quantum numbers, i.e. $J^{PC} = 0^{++}$. Since the $q\bar{q}$ pair corresponds to a $^3P_0$ quark–antiquark state, this model is known as the $^3P_0$ pair-creation model [1–3].

New studies have been conducted by the CLAS Collaboration [4]. These have tried to extract the flavor-dependence of the $q\bar{q}$ creation in two-body exclusive reactions. The study of $q\bar{q}$ creation can help us to understand how quarks become observable hadrons, which now is an open problem.

In this Letter, we will focus on the role of nucleon sea quarks in hadron production of baryon–meson final state for the exclusive reactions, when there are no decay chains. Since the evidence for the flavor asymmetry of the proton sea was found by NMC at CERN [5], many studies have been carried out to explain the importance of the quark–antiquark content in the nucleon and its role in the observables. We compute the ratios of this baryon–meson production by inferring them from the continuum components of the nucleon using the Unquenched Quark Model (UQM) for baryons [6–9]. We also extract the probabilities of the sea quarks and their relation with $q\bar{q}$ creation in electroproduction.

2. Unquenched quark model

The UQM is based on a quark model (QM) with continuum components, to which quark–antiquark pairs with vacuum quantum numbers are added as a perturbation employing a $^3P_0$ model for $q\bar{q}$ pair creation. This approach, which is a generalization of the unitarized quark model by Törnqvist and Zenczykowski [10], was motivated by the work by Isgur and coworkers on the flux-tube breaking model. They showed that the QM emerges as the adiabatic limit of the flux-tube model to which the effects of $q\bar{q}$ pair creation can be added as a perturbation [11]. 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. Under these assumptions, the baryon wave function consists of a zeroth order three-quark configuration

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$|A\rangle$ plus a sum over all the possible higher Fock components due to the creation of ${}^3P_0$ quark–antiquark pairs

$$|\psi_A\rangle = \mathcal{N}_A \left[|A\rangle + \sum_{BClJ} \int d\vec{K}\, k^2 dk\, |BC, l, J; \vec{K}, k\rangle \times \frac{\langle BC, l, J; \vec{K}, k|T^\dagger|A\rangle}{\Delta E_{A\to BC}(k)} \right] . \quad (1)$$

Here, A denotes the initial baryon and BC the asymptotic baryon–meson system; $k = |\vec{k}|$ and l are the relative momentum and orbital angular momentum between B and C respectively, and J is the total angular momentum $\vec{J} = \vec{J}_B + \vec{J}_C + \vec{l}$. The energy denominator represents the energy difference between initial and final hadrons calculated in the rest frame of the initial baryon $\Delta E_{A\to BC}(k) = M_A - \sqrt{M_B^2 + k^2} - \sqrt{M_C^2 + k^2}$. The operator $T^\dagger$ creates a quark–antiquark pair in the ${}^3P_0$ state with the quantum numbers of the vacuum, $L = S = 1$ and $J = 0$,

$$T^\dagger = -3\gamma_0 \int d\vec{p}_4\, d\vec{p}_5\, \delta(\vec{p}_4 + \vec{p}_5)\, C_{45}\, F_{45}\, e^{-\alpha_d^2(\vec{p}_4-\vec{p}_5)^2/8} \times \left[\chi_{45} \times \mathcal{Y}_1(\vec{p}_4 - \vec{p}_5)\right]_0^{(0)} b_4^\dagger(\vec{p}_4)\, d_5^\dagger(\vec{p}_5) , \quad (2)$$

where $b_4^\dagger(\vec{p}_4)$ and $d_5^\dagger(\vec{p}_5)$ are the creation operators for a quark and an antiquark with momenta $\vec{p}_4$ and $\vec{p}_5$, respectively. The quark–antiquark pair is characterized by a color singlet wave function C_{45}, a flavor singlet wave function F_{45}, a spin triplet wave function χ_{45} with spin $S = 1$ and a solid spherical harmonic $\mathcal{Y}_1(\vec{p}_4 - \vec{p}_5)$ that indicates that the quark and antiquark are in a relative P wave. The operator $T^\dagger$ creates a pair of constituent quarks with an effective size. Thus, the pair creation point is smeared out by a Gaussian factor whose width is given by α_d.

3. Production rates in the UQM

In the UQM, the asymptotic states are included in the wave function of the proton. These components are related to the creation of $q\bar{q}$ pairs, with the quantum numbers of the vacuum as it is described in the ${}^3P_0$ mechanism. Here we describe the production ratios from nucleon $N\gamma^* \to BC/N\gamma^* \to B'C'$ in exclusive reactions. The production ratios in exclusive reaction from proton target were just measured by the CLAS Collaboration [4]. We calculate these ratios from the probability to find a virtual baryon–meson component (BC) in the nucleon wave function as

$$P(BC) = |\langle BC|\psi_N\rangle|^2 . \quad (3)$$

In the electroproduction process we assume that the proportionality constant is the same for all baryon–meson final states, so the production ratio from a proton target can be written as follows

$$\frac{p \to \Lambda K^+}{p \to n\pi^+} \approx \frac{P(\Lambda K^+)}{P(n\pi^+)} . \quad (4)$$

Note that this assumption is not always true, since in the process a phase-space factor should be added, as the experimentalists have done in Ref. [4]. However, in the recent study by Mestayer et al. [4] the ratios between $W = 1.65$ GeV and $W = 2.55$ GeV are approximately independent of W (total hadronic energy in the center-of-mass frame) [4,12]. Obviously, in the case of $p\pi^0/n\pi^+$ the effect of phase-space corrections to the theoretical values vanishes. For the ratio $\Lambda K/N\pi$, the introduction of the phase space corrections causes a decrease of the order of 15–25% which brings the final value closer to the experimental central value. Due to the difference in phase space the corrections for the $\Sigma K/N\pi$ and $\Sigma^* K/N\pi$ ratios are expected to be even larger. The complete theoretical dependence of the results on the energy is the subject of subsequent article [13].

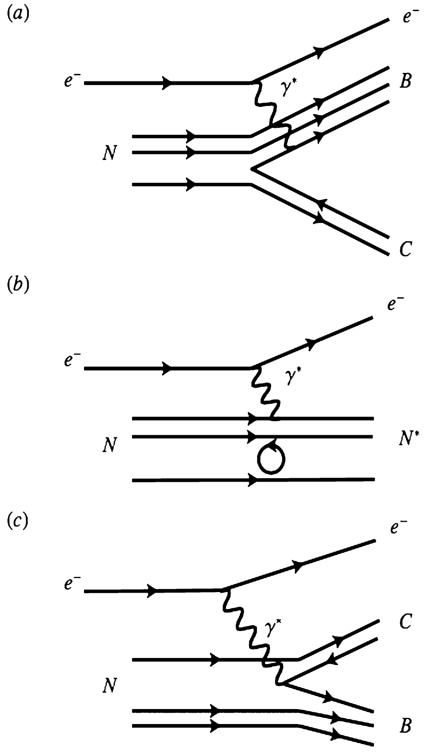

Fig. 1. Schematic diagrams of electroproduction processes. The virtual baryon B created by QCD vacuum fluctuations absorbs the virtual photon (a). The virtual photon is absorbed by a constituent quark in the nucleon, thus a N^* state is produced (b). The virtual photon creates a $q\bar{q}$ pair that can produce a baryon–meson state (BC) from nucleon (c). See the text for more details.

Eq. (4) comes from diagram (a) in the Fig. 1, where the virtual photon γ^* is absorbed by the virtual baryon B, by the quark created in the ${}^3P_0$ vertex. Under this picture, after the quark from the ${}^3P_0$ vertex absorbs the photon, it can not close the ${}^3P_0$ loop and the hadronization occurs. Since the final baryon–meson state BC is observed experimentally in exclusive reactions, only the virtual component BC in the nucleon wave function will contribute if BC virtual state is the same as the BC state that can be observed in exclusive reactions. In the ratios, the coupling constants and other factors due to the process cancel out, thus the ratios in exclusive reactions are inferred from the sea quarks of the nucleon.

Here we study the exclusive reactions where octet and decuplet baryons in combination with pseudoscalar meson could be observed, thus the other components do not contribute. To extend our study to the description of baryon-vector meson production, another process in diagram (a) of Fig. 1 should be considered, where the photon is absorbed by the antiquark in the meson C. The virtual photon can not couple to any valence quark, since if the virtual photon is absorbed by a valence quark the ${}^3P_0$ loop would close, diagram (b) in Fig. 1, as a result a N^* resonance is produced, that is not considered here because we are studying exclusive reactions.

There exists another process in which the virtual photon creates a $q\bar{q}$ pair, that may contribute to the electroproduction of baryon–meson states, see Fig. 1 diagram (c). The contribution of this creation process is expected to be small and is not considered here.

Table 1
Comparison between theoretical ratios of baryon–meson electroproduction from neutron and proton and experimental data. In the third column are the theoretical results of the first and second columns. Experimental data is just for proton.

Ratio from neutron	Ratio from proton	UQM	Exp. [4] from proton
$\Lambda K^0/p\pi^-$	$\Lambda K^+/n\pi^+$	0.227	$0.19 \pm 0.01 \pm 0.03$
$\Lambda K^0/n\pi^0$	$\Lambda K^+/p\pi^0$	0.454	$0.50 \pm 0.02 \pm 0.12$
$n\pi^0/p\pi^-$	$p\pi^0/n\pi^+$	0.5	$0.43 \pm 0.01 \pm 0.09$
$\Sigma^0 K^0/p\pi^-$	$\Sigma^0 K^+/n\pi^+$	0.007	–
$\Sigma^0 K^0/n\pi^0$	$\Sigma^0 K^+/p\pi^0$	0.014	–
$\Sigma^- K^+/p\pi^-$	$\Sigma^+ K^0/n\pi^+$	0.014	–
$\Sigma^- K^+/n\pi^0$	$\Sigma^+ K^0/p\pi^0$	0.028	–
$\Sigma^{*0} K^0/p\pi^-$	$\Sigma^{*0} K^+/n\pi^+$	0.045	–
$\Sigma^{*0} K^0/n\pi^0$	$\Sigma^{*0} K^+/p\pi^0$	0.090	–
$\Sigma^{*-} K^+/p\pi^-$	$\Sigma^{*+} K^0/n\pi^+$	0.090	–
$\Sigma^{*-} K^+/n\pi^0$	$\Sigma^{*+} K^0/p\pi^0$	0.18	–

In the UQM the probability of finding a BC component is the product of a spin–flavor-isospin factor and a radial integral

$$\frac{P(\Lambda K^+)}{P(n\pi^+)} = \frac{27}{50}\frac{I_{N\to\Lambda K}}{I_{N\to N\pi}} , \tag{5}$$

where the factor 27/50 is the ratio of the color-flavor-spin–isospin (CFSI) factors and the integral $I_{A\to BC}$ is an integral in momentum space corresponding to the production of a baryon–meson state BC from a baryon A

$$I_{A\to BC} = \int_0^\infty dk \frac{k^4 e^{-2F^2k^2}}{\Delta E^2_{A\to BC}(k)} . \tag{6}$$

The coefficient F^2 depends on the size of the harmonic oscillator wave functions for baryons and mesons, α_B and α_C, respectively, and the Gaussian smearing of the pair-creation vertex, α_D, which are taken from Ref. [8] to be $\alpha_B = 0.32$ GeV, $\alpha_C = 0.40$ GeV and $\alpha_D = r_q\sqrt{4/3} = 0.35$ fm. The corresponding value of F^2 is $2.275\ \text{GeV}^{-2}$.

The color-flavor-spin–isospin factor plays an important role in the production rates. In fact, for example if we consider the limit case in which, the two final BC states in the ratio are in the same isospin channels, the radial contribution is the same and the production rate will only depend on this factor. Thus the predicted ratio for $p \to p\pi^0/p \to n\pi^+ = 1/2$ is well understood on the basis of isospin symmetry which is conserved in the UQM. However, the general result is determined by a combination of ratios of CFSI factors and integrals over the relative momentum, see Eq. (5). In the case of flavor symmetry, the ratios are determined completely by the CFSI factors. For example, in the limit of flavor symmetry the ratio $\Lambda K^+/n\pi^+$ would be $27/50 = 0.54$. The effect of $SU(3)$ symmetry breaking in the UQM can be observed by a comparison with UQM result $\Lambda K^+/n\pi^+ = 0.227$ from Table 1. Inspection of Table 1 shows that the observed rates are reproduced very well by our calculations. In addition, we present the results for some other channels. Moreover, using the isospin symmetry we computed the production rates from the neutron. We are aware that the neutron target does not exist but eventually those results can be extracted from new experiments on deuterium or tritium.

4. Strangeness suppression factor

As we have already shown, the asymptotic states play an important role in exclusive two-body production, since the ratios of this process can be determined in a straightforward way by means of the UQM inferred from the virtual components produced by the quantum vacuum fluctuations. Likewise we can infer from the flavor content of the proton the $q\bar{q}$ creation probabilities on the BC final states. Within this approach the production of the $q\bar{q}$ in the asymptotic states of the proton is linked to the final states produced by electroproduction. Here, we extract the probabilities from sea quarks and we only point out the fact that the production of $q\bar{q}$ is related to the sea quarks in the nucleon. As an example, we study the strangeness suppression factor, λ_s, which is defined in the literature as [14]

Table 2
The production ratios of the $q\bar{q}$ probabilities and λ_s inferred from sea quarks of the proton (top) and neutron (bottom). The column UQM$^{(1)}$ contains the $q\bar{q}$ production ratios with π, K, η and η' mesons, while the column UQM$^{(2)}$ only takes into account π and K mesons.

Ratio	UQM$^{(1)}$	UQM$^{(2)}$	Exp.	Ref.
$s\bar{s}/d\bar{d}$	0.265	0.245	0.22 ± 0.07	[4]
$u\bar{u}/d\bar{d}$	0.568	0.568	0.74 ± 0.18	[4]
$2s\bar{s}/(u\bar{u}+d\bar{d})$	0.338	0.313	0.25 ± 0.09	[4]
			0.29 ± 0.02	[14]
$s\bar{s}/u\bar{u}$	0.265	0.245		
$d\bar{d}/u\bar{u}$	0.568	0.568		
$2s\bar{s}/(u\bar{u}+d\bar{d})$	0.338	0.313		

$$\lambda_s = \frac{2(s\bar{s})}{(u\bar{u}) + (d\bar{d})} , \tag{7}$$

where $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ are the mean numbers of quark–antiquark pairs in the proton. The probabilities to produce a $q\bar{q}$ pair are computed as

$$q\bar{q} = \sum_{B_iCi} \langle B_iC_i|\hat{P}(q\bar{q})|N\rangle^2 , \tag{8}$$

where $\hat{P}(q\bar{q})$ is the operator that counts the $q\bar{q}$ pairs created in the electroproduction from the nucleon; B_i and C_i are the all possible baryon and meson states that can be observed in exclusive reactions.

Our results for the $q\bar{q}$ production ratios are present in Table 2, the column UQM$^{(1)}$ contains the $q\bar{q}$ production ratios with pseudoscalar mesons in combination with octet and decuplet baryons ($N\pi$, $\Delta\pi$, ΣK, $\Sigma^* K$, ΛK, $N\eta$, $N\eta'$ channels), while the column UQM$^{(2)}$ only takes into account π and K mesons in combination with octet and decuplet baryons ($N\pi$, $\Delta\pi$, ΣK, $\Sigma^* K$, ΛK channels). Since the isospin symmetry is valid for the nucleon wave function in the UQM, we present our results for the $q\bar{q}$ production ratios of proton and neutron in Table 2. The value for the strangeness suppression factor λ_s is in good agreement with the observed values from exclusive reactions at JLab [4] and in high-energy production experiments at CERN [14].

5. Summary and conclusions

In summary, we computed the production ratios of baryon–meson final states in exclusive reactions and we found that our predictions of those ratios are in good agreement with the new experimental data at JLab [4] as a first theoretical calculation that explains the new data reported in [4]. We also computed other baryon–meson production ratios still unobserved but that in principle could be observed in exclusive reactions from proton or neutron initial states in future new experiments. In particular, for the neutron case we suggested new experiments on deuterium or tritium. We showed that sea quarks play an important role in the electroproduction since our predictions are in agreement with the experimental results, thus we found that the meson–baryon production in exclusive reactions could provide information on the sea components of the nucleon. Therefore, future experiments of exclusive reactions can provide another test of different predictions concerning the nucleon structure.

An interesting result was the production ratio $u\bar{u}/d\bar{d} = 0.568$ from the proton, which is compatible with the experimental value obtained by Mestayer et al. at JLab [4], unlike the unity value used in high-energy hadronization models. Those two findings reinforce each other (the experimental one by [4], and our theoretical prediction) and, in our view, are well explained by the fact that there is a excess of $d\bar{d}$ over $u\bar{u}$ pairs in the proton as seen by NMC and HERMES [5,15] and, if one believes that the $q\bar{q}$ production is governed by the sea quark on proton where the $d\bar{d}$ is bigger than the $u\bar{u}$ content, this result on the ratio different from one is a direct consequence. In the case of neutron, we predict $d\bar{d}/u\bar{u} = 0.568$ thus the $u\bar{u}$ production would be higher than the $d\bar{d}$ production, since isospin symmetry yields a $u\bar{u}$ excess over $d\bar{d}$ in neutron, but this prediction can be tested by future experiments at JLab and LHC. On the contrary, it is worthwhile noticing that λ_s is the same from proton and neutron.

The extraction of quark–antiquark production in exclusive reactions from nucleon gave us a suppression of strange quark–antiquarks compared to nonstrange pairs. This is in a good agreement with the available experimental data both from JLab [4] and CERN [14].

Finally, in Ref. [4] the experimentalists observed that the measured rates are independent from the type and energy of any resonance formed in the intermediate state. As such, the results should reflect some fundamental aspect of flavor production like the breaking of the underling $SU(3)$ symmetry induced by the sea quark components. Moreover, our picture can be extended to study photoproduction and hadron production with meson beams which eventually can be tested at J-PARC.

It is worthwhile noticing that the results for the UQM are independent of the overall parameter or strength of the ${}^3P_0$ quark–antiquark pair creation vertex, usually called γ_0. The values of the remaining parameters were taken from previous work and no attempt was made to optimize their values.

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