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Deep electroproduction of exotic hybrid mesons

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We evaluate the leading order amplitude for the deep exclusive electroproduction of an exotic hybrid meson in the Bjorken regime. We show that, contrarily to naive expectation, this amplitude factorizes at the twist 2 level and thus scales like usual meson electroproduction when the virtual photon and the hybrid meson are longitudinally polarized. Exotic hybrid mesons may thus be studied in electroproduction experiments at JLAB, HERA (HERMES) or CERN (Compass).

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The study of hadrons outside the constituent quark models multiplets is an interesting topic [1–4] which is of fundamental importance to understand the dynamics of quark confinement. Deep exclusive meson electroproduction (see, for instance [5,6]) is well described in the framework of the collinear approximation where generalized parton distributions (GPDs) [7] and distribution amplitudes encode the nonperturbative parts of a factorized amplitude [8]. In this Rapid Communication we focus on the investigation of the electroproduction of an isotriplet exotic meson with $J^{PC}=1^{-+}$ which we will denote as H. Candidates for such states include $\pi_1(1400)$ [9] which is mostly seen through its $\pi\eta$ decay. Our derivation applies as well to exotic hybrid mesons with other quantum numbers. However, our analysis of the normalization of the amplitude is only valid for the 1^{-+} state. Theoretically these states are the subject of intense studies [1], mostly through lattice simulations [4]. A naive argument based on a constituent quark picture of the exotic hybrid meson would lead to the expectation that the amplitude has a vanishing twist 2 component and then that the rate of such processes is suppressed at large Q^2 with respect to usual meson electroproduction. This is not true since the quark-antiquark correlator on the light cone includes a gluonic component due to gauge invariance and leads to a leading twist hybrid light-cone distribution. We study such a correlator in detail and calculate its contribution to the hybrid electroproduction amplitude. The reactions $\gamma^* p \to H^0 p, \gamma^* p \to H^+ n, \gamma^* n \to H^0 n, \gamma^* n \to H^- p$, or the coherent reaction on deuteron [10] $\gamma^* d \to H^0 d$ may be studied to experimentally access this amplitude. In this paper we restrict ourselves to the first of them and to longitudinally polarized virtual photon and hybrid meson.

Let us consider the hybrid-to-vacuum matrix element of the bilocal quark operators. As mentioned before, we suppose that the hybrid is the isotriplet state with $J^{PC}=1^{-+}$ quantum numbers. In the quark model where mesons are described as quark-antiquark states, such quantum numbers are forbidden.

Nonlocal quark operators necessarily involve gluon operators due to color gauge invariance. The key problem is whether this gluon admixture allows this quark matrix element to have exotic quantum numbers such as $J^{PC}=1^{-+}$. To answer this question we define, as usual, the meson distribution amplitude through the Fourier transformed correlator taken at $z^2=0$,

$$\begin{aligned}\langle H(p,\lambda)|\bar{\psi}(-z/2)\gamma_\mu[-z/2;z/2]\psi(z/2)|0\rangle \\ = if_H M_H\left[\left(e^{(\lambda)}_\mu - p_\mu \frac{e^{(\lambda)}\cdot z}{p\cdot z}\right)\int_0^1 dy\, e^{i(\bar{y}-y)p\cdot z/2}\phi^H_T(y)\right. \\ \left. + p_\mu \frac{e^{(\lambda)}\cdot z}{p\cdot z}\int_0^1 dy\, e^{i(\bar{y}-y)p\cdot z/2}\phi^H_L(y)\right], \qquad (1)\end{aligned}$$

where $\bar{y}=1-y$; f_H denotes a dimensionful coupling constant of the hybrid meson, so that the distribution amplitude ϕ^H is dimensionless. We will discuss its normalization later.

For the longitudinal polarization case

$$e^{(0)}_\mu = \frac{e^{(0)}\cdot z}{p\cdot z}p_\mu$$

only ϕ^H_L contributes, so that

$$\begin{aligned}\langle H(p,0)|\bar{\psi}(-z/2)\gamma_\mu[-z/2;z/2]\psi(z/2)|0\rangle \\ = if_H M_H e^{(0)}_\mu \int_0^1 dy\, e^{i(\bar{y}-y)p\cdot z/2}\phi^H_L(y). \qquad (2)\end{aligned}$$

In Eqs. (1) and (2), we insert the path-ordered gluonic exponential along the straight line connecting the initial and final points $[z_1;z_2]$ which provides the gauge invariance for bilocal operator and equals unity in a lightlike (axial) gauge. For simplicity of notation we shall omit from now on the index L from the hybrid meson distribution amplitude.

Let us now prove that it is possible to describe in this way an exotic $J=1$ meson state with quantum numbers $PC=-+$. From charge conjugation invariance, one can immediately deduce for the neutral member of the isotriplet H^0 with the flavor structure $1/\sqrt{2}(\bar{u}u-\bar{d}d)$ that the parametrizing function ϕ^H is antisymmetric, i.e.,

$$\phi^H(y) = -\phi^H(1-y). \tag{3}$$

Isospin invariance and G-parity imply the same relation for charged hybrids. The property (3) is similar to the case of two pion distribution amplitude [11]. In particular, the antisymmetric property implies

$$\int_0^1 dy\, \phi^H(y) = 0. \tag{4}$$

Let us pass to the analysis of the remaining quantum number, parity. For this purpose, it is convenient to expand the left-hand side of Eq. (1) in a Taylor series, which is possible because the matrix element is assumed to be UV regularized and does not contain any singularities in z (these singularities only appear in the hard scattering coefficient function). As a result, the hybrid-to-vacuum matrix element of this operator may be rewritten in the form:

$$\langle H(p,\lambda)|\bar{\psi}(-z/2)\gamma_\mu[-z/2;z/2]\psi(z/2)|0\rangle = \sum_{n\, odd} \frac{1}{n!} z_{\mu_1}\ldots z_{\mu_n} \times \langle H(p,\lambda)|\bar{\psi}(0)\gamma_\mu \overleftrightarrow{D}_{\mu_1}\ldots\overleftrightarrow{D}_{\mu_n}\psi(0)|0\rangle, \tag{5}$$

where D_μ is the usual covariant derivative and $\overleftrightarrow{D}_\mu = \frac{1}{2}(\overrightarrow{D}_\mu - \overleftarrow{D}_\mu)$. Due to the positive charge parity of H^0, see Eq. (3), only odd terms in Eq. (5) do contribute. The simplest case is provided by the $n=1$ twist 2 operator

$$\mathcal{R}_{\mu\nu} = \mathrm{S}_{(\mu\nu)}\bar{\psi}(0)\gamma_\mu\overleftrightarrow{D}_\nu\psi(0), \tag{6}$$

where $S_{(\mu\nu)}$ denotes the standard symmetrization operator $[S_{(\mu\nu)}T_{\mu\nu} = 1/2(T_{\mu\nu}+T_{\nu\mu})]$. $\mathcal{R}_{\mu\nu}$ is proportional to the quark energy-momentum tensor, i.e., $\mathcal{R}_{\mu\nu} = -i\Theta_{\mu\nu}$. Its matrix element of interest is

$$\langle H(p,\lambda)|\mathcal{R}_{\mu\nu}|0\rangle = \frac{1}{2} f_H M_H\, \mathrm{S}_{(\mu\nu)} e_\mu^{(\lambda)} p_\nu \times \int_0^1 dy(1-2y)\phi^H(y). \tag{7}$$

Note that it is the symmetry in $\mu\nu$ of the energy momentum tensor which selects the twist-2 function.

To determine the parity one should treat the meson polarization with some care. The equation $e_{L\mu} \sim p_\mu / M_H$ holds for a *fast* longitudinally polarized vector meson. On the other hand, the meson is an eigenstate of the parity operator P only in its *rest* frame. In this frame p_μ has only a zeroth component, while e_μ has a vanishing zeroth component. This leads to the negative parity of the relevant components $\mathcal{R}_{0k}$ with $k=1,2,3$.

$$P(\mathrm{S}_{(k0)}\bar{\psi}(0)\gamma_k\overleftrightarrow{D}_0\psi(0)) = -. \tag{8}$$

This explicitly shows that the nonlocal matrix element (2) may describe an exotic hybrid meson and its light-cone distribution amplitude is a leading twist quantity with vanishing first moment (3).

The nonzero matrix element of the quark energy-momentum tensor between vacuum and exotic meson state was explored long ago [12]. It may be related, by making use of the equations of motion, to the matrix element of quark-gluon operator and estimated with the help of the techniques of QCD sum rules [13], which allows to fix the normalization factor, or the coupling constant, f_H. One of the solutions corresponds to a resonance with mass around 1.4 GeV and the coupling constant at this scale [14]

$$f_H \approx 50 \text{ MeV}. \tag{9}$$

Note that the same exotic quantum numbers (except isospin) were found [2] for the gluonic energy momentum tensor (attributed therefore to the gluonium). It was noticed there that energy momentum conservation leads to a zero coupling of the operator to such an exotic state. This argument would be applicable in our case for the isosinglet combination, if the quark gluon interaction, leading to the nonconservation of both quark and gluon energy momentum tensor (while the sum is conserved), is assumed to be negligible. However, there is no reason to expect it to be applicable to isovector combinations or to each quark flavor separately. Moreover, even for isosinglet combination (including the pure gluonium case), this argument is no more applicable to the local operators of higher spin ($n=3,5\ldots$). The appearance of extra covariant derivatives,

$$\langle H(p,0)|\mathcal{R}_{\mu\nu_1\ldots\nu_n}|0\rangle = i^{n+1} f_H M_H\, \mathrm{S}_{(\mu\nu_1\ldots\nu_n)} e_\mu^{(0)} p_{\nu_1}\ldots p_{\nu_n} \times \int_0^1 dy\left(y-\frac{1}{2}\right)^n \phi^H(y), \tag{10}$$

preserves all the quantum numbers, but spoils the argument of the operator conservation, as it is not the energy-momentum tensor anymore. Such a situation is completely similar to the case of tensor spin structure or fragmentation function [15,16], which have two zero moments.

In summary, the hybrid light-cone distribution amplitude is a leading twist quantity which should have a vanishing first moment (3) because of the antisymmetry. This distribution amplitude obeys usual evolution equations [17] and has an asymptotic limit [18]

$$\Phi_{as}^H = 30y(1-y)(1-2y) \tag{11}$$

with assumed normalization of the distribution amplitude $\phi^H(y)$ as

$$\int_0^1 dy(1-2y)\phi^H(y) = 1. \tag{12}$$

The coupling constant f_H is the subject of evolution given by the formula, see e.g. [19],

$$f_H(Q^2)=f_H\cdot\left(\frac{\alpha_S(Q^2)}{\alpha_S(M_H^2)}\right)^{K_1},\quad K_1=\frac{2\gamma_{QQ}(1)}{\beta_1},\qquad(13)$$

where the anomalous dimension $\gamma_{QQ}(1)=16/9$ and $\beta_1=11-2n_f/3$. The exponent K_1 is thus a small positive number which drives slowly to zero the coupling constant $f_H(Q^2)$. Since experiments are likely to be feasible at moderate values of Q^2, we neglect this evolution and in the following estimate we use the value from Eq. (9).

The calculation of the production amplitude, at leading order in α_s, is now straightforward and leads to an expression completely similar to the one for the production of longitudinally polarized vector meson, see e.g. [5] and notation therein. It is well known that a leading twist estimate of the ρ electroproduction cross section overestimates the experimental rate, but we think that it is still reasonable to estimate the ratio of hybrid to ρ electroproduction cross sections through their Born order expression. We obtain

$$\mathcal{A}_{\gamma_L^* p\to H_L^0 p}=\frac{e\pi\alpha_s f_H C_F}{\sqrt{2}N_c Q}[e_u\mathcal{H}_{uu}^{-}-e_d\mathcal{H}_{dd}^{-}]\mathcal{V}^H,\qquad(14)$$

where

$$\mathcal{H}_{ff}^{\pm}=\int_{-1}^{1}dx\left[\bar{U}(p_2)\hat{n}U(p_1)H_{ff}(x,\xi)+\bar{U}(p_2)\frac{i\sigma_{\mu\alpha}n^\mu\Delta^\alpha}{2M}U(p_1)E_{ff}(x,\xi)\right]\times\left[\frac{1}{x+\xi-i\epsilon}\pm\frac{1}{x-\xi+i\epsilon}\right],\qquad(15)$$

and

$$\mathcal{V}^H=\int_0^1 dy\,\phi^H(y)\left[\frac{1}{y}-\frac{1}{1-y}\right].$$

Note that the simple pole in y in Eq. (14) does not lead to any infrared divergency since the function $\phi^H(y)$ is expected to vanish, as usual, when the fraction y goes to zero or unity.

We leave for a further work a full phenomenological study of hybrid electroproduction. Let us just note that the order of magnitude of hybrid electroproduction may be easily deduced through a direct comparison with ρ meson electroproduction amplitude [5]. We thus estimate that the ratio of hybrid and ρ electroproduction cross sections is

$$\frac{d\sigma^H(Q^2,x_B,t)}{d\sigma^\rho(Q^2,x_B,t)}=\left|\frac{f_H}{f_\rho}\frac{(e_u\mathcal{H}_{uu}^{-}-e_d\mathcal{H}_{dd}^{-})\mathcal{V}^H}{(e_u\mathcal{H}_{uu}^{+}-e_d\mathcal{H}_{dd}^{+})\mathcal{V}^\rho}\right|^2,\qquad(16)$$

where the ρ meson soft integral $\mathcal{V}^\rho$ is defined as

$$\mathcal{V}^\rho=\int_0^1 dy\,\phi^\rho(y)\left[\frac{1}{y}+\frac{1}{1-y}\right],$$

and $f_\rho=216$ MeV. Note that the symmetry under $x\to -x$ of the nucleon GPD's in the numerator of Eq. (16) corresponds to the "nonsinglet," i.e., $q-\bar{q}$, combination of quark distributions, while the antisymmetric form in the denominator—the "singlet," i.e., $q+\bar{q}$, combination.

If we neglect the antiquarks contribution, i.e., if we restrict the x integral to [0,1], one sees that the imaginary parts of the amplitudes for both meson electroproduction are equal in magnitude up to the factor $\mathcal{V}^M$. The ratio of the real parts depend much on the model used for guessing the generalized parton distributions. Since the imaginary part dominates in some kinematics, it is not unreasonable as a first estimate of the ratio of the cross sections, to assume that the full amplitude ratio is driven by the same quantity. Using the asymptotic forms for the hybrid and ρ mesons distribution amplitudes, which for the ρ-meson case is supported by QCD sum rule [20], we thus estimate that

$$\frac{d\sigma^H(Q^2,x_B,t)}{d\sigma^\rho(Q^2,x_B,t)}\approx\left(\frac{5f_H}{3f_\rho}\right)^2\approx 0.15.\qquad(17)$$

Exotic hybrid meson can be therefore electroproduced in an experimentally feasible way in actual experiments at JLAB, HERMES or Compass. Their study in high statistics experiments at JLAB should be fruitful. The signal may be discovered through a missing mass measurement provided the recoil proton energy-momentum is well measured. This allows to study all decay channels of these poorly known states. If one decay channel turns out to be dominant, as for instance a $\pi\eta$ channel [21], the formalism of generalized distribution amplitudes [22] may be used for estimating cross sections and interference signals [23].

As already noted above, higher twist corrections are likely to be sizable at measurable Q^2 [24]. Twist 3 contributions have already been considered in the case of deeply virtual Compton scattering [25] where their presence was dictated by gauge invariance. They have also been considered for transversely polarized vector mesons [26] where the leading twist 2 component vanishes. The analysis of such contributions is left for future work.

Let us finally note that hard exclusive electroproduction turns out to be a useful tool not only for studying the hybrid meson discussed in this paper but also for probing the structure of other exotic states like the recently discovered pentaquark [27]. In all cases, the scaling of the amplitudes is the same as the observed one for ρ electroproduction. The normalization of the cross sections is a more delicate story, and may turn in some cases to unobservable rates [28].

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