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Manifestations of anomalous glue: Light-mass exotic mesons and $g_{\eta' NN}$

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Abstract. The light-mass exotics with $J^{PC} = 1^{-+}$ observed at BNL and CERN may have a simple explanation as dynamically generated resonances in $\eta'\pi$ rescattering in the final-state interaction. This dynamics is mediated by the same anomalous glue which also generates the large mass of the η'. OZI-violating processes are also potentially important to η' production in proton-proton collisions close to threshold.

PACS. 12.39.Mk Glueball and nonstandard multi-quark/gluon states – 13.75.Lb Meson-meson interactions – 13.75.Cs Nucleon-nucleon interactions (including antinucleons, deuterons, etc.)

1 Introduction

Searching for evidence of gluonic degrees of freedom in low-energy QCD is one of the main themes driving present experimental and theoretical studies of the strong interaction. Key probes include glueball and $J^{PC} = 1^{-+}$ exotic-meson searches plus OZI violation in η' physics [1] which is sensitive to gluonic degrees of freedom through the $U(1)$ axial anomaly [2]. Exotic mesons are particularly interesting because the quantum numbers $J^{PC} = 1^{-+}$ are inconsistent with a simple quark-antiquark bound state [3]. Two such exotics, with masses 1400 and 1600 MeV, have been observed in experiments at BNL [4] and CERN [5] in decays to $\eta'\pi$ and $\eta\pi$. These exotics have been a puzzle to theorists and experimentalists alike because the lightest-mass $q\bar{q}g$ state with exotic quantum numbers predicted by lattice calculations [6,7] and QCD-inspired models [8] has mass about 1800–1900 MeV. As we explain here, the presently observed light-mass exotics seen at BNL and CERN may have a simple explanation [9] as dynamically generated resonances in $\eta'\pi$ rescattering (in the final-state interaction). The anomalous glue which generates the large η' mass plays an essential role in this dynamics.

The physics of anomalous glue also yields interesting phenomenology in the η'-nucleon system. The flavor-singlet Goldberger-Treiman relation [10] relates the flavor-singlet axial-charge $g_A^{(0)}$ extracted from polarized deep inelastic scattering [11] to the η'-nucleon coupling constant. The small value of $g_A^{(0)}$ (about 50% of the OZI value 0.6) measured in polarized DIS and the large mass of the η' point to large violations of OZI in the flavor-singlet $J^{PC} = 1^{++}$ channel. OZI-violating processes may also play an important role [12] in η' production in proton-nucleon collisions close to threshold [13]. This process is presently under investigation at COSY [14].

We first review the puzzle of light-mass exotics. We then explain how the presently observed states may be understood as dynamically generated resonances in $\eta'\pi$ rescattering. Here we briefly review the $U_A(1)$-extended effective Lagrangian for low-energy QCD [15,16]. This Lagrangian is constructed so that it successfully includes the effects of the strong $U(1)$ axial anomaly and the large η' mass. Finally, we discuss η' production in proton-nucleon collisions close to threshold where new effects [12] of OZI violation are suggested by coupling this Lagrangian to the nucleon.

2 Light-mass exotics

The $J^{PC} = 1^{-+}$ light-mass exotics discovered at BNL [4] and CERN [5] were observed in decays to $\eta\pi$ and $\eta'\pi$. Two such exotics, denoted π_1, have been observed through $\pi^- p \to \pi_1 p$ at BNL [4]: with masses 1400 MeV (in decays to $\eta\pi$) and 1600 MeV (in decays to $\eta'\pi$ and $\rho\pi$). The $\pi_1(1400)$ state has also been observed in $\bar{p}N$ processes by the Crystal Barrel Collaboration at CERN [5]. While the exotic quantum numbers $J^{PC} = 1^{-+}$ are inconsistent with a quark-antiquark bound state, they can be generated through a "valence" gluonic component —for example through coupling to the operator $[\bar{q}\gamma_\mu q G^{\mu\nu}]$. However, the observed exotics are considerably lighter than

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the predictions (about 1800–1900 MeV) of quenched lattice QCD [6,7] and QCD-inspired models [8] for the lowest mass $q\bar{q}g$ state with $J^{PC} = 1^{-+}$. These results suggest that, perhaps, the "exotic" states observed by the experimentalists might involve significant meson-meson bound-state contributions. Furthermore, the decays of the light-mass exotics to η- or η'-mesons plus a pion suggest a possible connection to axial $U(1)$ dynamics.

This idea has recently been investigated [9] in a model of final-state interaction in $\eta\pi$ and $\eta'\pi$ rescattering using the $U_A(1)$-extended chiral Lagrangian [15,16], coupled channels and the Bethe-Salpeter equation, following the approach of the Valencia group [17].

The $U_A(1)$-extended low-energy effective Lagrangian used in these calculations is

$$\begin{aligned}\mathcal{L}_{\rm m} = &\frac{F_\pi^2}{4}{\rm Tr}(\partial^\mu U \partial_\mu U^\dagger) + \frac{F_\pi^2}{4}{\rm Tr}\Big[\chi_0\ (U+U^\dagger)\Big]\\ &+\frac{1}{2}iQ{\rm Tr}\Big[\log U - \log U^\dagger\Big] + \frac{3}{\tilde{m}_{\eta_0}^2 F_0^2}Q^2\\ &+\lambda\ Q^2\ {\rm Tr}\ \partial_\mu U \partial^\mu U^\dagger\,. \end{aligned} \qquad (1)$$

Here $U = \exp\left(i\frac{\phi}{F_\pi} + i\sqrt{\frac{2}{3}}\frac{\eta_0}{F_0}\right)$ is the unitary meson matrix where $\phi = \sum_k \phi_k \lambda_k$ with ϕ_k denoting the octet of would-be Goldstone bosons (π, K, η_8) associated with spontaneous chiral $SU(3)_L \otimes SU(3)_R$ breaking, and η_0 is the singlet boson; Q denotes the topological charge density $\left(Q = \frac{\alpha_s}{4\pi}G\tilde{G}\right)$. Also, $\chi_0 = {\rm diag}[m_\pi^2, m_\pi^2, (2m_K^2 - m_\pi^2)]$ is the quark-mass–induced meson mass matrix, $\tilde{m}_{\eta_0}$ is the gluonic-induced mass term for the singlet boson and λ is an OZI-violating coupling —see below. The pion decay constant $F_\pi = 92.4$MeV and F_0 renormalizes the flavor-singlet decay constant $F_{\rm singlet} = F_\pi^2/F_0 \sim 100$MeV.

The gluonic potential involving Q is constructed so that the effective theory reproduces the QCD axial anomaly [2] in the divergence of the gauge invariantly renormalized axial-vector current. This potential also generates the gluonic contribution to the η and η' masses: Q is treated as a background field with no kinetic term; it may be eliminated through its equation of motion to yield

$$\frac{1}{2}iQ{\rm Tr}\Big[\log U - \log U^\dagger\Big] + \frac{3}{\tilde{m}_{\eta_0}^2 F_0^2}Q^2 \ \mapsto\ -\frac{1}{2}\tilde{m}_{\eta_0}^2\eta_0^2\,. \quad (2)$$

The η-η' mass matrix resulting from eq. (1) gives η and η' masses:

$$\begin{aligned} m_{\eta',\eta}^2 = &(m_{\rm K}^2 + \tilde{m}_{\eta_0}^2/2)\\ &\pm\frac{1}{2}\sqrt{(2m_{\rm K}^2 - 2m_\pi^2 - \frac{1}{3}\tilde{m}_{\eta_0}^2)^2 + \frac{8}{9}\tilde{m}_{\eta_0}^4}. \end{aligned} \qquad (3)$$

If the gluonic term $\tilde{m}_{\eta_0}^2$ were zero in this expression, one would have $m_{\eta'} = \sqrt{2m_{\rm K}^2 - m_\pi^2}$ and $m_\eta = m_\pi$. Without any extra input from glue, in the OZI limit, the η would be approximately an isosinglet light-quark state $(\frac{1}{\sqrt{2}}|\bar{u}u + \bar{d}d\rangle)$ degenerate with the pion and the η' would be a strange-quark state $|\bar{s}s\rangle$ —mirroring the isoscalar vector ω- and ϕ-mesons. Indeed, in an early paper [18] Weinberg argued that the mass of the η would be less than $\sqrt{3}m_\pi$ without any extra $U(1)$ dynamics to further break the axial $U(1)$ symmetry. The gluonic contribution to the η and η' masses is about 300–400 MeV [1].

In the model calculations [9] of FSI the meson-meson (re-)scattering potentials in the Bethe-Salpeter equation were derived from the Lagrangian (1). The OZI-violating interaction $\lambda\ Q^2\ {\rm Tr}\ \partial_\mu U \partial^\mu U^\dagger$ [16] was found to play a key role in the $J^{PC} = 1^{-+}$ channel. A simple estimate for the coupling λ can be deduced from the decay $\eta' \to \eta\pi\pi$ yielding two possible solutions with different signs. Especially interesting is the negative-sign solution. When substituted into the Bethe-Salpeter equation this solution was found to yield a dynamically generated p-wave resonance with exotic quantum numbers $J^{PC} = 1^{-+}$. Furthermore, this resonance was found to have mass $\sim$ 1400 MeV and width $\sim$ 300 MeV —close to the observed exotics. (The width of the $\pi_1(1400)$ state measured in decays to $\eta\pi$ is 385 ± 40 MeV; the width of the $\pi_1(1600)$ measured in decays to $\eta'\pi$ is 340 ± 64 MeV.) The topological charge density mediates the coupling of the dynamically generated light-mass exotic to the $\eta\pi$ and $\eta'\pi$ channels in these calculations. For detailed discussion and the amplitudes for the individual channels which contribute to this dynamics, see [9].

3 OZI violation in the η'-nucleon system

Going beyond the meson sector, it is interesting to look for evidence of OZI violation in the η'-nucleon system. Some guidance is provided by coupling the $U_A(1)$-extended chiral Lagrangian to the nucleon [12]. Here we find a gluon-induced contact interaction in the $pp \to pp\eta'$ reaction close to threshold:

$$\mathcal{L}_{\rm contact} = -\frac{i}{F_0^2}\ g_{QNN}\ \tilde{m}_{\eta_0}^2\ \mathcal{C}\ \eta_0\ \Big(\bar{p}\gamma_5 p\Big)\ \Big(\bar{p}p\Big)\,. \quad (4)$$

Here g_{QNN} is an OZI-violating coupling which measures the one-particle irreducible coupling of the topological charge density Q to the nucleon and $\mathcal{C}$ is a second OZI-violating coupling which also features in $\eta' N$ scattering. The physical interpretation of the contact term (4) is a "short distance" ($\sim$ 0.2 fm) interaction where glue is excited in the interaction region of the proton-proton collision and then evolves to become an η' in the final state. This gluonic contribution to the cross-section for $pp \to pp\eta'$ is extra to the contributions associated with meson exchange models [19,20]. There is no reason, *a priori*, to expect it to be small.

What is the phenomenology of this OZI-violating interaction?

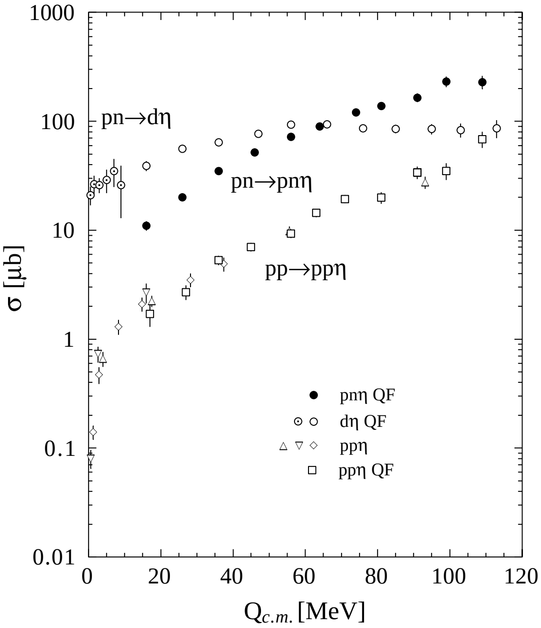

Fig. 1. CELSIUS data on η production.

Since glue is flavor-blind, the contact interaction (4) has the same size in both the $pp \to pp\eta'$ and $pn \to pn\eta'$ reactions. CELSIUS [21] have measured the ratio $R_\eta = \sigma(pn \to pn\eta)/\sigma(pp \to pp\eta)$ for quasifree η production from a deuteron target up to 100 MeV above threshold. They observed that R_η is approximately energy independent $\simeq 6.5$ over the whole energy range —see fig. 1. The value of this ratio signifies a strong isovector exchange contribution to the η production mechanism [21]. This experiment can be repeated for η' production. The cross-section for $pp \to pp\eta'$ close to threshold has been measured at COSY [14]. A new experiment [22] has been initiated to carry out the $pn \to pn\eta'$ measurement. In the formal limit that the $pp \to pp\eta'$ reaction were dominated by gluonic-induced production, the ratio

$$R_{\eta'} = \sigma(pn \to pn\eta')/\sigma(pp \to pp\eta') \qquad (5)$$

would approach unity close to threshold after we correct for the final-state interaction [23] between the two outgoing nucleons. It will be interesting to compare future measurements of $R_{\eta'}$ with the CELSIUS measurement [21] of R_η. Given that η' phenomenology is characterised by large OZI violations, it is natural to expect large OZI effects in the $pp \to pp\eta'$ process.

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