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

Steven D. Bass

High Energy Physics Group, Institute for Experimental Physics and Institute for Theoretical Physics, Universit"at Innsbruck, Technikerstrasse 25, A 6020 Innsbruck, Austria

Received: date / Revised version: date

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 $\eta'$. OZI violating processes are also potentially important to $\eta'$ 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

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 exotic meson searches plus OZI violation in $\eta'\pi$ physics [2] 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 $qqg$ state with exotic quantum numbers predicted by lattice calculations [6] and QCD inspired models [7] 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 as dynamically generated resonances in $\eta'\pi$ rescattering (in the final state interaction). The anomalous glue which generates the large $\eta'$ mass plays an essential role in this dynamics.

The physics of anomalous glue also yields interesting phenomenology in the $\eta'$-nucleon system. The flavour-singlet Goldberger-Treiman relation [8] relates the flavour-singlet axial-charge $g_A^{(0)}$ extracted from polarized deep inelastic scattering [9] to the $\eta'$-nuclear 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 $\eta'$ point to large violations of OZI in the flavour-singlet $J^{PC} = 1^{-+}$ channel. OZI violating processes may also play an important role [2] in $\eta'$ production in proton-nucleon collisions close to threshold [10]. This process is presently under investigation at COSY [11].

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 $U(1)$-extended effective Lagrangian for low-energy QCD [12]. This Lagrangian is constructed so that it successfully includes the effects of the strong U(1) axial anomaly and the large $\eta'$ mass. Finally, we discuss $\eta'$ production in proton-nucleon collisions close to threshold where new effects [2] 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 $\pi_1$, have been observed through $\pi^- p \rightarrow \pi_1 p$ at BNL [4] with masses 1400 MeV (in decays to $\eta\pi$) and 1600 MeV (in decays to $\eta'\pi$ and $\eta\pi$). The $\pi_1(1400)$ state has also been observed in $\bar{p}N$ processes by the Crystal Barrel Collaboration at CERN [11]. 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 $[\pi'^\mu q G^{\mu\nu}]$. However, the observed exotics are considerably lighter than the predictions (about 1800-1900 MeV) of quenched lattice QCD [12]. [2] and QCD inspired models [7] for the lowest mass $qqg$ 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 in a model of final state interaction in ηπ and η′π rescattering using the \( U_A(1) \)-extended chiral Lagrangian, 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:

\[
\mathcal{L}_m = \frac{F^2}{4} \text{Tr}(\partial^\mu U \partial_\mu U^\dagger) + \frac{F^2}{4} \text{Tr} \left[ \chi_0 (U + U^\dagger) \right] \\
+ \frac{1}{2} iQ Tr \left[ \log U - \log U^\dagger \right] + \frac{3}{m_0^2} Q^2 \\
+ \lambda Q^2 \text{Tr} \partial_\mu U \partial^\mu U^\dagger \tag{1}
\]

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

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

\[
\frac{1}{2} iQ Tr \left[ \log U - \log U^\dagger \right] + \frac{3}{m_0^2} Q^2 \rightarrow - \frac{1}{2} \tilde{m}_{\eta_0}^2 \tag{2}
\]

The \( \eta-\eta' \) mass-matrix resulting from Eq.(1) gives \( \eta \) and \( \eta' \) masses:

\[
m_{\eta^{'},\eta}^2 = (m_K^2 + \tilde{m}_{\eta_0}^2) / 2 \pm \frac{1}{2} \sqrt{(2m_K^2 - 2m_\pi^2 - \frac{1}{3} \tilde{m}_{\eta_0}^2)^2 + \frac{8}{9} \tilde{m}_{\eta_0}^4} \tag{3}
\]

If the gluonic term \( \tilde{m}_{\eta}^2 \) were zero in this expression, one would have \( m_{\eta'} = \sqrt{2m_K^2 - m_\pi^2} \) and \( m_\eta = m_{\pi} \). Without any extra input from glue, in the OZI limit, \( \eta \) would be approximately an isosinglet light-quark state \( (\bar{u}u + \bar{d}d) \) degenerate with the pion and the \( \eta' \) would a strange-quark state \( (\bar{s}s) \) — mirroring the isoscalar vector \( \omega \) and \( \phi \) mesons. Indeed, in an early paper [18] Weinberg argued that the mass of the \( \eta \) would be less than \( \sqrt{3m_{\pi}} \) without any extra U(1) dynamics to further break the axial U(1) symmetry. The gluonic contribution to the \( \eta \) and \( \eta' \) masses is about 300-400 MeV [19].

In the model calculations of FSI the meson-meson (re-)scattering potentials in the Bethe-Salpeter equation were derived from the Lagrangian (1). The OZI violating interaction \( \lambda Q^2 \text{Tr} \partial_\mu U \partial^\mu U^\dagger \) was found to play a key role in the \( J^{PC} = 1^{+-} \) channel. A simple estimate for the coupling \( \lambda \) can be deduced from the decay \( \eta' \rightarrow \eta \pi \) 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 \( \sim 1400 \text{MeV} \) and width \( \sim 300 \text{MeV} \) — close to the observed exotics. (The width of the \( \pi_1(1400) \) state measured in decays to \( \eta \pi \) is \( 385 \pm 40 \text{MeV} \); the width of the \( \pi_1(1600) \) measured in decays to \( \eta \pi \) is \( 340 \pm 64 \text{MeV} \)). The topological charge density mediates the coupling of the dynamically generated light-mass exotic to the \( \eta \) and \( \eta' \) channels in these calculations. For detailed discussion and the amplitudes for the individual channels which contribute to this dynamics, see [1].

### 3 OZI violation in the \( \eta' \)-nucleon system

Going beyond the meson sector, it is interesting to look for evidence of OZI violation in the \( \eta' \)-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 \( pp \rightarrow pp\eta' \) reaction close to threshold:

\[
\mathcal{L}_\text{contact} = -i \frac{g}{F_0} \tilde{m}_{\eta}^2 \mathcal{C} \eta_0 \left( \bar{p} \gamma_5 p \right) \left( \bar{p} p \right) \tag{4}
\]

Here \( g_{\eta \eta NN} \) is an OZI violating coupling which measures the one particle irreducible coupling of the topological charge density \( Q \) to the nucleon and \( C \) is a second OZI violating coupling which also features in \( \eta' \)-nucleon scattering. The physical interpretation of the contact term (4) is a “short distance” (\( \sim 0.2 \text{fm} \)) interaction where glue is excited in the interaction region of the proton-proton collision and then evolves to become an \( \eta' \) in the final state. This gluonic contribution to the cross-section for \( pp \rightarrow pp\eta' \) is extra to the contributions associated with meson exchange models [15-19]. There is no reason, a priori, to expect it to be small.

What is the phenomenology of this OZI violating interaction?

Since glue is flavour-blind the contact interaction (4) has the same size in both the \( pp \rightarrow pp\eta' \) and \( pn \rightarrow pn\eta' \) reactions. CELSIUS [21] have measured the ratio \( R_\eta = \sigma(pm \rightarrow pm\eta') / \sigma(pp \rightarrow pp\eta') \) for quasifree \( \eta \) production from a deuterium target up to 100 MeV above threshold. They observed that \( R_\eta \) is approximately energy independent \( \approx 6.5 \) over the whole energy range — see Fig.1. The value of this ratio signifies a strong isovector exchange contribution to the \( \eta \) production mechanism [21]. This experiment can be repeated for \( \eta' \) production. The cross-section for \( pp \rightarrow pp\eta' \) close to threshold has been measured at

---

**References:**

[1] Steven D. Bass: Manifestations of anomalous glue: light-mass exotic mesons and \( g_{\eta \eta NN} \)

---

---
COSY [14]. A new experiment [22] has been initiated to carry out the $pm \to pm\eta'$ measurement. In the formal limit that the $pp \to ppp\eta'$ reaction were dominated by gluonic-induced production, the ratio

$$R_{\eta'} = \frac{\sigma(pm \to pm\eta')}{\sigma(pp \to ppp\eta')}$$

(5)

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

Acknowledgements

SDB is supported by a Lise-Meitner Fellowship, M683, of the Austrian FWF. I thank W. Oelert and the COSY-11 Collaboration for hospitality in Juelich, P. Moskal for helpful discussions and E. Marco for collaboration on light-mass exotics.

References

1. S.D. Bass, Phys. Scripta T99 (2002) 96 [hep-ph/0111118].
2. G.M. Shore, Zuoz lecture, hep-ph/9812354, and these proceedings.
3. A. Dzierba, hep-ex/0106014, and these proceedings.
4. The E852 Collaboration (D.R. Thompson et al.) Phys. Rev. Lett. 79 (1997) 1630; (S.U. Chung et al.) Phys. Rev. D60 (1999) 092001; (G.S. Adams et al.) Phys. Rev. Lett. 81 (1998) 5760; (E.I. Ivanov et al.) Phys. Rev. Lett. 86 (2001) 3977.
5. The Crystal Barrel Collaboration (A. Abele et al.) Phys. Lett. B423 (1998) 246.
6. P. Lacock et al. (UKQCD), Phys. Rev. D54 (1996) 6997; P. Lacock et al. (UKQCD), Phys. Lett. B401 (1997) 308; C. Bernard et al. (MILC) Phys. Rev. D56 (1997) 7039; C. Bernard et al. (MILC) Nucl. Phys. B (Proc. Suppl.) 53 (1997) 228.
7. A.W. Thomas and A.P. Szczepaniak, Phys. Lett. B526 (2002) 72.
8. N. Isgur, R. Kokoski and J. Paton, Phys. Rev. Lett. 54 (1985) 869; F.E. Close and P.R. Page, Nucl. Phys. B443 (1995) 233; T. Barnes, F.E. Close and E.S. Swanson, Phys. Rev. D52 (1995) 5242.
9. S.D. Bass and E. Marco, Phys. Rev. D65 (2002) 075035.
10. G. Veneziano, Mod. Phys. Lett. A4 (1989) 1605; G.M. Shore and G. Veneziano, Nucl. Phys. B381 (1992) 23; T. Hatsuda, Nucl. Phys. B329 (1990) 376.
11. S.D. Bass, Eur. Phys. J A5 (1999) 17 [hep-ph/9902280]; E. Reya and B. Lampe, Phys. Rept. 332 (2000) 1; B.W. Filipone and X. Ji, hep-ph/0101224.
12. S. D. Bass, Phys. Lett. B463 (1999) 286 [hep-ph/9907373].
13. G. Fäl dt, T. Johansson and C. Wilkin, Phys. Scripta T99 (2002) 146-158.
14. The COSY-11 Collaboration (P. Moskal et al.), Phys. Rev. Lett. 80 (1998) 3202; Phys. Lett. B474 (2000) 416; Phys. Lett. B482 (2000) 356.
15. P. Di Vecchia and G. Veneziano, Nucl. Phys. B171 (1980) 253.
16. P. Di Vecchia, F. Nicodemi, R. Pettorino and G. Veneziano, Nucl. Phys. B181 (1981) 318.
17. J. A. Oller and E. Oset, Nucl. Phys. A620 (1997) 438; (E) A652 (1997) 407.
18. S. Weinberg, Phys. Rev. D11 (1975) 3583.
19. R. Machleidt, K. Holinde and Ch. Elster, Phys. Rept. 149 (1987) 1.
20. J-F. Germond and C. Wilkin, Nucl. Phys. A518 (1990) 308; G. Fäl dt and C. Wilkin, Z Physik A357 (1997) 241; K. Nakayama, H.F. Arellano, J.W. Durso and J. Speth, Phys. Rev. C61 (1999) 024001.
21. The CESLIUS Collaboration (H. Calen et al.), Phys. Rev. Lett. 80 (1998) 2069; Phys. Rev. C58 (1998) 2067.
22. The COSY-11, Uppsala University Collaboration (P. Moskal and T. Johansson et al.), COSY Proposal No.100; P. Moskal, nucl-ex/0110001.
23. G. Fäl dt and C. Wilkin, Phys. Scripta 56 (1997) 566; Am. J. Phys. 66 (1998) 876.