Non-conventional mesons at PANDA

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Abstract. Non-conventional mesons, such as glueballs and tetraquarks, will be in the focus of the PANDA experiment at the FAIR facility. In this lecture we recall the basic properties of QCD and describe some features of unconventional states. We focus on the search of the not-yet discovered glueballs and the use of the extended Linear Sigma Model for this purpose, and on the already discovered but not-yet understood X, Y, Z states.

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1. Introduction

Conventional mesons are bound states made by a quark and an antiquark. Yet, since the very beginning of QCD the search for other possibilities has attracted the attention of both experimentalists and theoreticians [1].

As a prominent example, glueballs were predicted long ago: they are (yet hypothetical) bound states of solely gluons. Computer simulations of QCD on the lattice have found a full spectrum of these states [2, 3], but their firm experimental discovery has not yet taken place. On the other hand, a plenty of mesons, denoted as X, Y, and Z states, has been unambiguously discovered in the last decade in the energy region of charm-anticharm and botton-antibotton states [4, 5]. A clear explanation about the nature of these states is still lacking (tetraquark and molecular hypotheses are a possibility).

The PANDA experiment at the FAIR facility [6] in Darmstadt/Germany is designed to shed light on these questions. It is a proton-antiproton scattering experiment in which the energy of the antiproton can be finely tuned in such a way that a wide energy range in the charmonium region can be scanned. Various resonances can be directly formed in proton-antiproton fusion processes. Glueball, if existent, shall be found by this experiment. On the other hand, many of the X, Y, and Z states can also be formed and/or produced with high statistics. In this lecture a theoretical view concerning the search of non-conventional mesons at PANDA will be presented.

2. Brief recall of the QCD Lagrangian and its symmetries

The Lagrangian of Quantum Chromodynamics (QCD) reads

$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} \ , \ D_\mu = \partial_\mu - ig_0 A_\mu \tag{1}$$

where $G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_0 f^{abc} A^b_\mu A^c_\nu$, $A_\mu = A^a_\mu t^a$, $a, = 1, ..., N_c^2 - 1 = 8$, and t^a and f^{abc} are the generators and the structure constants of the group $SU(N_c)$. $\mathcal{L}_{QCD}$ contains N_f quark

fields q_i with corresponding bare masses m_i ($i = 1, ..., N_f$, N_f is the number of quark flavors; in Nature $N_f = 6$: u, d, s, c, b, t). Each quark flavor has three colors (red, green, blue). A crucial property of Eq. (1) is that 3-gluon and 4-gluon vertices are present: gluons –contrary to photons– 'shine in their own light'. We list the main symmetries and their meaning.

(i) $\mathcal{L}_{QCD}$ is built under the requirement of invariance under *local* transformations of the $SU(3)$ groups. This means that one can rename at *each space-time point* the color of a quark via a $SU(3)$ matrix $U_C \equiv U_C(x)$ ($U_C U_C^\dagger = 1$, $\det U_C = 1$) and of the gluon field as:

$$q_i \to U_C q_i \ , \ A_\mu \to U_C(A_\mu - i\partial_\mu/g_0)U_C^\dagger \ . \tag{2}$$

One can, for instance, transform a blue quark in a red one in a certain space-time region without changing the properties of the system.

(ii) When the bare quark masses are equal ($m_1 = m_2 = ... = m_{N_f}$), $\mathcal{L}_{QCD}$ is invariant under the interchange of quark flavors via a $N_f \times N_f$ unitary matrix U_V ($U_V U_V^\dagger = 1$) as: $q_i \to U_{V,ij}q_j$. This is flavor symmetry, denoted also as $U(N_f)_V$: in simple terms, it means that gluons are 'democratic' and couple to each quark flavor with the same strength. Thus, one can rename also the quark flavor: it is allowed to interchange a u quark with a d quark, but this can be done only once for all space-time points (the symmetry is global and not local). For $N_f = 2$, $m_u \simeq m_d \simeq 5$ MeV: the symmetry $U(2)_V$ is well realized in Nature (this is isospin symmetry, responsible for instance for the almost equal mass of the three pions and of the proton and the neutron). For $N_f = 3$ the bare strange mass $m_s \simeq 100$ MeV is sizably larger than m_u and m_d: nevertheless, the emergence of flavor multiplets with strange mesons is evident in the PDG, showing that an approximate $U(3)_V$ is also realized [7].

The limit in which all quark masses vanish ($m_1 = ... = m_{N_f} = 0$) is called the *chiral limit* and is important for the understanding of QCD because additional symmetries are present: dilatation invariance and chiral symmetry.

(iii) Dilatation symmetry and its anomalous breaking. In the chiral limit, there is only one parameter in $\mathcal{L}_{QCD}$, the *dimensionless* coupling constant g_0. The theory is classically dilatation invariant. However, upon quantization, a running coupling $g_0 \to g(\mu)$ emerges. An ultraviolet cutoff Λ_{UV} is introduced in the process of regularization in such a way that g_0 is the coupling at this very high energy scale: $g_0 = g(\Lambda_{UV})$. Then, a low-energy scale Λ_{YM} emerges in the theory as

$$g^2(\mu) = \frac{g_0^2}{1 + 2bg_0^2 \log \frac{\mu}{\Lambda_{UV}}} \to \Lambda_{YM} = \Lambda_{UV}e^{-1/(2bg_0^2)} \text{ with } b = \frac{33 - 2N_f}{48\pi^2}. \tag{3}$$

Numerically, $\Lambda_{YM} \simeq 250$ MeV: all quantities in QCD depend crucially on it.

(iv) Chiral symmetry and its spontaneous breaking. One splits the quark field into the right-handed and left-handed components: $q_i = q_{i,L} + q_{i,R} = P_L q_i + P_R q_i$ with $P_{R(L)} = \frac{1}{2}\left(1 \pm \gamma^5\right)$. $\mathcal{L}_{QCD}$ is *separately* invariant under rotations of right-handed quarks and left-handed quarks

$$q_i = q_{i,L} + q_{i,R} \to U_{L,ij}q_{j,L} + U_{R,ij}q_{j,R} \ , \tag{4}$$

where U_R and U_L are two independent unitary matrices. Such a chiral transformation is also denoted as $U(N_f)_R \times U(N_f)_L$. Chiral transformation reduces to a flavor one for $U_V = U_L = U_R$. Conversely, the case $U_A = U_L = U_R^\dagger$ is called axial transformation $U(N_f)_A$ (which is not a group!), which mixes states with different parity, as pseudoscalar and scalar mesons and vector with axial-vector ones. This symmetry is not realized in the hadronic spectrum [7] because it is spontaneously broken by the nonperturbative QCD vacuum. As a consequence the quarks develop -even in the chiral limit- a large constituent (or effective) mass $m \to m^* \simeq \Lambda_{YM}$.

3. Mesons

Quarks and gluons are the basic degrees of freedom of the QCD Lagrangian of Eq. (1). However, these are *not* the asymptotic states that we measure in our detectors. Namely, quarks and gluons are *confined* into hadrons, where each hadron is *white* (i.e., invariant under the local color transformation introduced in Sec. 2).

We use the following *definition*: 'A meson is a strongly interacting particle (a hadron) with integer spin'. This definition is consistent with the PDG [7], in which all mesons are listed together independently of their inner structure.

3.1. Quark-antiquark mesons

A *conventional meson* is a meson constructed out of a quark and an antiquark. Although it represents only one of (actually infinitely many) possibilities to build a meson, the vast majority of mesons of the PDG can be correctly interpreted as belonging to a quark-antiquark multiple [7] (see also the results of the quark model [8]).

Mesons can be classified by their spatial angular momentum L, the spin S, the total angular momentum J and by parity P and charge conjugation C (summarized in J^{PC}). The lightest mesons are pseudoscalar states with $L = S = 0 \rightarrow J^{PC} = 0^{-+}$. Indeed, the pions and the kaons are pseudoscalar (quasi-)Goldstone bosons emerging upon the spontaneous breaking of chiral symmetry. As an example, we write down the wave function for the state K^+ (radial, angular, spin, flavor, color):

$$\left| K^+ \right\rangle = \left| n = 1 \right\rangle \left| L = 0 \right\rangle \left| S = 0(\uparrow\downarrow - \downarrow\uparrow) \right\rangle \left| u\bar{s} \right\rangle \left| \bar{R}R + \bar{G}G + \bar{B}B \right\rangle . \tag{5}$$

For $L = 0$, $S = 1$ one constructs the vector mesons (such as ρ and ω), for $L = S = 1$ one has three multiplets: tensor mesons $J^{PC} = 2^{++}$, axial-vector mesons $J^{PC} = 1^{++}$ and scalar mesons $J^{PC} = 0^{++}$ (scalar states are in the center of a long debate, see e.g. Refs. [9, 10, 11] and refs. therein). By further increasing L one can obtain many more multiplets [7].

It is interesting to notice that the quantum numbers $J^{PC} = 0^{+-}$ *cannot* be obtained in a quark-antiquark system, but is possible for unconventional mesonic states (such as glueballs). The experimental discovery of mesons with such *exotic quantum numbers* naturally points to a non-quarkonium inner structure.

3.2. Glueballs search and the eLSM

According to lattice QCD many glueballs should exist [2, 3], but up to now no glueball state has been unambiguously identified (although for some of them some candidates exist).

A suitable theoretical framework to study the decays of glueballs is the so-called extended linear Sigma Model (eLSM), which is an effective model of QCD built accordingly to the two fundamental symmetries mentioned in Sec. 2: chiral symmetry and dilatation invariance. The former is spontaneously broken by a Mexican-hat potential, the latter explicitly broken in order to mimic the trace anomaly of QCD of Eq. (3), see Ref. [12]. As a consequence, the eLSM Lagrangian contains only a finite number of terms. Moreover, (axial-)vector d.o.f. are included from the very beginning. The eLSM was first developed for $N_f = 2$ in Refs. [13, 14], for $N_f = 3$ in Refs. [15, 16], and for $N_f = 4$ in Ref. [17]. In particular, in Ref. [15] a fit to many experimental data was performed and a good description of low-hadron phenomenology (up to about 1.7 GeV) was obtained. Here we briefly recall the main results concerning glueballs.

The scalar glueball is the lightest gluonic state predicted in QCD and is naturally an element of the eLSM as the excitation of the dilaton field [14, 15, 16]. The result of the recent study of Ref. [16] shows that the scalar glueball is predominantly contained in the resonance $f_0(1710)$, in agreement with the lattice result of Ref. [18]. The eLSM makes predictions for the lightest (and peculiar) glueball state in a chiral framework, completing previous phenomenological works on the subject [9].

The pseudoscalar glueball is related to the chiral anomaly and couples in a chirally invariant way to light mesons [19], where it was shown that it decays predominantly in $\pi\pi K$ (50% of all decays into (pseudo)scalar mesons) and that it does *not* decay in $\pi\pi\pi$: these are simple and testable theoretical predictions which can be helpful in the experimental search at the PANDA experiment, where the pseudoscalar glueball can be directly formed in proton-antiproton fusion process.

A similar program can be carried out for a tensor glueball with a mass of about 2.2 GeV, e.g. Ref. [20], as well as for heavier glueballs, such as the (pseudo)vector ones.

3.3. X,Y,Z states and other non-quarkonium candidates

The discovery in the last years of a plenty of enigmatic resonances -the so called X,Y,Z states- shows that there are now many candidates of resonances beyond the standard quark-antiquark picture, see e.g. [4, 5] ($X(3872)$ was the first to be experimentally found by BELLE in 2003).The interpretation of these states is subject to ongoing debates: tetraquarks and molecular interpretations are at the top of the list, but it is difficult to distinguish among them [5, 21]. Moreover, distortions due to quantum fluctuations of nearby threshold(s) take place and make the understanding of these resonances more complicated [22]. Remarkably, the Z states are *charged* states in the charmonium region: a system made of four quarks is here necessary to understand them since a charmonium is necessarily chargeless (see e.g. Ref. [23]).

There are also other mesonic states which are not yet understood. An example is the strange-charmed scalar state $D_{S0}(2317)$, which is too light to be a $c\bar{s}$ state and could be a four-quark or a dynamically generated state. Historically, the scalar mesons below 1 GeV were among the first to be interpreted as non-quarkonium objects, but as a nonet of tetraquarks [11] or as dynamically generated states [10].

4. PANDA: formation and production of mesons

In the future PANDA experiment at the FAIR facility in Darmstadt [6], antiprotons reach a three-momentum $\mathbf{k}$ in the range $|\mathbf{k}|$ = 2.2-10 GeV and hit protons at rest. We consider here the case in which the proton and the antiproton completely annihilate and generate a particle X (as for instance a glueball) with mass m_X. The four-momentum of the antiproton reads $k_{\bar{p}} = (E_{\bar{p}} = \sqrt{\mathbf{k}^2 + m_p^2}, \mathbf{k})$ while that of the proton is $k_p = (m_p, \mathbf{0})$. By denoting $k_X = (\sqrt{\mathbf{k}^2 + m_X^2}, \mathbf{k})$ as the four-momentum of X, we obtain out of $k_p + k_{\bar{p}} = k_X$ that:

$$m_X = \sqrt{2m_p \left(m_p + E_{\bar{p}}\right)} = 2.25\text{-}4.53 \text{ GeV}. \tag{6}$$

By looking at the lattice spectrum of Ref. [2], we realize that -besides the scalar glueball which is too light- all non-exotic glueball states could be directly formed at the PANDA experiment. This represents a clean environment to study experimentally their decays. Glueballs with exotic quantum numbers (called oddballs) cannot be directly formed because a proton-antiproton system undergoes the same limitations of a quark-antiquark system for what concerns J^{PC} quantum numbers. Nevertheless, oddballs will also be produced together with other resonances and will be studied as well. Besides the search for glueballs, all mesonic states discussed above will be experimentally investigated.

5. Conclusions and outlook

In this work we have given a brief overview of some aspects of the theoretical as well as experimental search for unconventional mesons. The PANDA experiment will play a decisive role in the future of hadron physics, since it will help to clarify many open questions of hadron

spectroscopy in general and of exotic mesons in particular. The search for and hopefully the firm discovery of glueballs (and hybrids), as well as the confirmation and measurement with high statistics of the X, Y, Z states will be important milestones toward a better understanding of QCD.

Acknowledgments

References

[1] C. Amsler and N. A. Tornqvist, Phys. Rept. **389**, 61 (2004); E. Klempt and A. Zaitsev, Phys. Rept. **454**, 1 (2007) [arXiv:0708.4016 [hep-ph]]; F. Giacosa, Phys. Rev. D **80** , 074028 (2009) [arXiv:0903.4481 [hep-ph]].

[2] Y. Chen *et al.*, Phys. Rev. D **73,** 014516 (2006) [arXiv:hep-lat/0510074];

[3] C. J. Morningstar and M. J. Peardon, Phys. Rev. D **60,** 034509 (1999) [arXiv:hep-lat/9901004]; E. Gregory *et al.* JHEP **1210,** 170 (2012) [arXiv:1208.1858 [hep-lat]].

[4] N. Brambilla *et al.*, Eur. Phys. J. C **71** (2011) 1534 [arXiv:1010.5827 [hep-ph]].

[5] E. Braaten, C. Langmack and D. H. Smith, Phys. Rev. D **90** (2014) 014044 [arXiv:1402.0438 [hep-ph]]; G. T. Bodwin *et al.,* arXiv:1307.7425.

[6] M. F. M. Lutz *et al.* [PANDA Collaboration], arXiv:0903.3905 [hep-ex].

[7] K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).

[8] S. Godfrey and N. Isgur, Phys. Rev. D **32** (1985) 189.

[9] C. Amsler and F. E. Close, Phys. Lett. B **353** (1995) 385; W. J. Lee and D. Weingarten, Phys. Rev. D **61** (2000) 014015 [arXiv:hep-lat/9910008]; F. E. Close and A. Kirk, Eur. Phys. J. C textbf21 (2001) 531 [arXiv:hep-ph/0103173]; H. Y. Cheng, C. K. Chua and K. F. Liu, Phys. Rev. D **74** (2006) 094005 [arXiv:hep-ph/0607206]. F. Giacosa, T. Gutsche, V. E. Lyubovitskij and A. Faessler, Phys. Rev. D **72**, 094006 (2005) [arXiv:hep-ph/0509247]; F. Giacosa, T. Gutsche and A. Faessler, Phys. Rev. C **71** (2005) 025202 [hep-ph/0408085].

[10] E. van Beveren *et al.*, Z. Phys. C **30**, 615 (1986) [arXiv:0710.4067 [hep-ph]]; N. A. Tornqvist, Z. Phys. C **68**, 647 (1995) [arXiv:hep-ph/9504372]; M. Boglione and M. R. Pennington, Phys. Rev. D **65**, 114010 (2002) [arXiv:hep-ph/0203149]; ; J. R. Pelaez, Phys. Rev. Lett. **92**, 102001 (2004) [arXiv:hep-ph/0309292]; J. A. Oller and E. Oset, Nucl. Phys. A **620**, 438 (1997) [arXiv:hep-ph/9702314].

[11] R. L. Jaffe, Phys. Rev. D **15**, 267 (1977); L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. Lett. **93**, 212002 (2004) [arXiv:hep-ph/0407017]; F. Giacosa, Phys. Rev. D **74**, 014028 (2006) [arXiv:hep-ph/0605191]; A. H. Fariborz, R. Jora and J. Schechter, Phys. Rev. D **72**, 034001 (2005) [arXiv:hep-ph/0506170]; M. Napsuciale and S. Rodriguez, Phys. Rev. D **70**, 094043 (2004); F. Giacosa, Phys. Rev. D **75** (2007) 054007 [arXiv:hep-ph/0611388].

[12] A. A. Migdal and M. A. Shifman, Phys. Lett. B **114**, 445 (1982); R. Gomm, P. Jain, R. Johnson and J. Schechter, Phys. Rev. D **33**, 801 (1986).

[13] S. Gallas, F. Giacosa and D. H. Rischke, Phys. Rev. D **82**, 014004 (2010) [arXiv:0907.5084 [hep-ph]]; D. Parganlija, F. Giacosa and D. H. Rischke, Phys. Rev. D **82**, 054024 (2010) [arXiv:1003.4934 [hep-ph]].

[14] S. Janowski, D. Parganlija, F. Giacosa and D. H. Rischke, Phys. Rev. D **84**, 054007 (2011) [arXiv:1103.3238 [hep-ph]].

[15] D. Parganlija, P. Kovacs, G. Wolf, F. Giacosa and D. H. Rischke, Phys. Rev. D **87**, 014011 (2013) arXiv:1208.0585 [hep-ph]].

[16] S. Janowski, F. Giacosa and D. H. Rischke, Phys. Rev. D **90** (2014) 114005 [arXiv:1408.4921[hep-ph]].

[17] W. I. Eshraim, F. Giacosa and D. H. Rischke, arXiv:1405.5861 [hep-ph].

[18] L. -C. Gui *et al.*, Phys. Rev. Lett. **110** (2013) 021601 [arXiv:1206.0125 [hep-lat]].

[19] W. I. Eshraim, S. Janowski, F. Giacosa and D. H. Rischke, Phys. Rev. D **87**, 054036 (2013) [arXiv:1208.6474 [hep-ph]]; W. I. Eshraim, S. Janowski, A. Peters, K. Neuschwander and F. Giacosa, Acta Phys. Polon. Supp. **5**, 1101 (2012) [arXiv:1209.3976 [hep-ph]].

[20] F. Giacosa, T. Gutsche, V. E. Lyubovitskij, A. Faessler, Phys. Rev. D **72**, 114021 (2005) [hep-ph/0511171]; L. Burakovsky and J. T. Goldman, Phys. Rev. D **57**, 2879 (1998) [hep-ph/9703271].

[21] L. Maiani, A. D. Polosa and V. Riquer, Phys. Rev. Lett. **99** (2007) 182003 [arXiv:0707.3354 [hep-ph]].

[22] S. Coito, G. Rupp and E. van Beveren, Eur. Phys. J. C **73** (2013) 3, 2351 [arXiv:1212.0648 [hep-ph]].

[23] L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D **89** (2014) 114010 [arXiv:1405.1551 [hep-ph]].