Scalar Mesons and FAIR

To cite this article: Denis Parganlija 2013 J. Phys.: Conf. Ser. 426 012019

View the article online for updates and enhancements.

Related content
- Phenomenology of the pseudoscalar glueball with a mass of 2.6 GeV
  Walaa I Eshraim and Stanislaus Janowski
- Resonances $f_0(1370), f_0(1500) and f_0(1710)$ within the extended Linear Sigma Model
  Stanislaus Janowski and Francesco Giacosa
- Constituent quark model study of the meson spectra
  J Vijande, F Fernández and A Valcarce

Recent citations
- Excited scalar and pseudoscalar mesons in the extended linear sigma model
  Denis Parganlija and Francesco Giacosa
- Glueballs and vector mesons at NICA
  Denis Parganlija
- Mesons, PANDA and the scalar glueball
  Denis Parganlija
Scalar Mesons and FAIR

Denis Parganlija
Institute for Theoretical Physics, Vienna University of Technology, Wiedner Hauptstr. 8-10, A-1040 Vienna, Austria
E-mail: denisp@hep.itp.tuwien.ac.at

Abstract. I review issues related to the scalar-meson phenomenology considered of interest for the future PANDA experiments at FAIR.

1. Introduction
Scalar mesons are degrees of freedom of QCD (Quantum Chromodynamics) that possess quantum numbers $J^{PC} = 0^{++}$, where $J$ is the total spin, $P$ represents parity and $C$ is the charge conjugation. Mesons that possess isospin $I = 0$ are referred to as isoscalars. Scalars with $I = 0$ represent QCD degrees of freedom with some peculiar features: they are defined as carrying quantum numbers of vacuum but are identifiable as resonances; as mesons, they should be of $\bar{q}q$ (quarkonium) structure but are too many to simply represent $\bar{q}q$ objects; and they are strongly mixed with each other so that disentangling them is in the majority of cases a highly non-trivial task. However, they are also of extreme importance for QCD since their vacuum expectation values represent the cause of the spontaneous breaking of the chiral symmetry in QCD, and this "Higgs mechanism" is in turn expected to generate Goldstone bosons of QCD: pions, kaons and others. Thus understanding isoscalar mesons is a fundamental question of QCD, and one that has by no means been closed after decades of research and debate.

1.1. Scalar Mesons and Experiment
Listings of the Particle Data Group (PDG) cite the existence of five $IJ^{PC} = 00^{++}$ states in the energy region up to 1.8 GeV: $f_0(500)$ or $\sigma$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ \cite{1}. Let us review basic experimental data regarding these resonances.

- Historically, debates regarding scalar mesons have been mostly focused on the $f_0(500)$ resonance (also known as $\sigma$). The latter is characterised by a decay width that is of the same magnitude as the resonance mass – according to PDG, it has a mass of (400-500) MeV and a decay width of (400-700) MeV. The existence of this state was suggested in linear sigma models long ago: the state was introduced theoretically as the putative chiral partner of the pion \cite{2}. Since the pion is a well-established quarkonium state, then the chiral-partner state of the pion had to be of the same structure. Additionally, the pion is a pseudo-Goldstone bosone – its mass is the lowest in the meson spectrum. Therefore, naive expectations were that (i) the chiral partner of the pion would be the lightest scalar state with $I = 0$, i.e., the $\sigma$ meson, and consequently (ii) that the $\sigma$ meson was a $\bar{q}q$ state. However, currently it is by no means clear that $\sigma$ is truly a $\bar{q}q$ state, implying that its interpretation as the chiral partner of the pion is in doubt. We will come back to this issue later in this manuscript.
First hints about the existence of the $f_{0}(980)$ resonance were discovered in analyses of $\pi\pi$ scattering data found to exhibit a rapid drop in the cross-section in the energy region between 950 MeV and 980 MeV (i.e., close to the $KK$ threshold) in Saclay data on antiproton-proton [3] and Berkley data on pion-proton collisions [4]. The most precise modern-data analyses result in pole mass and pole decay widths values in the close vicinity of the mentioned energy region – see, e.g., Ref. [5] where the pole mass was determined as $m_{f_{0}(980)} = (996 \pm 7)$ MeV and the pole decay width as $\Gamma_{f_{0}(980)} = 50^{+20}_{-12}$ MeV.

- The $f_{0}(1370)$ resonance is a broad enhancement in the $\pi\pi$, $4\pi$ and, to a lesser extent, $KK$ and $\eta\eta$ channels in the energy region of approximately 1.3 GeV. It is characterised by emergence of two peaks, respectively in the $2\pi$ and $4\pi$ decay channels [6], the disentagement of which requires a simultaneous analysis of $\pi\pi \to \pi\pi$ and $\pi\pi \to 4\pi$ scattering data. The analysis of Ref. [6] demonstrates that the $2\pi$ decay channel is dominant in the energy region up to 1.35 GeV whereas the energy region thereafter is dominated by the opening of the $\rho\rho$ threshold leading to a strong $4\pi$ decay pattern. Note that $f_{0}(1370)$ represents a single resonance despite possessing two peaks since a combined dispersive analysis of both $2\pi$ and $4\pi$ channels yields only one pole. Historically, early hints of the $f_{0}(1370)$ existence were observed in $p\bar{p}$ collisions at CERN in 1969 with a possible $\rho\rho$ enhancement claimed at 1.4 GeV [7]. Current edition of the Particle Data Group listings accumulates all available data on $f_{0}(1370)$ estimating an interval for, rather than stating exact values of, its mass and decay width: $m_{f_{0}(1370)} = (1200-1500)$ MeV and $\Gamma_{f_{0}(1370)} = (200-500)$ MeV [1].

- The discovery of the $f_{0}(1500)$ resonance originated in search for the scalar glueball state. This resonance is found mostly in pion final states from nucleon-nucleon (or antinucleon-nucleon) and pion-nucleon scattering processes. If such processes produce four pions, then $f_{0}(1500)$ is reconstructed from $\rho\rho$ final states in the $2(\pi^{+}\pi^{-})$ channel and from $\sigma\sigma$ final states in the $2(\pi^{0}\pi^{0})$ or $2(\pi^{0}\pi^{\pm})$ channels. The resonance is therefore at least partly reconstructed in channels containing a double Pomeron exchange rendering the state a glueball candidate [20]. The PDG cites a world-average mass $m_{f_{0}(1500)} = (1505 \pm 6)$ MeV and decay width $\Gamma_{f_{0}(1500)} = (109 \pm 7)$ MeV [1].

- The $f_{0}(1710)$ resonance is characterised by a predominant $KK$ decay channel, marking a clear point of distinction between this resonance and the above mentioned ones. The earliest evidence for the $f_{0}(1710)$ resonance was obtained from the decay $J/\psi \to \gamma\eta\eta$ at the SLAC Crystal Ball detector from $e^{+}e^{-}$ annihilation [8]; a resonance with a mass of $(1640 \pm 50)$ MeV, a decay width of $220^{+100}_{-70}$ MeV and the charge conjugation $C = +1$ was found (the latter was because the resonance had been produced in a radiative $J/\psi$ decay but, interestingly, no final determination of the total spin and parity was possible from these first data). Subsequent analyses, such as those in Ref. [9], determined the resonance to be of $J^{P} = 0^{+}$ nature. The PDG cites a world-average mass $m_{f_{0}(1710)} = (1720 \pm 6)$ MeV and a decay width $\Gamma_{f_{0}(1710)} = (135 \pm 8)$ MeV [1].

1.2. Scalar Mesons and Theory

Assuming a $\bar{q}q$ structure for mesons (where $q$ denotes a constituent quark) it is possible to construct two $I^{PC} = 0^{++}$ states for three quark flavours (up $u$, down $d$ and strange $s$) once the approximate isospin symmetry in the nonstrange-quark sector is considered ($u = d$): $f_{0}^{N} = (\bar{u}u + \bar{d}d)/\sqrt{2}$ and $f_{0}^{S} = \bar{s}s$. The latter are per construction pure states. They can obviously mix by virtue of carrying the same quantum numbers; mixed states are expected to be those appearing in the physical spectrum. Clearly, two pure states will produce the same number of mixed states – thus only two of the five previously discussed physical states can conceivably be described in this approach. Hence the natural questions regard (i) location of isoscalar $\bar{q}q$ states in the physical spectrum and (ii) structure of the remaining isoscalar states. Answers to these
questions are complicated by the mentioned mixing of isoscalar states. An isoscalar (or indeed any other) meson need not necessarily be of $\bar{q}q$ structure – it can also possess admixtures (or even be predominantly composed) of tetraquark ($\bar{q}q\bar{q}q$), glueball (bound states of QCD gauge bosons – gluons) or molecular (e.g., $\pi\pi$ or $KK$) contributions. Note that the hadronic spectrum is additionally influenced by confinement via Regge trajectories; expectation value of the Polyakov loop (confinement order parameter, "a loop of confining string") and the chiral condensate mix. Highly excited scalar mesons are all mixtures of spin waves, quarkonium or gluonium states, string excitations and isospin waves.

Neglecting confinement effects, for the cases of the above-stated isoscalar mesons I consider the following to be of importance:

- As indicated above, the $f_0(500)$ resonance is usually considered as the natural option for the chiral partner of the pion, implying that $f_0(500)$ possesses the $\bar{q}q$ structure as suggested, e.g., by Ref. [10]. However, a $\bar{q}q$ scalar state possesses the intrinsic angular momentum $L = 1$ as well as the relative spin of the quarks $S = 1$. For this reason one could also easily expect the scalar $\bar{q}q$ state to be in the region above 1 GeV. This would imply that (i) isoscalars above 1 GeV possess the $\bar{q}q$ structure and (ii) $f_0(500)$ represents a tetraquark state or a $\pi\pi$ bound state. For details on both statements see, e.g., Refs. [11, 12, 13].
- As already discussed, the $f_0(980)$ resonance is close to the kaon-kaon threshold rendering a structure analysis for this state rather difficult. The resonance may be interpreted as a quarkonium [14], as a $q^2\bar{q}^2$ state [15], as a $KK$ bound state [16], as a glueball [17] or even as an $\eta\eta$ bound state [18].
- The $f_0(1370)$ resonance appears to be a suitable candidate for a non-strange $\bar{q}q$ state [12, 13] or a dynamically generated state [19].
- The $f_0(1500)$ resonance seems to represent a (predominant) glueball state [20, 21] although claims have also been made that, contrarily, $f_0(1710)$ is of predominantly glueball nature [22]. Alternatively, $f_0(1710)$ can also be interpreted as a predominantly $ss$ state [13].

Hence the current state of knowledge allows us to only claim with certitude that all the above mentioned states mix [23]; some of them even overlap due to large decay widths [1]. As yet, no definitive statement is possible about their structure. The situation is thus rather complicated – and it is enhanced even further by the possible existence of a sixth isoscalar state, located very proximal to the set of the already mentioned isoscalars: the $f_0(1790)$ resonance.

2. The $f_0(1790)$ Resonance and FAIR

The existence of the putative new $f_0(1790)$ resonance has been claimed by the BES II Collaboration in 2004 [24]. The mass and decay width of the resonance were determined by the Collaboration as $m_{f_0(1790)} = 1790^{+40}_{-30}$ and $\Gamma_{f_0(1790)} = 270^{+60}_{-30}$ MeV. The stated large decay width implies a strong overlap of this resonance with $f_0(1710)$; however, there is a clear point of distinction between the two resonances: $f_0(1710)$ is reconstructed predominantly in the kaon decay channels whereas $f_0(1790)$ is reconstructed predominantly in the pion decay channels. There are four basic production mechanisms for $f_0(1710)$ and $f_0(1790)$ via $J/\psi$ decays [24]:

- (i) $J/\psi \to \varphi K^+K^-$,
- (ii) $J/\psi \to \varphi\pi^+\pi^-$,
- (iii) $J/\psi \to \omega K^+K^-$,
- (iv) $J/\psi \to \omega\pi^+\pi^-.$

Reactions (i) and (iii) allow for reconstruction of $f_0(1710)$ [1] whereas reactions (ii) and (iv) allow for reconstruction of $f_0(1790)$. Importantly, assuming $f_0(1710)$ and $f_0(1790)$ to be
the same resonance leads to a contradiction: such a resonance would have to possess a pion-to-kaon-decay ratio of $1.82 \pm 0.33$ according to reactions (i) and (ii) and, simultaneously, the pion-to-kaon-decay ratio $< 0.11$ according to reactions (iii) and (iv) [24]. There can be no one resonance with these simultaneous features – thus BES II data suggest $f_0(1710)$ and $f_0(1790)$ to represent two distinct resonances.

Let us finally discuss the relevance of the deliberations in this paper for FAIR. The proposed PANDA experiments at FAIR will study interactions between antiprotons and fixed-target protons and nuclei in the momentum range of 1.5-15 GeV. A stated goal of the PANDA Collaboration is the exploration of light-hadron spectroscopy, including search for glueballs and multiquark states [25]. In this regard I would like to suggest the following courses of action in the particular case of possible mixing scenarios in the scalar sector:

- Any viable search for members of a glueball spectrum must include the ground state as otherwise the spectrum would be incomplete. The PANDA Collaboration is in a unique position to greatly advance our search for glueballs since (i) the Collaboration can build upon extensive experimental work performed in the last decades and (ii) the technical specifications of the PANDA detector allow for a search for glueballs with unprecedented accuracy in comparison with similar undertakings in the past. However, the glueball state will inevitably overlap with other states that possess the same quantum numbers (and may be of $\bar{q}q$, $\bar{q}qqq$ or molecular structure) and the disentanglement of various signals from each of the mentioned resonances will represent a formidable task.

- Current theoretical results [21, 22] suggest the scalar glueball to be positioned at (1.5-1.7) GeV, i.e., in the vicinity of the established resonances $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ as well as the newly proposed $f_0(1790)$ state. Consequently, a viable search for the scalar glueball will have to consider overlap of the glueball not only with $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ but also with $f_0(1790)$. In other words: a viable search for the glueball ground state at PANDA must consider the possibility of the existence of $f_0(1790)$. If $f_0(1790)$ is not found at PANDA, then BES results may be put in doubt; but if $f_0(1790)$ is ascertained then its signal will have to be disentangled from the glueball signal in order for the glueball search to be successful, making the search even more challenging and thus even more interesting.

3. Conclusions
Scalar mesons represent an interesting challenge for the future PANDA experiments at FAIR: the planned search for the glueball state in the $IJ^{PC} = 00^{++}$ channel will have to consider mixing/overlap between non-strange $\bar{q}q$, strange $\bar{q}q$, non-strange and strange $\bar{q}qqq$ as well as possible molecular-type states. Additionally, obtaining a clear signal for the glueball will inevitably require the confirmation (or negation) of the existence of a putative new isoscalar state referred to as $f_0(1790)$ by the BES II Collaboration [24]. If $f_0(1790)$ exists, it will most certainly overlap with the glueball. Thus a viable search for a glueball state simultaneously implies a search for $f_0(1790)$: ignoring $f_0(1790)$ will strongly distort any signal for the glueball. For this reason, the search for a glueball at PANDA is more than a search for merely one state – it is a search where several very close-by states have to be considered simultaneously.

References
[1] J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012).
[2] J. S. Schwinger, Annals Phys. 2, 407 (1957); M. Gell-Mann and M. Levy, Nuovo Cim. 16, 705 (1960); S. Weinberg, Phys. Rev. Lett. 18, 188 (1967).
[3] R. Bizzarri, M. Foster, P. Gavillet, G. Labrosse, L. Montanet, R. Salmeron, P. Villemoes, C. Ghesquiere et al., Nucl. Phys. B 14, 169 (1969).
[4] M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatte, J. H. Friedman, G. R. Lynch, S. D. Protopopescu, M. S. Rabin, F. T. Solmitz, Phys. Lett. B 36, 152 (1971); S. M. Flatte, M. Alston-Garnjost, A. Barbaro-Galtieri, J. H. Friedman, G. R. Lynch, S. D. Protopopescu, M. S. Rabin, F. T. Solmitz, Phys. Lett. B 338, 232 (1997); S. D. Protopopescu, M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatte, J. H. Friedman, T. A. Lasinski, G. R. Lynch, M. S. Rabin et al., Phys. Rev. D 7, 1279 (1973).

[5] R. Garcia-Martín, R. Kaminski, J. R. Pelaez and J. Ruiz de Elvira, Phys. Rev. Lett. 107, 072001 (2011) [arXiv:1107.1635 [hep-ph]].

[6] D. V. Bugg, Eur. Phys. J. C 52, 55 (2007) [arXiv:0706.1341 [hep-ex]].

[7] R. A. Donald et al., Nucl. Phys. B 11, 55 (1969).

[8] C. Edwards, R. Partridge, C. Peck, F. Porter, D. Antreasyan, Y. F. Gu, W. S. Kollmann, M. Richardson et al., Phys. Rev. Lett. 48, 458 (1982).

[9] D. Alde et al. [Serpukhov-Brussels-Los Alamos-Annecy(LAPP) Collaboration], Phys. Lett. B 182, 105 (1986); D. Alde et al. [IFVE-Brussels-Annecy(Los Alamos Collaboration], Phys. Lett. B 284, 457 (1992); T. A. Armstrong et al. [ET60 Collaboration], Phys. Lett. B 307, 394 (1993); D. V. Bugg, I. Scott, B. S. Zou, V. V. Anisovich, A. V. Sarantsev, T. H. Burnett and S. Sutlief, Phys. Lett. B 353, 378 (1995); D. Barberis et al. [WA102 Collaboration], Phys. Lett. B 462, 462 (1999) [arXiv:hep-ex/9907055]; S. Chekanov et al. [ZEUS Collaboration], Phys. Rev. Lett. 101, 112003 (2008) [arXiv:0806.0807 [hep-ex]].

[10] Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122, 345 (1961); R. Delbourgo and M. D. Scadron, Phys. Rev. Lett. 48, 379 (1982); R. Delbourgo and M. D. Scadron, Mod. Phys. Lett. A 10, 251 (1995) [hep-ph/9910242]; R. Delbourgo and M. D. Scadron, Int. J. Mod. Phys. A 13, 657 (1998) [hep-ph/9807504].