Structure of scalar mesons and the Higgs sector of strong interaction

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The σ meson may be considered as the Higgs boson of strong interaction. While the observation of the electroweak Higgs boson is the primary goal in ongoing experiments at the LHC, the σ meson is by now well studied both as an on-shell particle and as a virtual particle while being part of the constituent quark. This makes it timely to give an overview of the present status of the Higgs sector of strong interaction which includes the scalar mesons $\sigma(600)$, $\kappa(800)$, $f_0(980)$ and $a_0(980)$ together with the pseudo Goldstone bosons π, K and η.

1 Introduction

Scalar mesons below 1 GeV together with the pseudo Goldstone bosons π, K and η may be considered as the Higgs sector of strong interaction. While the EW Higgs boson up to now appears to escape experimental observation in the ongoing LHC experiments [1] the strong counterpart, the σ meson is by now well studied both as on-shell particle and as a virtual particle while being part of the constituent quark. The latter observation has been facilitated through Compton scattering by the proton in an experiment carried out at MAMI (Mainz) published in 2001 [2, 3]. In this experiment it has been shown that the scalar t-channel makes a strong contribution to the Compton scattering amplitude, being successfully represented in terms of a t-channel pole located at m_σ^2 where m_σ is the bare mass of the σ meson, determined in this experiment to be $\sim$ 600 MeV. Inspite of this great success the physical interpretation of the experiment remained uncertain because an explicit σ meson is a strongly unwanted particle in chiral perturbation theory. This led to an unnecessary delay, because a detailed theoretical investigation was required extending until 2010, when it was shown that the t-channel pole at m_σ^2 is a well founded concept and that the related t-channel amplitude may be understood as being due to Compton scattering by the σ meson while being part of the constituent quark [4]. The findings in [4] were extended to include the whole scalar nonet below 1 GeV in [5]. The present work is in part based on this latter publication where more details may be found.

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2 The doorway model and the structure of scalar mesons

The scalar nonet below 1 GeV cannot be understood in terms of flavor structures as provided by $SU(3)_f$ [6] because of the ordering of the meson masses. This problem was solved by introducing tetraquarks $(q\bar{q})^2$ [6]. The tetraquark model implies the possibility of a dissociation of the kind $(q\bar{q})^2 \rightleftarrows (q\bar{q}+q\bar{q})$, leading to $q\bar{q}$ as a small structure component. In [5] this small $q\bar{q}$ structure component was interpreted in terms of a doorway state which serves as the entrance channel in a two-photon fusion reaction and is in agreement with the experimental two-photon widths of the mesons:

$$\sigma(600): \quad \gamma\gamma \to \frac{u\bar{u}+d\bar{d}}{\sqrt{2}} \to u\bar{u}d\bar{d} \to \pi\pi, \tag{1}$$

$$f_0(980): \quad \gamma\gamma \to \frac{1}{\sqrt{2}}\left(\frac{u\bar{u}+d\bar{d}}{\sqrt{2}} - s\bar{s}\right) \to \frac{s\bar{s}(u\bar{u}+d\bar{d})}{\sqrt{2}} \to \pi\pi, K\bar{K}, \tag{2}$$

$$a_0(980): \quad \gamma\gamma \to \frac{1}{\sqrt{2}}\left(\frac{-u\bar{u}+d\bar{d}}{\sqrt{2}} + s\bar{s}\right) \to \frac{s\bar{s}(u\bar{u}-d\bar{d})}{\sqrt{2}} \to \eta\pi, K\bar{K}. \tag{3}$$

The $q\bar{q}$ configuration of the $a_0(980)$ meson violates isospin conservation. This is of no problem because we consider the $q\bar{q}$ configuration only as a small structure component.

In t-channel nucleon Compton scattering the reaction chain

$$\gamma\gamma \to \{\sigma(600), f_0(980), a_0(980)\} \to N\bar{N} \tag{4}$$

is considered where the excitation of the $N\bar{N}$ pair is virtual. This leads to the consequence that the masses of the scalar mesons entering into (4) are the bare masses, i.e. the masses for the case of zero particle decay width. The validity of this concept has been shown in [7] where quantitative predictions of electromagnetic polarizabilities of the nucleon led to excellent agreement with experimental data.

3 Mass prediction for scalar mesons in terms of spontaneous, dynamical and explicit symmetry breaking

In case of pseudoscalar and scalar mesons the following phenomena contribute to the generation of the masses of the mesons:
(i) The $U(1)_A$ anomaly,
(ii) spontaneous or dynamical symmetry breaking,
(iii) explicit symmetry breaking leading to non-zero current-quark masses.
The $U(1)_A$ anomaly is a gluonic (instanton [8]) effect which works on $SU(3)_f$ flavor states which are completely symmetric in the chiral limit. For pseudoscalar and scalar mesons this is only the case for the η_0 flavor state and has the consequence that η_0 has a mass

in the chiral limit whereas all the other pseudoscalar mesons are massless. These latter pseudoscalar mesons form the octet of Goldstone bosons as depicted in the left panels of Figures 1 and 2. The left panel of Figure 1 shows the mexican-hat potential where the

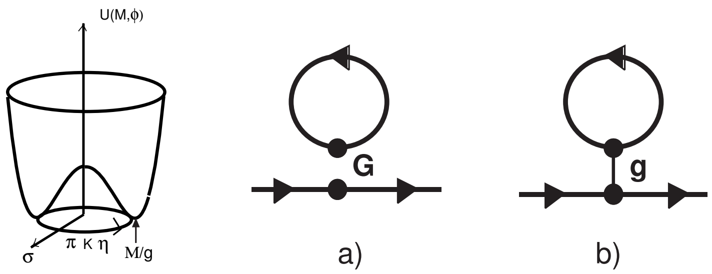

Figure 1: Left panel: Spontaneous symmetry breaking in the chiral limit (cl) illustrated by the LσM: In the $SU(2)$ sector there is one "strong Higgs boson", the σ meson having a mass of $m_\sigma^{\rm cl} = 652$ MeV taking part in spontaneous symmetry breaking, accompanied by an isotriplet of massless π mesons serving as Goldstone bosons. In the $SU(3)$ sector there are 8 massless Goldstone bosons π, K, η, and nine scalar mesons σ, κ, f_0 and a_0, all of them having the same mass as the σ meson in the chiral limit. The mass degeneracy is removed by explicit symmetry breaking. Right panel: Tadpole graphs of dynamical symmetry breaking. a) Four fermion version of the Nambu-Jona–Lasinio (NJL) model, b) bosonized NJL model.

Goldstone bosons correspond to the minimum of the potential. The mexican-hat potential describes spontaneous symmetry breaking in terms of a mass parameter μ and a self-coupling parameter λ. Since these parameters are unknown no quantitative prediction of the masses of the constituent quark and of the scalar mesons is possible. This is different in the quark-level linear σ model (QLLσM) where the graphs shown in Figure 1 a) and b) are taken into account. In this way the Delbourgo-Scadron relation [9]

$$M = g\, f_0 \tag{5}$$

is obtained with $g = 2\pi/\sqrt{3}$ being the σ-quark coupling constant and $f_0 = 89.8$ MeV the pion decay constant in the chiral limit. Eq. (5) leads to $m^{\rm cl} = 2M = 652$ MeV as given in the caption of Figure 2. Explicit symmetry breaking is described by generalizing the mass formula valid for the σ meson

$$m_\sigma^2 = \frac{16\pi^2}{3} f_\pi^2 + m_\pi^2 \tag{6}$$

by taking into account the larger fraction of strange quarks in the $\kappa(800)$ and the $(f_0(980), a_0(980))$ mesons in their tetraquark structures. This leads to

$$m_\kappa^2 = \frac{16\pi^2}{3}\frac{1}{2}(f_\pi^2 + f_K^2) + \frac{1}{2}(m_\pi^2 + m_K^2) \tag{7}$$

$$m_{a_0,f_0}^2 = \frac{16\pi^2}{3} f_K^2 + m_\eta^2 \tag{8}$$

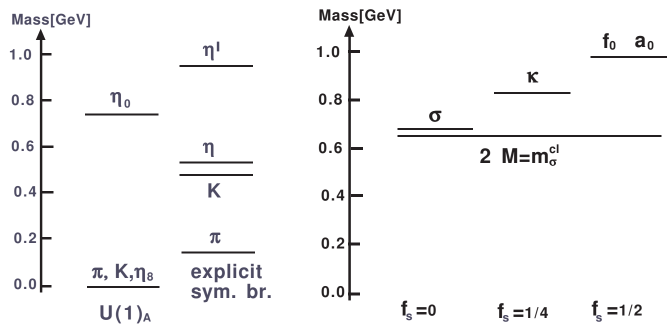

Figure 2: Left panel: Pseudoscalar mesons after $U(1)_A$ symmetry breaking (left column) and after additional explicit symmetry breaking (right column). Right panel: Masses of the members of the scalar nonet. In the chiral limit all the scalar mesons have the same mass amounting to $2M = m_\sigma^{\rm cl} = 652$ MeV, where M is the mass of the constituent quark in the chiral limit and $m_\sigma^{\rm cl}$ the mass of the σ mesons in the chiral limit (cl). Explicit symmetry breaking shifts the masses upward with the fraction f_s of strange quarks in the tetraquark structure being the parameter determining the size of the shift.

where $f_\pi = 92.42 \pm 0.26$ MeV and $f_K = 113.0 \pm 1.0$ MeV. The masses predicted in this way are $m_\sigma = 685$ MeV, $m_\kappa = 834$ MeV and $m_{a_0,f_0} = 986$ MeV in close agreement with the experimental data.

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