Investigation of light scalar resonances at COSY

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The $a_0(980)$ and $f_0(980)$ resonances are two well established states in the excited meson spectrum. We review the most prominent theoretical models which try to explain the structure of these states. It is discussed whether data from COSY on $a_0$ and $f_0$ production in $pp$, $pn$, $pd$ and $dd$ collisions allow to distinguish between the different approaches. Very promising in this respect seems to be the measurement of the reaction $dd \rightarrow (^4\text{He} a_0^0 \rightarrow) ^4\text{He} \pi^0 \eta$ which violates isospin conservation and can be related to $a_0$-$f_0$ mixing.

1. Overview of theoretical models

So far a final consensus on the nature of the light scalar mesons has not been reached. In contrast to the case of the $\sigma$ where new data on the in-medium modifications support the picture of two correlated pions the subject remains quite open concerning the nature of the $a_0$ and $f_0$. In the following a short list of some interpretations given.

$q\bar{q}$-state: Despite the very successful mass predictions, e.g. for vector mesons, coming from relativistic constituent quark models, mass predictions in the scalar sector still vary considerably. The predictions depend
strongly on the choice for the Dirac structure of the confining potential and the models cannot explain the reason for the $a_0/f_0$-mass degeneracy. In Ref. [2] either the mass of the $a_0$ or the $f_0$ is reproduced depending on the spin parametrisation of confinement. Other authors [3] deduce from their relativistic quark model the need for a glueball mixing with the calculated states to reproduce experimental data. Within those mixing schemes interpretations vary from minimal gluonic admixture to the $q\bar{q}$-states $f_0$ and $a_0$ [4] up to large gluonic components [5]. Thus the answers coming from $q\bar{q}$-models are not conclusive yet.

$(q\bar{q})(\bar{q}\bar{q})$-states: This structure allows for two configurations in colour space: \{33\} and \{66\}. Of course those two configurations may mix/rearrange to form a state like $(q\bar{q})(\bar{q}\bar{q})$ with colour configuration \{11\}. Therefore, the number of expected tetraquark states and their interpretation vary for different calculations and it is difficult to distinguish a mesonic molecule from a tetraquark state. In Ref. [6] for example 5 tetraquarks are found. From those two are nearly mass degenerate and obtain the mass of the $a_0$ and $f_0$ when a fudge factor is used to account for neglected three and four body forces. This opposes the complete tetraquark nonet expected in Ref. [7], which might result from the authors considering pure $(qq)\{\bar{q}\bar{q}\}$3 and only allowing $(q\bar{q})_1(q\bar{q})_1$ admixture for large distances, whereas this component might occur at small distances by mixing of \{33\}, \{66\} configurations, resulting in a less attractive interaction. This was for example pointed out in Ref. [8]. In the latter paper it was observed, that the four quarks in the confining potential are mainly arranged as two colour singlets at large (1.5 fm) distance and the notion of a mesonic molecule was introduced.

Mesonic molecules: Inspired by the original mesonic molecule in Ref. [8] (see the $(qq)(\bar{q}\bar{q})$ case) a second molecule picture [9] was developed in which only mesonic degrees of freedom (i.e. colour singlets) were considered. Since $\rho$-exchange between the $K\bar{K}$-pair sets the scale for the bound state identified as $f_0$, it might be even more compact than the molecule of Ref. [8]. This is why radiative $\phi$ decays exclude the extended molecule of Ref. [8] while still giving strong evidence in favour of a compact $K\bar{K}$-state or, as it is phrased in Ref. [10], a compact four-quark state. Furthermore the chiral unitary approach, which in its structure is very close to the mesonic model, has no problems to describe radiative $\phi$-decays [11], which is a hint that the discussed $K\bar{K}$ state really is compact.
Chiral unitary approach: Inspired by chiral perturbation theory, schemes have been developed to deal with unitarity. As above those methods generate bound states from two mesons \[12\]. These states differ from mesonic molecules only by the theoretical framework used to calculate them and not by physical content.

Semi-bound states: In some models the attraction for the mesonic sector is not sufficient to generate bound states. One example for this is the cusp-effect in Ref. \[9\] which is identified with an \(a_0\) signal. Another example would be the model of Ref. \[13\]. Here the light scalar mesons do not stem from the confining potential but they have their origin in the \(^3P_0\)-barrier, which is just too low to generate bound meson-meson states.

Mixing-schemes: A different approach to explain the abundance of observed scalar states is to introduce a scalar glueball around 1.4–1.8 GeV as predicted by lattice calculations. This glueball then mixes with the other scalar states to form the observed resonances. Depending on the predicted masses of the glueball and the bare states different mixings are obtained, e.g. \[14\].

Vacuum scalars: This idea of identifying \(f_0\) and \(a_0\) as systems formed of negative kinetic energy \(u\) and \(d\) flavours \[15\] seems to be ruled out by experiment even though the predictive power of this model was plagued by the complexity of the calculations. The predicted compact size of the object contrasts too much with the decay constant ratio of \(a_0\) and \(K^*_0\) as shown in \[16\].

During the discussion in the workshop, tetraquark models were favoured whereas no conclusion was drawn on the characteristic of the different four-quark states. No key observables have been identified to discriminate mesonic molecules, chiral unitarity effects and \((qq)(\bar{q}\bar{q})\)-states. It was pointed out that the available data set on the production of the light scalars in hadronic interactions needs to be extended. Measurements of as many observables as possible with different beam\((p,\bar{p},d)\)-target\((p,n,d)\) combinations and tests of isospin ratios should be performed. In particular, the observation of the process \(dd \rightarrow ^4He\pi^0\eta\) which is forbidden by isospin conservation might yield information about the strength of the \(a_0^0-f_0\) mixing.

2. Available data from COSY

Data about the production and decay of the light scalar resonances from COSY are rather scarce yet. Some information about the \(a_0^0/f_0\)-production cross sections in \(pp\) and \(pd\) reactions can be deduced model dependently \[17\].
from data on $K^+K^-$ production. Such measurements have been performed at the COSY-11 and MOMO facilities at beam energies close to the $K^+K^-$ production threshold, see Table 1.

| Experiment | Reaction | $Q$ (MeV) | $\sigma_{\text{tot}}$ (nb) | contribution via $a_0^0/f_0$ |
|------------|----------|-----------|-------------------------|-------------------------------|
| COSY-11    | $pp \rightarrow pp K^+K^-$ | 17        | $1.8 \pm 0.27^{+0.26}_{-0.35}$ | small [17]                    |
| MOMO       | $pd \rightarrow ^3\text{He} K^+K^-$ | 40        | $9.6 \pm 1.0$ | ?                              |
|            |          | 56        | $17.5 \pm 1.8$ | ?                              |
| ANKE       | $pp \rightarrow d K^+\bar{K}^0$ | 44        | $45 \pm 6 \pm 16$ (preliminary) | $\sim 70\%$ [20]             |

Table 1. Overview over the available data from COSY

According to the model calculations outlined in Ref. [17], the fraction of resonantly produced $K\bar{K}$ pairs (via the $a_0^0/f_0$) in $pp \rightarrow pn K^+\bar{K}^0$ reactions is significantly larger than for the $pp \rightarrow pp K^+K^-$ case. Following this idea, two measurements of the reactions $pp \rightarrow d K^+\bar{K}^0/\pi^+\eta$ have been performed at the ANKE spectrometer for $Q = 44$ and 104 MeV. The total $pp \rightarrow d K^+\bar{K}^0$ cross section at $Q=44$ MeV is about $\sim 45 \text{ nb}$ [21], in excellent agreement with the model predictions ($\sim 40 \text{ nb}$). The same model predicts a resonant contribution of $\sim 70\%$ for this $Q$ value [20]. This interpretation is in line with a preliminary analysis of the $\pi^+\eta$ decay channel where a resonant structure around 980 MeV/$c^2$ is seen in the invariant $\pi^+\eta$-mass distribution with a width of $\Gamma \sim 40 \text{ MeV}/c^2$ [21]. From these data it can be concluded that systematic studies of the light scalar mesons are possible with ANKE.

### 3. Planned measurements

It was suggested long ago that the coupling of the $a_0(980)$- and $f_0(980)$-resonances to the $K\bar{K}$ continuum should give rise to a significant $a_0^0$-$f_0$ mixing in the vicinity of the $K\bar{K}$ threshold [22]. Different aspects of this mixing, the underlying dynamics, and the possibilities to measure this effect have been discussed in Refs. [23] [24] [25] [26] [27]. It has been suggested by Close and Kirk [28] that new data from the WA102 collaboration at CERN [29] on the central production of $a_0$ and $f_0$ in the reaction $pp \rightarrow p_\pi X p_t$ provide evidence for a significant $a_0$-$f_0$-mixing intensity $|\xi|^2 = 8 \pm 3\%$. 

Possible experimental tests of isospin violation due to $a_0$-$f_0$ mixing based on a combined analysis of the reactions

\begin{align}
pp &\rightarrow d a_0^+ \quad \text{and} \quad pn \rightarrow d a_0^0 \\
pd &\rightarrow ^3\text{He} a_0^+ \quad \text{and} \quad pd \rightarrow ^3\text{He} a_0^0
\end{align}

are discussed in Ref. [25]. A corresponding proposal for measurements at ANKE [30] has already been approved by the COSY-PAC and the measurements are planned for winter 2003/04.

Direct production of the $a_0$ resonance in the reaction $dd \rightarrow ^4\text{He} a_0^0$ is forbidden if isospin is conserved. It can, for example, be observed due to $a_0$-$f_0$ mixing

$$\sigma(dd \rightarrow ^4\text{He} a_0^0) = |\xi|^2 \cdot \sigma(dd \rightarrow ^4\text{He} f_0).$$

Therefore it is very interesting to study the reaction

$$dd \rightarrow ^4\text{He} (\pi^0 \eta)$$

at $m_{\pi^0}\eta \sim (980\text{ MeV})^2$. Any signal of reaction (4) will be related to isospin breaking, which is expected to be more pronounced near the $f_0$ threshold as compared to the region below (or above).

An important point for the feasibility of such measurements is the magnitude of the cross sections $\sigma(dd \rightarrow ^4\text{He} a_0^0)$ and $\sigma(dd \rightarrow ^4\text{He} f_0)$. Experimental data are not available yet and we try to give a qualitative estimate of these cross sections: According to Refs. [31, 32, 33], the cross-section ratio $\sigma(dd \rightarrow ^4\text{He} \eta)/\sigma(dd \rightarrow ^3\text{He} \eta)$ is about 0.04 at $Q \simeq 10\text{ MeV}$. We assume an approximately equal ratio for the case of $K^+K^-$ production near the threshold:

$$\sigma(dd \rightarrow ^4\text{He} K^+K^-) = 0.04 \cdot \sigma(pd \rightarrow ^3\text{He} K^+K^-).$$

Using the MOMO data [19] on the reaction $pd \rightarrow ^3\text{He} K^+K^-$ (see Table 1) we find:

$$\sigma(dd \rightarrow ^4\text{He} K^+K^-) \simeq 0.4 \text{ nb}$$

at $Q=40\text{ MeV}$. The MOMO collaboration notes that their invariant $K^+K^-$ mass distributions follow phase space. However, as it was shown for the case of the $a_0$ resonance in Ref. [17], the shape of the invariant mass spectrum following phase space cannot be distinguished from resonance production at $Q \leq \Gamma \leq 70\text{ MeV}$.

Therefore, the broad mass distribution of the MOMO data may also be related to the $f_0$ (or $a_0$). This statement is supported by a two-step model where the amplitude of the reaction $pd \rightarrow ^3\text{He} f_0$ can be constructed from the subprocesses $pp \rightarrow d\pi^+$ and $\pi^+n \rightarrow pf_0$ (cf. Refs. [34, 35]). As it is
known from the available experimental data [36] the cross section of the reaction $\pi N \rightarrow NK\bar{K}$ near threshold has an essential contribution from the $f_0$ resonance in the case of isoscalar $K\bar{K}$ production. Thus the cross section of the reaction $pd \rightarrow ^3\text{He} f_0 \rightarrow ^3\text{He} K^+K^-$ near threshold is expected to be not significantly smaller than the upper limit from MOMO of about $10 \div 20$ nb at $Q = 40 \div 60$ MeV.

For an estimate of $\sigma(dd \rightarrow ^4\text{He} \pi^+\pi^-)$ at $m_{\pi\pi} \sim m_{f_0}$ we assume that the cross section $\sigma(dd \rightarrow ^4\text{He} K^+K^-)$ is also dominated by resonant $f_0$ production at $m_{K\bar{K}} \sim m_{f_0}$, and that $\Gamma_{f_0 \rightarrow K\bar{K}} = (0.1 \div 0.4) \cdot \Gamma_{f_0 \rightarrow \pi\pi}$ [37]. This yields

$$\sigma(dd \rightarrow ^4\text{He} f_0 \rightarrow ^4\text{He} \pi^+\pi^-) = 1 \div 4 \text{ nb}. \quad (7)$$

Finally, using Eq. (3), we get for $|\xi|^2 \simeq 0.05$:

$$\sigma(dd \rightarrow ^4\text{He} a_0^0) \simeq 0.05 \div 0.2 \text{ nb}. \quad (8)$$

The measurement of reactions (6) and (7) with cross sections in the sub-nb range are possible at the ANKE spectrometer. Using a cluster-jet target with Hydrogen as target material luminosities of $\sim 2.7 \cdot 10^{31}$ cm$^{-2}$cm$^{-1}$ have been achieved [21]. Assuming that comparable luminosities can be reached with Deuterium, about 10–40 ($^4\text{He} K^+K^-$) events can be detected within one week of beam time (based on the experience of the previous $a_0^+$ beam times). The pions from reaction (7) have broader angular distributions and, thus, the acceptance of ANKE is about one order of magnitude smaller which is partially compensated by the larger cross section.

It is planned that within a few years ANKE will be equipped with a frozen-pellet target [38] and a large-acceptance photon detector [39]. Since the achievable luminosities then will be roughly one order of magnitude higher, the isospin-violating process (4) can be investigated by detecting the decay photons $\pi^0 \rightarrow 2\gamma$ and $\eta \rightarrow 2\gamma$ in coincidence with the $^4\text{He}$. The latter will be again identified and momentum reconstructed with ANKE.

Based on our cross section estimate (8) we conclude that a few weeks of beam time will be sufficient to collect several 100 events.

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