The Scalar Resonances $a_0/f_0(980)$ at COSY

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Abstract. Fundamental properties of the scalar resonances $a_0/f_0(980)$, like their masses, widths and couplings to $K\bar{K}$, are poorly known. In particular, precise knowledge of the latter quantity would be of great importance since it can be related to the $K\bar{K}$ content of these resonances.

An experimental program is under way at COSY-Jülich aiming at the extraction of the isospin violating a_0/f_0 mixing amplitude Λ which is in leading order proportional to the product of the coupling constants of the a_0 and f_0 to kaons. a_0/f_0 production is studied in pp, pn and dd interactions, both for the $K\bar{K}$ and the $\pi\eta/\pi\pi$ decays, using the ANKE and WASA spectrometers. The latter will be available for measurements at COSY in 2007.

As a first step, isovector $K\bar{K}$ production has been measured in the reaction $pp \to dK^+\bar{K}^0$. The data reveal dominance of the a_0^+ channel, thus demonstrating the feasibility of scalar meson studies at COSY. Analyses of $K\bar{K}$- and $\bar{K}d$-FSI effects yield the corresponding scattering lengths, $a(K\bar{K})_{I=1} = -(0.02 \pm 0.03) - i(0.61 \pm 0.05)$ fm and $|\mathrm{Re}\ a(\bar{K}d)| \leq 1.3$ fm, $\mathrm{Im}\ a(\bar{K}d) \leq 1.3$ fm.

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THE LIGHT SCALAR RESONANCES

QCD is the fundamental theory of the strong interactions. How quarks and gluons are bound into hadrons is a yet unsolved strong coupling problem. QCD can be treated explicitly in this regime using lattice techniques [1], which are, however, not yet in the position to make quantitative statements about the light scalar mesons. Alternatively, QCD-inspired models, which employ effective degrees of freedom, can be used. The constituent quark model is one of the most successful in this respect (see *e.g.* [2]). However, more states with quantum numbers J^P=0^+ have been identified experimentally than would fit into a single SU(3) scalar nonet: the $f_0(600)$ (or σ), $f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ with I=0, the $\kappa(800)$ and the $K^*(1430)$ (I=1/2), as well as the $a_0(980)$ and $a_0(1450)$ (I=1) [3]. Consequently, the $a_0/f_0(980)$ have been associated with crypto-exotic states like $K\bar{K}$ molecules [4] or compact qq-$\bar{q}\bar{q}$ states [5].

In the sixties Weinberg suggested how to decide whether a (stable) particle is composite or elementary [6]. The formalism was applied to the deuteron and it was shown that it is not an elementary particle but made of a proton and a neutron. Baru *et al.* [7] have extended Weinberg's approach to the (unstable) $a_0/f_0(980)$ and find evidence for significant mesonic components in these states. From the formalism in Ref. [7] it follows that precise knowledge of the resonance parameters, in particular the coupling constants of the a_0 and f_0 to kaons, would allow one to model independently determine the $K\bar{K}$ content of the a_0/f_0. However, the values for $g_{a_0K\bar{K}}$ and $g_{f_0K\bar{K}}$ are still poorly known and range from 0.224 to 0.834 and from 1.31 to 2.84, respectively [8] — depending on the fitted Flatté parameterizations of measured $\pi\eta/\pi\pi$ and $K\bar{K}$ spectra.

EXPERIMENTAL PROGRAM AT COSY

An experimental program is under way at COSY-Jülich aiming at the extraction of the isospin-violating (IV) a_0/f_0 mixing amplitude Λ which is in leading order proportional to the product of $g_{a_0K\bar{K}}$ and $g_{f_0K\bar{K}}$ [9, 10]. a_0/f_0 production has been or will be studied in pp, pn and dd interactions, both for the $K\bar{K}$ and the $\pi\eta/\pi\pi$ decay channels [11]. While decay channels with at least one charged kaon can well be investigated with the magnetic spectrometer ANKE ("Apparatus for the detection of Nucleonic and Kaon Ejectiles"), the $\pi\eta$ and $\pi\pi$ final states will be measured with WASA ("Wide Angle Shower Apparatus") which will be available for measurements at COSY in 2007 [12].

Isospin filters and violation

A $pp \to dX$ reaction must lead to a_0^+ (I=1) production, a $pn \to dX$ interaction is not isospin selective, whereas the $dd \to \alpha X$ reaction — neglecting the small IV contributions which are the final goal of the proposed experimental program — is a filter for the f_0 (I=0) resonance, since the initial deuterons and the α particle in the final state have isospin I=0 ("isospin filter").

Since at COSY it is possible to fix the initial isospin one can selectively produce the a_0 or f_0 resonances and can identify observables that vanish in the absence of IV. The idea behind the proposed experiments is the similar to recent measurements of IV effects in the reaction $dd \to \alpha\pi^0$ [13]. However, the interpretation of the signal from the scalar mesons is much simpler as compared to the pion case. Since the a_0 and the f_0 are rather narrow overlapping resonances, the a_0-f_0 mixing in the final state is enhanced by more than an order of magnitude compared to IV in the production operator (*i.e.* "direct" IV $dd \to \alpha a_0$ production) and should give the dominant contribution to the IV effect via the reaction chain $dd \to \alpha f_0(I{=}0) \to \alpha a_0^0(I{=}1) \to \alpha(\pi^0\eta)$ [10, 14].

Any observation of $\pi^0\eta$ production in the $dd \to \alpha X$ reaction is a direct indication of IV and the cross section $\mathrm{d}\sigma/\mathrm{d}m_{\pi\eta}$ is given by the product of the mixing amplitude $\Lambda(m)$ and the $dd \to \alpha f_0$ production operator. It is therefore compulsory to determine the latter in an independent measurement in order to extract the mixing amplitude. A corresponding measurement of the $dd \to \alpha(K^+K^-)_{I=l=0}$ cross section is foreseen for winter 2005/06 at ANKE. These data, together with the information on the $dd \to \alpha(\pi^0\eta)$ reaction from WASA will allow one to determine the a_0-f_0 mixing model independently.

First measurements with ANKE: isovector $K\bar{K}$ production

As a first measurement, the production of $K\bar{K}_{I=1}$ pairs has been investigated in the reaction $pp \to dK^+\bar{K}^0$ at excitation energies $Q_{K\bar{K}} = 48$ and 105 MeV. This reaction has the advantage of lower background as compared to dd scattering, a $K\bar{K}$ production cross section which is expected to be $\sim$100 times larger, and the fact that admixtures of $I = 0$ components are forbidden by charge conservation. So far, in pp collisions the $a_0(980)$ production has been measured at $p_p = 450$ GeV/c *via* $f_1(1285) \to a_0^{\pm}\pi^{\mp}$

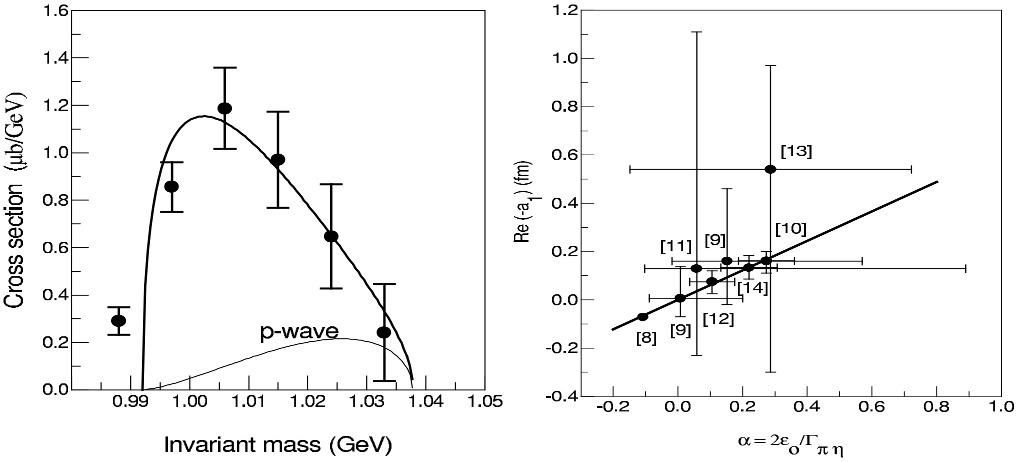

FIGURE 1. Left: $K^+\bar{K}^0$ mass distribution from the reaction $pp \to dK^+\bar{K}^0$ measured at an excitation energy of $Q = 48$ MeV with ANKE [18]. The solid line shows a fit to the data from which the imaginary part of the isovector $K\bar{K}$ scattering length has been determined [22]. Right: Plot of $Re(a_1)$ (filled circles) *vs.* the dimensionless parameter $\alpha = 2\varepsilon_0/\Gamma_{\pi\eta}$. The error bars show the errors introduced into α and $Re(a_1)$ by the uncertainties in the associated $a_0(980)$ mass values.

decays [15] and in inclusive measurements of the $pp \to dX^+$ reaction at $p_p = 3.8$, 4.5, and 6.3 GeV/c [16]. The best data so far on the $K\bar{K}_{I=1}$ decay mode of the a_0 have been obtained with Crystal Barrel at LEAR, with a mass resolution of $\delta(m_{K\bar{K}}) \approx$ 20 MeV [17].

A model-independent analysis of the ANKE angular distributions at $Q = 48$ MeV shows dominance of an s-wave between the two kaons accompanied by a p-wave deuteron with respect to the mesons. This has been interpreted as dominant production via the $a_0(980)$ channel near threshold [10, 18]. Model calculations of the reaction $pp \to dK^+\bar{K}^0$ performed by Grishina *et al.* [19] confirm this conclusion. In particular, the non-resonant (p-wave) $K^+\bar{K}^0$ production is shown to be small for excess energies Q less than $\sim$ 100 MeV.

In principle, the $dK^+\bar{K}^0$ final state is sensitive to three FSIs, dK^+, $d\bar{K}^0$ and $K^+\bar{K}^0$. The former is known to be small and can be neglected for the extraction of the latter two. The FSI in the $\bar{K}d$ system reduces the cross section, but leaves the invariant mass distributions virtually unaffected [19]. Sibirtsev *et al.* [20] have extracted limits for the $\bar{K}d$ scattering length from the ANKE data [18] and found $|\text{Re } a(\bar{K}d)| \leq 1.3$ fm, Im $a(\bar{K}d) \leq 1.3$ fm. A recent study [21] based on this formalism finds an optimal fit to the COSY data for a purely imaginary $d\bar{K}$ scattering length of $a_{d\bar{K}} = (0.0 + i1.0)$ fm.

The ANKE experiment has achieved a resolution of $1 - 8$ MeV for the invariant $K\bar{K}$ mass-spectrum (see Fig. 1) which is considerably better than in previous measurements. The relatively small influence of the antikaon-deuteron FSI on the shape of the measured invariant mass distributions as indicated in Refs. [19, 20, 21] allows one to determine the $K\bar{K}$ scattering length by a fit to the measured mass spectrum assuming that the deuteron's role is that of a spectator [22].

In Ref. [22] it has been assumed that $K^+\bar{K}^0$ production in $pp \to dK^+\bar{K}^0$ is dominated by FSI in the meson-meson channels only via the resonant intermediate mode $\pi^+\eta \to$

$a_0^+ \to K^+\bar{K}^0$. Then the cross section is proportional to the $I = 1$, $I_3 = +1$ cross section $\sigma(\pi^+\eta \to K^+\bar{K}^0)$ and the s- (p-)wave contributions to the cross section can be expressed as

$$\frac{\mathrm{d}\sigma^{(s)}}{\mathrm{d}m_{K\bar{K}}} = C_s \frac{k\Delta t}{p^2}[1 + 2Im(a_1)k] \quad \text{and} \quad \frac{\mathrm{d}\sigma^{(p)}}{\mathrm{d}m_{K\bar{K}}} \approx C_p \frac{k^3\Delta t}{p^2} \tag{1}$$

with overall normalizations $C_{s,p}$, and factors k, Δt and p which are given by the reaction kinematics. A fit to the data (solid lines in Fig. 1) yields for the imaginary part of the scattering length $Im(a_1) = -(0.61 \pm 0.05)$ fm at $\chi^2_{\text{min}} = 0.81$ [22].

The spectator model only fixes the imaginary part of the scattering length. In order to determine $Re(a_1)$ one has to introduce further assumptions regarding the structure of the $K\bar{K}$ scattering amplitude in the isovector channel. If one expresses the $a_0(980)$ mass distribution by the Flatté formula, there is a linear relation between the real and imaginary parts of the scattering lengths, $Re(a_1) = Im(a_1)\alpha$ with $\alpha = 2\varepsilon_{a_0}/\Gamma_{\pi\eta}$. ε_{a_0} is the binding energy M_{a_0} relative to the $K\bar{K}$ threshold and $\Gamma_{\pi\eta}$ the $a_0(980)$ partial decay width. If one takes $Im(a_1) = -0.61$ fm from the spectator model fit, this fixes the slope of the straight line in a $Re(a_1)$-*vs.*-α plot, see right hand side of Fig. 1. The result can then be compared with the values of $Re(a_1)$ and α extracted from data obtained at other experiments [8, 22]. This comparison is also shown in Fig. 1. The spectator model fit is seen to be consistent with all of the data once the uncertainties in α and hence $Re(a_1)$ due to the experimental error in the $a_0(980)$ mass are taken into account.

By assuming scale invariance of Flatté distributions [8], one can infer a value for α by calculating the mean of the α's shown in Fig. 1, $\alpha_c = 0.031 \pm 0.054$. Inserting this estimate one obtains $Re(a_1) = -(0.02 \pm 0.03)$ fm. The final result for the extracted isovector scattering length thus reads

$$a_1 = -[(0.02 \pm 0.03) + i(0.61 \pm 0.05)]\text{fm}\,. \tag{2}$$

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