Investigation of the neutral scalar mesons $a_0/f_0(980)$ in the reaction $dd \to \alpha\, K^+K^-$ with ANKE

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Abstract

We intend to study isospin violating processes in the $a_0/f_0(980)$-system by measuring the isospin forbidden reaction $dd \to \alpha\pi^0\eta$ with WASA. As a first step we propose to use ANKE for a measurement of the (isospin allowed) process $dd \to \alpha K^+K^-$. The estimated beam time needed to collect a few hundred (background free) events is four weeks.

Contents

1 Introduction

A primary goal of hadronic physics is to understand the structure of mesons and baryons, their production and decays, in terms of quarks and gluons. The non-perturbative character of the underlying theory — Quantum Chromo Dynamics (QCD) — hinders straight forward calculations. QCD can be treated explicitly in the low momentum-transfer regime using lattice techniques [1], which are, however, not yet in the status to make quantitative statements about light scalar states (J^P=0^+). Therefore, QCD inspired models, which use effective degrees of freedom, are to be used. The constituent quark model is one of the most successful in this respect (see e.g. Ref. [2]). This approach treats the lightest scalar resonances $a_0/f_0(980)$ as conventional $q\bar{q}$ states. However, they have also been described as $K\bar{K}$ molecules [3] or compact qq-$\bar{q}\bar{q}$ states [4]. It has even been suggested that at masses below 1.0 GeV/c^2 a full nonet of 4-quark states might exist [5]. Such possible deviations from the minimal quark model have a parallel in the baryon sector, where the recently found Θ^+ state requires at least five quarks.

The existing data are insufficient to conclude on the structure of the light scalars and additional observables are urgently called for. In this context the charge-symmetry breaking (CSB) a_0-f_0 mixing plays an exceptional role since it is sensitive to the overlap of the two wave functions. It should be stressed that, although predicted to be large long ago [6], this mixing has not been identified unambiguously in corresponding experiments.

2 Physics case

2.1 The isospin-violating reaction $dd \to \alpha\,\pi^0\eta$

Both the a_0^0- and the f_0-resonances can decay into K^+K^- and K_SK_S whereas in the non-strange sector the decays are into different final states according to their isospin, $a_0^\pm \to \pi^\pm\eta$, $a_0^0 \to \pi^0\eta$ and $f_0 \to \pi^0\pi^0$ or $\pi^+\pi^-$. Thus, only the non-strange decay channels have defined isospin and allow one to directly discriminate between the two mesons. It is also only by measuring the non-strange decay channels that CSB can be investigated. Such measurements have been identified as an important goal for the future physics program with WASA at COSY during a workshop in January 2004. A detailed proposal for WASA at COSY is being prepared and will be submitted to the next meeting of the COSY-PAC.

Since it is possible to manipulate the initial isospin of purely hadronic reactions one can identify observables that vanish in the absence of CSB [7, 8]. The idea behind the proposed experiments is the same as behind recent measurements of CSB effects in the reaction $dd \to \alpha\pi^0$ [9]. 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 as compared to CSB in the production operator (*i.e.* "direct" CSB violating $dd \to \alpha a_0$ production) and should give the dominant contribution to the CSB 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]. This reaction seems to be most promising for the extraction of CSB effects, since the initial deuterons and the α particle in the final state have isospin $I{=}0$ ("isospin filter"). Thus, any observation of $\pi^0\eta$ production in this particular channel is a direct indication of CSB and can give information about the a_0-f_0 mixing amplitude [10, 11].

In Ref. [6] it was demonstrated, that the leading piece of the a_0-f_0 mixing amplitude can be written as

$$\Lambda = \langle f_0|T|a_0\rangle = i g_{f_0K\bar{K}} g_{a_0K\bar{K}} \sqrt{s}\,(p_{K^0} - p_{K^+}) \; + \mathcal{O}\left(\frac{p_{K^0}^2 - p_{K^+}^2}{s}\right) , \qquad (1)$$

where the effective coupling constants are defined through $\Gamma_{xK\bar{K}} = g_{xK\bar{K}}^2 p_K$. Obviously, this leading contribution is just that of the unitarity cut of the diagrams shown in Fig. 1 and is therefore model independent. The contribution shown in Eq. (1) is unusually enhanced between the K^+K^- and the $\bar{K}^0K^0$ thresholds, a regime of only 8 MeV width. Here it scales as

$$\sqrt{\frac{m_{K^+}^2 - m_{K^0}^2}{m_{K^+}^2 + m_{K^0}^2}} \sim \sqrt{\frac{m_d - m_u}{(m_d + m_u)/2 + m_s}} , \qquad (2)$$

where m_u and m_d denote the current quark mass of the up and down quark respectively. This is in contrast to common CSB effects (*i.e.* occuring at the Lagrangian level) which scale as $(m_d - m_u)$, since they have to be analytic in the quark masses. It is easy to see that away from the kaon thresholds Λ returns to a value of natural size. This $\sqrt{s}$ dependence of Λ is depicted in Fig. 2. Note, in Eq. (1) electro magnetic effects were neglected for they are also subleading [6].

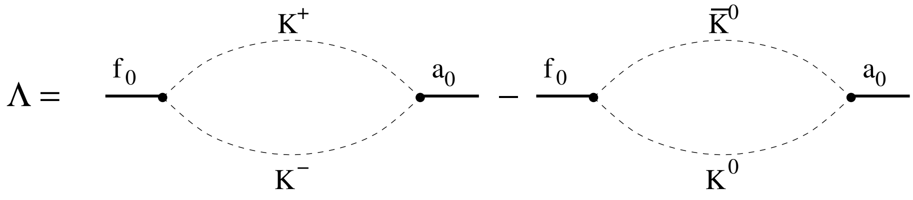

Figure 1: Graphical illustration of the leading contribution to the $a_0 - f_0$ mixing matrix element Λ, see Ref. [12] for details.

So far, little is known about the effective coupling of the f_0 to kaons. An accurate measurement of Λ therefore will strongly constrain $g_{f_0 K\bar{K}}$. It should be stressed that in the couplings of physical particles to mesons important information about the nature of that particle is contained [13], as was shown by Weinberg for the case of the deuteron [14].

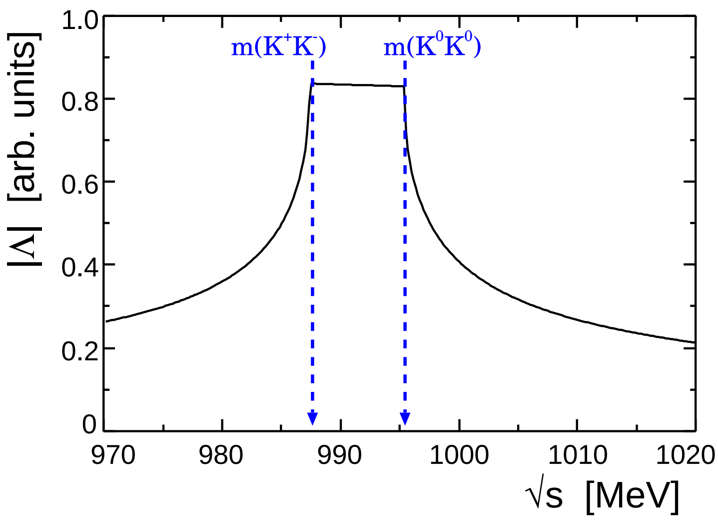

Figure 2: Modulus of the leading piece of the mixing amplitude Λ defined in Eq. (1). The two kinks occur at the K^+K^- (at 987.35 MeV) and the $\bar{K}^0 K^0$ (995.34 MeV) threshold respectively.

It is important to stress that a_0-f_0 mixing might have a significant impact also on the decay $\eta \to 3\pi$ and $\eta' \to 3\pi$ [15], however, in a very different kinematic regime compared to what we are looking at here. Thus one should expect that in addition to kaon loops also other CSB effects play a role. For a complete understanding of the a_0-f_0 mixing mechanisms knowledge about both kinematic regimes, that close to the resonance poles as well as that of the η decay, is necessary.

With recent papers by Close and Kirk [16, 17] the interest in a_0-f_0 mixing was revived. Based on an analysis of central pp collisions at high energy as well as radiative ϕ decays the authors extracted a mixing matrix element that was a factor of five larger than that given in Eq. (1) and independent of the invariant mass of the system produced. If confirmed, such a large mixing would indicate a completely different mechanism at work compared to what we believe in at present. Please note, that the work of Close and Kirk was heavily criticized in the literature [18, 19]. In any case, further experimental information is called for.

2.2 The reaction $dd \to \alpha K^+K^-$

2.2.1 A first step towards the measurement of isospin violating a_0-f_0 mixing

As was stressed in the previous section, the far end goal of our investigations is the extraction of the a_0-f_0 mixing matrix element from the reaction $dd \to \alpha\,\pi^0\eta$. It was argued that the reaction cross section is expected to be dominated by a primary reaction of the type $dd \to \alpha f_0$ followed by a $f_0 \to a_0$ conversion through the matrix element of interest. Therefore, the measured $dd \to \alpha\,\pi^0\eta$ cross section will be given by $|\Lambda|^2 \times \sigma_{tot}(dd \to \alpha\, f_0)$, where for simplicity we supress the additional complications due to the finite width of the f_0. Thus, if we want to extract from the experiment $|\Lambda|$ quantitatively, we will need some normalization reaction. For that purpose the reaction $dd \to \alpha\, K^+K^-$ is ideally suited.

In the analysis of the proposed experiment a partial wave decomposition will have to be performed in order to isolate the $\bar{K}K$ s-wave contribution that may be identified with f_0 production, for low energy kaon pairs in the S-wave will feel the strong $\bar{K}K$ interaction that stems from the existence fo the f_0 (note: isospin conservation forces the kaon pairs into the isoscalar state since for this reaction isospin violation should be supressed by about two orders of magnitude). A similar analysis has been performed for data from ANKE on the reaction $pp \to dK^+\bar{K}^0$, see Sect. 3.1. From this analysis the primary f_0 production amplitude can be determined which is later needed as input for the extraction of $|\Lambda|$. To make the latter step we need to assume that the production amplitude iteself is energy independent. This, however, should be justified in the close to threshold regime of relevance here.

A measurement of the reaction $dd \to \alpha\, K^+K^-$ with ANKE is also the ideal testing ground for the later measurements of the isospin violating process with WASA, which is accompanied by a smaller cross section. Valuable information about count rates and background processes will be obtained from the measurements proposed here.

2.2.2 An important by-product: αK^- final-state interaction

Recently, exotic nuclear systems involving a $\bar{K}$-meson as constituent were studied by Akaishi and Yamazaki [20]. They constructed a phenomenological $\bar{K}N$ potential which describes data on low energy $\bar{K}N$ scattering and kaonic hydrogen-atoms, and the decay width of the $\Lambda(1405)$. The potential is characterized by a strongly attractive I=0 contribution. This property of the Akaishi and Yamazaki potential is consistent with results obtained within the chiral SU(3) effective Lagrangian considered by Weise *et al.* [21]. Such a dynamics implies the existence of deeply bound $K^-\ {}^3$He and $K^-\alpha$ states [20]. In this respect it is important to the study low-energy $K^-\alpha$ interaction. Moreover, this topic is closely related to the in-medium strange hadron mass spectroscopy. A better knowledge of the kaon-baryon interaction in dense nuclear matter is important to understand the strangeness content of neutron stars (see *e.g.* Ref. [22]). Here we propose to exploit the sensitivity of the near-threshold differential $dd \to \alpha K^+K^-$ cross section to the $K^-\alpha$ final-state interaction (FSI).

It has been stressed in Ref. [23] that the reaction $NN \to d\bar{K}K$ should be sensitive to the $\bar{K}d$ FSI. In a recent paper [24] we have estimated the role of the S-wave $\bar{K}d$ FSI using the Foldy-Bruckner adiabatic approach based on the multiple scattering formalism. This method has been applied previously for the calculation of the enhancement factor for the reactions $pd \to {}^3\mathrm{He}\,\eta$ [25], and $pn \to d\eta$ [26]. In Fig. 3 we show the invariant mass distribution for the $d\bar{K}^0$ system in the reaction $pp \to dK^+\bar{K}^0$ at Q=46 MeV. The calculations have been performed within the Quark-Gluon Strings model and normalized to the integral cross section. The $\bar{K}N$ scattering lengths for the $I = 0, 1$ isospin channels a_0 and a_1 have been taken from Ref. [27]:

$$a_0 = (-1.59 + i\ 0.76)\,\mathrm{fm},\ \ a_1 = (0.26 + i\ 0.57)\,\mathrm{fm} \qquad (3)$$

With this so-called "K-matrix set", the $\bar{K}d$ scattering length was found to be

$$A_{\bar{K}d} = (-0.78 + i\ 1.23)\,\mathrm{fm}. \qquad (4)$$

It can be seen from the figure that the influence of the FSI on the shape of the invariant mass distribution is negligible.

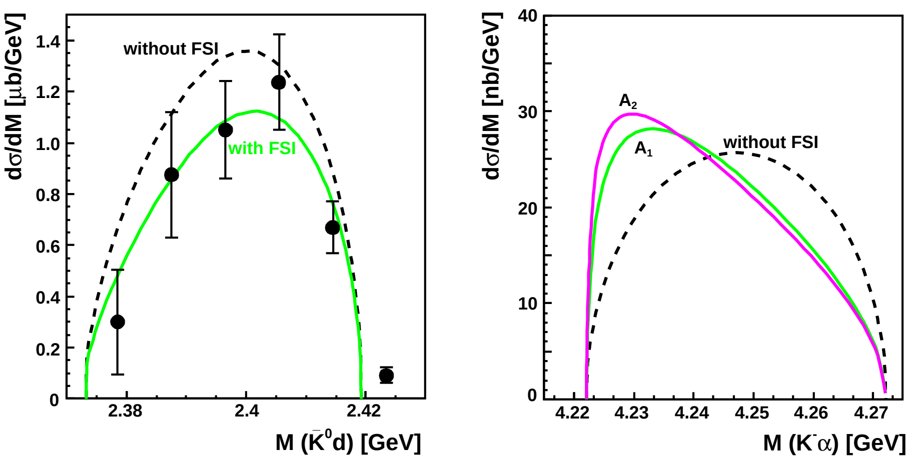

Figure 3: Left: Invariant $\bar{K}^0d$ mass distribution for the reaction $pp \to dK^+\bar{K}^0$ for Q=46 MeV measured at ANKE (see Sect. 3.1 for details). The dashed (solid) line corresponds to calculations without (with) the $\bar{K}d$ FSI (see text). Right: Invariant $K^-\alpha$ mass distribution calculated for the reaction $dd \to \alpha\,K^+K^-$ and Q=50 MeV. The dashed line indicates a pure phase-space distribution, whereas the result of our calculations using different values of the $K^-\alpha$ scattering length A (see text) are shown by the solid lines. All curves have been normalized to a total cross section of 1 nb.

Similar calculations on the $\bar{K}\alpha$ FSI effect have been made for the reaction $dd \to \alpha K^+K^-$. In the calculations the α particle is described by the dd:α

cluster function of Forest *et al.* [28]. This function has successfully been used by Gardestig and Wilkin [29] for the description of inclusive data from SATURNE on the reaction $dd \to \alpha X$ [30]. The shape of the the $dd{:}\alpha$ cluster function has been assumed to be Gaussian, $\exp(-\beta^2 r^2)$, with $\beta = 0.5$ fm^{-1} (which corresponds to the correct value of the α r.m.s. radius). The FSI effect on the invariant mass distribution of the $K^-\alpha$ system is shown in Fig. 3. The solid lines labeled by A_1 and A_2 correspond to the following values of the $\bar{K}\alpha$ scattering length (all values in fm):
"K-matrix set" for $a_{\bar{K}N}$ [27]:

$$A_1 = -1.39 + i\ 0.67,\ (A_{\bar{K}d} = -0.78 + i\ 1.23), \tag{5}$$

"CSL set" for $a_{\bar{K}N}$ [27]:

$$A_2 = -1.94 + i\ 1.25\ ,\ (A_{\bar{K}d} = -0.38 + i\ 2.15) \tag{6}$$

Note that the calculated invariant $\bar{K}^0 d$ mass distributions for the two sets practically coincide [24].

In contrast to the $\bar{K}^0 d$ case, the shapes of the $K^-\alpha$ mass distributions for the two choices of A are very different from the one calculated without FSI. Thus the $dd \to \alpha\, K^+K^-$ reaction is comparably sensitive to $\bar{K}N$ FSI effects. If we devide the full invariant mass interval into 5 bins of 10 MeV each, then the largest FSI enhancement will be in the first bin. The fractions of the integrated cross sections in this bin are equal to 0.13 without FSI, 0.215 for A_1 and 0.25 for A_2. Therefore, the enhancement factor in the first bin will be 1.65 and 1.9 for A_1 and A_2, respectively. The main aim of the experiment will be to distinguish between the phase-space distrubution and curve A_1 which has been calculated for the standard values of the $\bar{K}N$ scattering length ("K matrix set" [27]).

2.3 The reaction $dd \to \alpha\,\pi^+\pi^-$

The reaction $dd \to \alpha\pi^+\pi^-$ provides an interesting tool to study mesons with isospin I=0 since the two pions are produced in a pure isoscalar state. From a first experimental study of the inclusive reaction $dd \to \alpha X$ for $p_d = 1.89 - 3.82$ GeV/c performed at SATURNE [30] it has been concluded that the strong variation of the cross section with energy is essentially due to the ABC effect. However, at $p_{\rm lab} \geq 3.3$ GeV/c and missing masses $M_X \geq 0.5$ GeV this effect disappears. The characteristics of the ABC effect were explained in Refs. [29, 31] using a model with two parallel $NN \to d\pi$ and $NN \to d\pi\pi$ reactions. It was demonstrated that at $p_{\rm lab} \simeq 2.8$ GeV/c two pion production is already small and the main contribution to the inclusive reaction $dd \to \alpha X$ comes from four pion production. Therefore one may expect that for the mising mass region around 0.9–1.0 GeV the main background to f_0 production will be from the four pion channel. This property of the reaction $dd \to \alpha\pi^+\pi^-$ can be used to separate an f_0 signal from the background because the f_0 decays mainly to two pions. The cross section for f_0 production in the reaction $dd \to \alpha f_0 \to \alpha\pi^+\pi^-$ might be similar to the cross section of the ω production, *i.e.* 4–8 nb (see Appendix). However, in Sect. 4.3 it is shown that the expected count rates are too low for, *e.g.*, partial waves analyses. Therefore, the measurement of the reaction $dd \to \alpha\,\pi^+\pi^-$ is not regarded as a strong motivation for the present proposal.

3 Experience in a_0/f_0-production at ANKE

3.1 The reaction $pp \to dK^+\bar{K}^0$

Investigation of a_0^+-production in pp reactions has been the goal of two ANKE beam times in the beginning of 2001 and 2002, respectively. The reaction $pp \to dK^+\bar{K}^0$ has been measured exclusively (by reconstructing the $\bar{K}^0$ from the measured dK^+ missing mass) at beam momenta of p=3.46 and 3.65 GeV/c, corresponding to excess energies Q=46 and 103 MeV above the $K\bar{K}$ threshold. These measurements crucially depend on the high luminosities achievable with the ANKE cluster-jet target, the large acceptance of ANKE for close-to-threshold reactions, and the excellent kaon identification with the ANKE detectors. The obtained differential spectra for the lower beam momentum are shown in Fig. 4 [32].

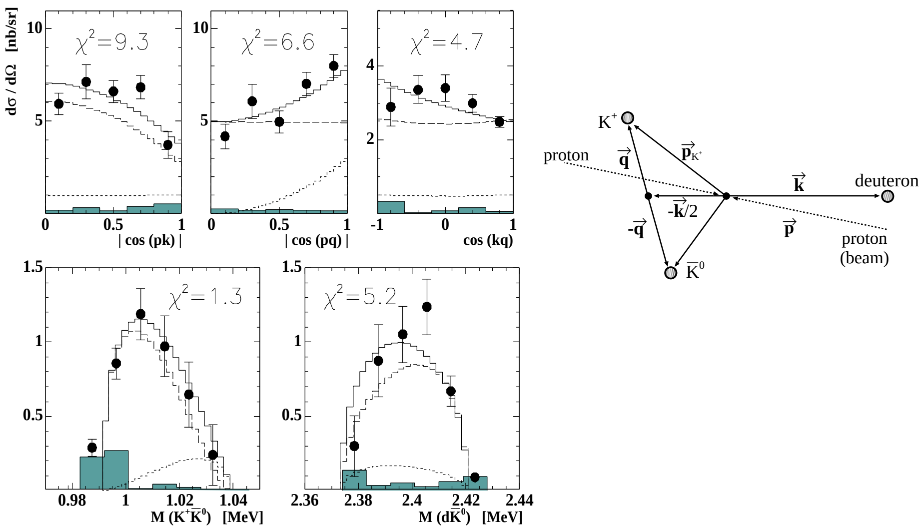

Figure 4: ANKE data for the reaction $p(3.46\,\mathrm{GeV/c})p \to dK^+\bar{K}^0$ [32]. The shaded areas correspond to the systematic uncertainties of the acceptance correction. The dashed (dotted) line corresponds to $K^+\bar{K}^0$-production in a relative S-(P-) wave and the solid line is the sum of both contributions. For definition of the vectors p, q and k in the cms of the reaction $pp \to dK^+\bar{K}^0$ see right hand part of the figure. Angular distributions with respect to the beam direction $\vec{p}$ have to be symmetric around 90° since the two protons in the entrance channel are indistinguishable.

The background of misidentified events in the spectra of Fig. 4 is less than 10% which is crucial for the partial-wave analysis. This analysis reveals that the $K^+\bar{K}^0$ pairs are mainly (83%) produced in a relative S-wave (dashed line in Fig. 4), which has been interpreted in terms of dominant a_0^+-resonance production [32, 24]. Based on these data, which are in line with our model predictions for the total a_0/f_0-production cross sections in different initial isospin configurations [33], it is concluded that the production cross section for the light scalar resonances in hadronic interactions is sufficiently large to permit systematic studies at COSY (during our first beam time $\sim$1000 events have been collected within five days of beam time using a hydrogen target providing an average luminosity of $\mathcal{L} = 2.7 \cdot 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$).

The data for the higher beam momentum (Q=103 MeV) are still being analyzed. Figure 5 shows the preliminary invariant $K^+\bar{K}^0$-mass distribution from ANKE which reveals the significantly larger accessible mass range. Final results — like the spectra shown in Fig. 4 — will be available soon. Also shown in Fig. 5 is our prediction [24] for the invariant mass distribution which shows that also at the higher beam momentum $K^+\bar{K}^0$-production via the a_0^+-channel should dominate.

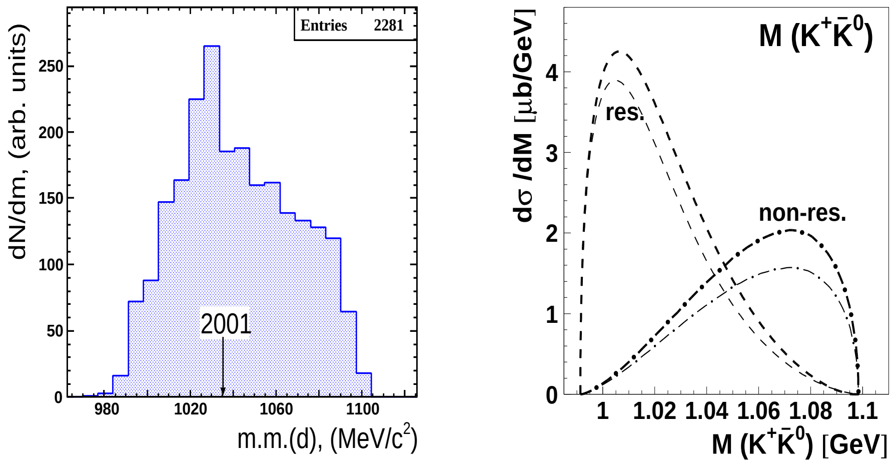

Figure 5: Left: Preliminary ANKE data (without acceptance correction) for the reaction $pp \to dK^+\bar{K}^0$ at $p = 3.65$ GeV/c, cf. lower left spectrum in Fig. 4. Right: Predicted mass distributions for resonant (via the a_0^+) and non-resonant (two kaons in a relative P-wave) $K^+\bar{K}^0$-production [24]. The thin (thick) lines show the result of our calculations (not) taking into account the $\bar{K}d$ final-state interaction.

3.2 The reactions $pn \to dK^+K^-$ and $pp \to ppK^+K^-$

The production of the neutral scalar mesons a_0^0/f_0 has been investigated in a recent ANKE beam time (Feb. 2004) where the reaction $pn \to dK^+K^-$ has been measured at a beam momentum of p=3.46 GeV/c. For these measurements the cluster-jet target has been operated with D_2 as target material. Figure 6 shows a very preliminary K^+K^- invariant mass spectrum for this reaction. While at low masses the spectrum should be dominated by the decays $a_0/f_0 \to K^+K^-$ [33], the pronounced peak around $m_{K^+K^-} = 1020$ MeV marks the first measurement of the reaction $pn \to d\phi \to dK^+K^-$ as a "by-product" of this experiment. According to a rough extimate, in total 4000–5000 background free $pn \to dK^+K^-$ events have been identified during ~ 3 weeks of beam time.

K^+K^--pair production has also been measured at ANKE in April 2002 and Jan. 2004 for the reaction $pp \to ppK^+K^-$. These data are still being analyzed, however, according to our model calculations [33] it is expected that K^+K^- production via the a_0^0/f_0 channel (*i.e.* kaons in a relative S-wave) is significantly smaller than in case of the pn reaction.

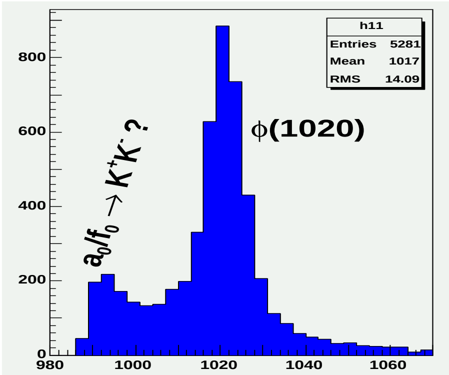

Figure 6: Very preliminary ANKE data (without acceptance correction) for the reaction $p(3.65\,\mathrm{GeV/c})n \to dK^+K^-$, cf. lower left spectrum in Fig. 4.

4 Measurement of the reaction $dd \to \alpha K^+K^-$

We propose to measure the production of the f_0-resonance in the reaction $dd \to \alpha K^+K^-$ at an excess energy roughly similar to the one of our first a_0^+ beam time, *i.e.* $Q \sim 46$ MeV. For the $dd \to \alpha X$ reaction this corresponds to a beam momentum of $p_d \sim 3.7$ GeV, thus slightly higher than the proton beam momentum of the second a_0^+ experiment. This beam momentum has already been reached with COSY and been used during the recent ANKE beam time on Θ^+ production.

The invariant mass and angular resolutions for the proposed measurements will be comparable to our $pp \to dK^+\bar{K}^0$ experiment (Fig. 4), where the following values have been achieved: $\delta m_{K^+\bar{K}^0}$=(8−1) MeV/c^2 in the range (0.991−1.038) GeV/c^2 and $\delta m_{d\bar{K}^0} \sim 3\,\mathrm{MeV/c^2}$ in the full mass range (FWHM values).

4.1 Detection of $dd \to \alpha K^+K^-$ ($\pi^+\pi^-$) events with ANKE

The $dd \to \alpha K^+K^-$ events can be identified at ANKE by detecting all three final particles in coincidence, see Fig. 7. However, we argue in the following that it will be sufficient to carry out a (αK^+) coincidence measurement which has the advantage of ~ 5 times higher count rates.

A similar detection scheme has already been applied for the $pp \to dK^+\bar{K}^0$ measurements where coincident (dK^+) pairs have been detected and the missing anti-kaon has been reconstructed by a missing-mass criterion. This is illustrated in Fig. 8 where we show the time difference for the detection of the kaon and the deuteron as a function of the deuteron (or background proton) momentum. The selection criterion indicated by the dashed lines allows one to, almost background free, identify the $pp \to dK^+\bar{K}^0$ events which are produced with a total cross section of $(38\pm2_{\mathrm{stat}}\pm14_{\mathrm{syst}})$ nb.

Identification of α particles at ANKE has been achieved inclusively in an experiment aiming at the investigation of η-meson production in $dd \to \alpha X$ reactions. Like in the measurements proposed here the α particles have been detected in the ANKE forward detectors (see Fig. 7) consisting of three layers of scintillators and MWPC's for particle tracking. After exploiting the informa-

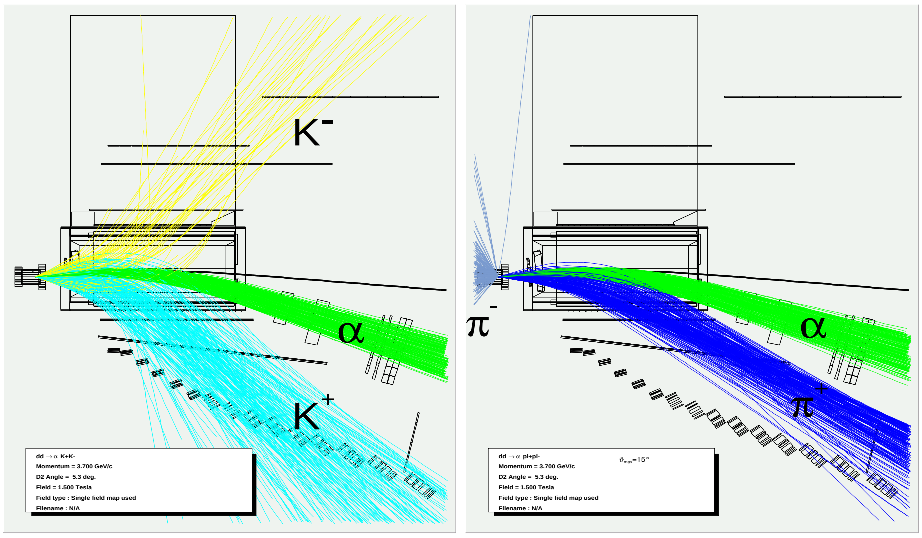

Figure 7: Simulated trajectories of particles from the reactions $dd \to \alpha\, K^+K^-$ (left) and $dd \to \alpha\, \pi^+\pi^-$ (right) in ANKE. Detection of the K^--mesons is not required for a clean event identification, whereas negatively charged pions are emitted in backward direction in the lab and cannot be detected with ANKE. The geometrical acceptances (including decay-in-flight) amount to $\epsilon_{\alpha K^+} = 10\%$ and $\epsilon_{\alpha\pi^+} = 0.21\%$.

tion on energy losses in all three scintillator planes as well as the time-of-flight between them, a clean α identification has been achieved, see lowest histogram in the right spectrum of Fig. 8.

According to our cross section estimate given in the Appendix, we expect $\sigma_{\rm tot}(dd \to \alpha K^+K^-) \sim 0.4$ nb, *i.e.* roughly 100 times smaller than $\sigma_{\rm tot}(pp \to dK^+\bar{K}^0)$. Taking into account the excellent background suppression for the (dK^+) case together with the significantly better α identification, as compared to deuterons, it is concluded that a (αK^+) coincidence measurement will suffiently suppress the background from other reaction channels.

The (isospin allowed) decay $f_0 \to \pi\pi$ has a significantly larger Q value as compared to $f_0 \to K\bar{K}$. Thus the angular distributions get wider and the acceptance $\epsilon_{\alpha\pi^+}$ of ANKE (being a forward spectrometer) drops. Furthermore, if one of the pions is within the acceptance of ANKE, the second one will be emitted in backward direction and cannot be observed, see Fig. 7. The reaction $dd \to \alpha\, \pi^+\pi^-$ therefore has to be identified by a $(\alpha\pi^+)$ missing-mass criterion. The mass resolution of ANKE is sufficient to discriminate against 3- or multi-pion production.

4.2 Luminosity determination

Absolute cross sections will be obtained by normalizing the data to the number of detected $dd \to \alpha X$ events which will be measured in parallel. The corresponding inclusive double differential cross sections are known from the experiment at SATURNE [30] for beam momenta $p_d = 3.66$ and 3.82 GeV/c, a wide range

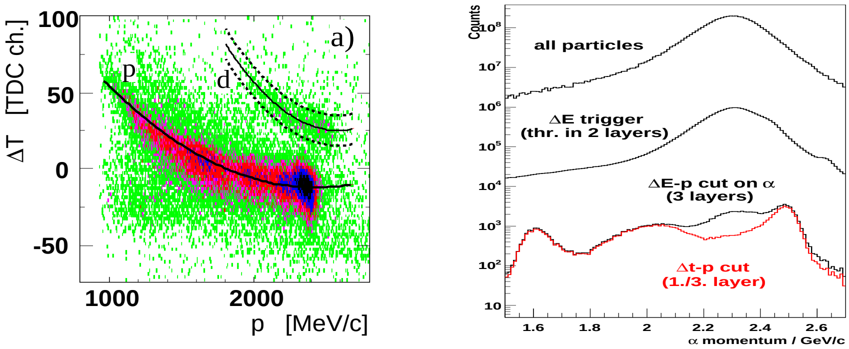

Figure 8: Left: Identification of deuterons from the reaction $pp \to dK^+X$ at p=3.46 GeV/c with a time-of-flight vs. momentum criterion [32]. Right: Inclusive momentum spectra of particles from dd interactions at $p_d = 2.345$ GeV/c measured in the ANKE forward detector. The red distribution depicts the momentum distribution of α particles from the reaction $dd \to \alpha X$ after cuts on energy loss and time-of-flight [34].

of deuteron momenta $p_d \sim 1.95 - 2.6$ GeV/c and emission angles $\vartheta_d^{\mathrm{lab}} = 0.3°$. The values for $\mathrm{d}^2\sigma/\mathrm{d}p\mathrm{d}\Omega_{dd\to\alpha X}$ are in the range $0.1 - 1.2\,\mu$b/(sr GeV/c) with statistical uncertainties of about 5% and an overall systematic error of 15%. It can thus be expected that in our experiment absolute cross sections can be determined with an uncertainty of about 20%.

4.3 Rate and beam-time estimate

Based on the experience from the previous ANKE beam times a D_2 target density of $\rho \sim 1 \cdot 10^{14}\,\mathrm{cm}^{-2}$ and a COSY beam intensity of $n_d \sim 5 \cdot 10^{10}$ in flat top can be expected. This leads to a luminosity of $\mathcal{L} = 7.4 \cdot 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Together with the geometrical acceptance $\epsilon_{\alpha K^+}$ ($\epsilon_{\alpha\pi^+}$) of ANKE and taking into account a reduction of the useful luminosity due to detection efficiencies and dead-time effects the estimated rate for the detection of $dd \to \alpha\, K^+K^-$ ($\pi^+\pi^-$) events is:

$$\dot{n}_{\alpha K^+} = \mathcal{L}_{\mathrm{eff}} \cdot \sigma \cdot \epsilon_{\alpha K^+} \sim 5 \cdot 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \cdot 0.4\,\mathrm{nb} \cdot 10\% \sim 2 \cdot 10^{-4}\,\mathrm{s}^{-1} \sim 17\,\mathrm{d}^{-1} \quad (7)$$

and

$$\dot{n}_{\alpha\pi^+} = \mathcal{L}_{\mathrm{eff}} \cdot \sigma \cdot \epsilon_{\alpha\pi^+} \sim 5 \cdot 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \cdot 2\,\mathrm{nb} \cdot 10\% \sim 2.1 \cdot 10^{-5}\,\mathrm{s}^{-1} \sim 2\,\mathrm{d}^{-1} \quad (8)$$

Thus, within one week of beam time about 120 (15) events can be collected.

As outlined in Sect. 2.2.1 the extraction of the total $dd \to \alpha\, f_0$ cross section from the detected $dd \to \alpha\, K^+K^-$ events requires a partial wave analysis like the one shown in Fig. 4 for the $pp \to dK^+\bar{K}^0$ channel. Such an analysis requires at least ~ 500 events which can be collected within four weeks of beam time. The same number of events will also be needed to observe the effect of the $K^-\alpha$ FSI presented in Fig. 3.

Whereas for the K^+K^- channel the clean background conditions together with the comparably large number of events will allow one to construct differential mass and angular spectra, for the pion channel the situation seems questionable. Due to the rather large expected width of the f_0 resonance (few 10 MeV in the $K\bar{K}$ decay channel) it might be difficult to discriminate an $f_0 \to \pi^+\pi^-$ signal against the background of 2π production from other sources [29, 31]. However, as it has been argued in Sect. 2.3, a possible background of two pion production might be significantly smaller than the f_0 signal. As a consequence, one should only expect a rough estimate for the total $dd \to \alpha\, f_0 \to \alpha\, \pi^+\pi^-$ cross section from the proposed measurements. However, such an estimate could be useful for the preparation of a high-statistics experiment with WASA at COSY.

5 Beam-time request

Summarizing, we apply for **four weeks** of beam time to study the reaction $dd \to \alpha\, K^+K^-$ (and, possibly, $dd \to \alpha\, \pi^+\pi^-$) at maximum COSY momentum (p = 3.7 GeV/c, unpolarized and uncooled beam). It is expected that $\sim$ 500 kaon pairs can be identified by the detection of a K^+ in coincidence with the α particle. For the development of the deuteron beam at maximum COSY energy additional two days of machine development time have to be foreseen. The measurements should be scheduled in one block with the requested ANKE beam times on the reactions $dp \to {}^3\mathrm{He}\,\eta$ (two weeks) and $dd \to {}^3\mathrm{He}\,N\pi/{}^3\mathrm{H}\,N\pi$ (two weeks) plus one week of machine development and detector tuning before these measurements. Since this experiment requires maximum COSY momentum it must be scheduled in winter 2004/05.

6 Concluding remarks

The proposed measurements will finalize the ANKE experimental program on scalar mesons decaying into kaon-antikaon pairs:

$pp \to dK^+\bar{K}^0$ at p=3.46 GeV/c: 2 weeks of beam time requested/2 weeks granted by PAC/Measurements in Jan. 2001/Results published in: V. Kleber et al., *Phys. Rev. Lett.* **91** 172304 (2003).

$pp \to dK^+\bar{K}^0$ at p=3.65 GeV/c: 3 weeks/3 weeks/Jan. 2002/Analysis almost finalized.

$pn \to dK^+K^-$ at p=3.46 GeV/c: 3 weeks/3 weeks/Feb. 2004/Analysis in progress.

$dd \to \alpha\, K^+K^-$ at p=3.70 GeV/c: 4 weeks/?/Winter 2004/05?.

The next and final set of measurements on scalar mesons will be performed with WASA. It is planned to measure the decay channels $a_0 \to \pi\eta$ and $f_0 \to \pi\pi$ for the above listed initial isospin configurations.

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Appendix: Cross section estimates

The following two articles have been taken from the IKP Annual Reports 2002 and 2003, respectively.

$a_0(980)$ production in the reaction $dd \to {}^4\text{He}\ a_0^0$ and $a_0(980)$-$f_0(980)$ mixing*

M. Büscher, V. Yu. Grishina[a,b], V. Kleber, L.A. Kondratyuk[b], V. Koptev[c] and H. Ströher

It is known (see e.g. Ref. [1]) that the coupling of the $a_0(980)$- and $f_0(980)$-resonances to the $K\bar{K}$ continuum may lead to $a_0(980)$-$f_0(980)$ mixing. As it was noted by Close and Kirk [2] the data from the WA102 collaboration at CERN [3] on central f_0 and a_0 production in the reaction $pp \to p_s X p_f$ provide evidence for a significant f_0-a_0 mixing intensity as large as $|\xi|^2 = 8 \pm 3\%$. In Ref. [4] we have discussed the effects of isospin violation in the reactions $pN \to da_0$, $pn \to df_0$, $pd \to {}^3\text{He}/{}^3\text{H}\, a_0$ and $dd \to {}^4\text{He}\, a_0^0$ which can be induced by f_0-a_0 mixing. It has been demonstrated that for a mixing intensity of about $(8 \pm 3)\%$, the effect of isospin violation in the ratio of the differential cross sections of the reactions $pp \to da_0^+ \to d\pi^+\eta$ and $pn \to da_0^0 \to d\pi^0\eta$ as well as in the forward-backward asymmetry in the reaction $pn \to da_0^0 \to d\pi^0\eta$ not far from threshold may be about 50–100%. A similar isospin violation is expected in the ratio of the differential cross sections of the reactions $pd \to {}^3\text{H}\, a_0^+(\pi^+\eta)$ and $pd \to {}^3\text{He}\, a_0^0(\pi^0\eta)$.

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

$$\sigma(dd \to {}^4\text{He}\, a_0^0) = |\xi|^2 \cdot \sigma(dd \to {}^4\text{He}\, f_0). \qquad (1)$$

Therefore it is very interesting to study the reaction

$$dd \to {}^4\text{He}\,(\pi^0\ \eta) \qquad (2)$$

at $m_{\pi\eta}^2 \sim (980\text{MeV})^2$. Any signal of reaction (2) can 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 $\sigma(dd \to {}^4\text{He}\, a_0^0)$ and $\sigma(dd \to {}^4\text{He}\, f_0)$. Experimental data are not available yet and we try to give a qualitative estimate of these cross sections.

According to Refs. [5, 6, 7], the cross-section ratio $\sigma(dd \to {}^4\text{He}\,\eta)/\sigma(dd \to {}^3\text{He}\,\eta)$ is about 0.04 at $Q \simeq 10$ MeV. We assume an approximately equal ratio for the case of K^+K^- production near the threshold:

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

Using the MOMO data [8] on the reaction $pd \to {}^3\text{He}\, K^+K^-$ we find:

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

at $Q = 40$ MeV. The MOMO collaboration notes that their invariant K^+K^- mass distributions contain a broad peak which follows phase space. However, as it was shown for the case of the a_0 resonance in Ref. [9], the shape of the invariant mass spectrum following phase space cannot be distinguished from resonance production at $Q \le \Gamma \le 70$ MeV.

Therefore the broad mass distribution of the MOMO data may also be related to the f_0. This statement is supported by the two-step model where the amplitude of the reaction $pd \to {}^3\text{He}\ f_0$ can be constructed from the subprocesses $pp \to d\pi^+$ and $\pi^+ n \to p\ f_0$ (cf. Refs. [10, 11]). As it is known from the available experimental data [12] the cross section of the reaction $\pi N \to NK\bar{K}$ 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 $pd \to {}^3\text{He}\ f_0 \to {}^3\text{He}\ K^+K^-$ near threshold is expected to be not essentially smaller than its upper limit from MOMO of about $10 \div 20$ nb at $Q = 40 \div 60$ MeV.

For an estimate of $\sigma(dd \to {}^4\text{He}\ \pi^+\pi^-)$ at $m_{\pi\pi} \sim m_{f_0}$ we assume that the cross section $\sigma(dd \to {}^4\text{He}\ K^+K^-)$ is also dominated by the resonant f_0 contribution at $m_{K\bar{K}} \sim m_{f_0}$, and that $\Gamma_{f_0 \to K\bar{K}} = (0.1 \div 0.4) \cdot \Gamma_{f_0 \to \pi\pi}$ [13]. This yields:

$$\sigma(dd \to {}^4\text{He}\ f_0 \to {}^4\text{He}\,\pi^+\pi^-) = 1 \div 4\ \text{nb}\ . \qquad (5)$$

Finally, using Eq.(1), we get for $|\xi|^2$=0.05:

$$\sigma(dd \to {}^4\text{He}\, a_0^0) \simeq 0.05 \div 0.2\ \text{nb}. \qquad (6)$$

The measurement of reactions (4) and (5) with cross sections in the sub-nb range are possible at the ANKE spectrometer (see Ref. [14]).

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$f_0(980)$ and $a_0(980)$ Production in the Reaction $dd \to {}^4$HeX (*

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

$$\sigma(dd \to {}^4\mathrm{He\,a_0^0}) = |\xi|^2 \cdot \sigma(\mathrm{dd} \to {}^4\mathrm{He\,f_0}) \ , \qquad (1)$$

where $|\xi|^2$ is the f_0-a_0 mixing intensity. Therefore it is very interesting to study the reaction $dd \to {}^4\mathrm{He}\,(\pi^0\ \eta)$ at $m^2_{\pi\eta} \sim (980\mathrm{MeV})^2$. Any signal of this reaction 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 $\sigma(dd \to {}^4\mathrm{He}\,a_0^0)$ and $\sigma(dd \to {}^4\mathrm{He}\,f_0)$. Experimental data are not available yet. In Ref. [1] a qualitative estimate of these cross sections was given based on an assumption on the similarity of the cross-section ratios $\sigma(dd \to {}^4\mathrm{He}\,K^+K^-)/\sigma(pd \to {}^3\mathrm{He}\,K^+K^-)$ and $\sigma(dd \to {}^4\mathrm{He}\,\eta)/\sigma(pd \to {}^3\mathrm{He}\,\eta)$. Here we present another estimate by comparing the production of f_0- and ω-mesons in the reactions $dd \to \alpha X$ and $pn \to dX$.

The binary reaction $d_1d_2 \to \alpha X$ proceeds via two-nucleon exchange. We can write the corresponding matrix element as a convolution of two amplitudes, where each amplitude can be described by the one-nucleon exchange. Moreover we consider Reggeized nucleon exchanges. Then we have

$$A^{d_1d_2\to\alpha X}(s, \mathbf{q}_\perp) = \frac{i}{8\pi^2 s}\int d^2\mathbf{k}_\perp\ T_1(s,\mathbf{k}_\perp)\,T_2(s,\mathbf{q}_\perp - \mathbf{k}_\perp)\,, \qquad (2)$$

with

$$T_j(s,t) = F_j(t)\left(\frac{s}{s_{0j}}\right)^{\alpha_N(t)} \times \exp\left[-i\,\frac{\pi}{2}\left(\alpha_N(t) - \frac{1}{2}\right)\right],$$

where $\sqrt{s}$ is the total c.m. energy and t is the squared 4-momentum transfer. Here we indroduced the two amplitudes $T_1 = T(d_1d_2 \to He^3n)$, $T_2 = T(He^3n \to \alpha X)$. It is also useful to define $T_3 = T(pn \to dX)$. All these amplitudes are described by the nucleon Reggeon exchange; $\alpha_N(t)$ is the nucleon Regge trajectory. The residues of the nucleon Regge trajectory for all the reactions considered can be written in the factorized form: $F_1 \sim g_{d_1He^3N_{R1}}g_{d_2nN_{R1}}$, $F_2 \sim g_{He^3\alpha N_{R2}}g_{XnN_{R2}}$, $F_3 \sim g_{XpN_R}g_{dnN_R}$. Due to this factorization the following relations are satisfied

$$\frac{|T(d_1d_2 \to \alpha f_0)|^2}{|T(d_1d_2 \to \alpha\omega)|^2} = \frac{|T(pn \to df_0)|^2}{|T(pn \to d\omega)|^2} = R(f_0/\omega) = \frac{|g_{f_0nN_R}|^2}{|g_{\omega nN_R}|^2}. \qquad (3)$$

Of course the ratio R might depend on kinematical variables like energy and momentum transfer. To minimize this dependence we take all amplitudes (or corresponding cross sections) at the same c.m. energy release Q.

Recent measurements at ANKE [2] gave $\sigma(pn \to d\omega) = (8.6\pm1.5)\mu$b at $Q = (60\pm18)$ MeV. The cross section for f_0 production in the reaction $pn \to df_0$ was calculated in Ref. [3] as $\sigma(pn \to df_0) = 4 \div 8\ \mu$b at the same Q value (see Fig. 1). Therefore, we have $R = 0.5 \div 1$ at $Q = 40 \div 80$ MeV. The forward differential cross section for the reaction $dd \to \alpha\omega$ has been measured at Saclay [4]: $d\sigma/d\Omega = (1 \pm 0.28)$ nb/sr at 3.32 GeV/c ($Q = 110$ MeV). Assuming angular isotropy we find $\sigma(dd \to \alpha\omega) \simeq (12 \pm 3.5)$ nb at $Q = 110$ MeV. Taking the ratio $R \simeq 1$ at $Q = 110$ MeV we finally get

$$\sigma(dd \to \alpha f_0) \simeq \sigma_0\sqrt{Q/Q_0}, \qquad (4)$$

where $\sigma_0 = (9 \div 15)$ nb and $Q_0 = 110$ MeV. This estimate is by a factor of 3÷5 larger than one presented in Ref.[1].

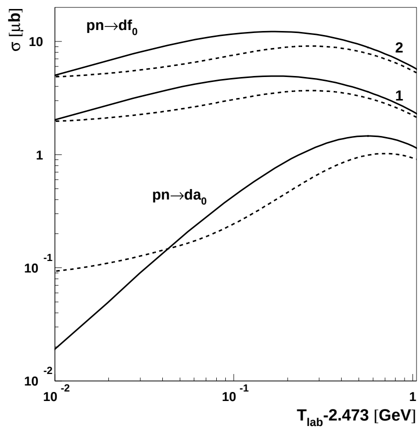

Fig. 1: Total cross sections for the reactions $pn \to da_0$ and $pn \to df_0$. The solid and dashed curves are calculated using narrow and finite resonance widths, respectively. The curves denoted by 1 and 2 correspond to different choices of the f_0NN and a_0NN coupling constants (see [3]).

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