

Determination of the $\bar{K}^0d$ scattering length from the reaction $pp \rightarrow d\bar{K}^0K^+$

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The real and imaginary parts of the $\bar{K}^0d$ scattering length are extracted from the $\bar{K}^0d$ mass spectrum obtained from the reaction $pp \rightarrow d\bar{K}^0K^+$ measured recently at the Cooler Synchrotron COSY at Jülich. We extract a new limit on the K^-d scattering length, namely $\text{Im } a \leq 1.3$ fm and $|\text{Re } a| \leq 1.3$ fm. The limit for the imaginary part of the K^-d scattering length is supported by data on the total K^-d cross sections.

During the last two decades the physics of the low-energy $\bar{K}N$ and $\bar{K}A$ interactions has gained substantial interest. A well-known K -matrix analysis [1] of the available K^-N data led to the conclusion that the real part of the s -wave K^-p scattering length is repulsive, $\text{Re } a_{K^-p} = -0.7$ fm, while the real part of the K^-n scattering length is attractive, $\text{Re } a_{K^-n} = 0.37$ fm. In a recent KEK experiment the strong interaction shift of the kaonic hydrogen atom $1s$ state was found to be repulsive [2], corresponding to a negative K^-p scattering length. The first results for kaonic hydrogen from the DEAR experiment also indicate a repulsive shift [3]. However, at the same time there are no direct experimental results available for the K^-n scattering length. From a theoretical point of view it is natural to expect that the K^-N interaction, averaged over proton and neutron targets, is attractive. One of the fundamental reasons for this expectation is given by the leading order term in the chiral expansion for the K^-N channel which appears to be attractive (in contrast to the isoscalar pion-nucleon scattering amplitude). In fact it is possible to have a negative scattering length $\text{Re } a_{K^-p}$ for the attractive $\bar{K}N$ interaction if the $\Lambda(1405)$ resonance is

a bound state of $\bar{K}N$ system [4,5]. Such a peculiar dynamics of the elementary $\bar{K}N$ interaction implies non-trivial properties of anti-kaons in finite nuclei and dense nuclear matter, including neutron stars, see e.g. Refs. [6,7,8,9] (and references therein). A renewed interest in physics with low-energy kaons was initiated by substantial progress in effective low energy hadronic methods, in particular by approaches based on extensions of chiral perturbation theory, for early reviews see Refs. [10,11,12,13]. The coupled channel dynamics of the $\bar{K}N$ interaction based on tree level chiral Lagrangians was developed in order to describe low-energy scattering data [14,15,16] and giving further support to the description of the $\Lambda(1405)$ as a meson-baryon bound state (a new twist on this story was given in Ref. [17], where the two-pole structure of this state was investigated). However, it was shown recently [18] that a reliable extraction of the elementary $\bar{K}N$ scattering length from such type of approach requires an explicit matching of the amplitudes generated from the coupled channel dynamics to the ones given from chiral perturbation theory [19]. This matching can even be done in some unphysical region of the corresponding Mandelstam plane. If

this is not done, the calculations result in very large K^-p and K^-n scattering lengths, which contradict the experimental results [1] and might stem from the implicit violation of chiral symmetry. Therefore, new and more exact experimental results on K^-p and K^-n scattering are necessary in order to obtain reliable constraints on the K^-N dynamics and to gain a better understanding of the description of SU(3) chiral symmetry breaking. The measurement of the K^-d scattering length is one of the main goals of the SIDHARTA experiment at DAΦNE [20]. In [18] the precise relation between the energy-shift in kaonic hydrogen and the appropriate scattering lengths combination is worked out.

In this paper we show that constraints on the $\bar{K}d$ scattering length can be obtained through an analysis of the $\bar{K}^0d$ final-state interaction (FSI) in the reaction $pp \rightarrow d\bar{K}^0K^+$ near threshold measured very recently at COSY [21]. Theoretical analyses of the reaction $pp \rightarrow \bar{K}^0dK^+$ near threshold have been performed in Refs. [22,23,24,25,26,27]. As has been stressed in Ref. [23], the $NN \rightarrow d\bar{K}K$ reaction should be sensitive to the $\bar{K}d$ FSI. Thus one can expect that the experimental results on the $pp \rightarrow d\bar{K}^0K^+$ reaction may provide a new way to extract the $\bar{K}^0d$ scattering length.

In this paper we focus on the potential influence of the $\bar{K}d$ interaction on the observables for the process $pp \rightarrow d\bar{K}^0K^+$. The effect of the $\bar{K}K$ s -wave interaction can be investigated via the inclusion of a Flatté distribution for the $a_0(980)$. This had a negligible effect on the shape spectra [21]. A study of a possible interplay of the $\bar{K}d$ and the $\bar{K}K$ interaction will be presented in a subsequent publication. However, the data is compatible with a quite weak $\bar{K}d$ interaction only and therefore adding the $\bar{K}K$ interaction is not expected to change the picture significantly.

Near threshold the partial wave structure of the final-state for the $pp \rightarrow d\bar{K}^0K^+$ reaction can be described by the superposition of two configurations $[(\bar{K}^0K^+)_s d]_P$ and $[(\bar{K}^0K^+)_p d]_S$ with the $\bar{K}^0K^+$ -system in the s - and p -wave, respectively. Correspondingly, the deuteron is in a p -wave (or s -wave) with respect to the $\bar{K}^0K^+$ -system in the first (or second) case. An overall s -wave is for-

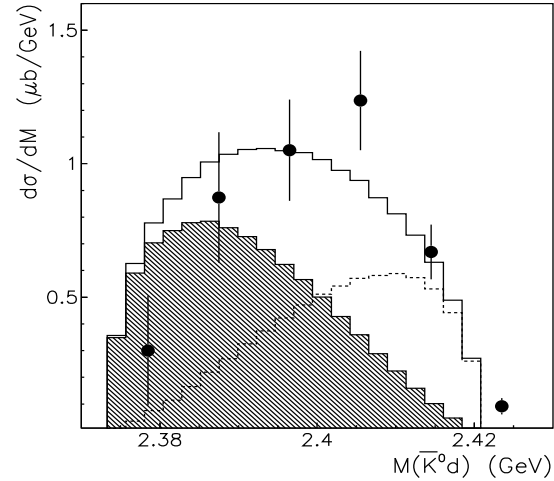


Figure 1. $\bar{K}^0d$ mass spectra from the reaction $pp \rightarrow d\bar{K}^0K^+$ at $T_p=2.65$ GeV, i.e. an excess energy of 46 MeV. The experimental results are taken from Ref. [21]. The experimental mass resolution is $\simeq 3$ MeV. The hatched histogram indicates the $\bar{K}^0d$ s -wave contribution, dashed- p -wave and solid is their sum.

bidden by selection rules.

Therefore, if we restrict ourselves to these partial waves, the most general spin-averaged squared matrix element is given as

$$\begin{aligned} |\overline{M(\mathbf{q}, \mathbf{k})}|^2 = & C_0^q q^2 + C_0^k k^2 + C_1(\hat{\mathbf{p}} \cdot \mathbf{k})^2 \\ & + C_2(\hat{\mathbf{p}} \cdot \mathbf{q})^2 + C_3(\mathbf{k} \cdot \mathbf{q}) + C_4(\hat{\mathbf{p}} \cdot \mathbf{k})(\hat{\mathbf{p}} \cdot \mathbf{q}) \end{aligned} \quad (1)$$

where $\hat{\mathbf{p}} = \mathbf{p}/|\mathbf{p}|$ and $\mathbf{p}$ is the initial center-of-mass (c.m.) momentum, $\mathbf{k}$ is the final c.m. momentum of the deuteron, and $\mathbf{q}$ is the relative c.m. momentum of the $\bar{K}^0K^+$ -system. Furthermore, the six real coefficients C_i can be expressed through the corresponding partial wave amplitudes [24,25].

In Ref. [21] the parameters C_i were extracted from the data at a proton beam energy of $T_p=2.65$ GeV. The parameters C_0^q and C_2 account for the contributions from the $K\bar{K}$ p -wave, C_0^k and C_1 from the $K\bar{K}$ s -wave and C_3 and C_4 stem from s - p interference.

To analyze the $\bar{K}^0d$ FSI in the s -wave it is necessary to isolate the $\bar{K}^0d$ s -wave contribution from the $pp \rightarrow d\bar{K}^0K^+$ reaction. Therefore we should express the matrix element in terms of

the partial amplitudes in a basis that is different to the one given above, namely in terms of $[(\bar{K}^0 d)_s K^+]_P$ and $[(\bar{K}^0 d)_p K^+]_S$ states, where the $\bar{K}^0 d$ -system is in the s - and p -wave, respectively. As was proposed in Ref. [26] the vectors of Eq. (1) can be expressed in terms of the c.m. momentum of the K^+ , $\mathbf{P}$, and the relative momentum of the $\bar{K}^0 d$ system, $\mathbf{Q}$, as

$$\mathbf{q} = \mathbf{Q} - \alpha \mathbf{P}, \quad \mathbf{k} = \frac{1}{2}((2 - \alpha)\mathbf{P} + \mathbf{Q}), \quad (2)$$

where $\alpha = m_d / (m_d + m_{\bar{K}})$. The squared amplitude expressed in the new frame reveals the same structure as Eq. (1), namely:

$$\begin{aligned} |M(\mathbf{Q}, \mathbf{P})|^2 = & B_0^Q Q^2 + B_0^P P^2 + B_1(\mathbf{P} \cdot \hat{\mathbf{p}})^2 \\ & + B_2(\mathbf{Q} \cdot \hat{\mathbf{p}})^2 + B_3(\mathbf{P} \cdot \mathbf{Q}) + B_4(\mathbf{P} \cdot \hat{\mathbf{p}})(\mathbf{Q} \cdot \hat{\mathbf{p}}), \end{aligned} \quad (3)$$

where the B_i coefficients can be expressed in terms of the C_i from Eq. (1) and

$$\begin{aligned} B_0^P = & \frac{(2 - \alpha)^2}{4} C_0^k + \alpha^2 C_0^q - \frac{\alpha(2 - \alpha)}{2} \frac{1}{2} C_3, \\ B_1 = & \frac{(2 - \alpha)^2}{4} C_1^k + \alpha^2 C_1^q - \frac{\alpha(2 - \alpha)}{2} \frac{1}{2} C_4. \end{aligned} \quad (4)$$

Using the results of the fit for C_i from Ref. [21] we obtain the following values for the coefficients B_i : $B_0^Q = 0.81$, $B_0^P = 0.705$, $B_1 = -0.267$, $B_2 = -0.267$, $B_2 = -1.45$, $B_3 = 1.41$. It follows from this that the $\bar{K}^0 d$ s -wave contributes 57% to the total cross section. Fig. 1 shows the $\bar{K}^0 d$ mass spectra from the $pp \rightarrow d \bar{K}^0 K^+$ reaction at the beam energy $T_p = 2.65$ GeV [21]. The histograms show our calculations with the parameters B_i given above. The hatched histogram shows the $\bar{K}^0 d$ s -wave contribution, the dashed line illustrates the p -wave contribution, while the solid histogram shows the result of our full calculation. We recall that in Ref. [21] the parameters C_i were obtained from a joint fit to $\bar{K}^0 K^+$ and $\bar{K}^0 d$ mass spectra as well as $\cos(\mathbf{p}\mathbf{k})$, $\cos(\mathbf{p}\mathbf{q})$ and $\cos(\mathbf{k}\mathbf{q})$ angular distributions.

Since we isolate the s -wave contribution from the $\bar{K}^0 d$ mass spectrum it is now possible to study the interaction between the final $\bar{K}^0$ -meson and the deuteron. Following the standard Watson and Migdal theorem [32,33,34] we include the FSI by multiplying the $B_0^P P^2$ and $B_1(\hat{\mathbf{p}} \cdot \mathbf{P})^2$ terms by

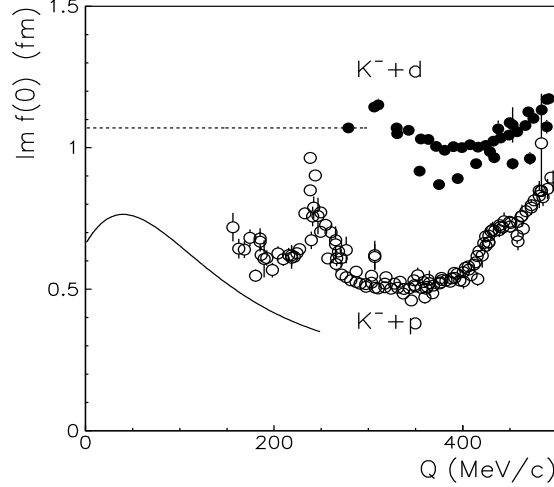


Figure 2. Imaginary part of the $K^- d$ and the $K^- p$ forward scattering amplitudes, respectively, as a function of the cms momentum Q . The data were obtained from total cross sections using the optical theorem. The solid line shows the K -matrix solution for $K^- p$ s -wave amplitude given by Martin [1]. The dashed line shows our extrapolation for $K^- d$ amplitude.

the enhancement factor $|1 - iQa|^{-2}$, where a is the complex scattering length. After that correction we refit the experimental $\bar{K}^0 d$ invariant mass distribution with two free parameters, namely the real and imaginary parts of the $\bar{K}^0 d$ scattering length, while keeping the $\bar{K}^0 d$ s -wave distribution fixed. We also checked that the influence of this additional energy dependence does not significantly change the other observables given in Ref. [21] that went into the fit of the C_i parameters.

Before performing the fit, we have to specify the boundary conditions for the $\bar{K}^0 d$ scattering length a . While there are no experimental constraints on the real part $\text{Re } a$ of the $\bar{K}^0 d$ scattering length, it is clear that $\text{Im } a$ must be positive because of unitarity. Furthermore, a lower bound on the imaginary part can be deduced from the experimental data on the $K^- d$ total cross section σ_{tot} using the optical theorem for the forward scattering amplitude

$$\text{Im } f(0) = \frac{Q \sigma_{\text{tot}}}{4\pi}, \quad a = f(0) |_{Q \rightarrow 0}. \quad (5)$$

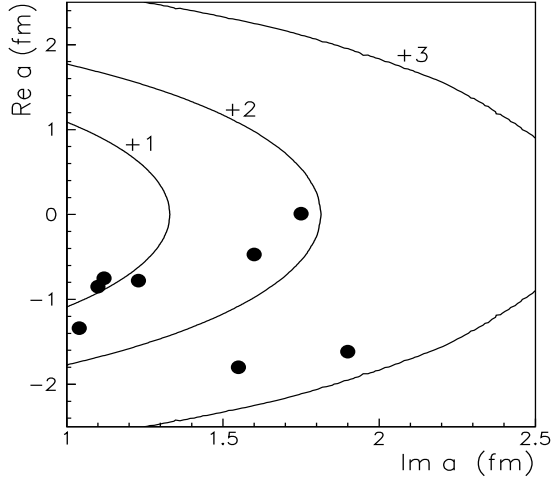


Figure 3. Real versus imaginary part of the $\bar{K}^0 d$ scattering length. The solid contour lines show the results of our fit to the $pp \rightarrow d\bar{K}^0 K^+$ data [21] for χ^2+1 , χ^2+2 and χ^2+3 . The solid circles show the results from model calculations collected in Table 1.

Fig. 2 shows the imaginary part of the $K^- d$ forward scattering amplitude as a function of the c.m. momentum Q deduced from the data on the $K^- d$ total cross section (solid circles). The extrapolation below 300 MeV/c by a straight dashed line gives $\text{Im } a \simeq 1.1$ fm. However, one might argue whether this momentum independent extrapolation can be considered as being realistic, since the contribution from the $\Lambda(1405)$ and $\Sigma(1385)$ resonances might be quite strong at small Q .

To investigate that problem we show by the open circles in Fig. 2 the imaginary part of the $K^- p$ forward scattering amplitude. The extrapolation below 200 MeV/c by the straight line gives for the imaginary part of $K^- p$ scattering length $\simeq 0.7$ fm. This bound for the imaginary part of the $K^- p$ scattering length agrees with the K -matrix solution for the $K^- p$ s -wave amplitude found by Martin [1]. Note that the K -matrix solution includes the $\Lambda(1405)$ and $\Sigma(1385)$ resonances and the momentum dependence of $f(0)$ obtained from the K -matrix is shown by the solid line in Fig. 2. Obviously the K -matrix result underestimates the data on the imaginary part of the $K^- p$

Table 1

The $K^- d$ scattering lengths predicted by different calculations with various elementary $K^- p$ and $K^- n$ scattering lengths. Here, FCA denotes the fixed center approximation, while FE stands for the calculations by Faddeev equations. All values are in fm.

$a(K^- N)$	$K^- d$	Ref.
$K^- p = -0.66 + i0.67$ $K^- n = 0.264 + i0.57$	FCA $-0.78 + i1.23$	[27]
$K^- p = -0.70 + i0.71$ $K^- n = 0.28 + i0.67$	FE $-1.34 + i1.04$	[28]
$K^- p = -0.66 + i0.67$ $K^- n = 0.26 + i0.57$	FCA $-0.75 + i1.12$	[29]
$K^- p = -0.66 + i0.67$ $K^- n = 0.26 + i0.57$	FE $-0.85 + i1.10$	[29]
$K^- p = -0.045 + i0.835$ $K^- n = 0.94 + i0.72$	FCA $-0.01 + i1.75$	[29]
$K^- p = -0.045 + i0.835$ $K^- n = 0.94 + i0.72$	FE $-0.47 + i1.60$	[29]
$K^- p = -0.789 + i0.929$ $K^- n = 0.574 + i0.619$	FCA $-1.615 + i1.909$	[30]
$K^- p = -1.01 + i0.95$ $K^- n = 0.54 + i0.53$	FE $-1.92 + i1.58$	[31]

forward scattering amplitude at $Q \geq 160$ MeV/c, since this solution does not include all channels that are open at high momenta. Based on these arguments we finally conclude that a reasonable estimate of the lower limit for the imaginary part of $\bar{K}^0 d$ scattering length is about 1 fm. Therefore, we fit the experimental results [21] for the $\bar{K}^0 d$ invariant mass spectrum using the lower bound $\text{Im } a \geq 1$ fm.

The results of our fit are shown in Fig. 3. With the lower limit $\text{Im } a \geq 1$ fm we obtained the total $\chi^2 = 9.6$. The solid lines in Fig. 3 indicate the χ^2+1 , χ^2+2 and χ^2+3 contour lines. Furthermore, the solid circles show different results for $K^- d$ scattering length from the calculations collected in Table 1. It is important to remark that the prediction from Ref. [28] was based on a combined analysis of the experimental results on $K^- d \rightarrow N\Lambda\pi$ and $K^- d \rightarrow N\Sigma\pi$ relative rates and spectra and is quite close to our solution.

Our analysis of the $\bar{K}^0 d$ mass spectra for the $pp \rightarrow d\bar{K}^0 K^+$ reaction allows one to accept

some predictions [28,29,27] for the K^-d scattering length within the range $\text{Im } a \leq 1.3$ fm and $|\text{Re } a| \leq 1.3$ fm. The limit for the imaginary part of the K^-d scattering length is also strongly supported by the data on the total K^-d cross section shown in Fig. 2. Note that the model results listed in Table 1 have been calculated with different input parameters for the elementary K^-p and K^-n scattering lengths, also given in Table 1. The different input as an elementary K^-p and K^-n scattering lengths largely explains the variations in the final results for the K^-d scattering length.

As a next step the elementary K^-p and K^-n scattering lengths might be extracted from our results obtained from the $pp \rightarrow d\bar{K}^0 K^+$ data applying established few-body techniques. In addition the possible interplay of the $\bar{K}K$ interaction and the $\bar{K}d$ interaction, also the influence of a non-vanishing $\bar{K}d$ effective range should be studied.

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