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

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Abstract

The real and imaginary parts of the $\bar{K}^0 d$ scattering length are extracted from the $\bar{K}^0 d$ mass spectrum obtained from the reaction $pp \to d\bar{K}^0 K^+$ measured recently at the Cooler Synchrotron COSY at Jülich. We extract a new limit on the $K^- d$ scattering length, namely $\mathrm{Im}\, a \leqslant 1.3$ fm and $|\mathrm{Re}\, a| \leqslant 1.3$ 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, $\mathrm{Re}\, a_{K^- p} = -0.7$ fm, while the real part of the $K^- n$ scattering length is attractive, $\mathrm{Re}\, a_{K^- n} = 0.37$ 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 $\mathrm{Re}\, a_{K^- p}$ for the attractive $\bar{K}N$ in-

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teraction 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 antikaons in finite nuclei and dense nuclear matter, including neutron stars, see, e.g., Refs. [6–9] (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. [10–13]. 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 [14–16] 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 SIDDHARTA 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 Letter 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 $pp\to d\bar{K}^0K^+$ near threshold measured very recently at COSY [21]. Theoretical analyses of the reaction $pp\to\bar{K}^0dK^+$ near threshold have been performed in Refs. [22–27]. As has been stressed in Ref. [23], the $NN\to d\bar{K}K$ reaction should be sensitive to the $\bar{K}d$ FSI. Thus one can expect that the experimental results on the $pp\to d\bar{K}^0K^+$ reaction may provide a new way to extract the $\bar{K}^0d$ scattering length.

In this Letter we focus on the potential influence of the $\bar{K}d$ interaction on the observables for the process $pp\to d\bar{K}^0K^+$. 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 $pp\to d\bar{K}^0K^+$ reaction can be described by the superposition of two configurations $[(\bar{K}^0K^+)_sd]_P$ and $[(\bar{K}^0K^+)_pd]_S$ 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 forbidden by selection rules.

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

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

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 $pp\to d\bar{K}^0K^+$ 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 $[(\bar{K}^0d)_sK^+]_P$ and $[(\bar{K}^0d)_pK^+]_S$ states, where the $\bar{K}^0d$-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

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

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:

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

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

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

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 $\bar{K}d$ s-wave contributes 57% to the total cross section. Fig. 1 shows the $\bar{K}^0 d$ mass spectra from the $pp \to d\bar{K}^0 K^+$ 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 $\cos(\mathbf{pk})$, $\cos(\mathbf{pq})$ and $\cos(\mathbf{kq})$ 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 [32–34] we include the FSI by multiplying the $B_0^P P^2$ and $B_1(\hat{\mathbf{p}}\cdot\mathbf{P})^2$ terms by 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 contribution 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.

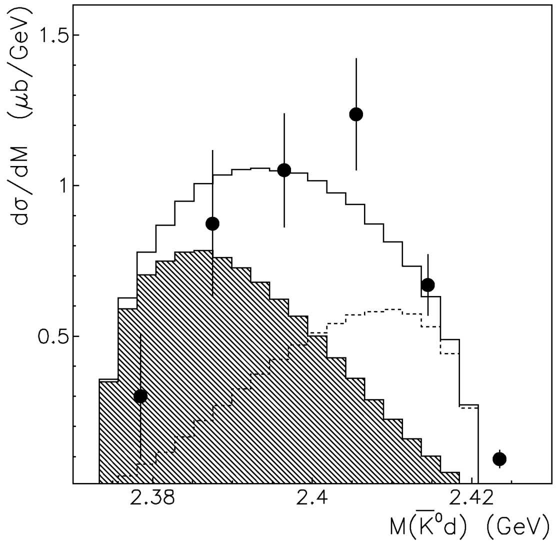

Fig. 1. $\bar{K}^0 d$ mass spectra from the reaction $pp \to d\bar{K}^0 K^+$ at $T_p = 2.65$ GeV, i.e., an excess energy of 46 MeV. The experimental results are taken from Ref. [21]. The experimental mass resolution is $\simeq 3$ MeV. The hatched histogram indicates the $\bar{K}^0 d$ s-wave contribution,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

Before performing the fit, we have to specify the boundary conditions for the $\bar{K}^0 d$ scattering length a. While there are no constraints on the real part $\mathrm{Re}\,a$ of the $\bar{K}^0 d$ scattering length, it is clear that $\mathrm{Im}\,a$ 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

$$\mathrm{Im}\, f(0) = \frac{Q\sigma_{\mathrm{tot}}}{4\pi}, \qquad a = f(0)|_{Q\to 0}.$$

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 $\mathrm{Im}\,a \simeq 1.1$ 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.

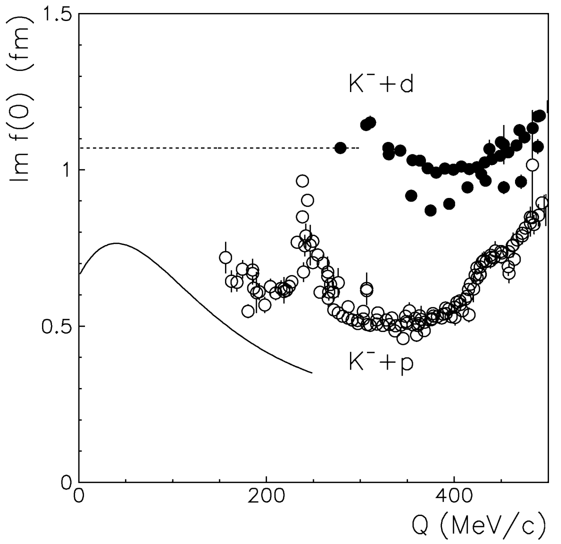

Fig. 2. Imaginary part of the K^-d and the K^-p forward scattering amplitudes, respectively, as a function of the c.m. momentum Q. The data were obtained from total cross sections using the optical theorem. The solid line shows the K-matrix solution for K^-p s-wave amplitude given by Martin [1]. The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

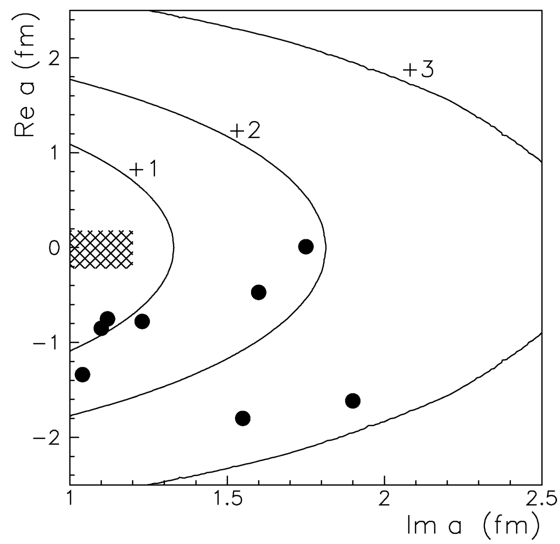

Fig. 3. Real versus imaginary part of the $\bar{K}^0d$ scattering length. The solid contour lines show the results of our fit to the $pp \to d\bar{K}^0K^+$ data [21] for χ^2+1, χ^2+2 and χ^2+3. The shaded area indicates the best solution. The solid circles show the results from model calculations collected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

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]

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 forward scattering amplitude at $Q \geqslant 160$ 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 $\bar{K}^0d$ scattering length is about 1 fm. Therefore, we fit the experimental results [21] for the $\bar{K}^0d$ invariant mass spectrum using the lower bound $\mathrm{Im}\,a \geqslant 1$ fm.

The results of our fit are shown in Fig. 3. With the lower limit $\mathrm{Im}\,a \geqslant 1$ fm we obtained the total $\chi^2 = 9.6$ per 6 experimental points. 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 $K^-d \to N\Lambda\pi$ and $K^-d \to N\Sigma\pi$ relative rates and spectra and is quite close to our solution.

Our analysis of the $\bar{K}^0d$ mass spectra for the $pp \to d\bar{K}^0K^+$ reaction allows one to accept some predictions [27–29] for the K^-d scattering length within the range $\mathrm{Im}\, a \leqslant 1.3$ fm and $|\mathrm{Re}\, a| \leqslant 1.3$ 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 $pp \to d\bar{K}^0K^+$ 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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