On a Quasi-Bound State in the $K^-d$ System Caused by Strong Interactions

Abstract It was found that $NN$ potential could influence the results of the quasi-bound state search in the $K^-d$ system, where the corresponding pole is situated close to the threshold. Three-body Faddeev-type calculations of the $\bar{K}NN - \pi \Sigma N\bar{N}$ system performed with a new model of nucleon-nucleon interaction predict the existence of the quasi-bound $K^-d$ state caused by strong interactions. Its binding energy is small (1–2 MeV), while the width is comparable with the width of the $K^-pp$ quasi-bound state (40–60 MeV).

1 Introduction

Many theoretical works and several experiments were devoted to the question of a quasi-bound state in systems consisting of an antikaon(s) and nucleons, see e.g. [1]. Particular interest was attracted to the lightest possible system $\bar{K}NN$ with zero spin (usually denoted as $K^-pp$): all theoretical works predicted the quasi-bound state in it. The methods of and the inputs for the calculations are quite different, and the predicted binding energy and width of the state also variate in quite a wide range. We also predicted a quasi-bound state in the spin zero $\bar{K}NN$ system [1] with binding energy and width strongly depending on the particular form of the antikaon–nucleon potential, which is used as a input. We solved three-body Faddeev-type AGS equations [2] with coupled $\bar{K}NN$ and $\pi \Sigma N\bar{N}$ channels and used three different models of $\bar{K}N$ interaction: two phenomenological potentials and one chirally motivated model.

We also studied another state of the $\bar{K}NN$ system with spin one (which will be denoted as $K^-d$). It has an atomic state, kaonic deuterium, which is mainly caused by Coulomb attraction between $K^-$ and $p$, while the strong interactions give corrections to the binding energy and width (see [3] and references therein). But we did not find a pole caused by purely strong interactions corresponding to the quasi-bound state in $K^-d$ [4] similar to that one in the $K^-pp$ system. We demonstrated, that the strong quasi-bound state appears in the $K^-d$ system if the attraction in the isospin-zero $\bar{K}N - \bar{K}N$ part of the coupled-channel $\bar{K}N - \pi \Sigma$ potential is increased by hands.

After studying $\bar{K}NN$ and $\bar{K}\bar{K}N$ systems (the last one also has a quasi-bound state [5]) we started investigations of the four-body $\bar{K}NN\bar{N}$ system. We are using four-body Faddeev-type equations [6] on four-body transition amplitudes, which contain, among others, three-body transition amplitudes evaluated at every step of the four-body calculations. We constructed a new nucleon-nucleon potential for these calculations, and found out that the quasi-bound state caused by the strong interactions appeared in the $K^-d$ system. The present paper is devoted to this state.

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2 Three-Body AGS Equations and Two-Body Input

The calculations of the quasi-bound state in the $K^-d$ system caused by strong interactions were performed using the same method and input as those used for the $K^-pp$ system [1]. We solved Faddeev-type three-body equations in AGS form [2] with coupled $\bar{K}NN$ and $\pi\Sigma N$ channels. The three-body equations in operator form for the $\bar{K}NN$ system with spin one ($K^-d$) are those for the spin-one $\bar{K}NN$ ($K^-pp$): Eqs. (23–25) of [1]. Written in momentum representation they differ from the $K^-pp$ case by the antisymmetrization and 6j recoupling coefficients.

The three-body AGS equations in momentum representation are integral equations. We solved them in two ways. One of them is the direct search of the pole position in the complex plane. Another one is the $1/|\text{Det}|^2$ method proposed and successively used for the $K^-pp$ system in [7]. The idea of the method is that a pole, situated under the threshold, must be seen at the real energy axis as a bump. The position and the width of the quasi-bound state can be evaluated by fitting the bump by Breit-Wigner formula with some arbitrary background. The two methods supplement each other: the direct search needs initial values for the eigenvalue problem solving, and they can be provided by the $1/|\text{Det}|^2$ method. On the other hand, the binding energy and width obtained from bump fitting could be used as a control of the direct search result.

The input for the AGS equations describing the $\bar{K}NN - \pi \Sigma N$ system are $T$-matrices corresponding to the $\bar{K}N - \pi \Sigma$, $NN$, $\Sigma N$ and $\pi N$ potentials. All the potentials have separable form, which simplifies the three-body equations, all of them reproduce low-energy experimental data for the corresponding subsystem quite accurately. Keeping in mind uncertainties in experimental data used for construction of the interaction models, we see no reason to introduce some three-body force and by this increase ambiguity of the calculations. Coulomb interaction between $K^-$ and $p$ was not included into the equations, since in contrast to atomic state calculations, where Coulomb plays the main role, the present work is devoted to the quasi-bound $K^-d$ state caused by strong interactions, where Coulomb should lead to some small corrections only.

Interaction of an antikaon with a nucleon plays the main role in the calculations. It is strongly attractive in the isospin zero state, which had lead to the question of a quasi-bound state in few- and/or many-body systems consisting of antikaon(s) and nucleons existence. The $\bar{K}N$ system is coupled to the $\pi\Sigma$ channel through the $\Lambda(1405)$ resonance, which is usually assumed as a resonance in the $\pi\Sigma$ channel and a quasi-bound state in the $\bar{K}N$ channel. The resonance is formed by one or two poles (this question rose quite vivid discussions) and, according to the Particle Data Group [8] has a mass $1405.1^{+1.2}_{-1.0}$ MeV and a width $50.5 \pm 2.0$ MeV.

We used three our models of antikaon–nucleon interaction, constructed and used before. They are: two phenomenological potentials with coupled $\bar{K}N$ and $\pi\Sigma$ channels and one- or two-pole structure of the $\Lambda(1405)$ resonance ($V^{1,\text{SIDD}}_{\bar{K}N}$ and $V^{2,\text{SIDD}}_{\bar{K}N}$ correspondingly), and the chirally motivated $\bar{K}N - \pi\Sigma - \pi\Lambda$ potential $V_{\text{Chiral}}^{\bar{K}NN}$ (with two-pole $\Lambda(1405)$ structure). Parameters of the phenomenological and the chirally motivated potentials are presented in [4,9] correspondingly. Yamaguchi form-factors were used for the one-pole phenomenological and chirally-motivated potentials together with the $\bar{K}N$ form-factor of the two-pole phenomenological potential. The $\pi\Sigma$ form-factor of the two-pole $V^{2,\text{SIDD}}_{\bar{K}NN}$ has more complicated form. The chirally-motivated potential is energy-dependent one.

All three potentials were fitted to the experimental data on kaonic hydrogen and low-energy $K^-p$ scattering. In particular, they reproduce $1s$ level shift and width in kaonic hydrogen, caused by the strong interaction additional to the main Coulomb interaction, measured by SIDDHARTA experiment [10]. In contrast to other authors we reproduce these observables directly without using a Deser-like approximate formula connecting the characteristics of kaon hydrogen with the $K^-p$ scattering length. Our three models of the antikaon–nucleon interaction also reproduce elastic and inelastic cross-sections of $K^-p$ scattering [11–16] together with threshold branching ratios $\gamma$, $R_c$ and $R_\pi$ [17,18] (or $R_{\pi\Sigma}$ constructed from the last two in the case of phenomenological potentials).

The phenomenological models with coupled $\bar{K}N$ and $\pi\Sigma$ channels were used in the three-body coupled-channel $\bar{K}NN - \pi\Sigma N$ calculations, while the corresponding exact optical $\bar{K}N(\pi\Sigma)$ potentials [1] were taken in approximate one-channel $\bar{K}\bar{N}N$ calculations. The chirally motivated $\bar{K}N - \pi\Sigma - \pi\Lambda$ interaction model was used as $\bar{K}N - \pi\Sigma(\pi\Lambda)$ in the three-body calculation with coupled channels since three-body channel with $\Lambda$ is not included into the equations. The exact optical $\bar{K}N(\pi\Sigma - \pi\Lambda)$ version of interaction entered the approximate three-body equations.

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1 The exact optical potential is the one-channel potential, which provides exactly the same elastic amplitude as the coupled-channel model of interaction (see e.g. [19]).
Spin dependent and spin independent potentials of the $\Sigma N$ interaction were constructed in [19]. They are one-term separable potentials with Yamaguchi form-factors. The parameters were fitted to the experimental data on $\Sigma N$ and $\Lambda N$ cross-sections [20–24]. Isospin 1/2 $\Sigma N - \Lambda N$ potential is a two-channel one, it is used in the three-body calculations in a form of the exact optical $\Sigma N(\Lambda N)$ potential. The isospin 3/2 $\Sigma N$ potential has only one channel. In the present calculations we used the $\Sigma N$ interaction model, which does not depend on spin.

The $\pi N$ potential is assumed to play negligible role, and was omitted. Finally, the new nucleon-nucleon potential, which lead to the $K^-d$ quasi-bound state appearance, is described in the next section.

### 3 New Separable $NN$ Potential

The Two-term Separable New potential (TSN) of nucleon-nucleon interaction has a form

$$V_{NN}^{TSN}(k, k') = \sum_{m=1}^{2} g_m(k) \lambda_m \gamma_m(k'),$$

with form-factors

$$g_m(k) = \sum_{n=1}^{3} \frac{\gamma_{mn}}{(\beta_{mn})^2 + k^2}, \quad \text{for } m = 1, 2.$$ (2)

It was fitted to Argonne V18 potential [25] phase shifts without the condition, which was imposed on the previously used $V_{NN}^{TSA}$ potential [26]: one of the normalization constants of the deuteron wave function must be equal to zero. Technically the new $V_{NN}^{TSN}$ and previously used $V_{NN}^{TSA}$ models differ by the number of terms in the form-factors, Eq. (2). The parameters of the new two-term separable potential are presented in Table 1 for the triplet and in Table 2 for the singlet case.

Four parameters ($\lambda_m, \gamma_{m1}, \gamma_{m2}, \gamma_{m3}$) for every $m$ can be replaced by three independent parameters ($\lambda'_m = \lambda_m * \gamma_{m3}^2, \gamma'_m = \gamma_{m1}/\gamma_{m3}, \gamma''_m = \gamma_{m2}/\gamma_{m3}$), correspondingly, with $\gamma''_m = 1$. Therefore, $np$ and $pp$ potentials contain 12 independent parameters each. Such transformation does not change the potential Eq.(1) and can be done with $\gamma_{m1}$ or $\gamma_{m2}$ as well. However, the "natural" values of the parameters, presented in Tables 1 and 2 are more convenient for numerical calculations.

The triplet and singlet scattering lengths $a$ and effective ranges $r_{\text{eff}}$ provided by the TSN potential are:

$$a_{np}^{TSN} = -5.400 \text{ fm}, \quad r_{\text{eff}, np}^{TSN} = 1.744 \text{ fm}$$

$$a_{pp}^{TSA} = 16.325 \text{ fm}, \quad r_{\text{eff}, pp}^{TSA} = 2.792 \text{ fm},$$

the binding energy of the deuteron is $E_{\text{deu}} = 2.2246 \text{ MeV}$. The previously used TSA potential (its TSA-B version) provides slightly different scattering lengths and effective ranges:

$$a_{np}^{TSA-B} = -5.413 \text{ fm}, \quad r_{\text{eff}, np}^{TSA-B} = 1.760 \text{ fm}$$

$$a_{pp}^{TSA-B} = 16.559 \text{ fm}, \quad r_{\text{eff}, pp}^{TSA-B} = 2.880 \text{ fm}$$

and the same binding energy of deuteron (2.2246 MeV).

Phase shifts of $np$ and $pp$ scattering calculated using the new $V_{NN}^{TSN}$ potential are plotted together with those calculated using TSA-B version of the previously used model in Fig. 1. It is seen that the phase shifts given by Argonne V18 potential [25] (black circles for $\delta_{np}$ and circles filled with dots for $\delta_{pp}$) are reproduced by the new potential with high accuracy. The phases of the new TSN and the previously used TSA-B potentials are practically indistinguishable for the case of $\delta_{np}$ (dashed and dotted lines), while $pp$ phases are slightly different (solid and dash-dotted lines for TSN and TSA-B potentials correspondingly). The phases change their signs, which means that all three potentials are repulsive at short distances.
Table 2 Parameters of the new $V_{NN}^{TSN}$ potential, singlet: strength constants $\lambda_m$, range $\beta_{m,n}$ and additional $\gamma_{m,n}$ parameters

|   | $\lambda_m$ | $\beta_{m1}$ | $\beta_{m2}$ | $\beta_{m3}$ | $\gamma_{m1}$ | $\gamma_{m2}$ | $\gamma_{m3}$ |
|---|-------------|--------------|--------------|--------------|--------------|--------------|--------------|
| m = 1 | 1.9793      | 1.8855       | 2.8396       | 1.1834       | -0.1800      | 1.9999       | 0.0362       |
| m = 2 | 1.7815      | 3.9897       | 3.9919       | 0.5000       | -1.8881      | -1.9914      | 0.0014       |

The results obtained by coupled-channel $\bar{K}NN - \pi \Sigma N$ equations solving and one-channel $\bar{K}NN$ variant with exact optical antikaon–nucleon potentials were presented. Phenomenological $\bar{K}N$ potentials with one-pole $V_{\bar{K}N}^{1, SIDD}$ and two-pole $\Lambda(1405)$ structure $V_{\bar{K}N}^{2, SIDD}$ were used together with the chirally-motivated model $V_{\bar{K}N}^{Chiral}$ of the antikaon–nucleon interaction. The binding energy is counted from the threshold energy of the $K^{-d}$ system: $z_{th,K^{-d}} = m_{\bar{K}} + 2m_N + E_{deu} = 2371.26$ MeV.

4 Results and Discussion

The results of the direct search of the pole in the $K^{-d}$ system corresponding to the quasi-bound state caused by strong interactions are shown in Table 3. The new nucleon-nucleon $V_{NN}^{TSN}$ potential was used together with the three models of antikaon–nucleon interaction. The calculations with coupled $\bar{K}NN - \pi \Sigma N$ channels using the phenomenological $\bar{K}N$ potential with one-pole structure of the $\Lambda(1405)$ resonance $V_{\bar{K}N}^{1, SIDD}$ provide no quasi-bound state. In contrast to it, the models with two-pole structure: the phenomenological $V_{\bar{K}N}^{2, SIDD}$ and chirally-motivated $V_{\bar{K}N}^{Chiral}$ potentials, provide a quasi-bound state with small binding energy $B_{K^{-d}}$. The energy is counted from the $K^{-d}$ threshold $z_{th,K^{-d}} = m_{\bar{K}} + 2m_N + E_{deu} = 2371.26$ MeV.
No $K^-d$ quasi-bound state was found in our previous work [4], where similar calculations were performed with $V_{N N}^{TSA}$ potential. Therefore the particular model of nucleon-nucleon interaction, not only of antikaon–nucleon one, can influence the result of the quasi-bound pole search in the $K^-d$ system.

It was demonstrated in [4] that gradual increasing of the absolute value of the isospin zero constant $\lambda_{I=0}^{\bar{K}K}$ of the $\bar{K}N - \pi \Sigma$ potential leads to the quasi-bound state appearance in the $K^-d$ system. And the necessary changes are small, as minimum, for the system described by the two-pole phenomenological $\bar{K}N$ potential. Indeed, it is seen at Fig. 6 of [4], that the pole calculated with $V_{\bar{K}N}^{2, SIDD}$ potential with multiplication factor 1 is situated slightly above the $K^-d$ threshold, so that the $K^-d$ system is almost bound. On the other hand, we have shown in [19], that $NN$ interaction plays a minor role in $K^-d$ and $K^-p$ scattering length calculations. It is seen at Fig. 12 of [19] that use of PEST nucleon-nucleon potential which is not repulsive at short distances changes are small, as minimum, for the system described by the two-pole phenomenological $\bar{K}N$ potential.

On the other hand, we have shown in [19], that $NN$ interaction plays a minor role in $K^-d$ and $K^-p$ scattering length calculations. It is seen at Fig. 12 of [19] that use of PEST nucleon-nucleon potential which is not repulsive at short distances changes are small, as minimum, for the system described by the two-pole phenomenological $\bar{K}N$ potential. Keeping all this in mind, the few MeV binding energy of the $K^-d$ quasi-bound state caused by strong interactions is an expected result. The positions of the poles calculated with the previously used nucleon-nucleon $V_{N N}^{TSA}$ potential are so close to the $K^-d$ threshold (from above), that use of another $V_{N N}$ pushes the poles downward under the threshold, so that the quasi-bound state appeared.

The widths of the $K^-d$ quasi-bound states presented in Table 3 confirm our suggestions [4] that it must be comparable with those for the $K^-pp$ quasi-bound state.

The results of the approximate calculations performed with the exact optical versions of the three antikaon–nucleon potentials are also shown in Table 3. In that case the quasi-bound state also appeared in the $K^-d$ system described by the one-pole $V_{\bar{K}N}^{1, SIDD}$ potential in addition to the two others. The binding energies of the already existing $K^-d$ quasi-bound states (described by the two-pole $V_{\bar{K}N}$) has changed, and they become broader.

An atomic state, kaonic deuterium (see [3] and references therein) exists in the spin one $\bar{K}NN$ system, however it cannot be misidentified with the quasi-bound state caused by the strong interactions. Indeed, the binding energy of kaonic deuterium is $\sim 10$ keV, while strong interactions bound the system with $1 - 2$ MeV. The differences in widths of the atomic and strong $K^-d$ states is even more drastic: tens of MeV for the strong quasi-bound states in contrast to $\sim 1$ keV for kaonic deuterium [3].

We also performed calculations of the $1/|\text{Det}|^2$ functions, which provided quite good results for the $K^-pp$ system [7]. The bumps corresponding to the $K^-pp$ poles evaluated with the three models of antikaon–nucleon interaction were clearly pronounced and have a resonance-like form. On the contrary, the $K^-d$ bumps in the $1/|\text{Det}|^2$ functions are situated very close to the $\bar{K}NN$ threshold and are not clearly pronounced, especially those obtained with the phenomenological potentials. It is seen in Fig. 2, where the points calculated using one-pole phenomenological $V_{\bar{K}N}^{1, SIDD}$ (circles), two-pole phenomenological $V_{\bar{K}N}^{2, SIDD}$ (triangles) and chirally motivated $V_{\bar{K}N}^{\text{Chiral}}$ (squares) potentials are joined by the fitting lines. Breit-Wigner fits of the calculated $1/|\text{Det}|^2$ functions with arbitrary background in the $K^-d$ system are far not so accurate as in the case of $K^-pp$ system:

\begin{align}
B_{K^-d, BW}^{1, SIDD} &= 9.2 \text{ MeV}, & \Gamma_{K^-d, BW}^{1, SIDD} &= 59.6 \text{ MeV}, \\
B_{K^-d, BW}^{2, SIDD} &= 11.4 \text{ MeV}, & \Gamma_{K^-d, BW}^{2, SIDD} &= 52.2 \text{ MeV}, \\
B_{K^-d, BW}^{\text{Chiral}} &= 5.3 \text{ MeV}, & \Gamma_{K^-d, BW}^{\text{Chiral}} &= 48.6 \text{ MeV}.
\end{align}

It seems that the $1/|\text{Det}|^2$ method is not good for quasi-bound states situated so close to the threshold.

For comparison we studied, how the new NN potential changes binding energies and widths of the $K^-pp$ quasi-bound states. The results are presented in Table 4, where the characteristics of the $K^-pp$ quasi-bound state calculated using the system of equations with coupled $\bar{K}NN$ and $\pi \Sigma N$ channels are shown together with the results of one-channel calculations with exact optical $\bar{K}N$ potentials. The $K^-pp$ binding energies and widths obtained with the previously use TSA-B NN potential and published in [7] are also shown. The binding energy is counted from the threshold energy of the $K^-pp$ system: $z_{th, K^-pp} = m_{\bar{K}} + 2 m_N = 2373.485$ MeV. It is seen that the new model of NN interaction also changed the pole positions on few MeV. However, since the quasi-bound state in the $K^-pp$ system, in contrast to $K^-d$, is situated far from the $\bar{K}NN$ and $\pi \Sigma N$ thresholds, these changes do not have so drastic effect.

Comparing the $K^-d$ and $K^-pp$ characteristics of the quasi-bound states caused purely by strong interactions in Tables 3 and 4 correspondingly, we see large difference between the binding energies in the both systems: the $K^-pp$ is bound much stronger than $K^-d$. The $K^-d$ and $K^-pp$ widths are comparable. We see, that the particular model of $V_{N N}$ plays a minor role in the $K^-pp$ system, differences in the pole positions (below and above the threshold) in the $K^-d$ system are also not very big. However, since the $K^-d$ poles are
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situated very close to the $K^-d$ threshold, these small differences resolve the question of the quasi-bound state existence.

5 Summary

We found that $NN$ potential could influence the results of the quasi-bound state search in the $K^-d$ system, where the corresponding pole is situated close to the $K^-d$ threshold, and predicted possibility of the $K^-d$ quasi-bound state existence caused by the strong interactions. Three-body Faddeev-type calculations performed with the new TSN model of nucleon-nucleon interaction found out the quasi-bound state in this system with binding energy $1 - 2$ MeV and width comparable with those obtained for the $K^-pp$ system, $40 - 60$ MeV. The quasi-bound state caused by strong interactions is stronger bound and is much broader than kaonic deuterium, therefore, the atomic and the strong quasi-bound states cannot be misidentified.
References

1. N.V. Shevchenko, Three-body Antikaon–Nucleon systems. Few Body Syst. 58, 6 (2017)
2. E.O. Alt, P. Grassberger, W. Sandhas, Reduction of the three-particle collision problem to multi-channel two-particle Lippmann–Schwinger equations. Nucl. Phys. B 2, 167 (1967)
3. J. Révai, Three-body calculation of the 1s level shift in kaonic deuterium with realistic $\bar{K}N$ potentials. Phys. Rev. C 94, 054001 (2016)
4. N.V. Shevchenko, J. Révai, Faddeev calculations of the $\bar{K}NN$ system with chirally-motivated $\bar{K}N$ interaction. I. Low-energy $K^-d$ scattering and antikaonic deuterium. Phys. Rev. C 90, 034003 (2014)
5. N.V. Shevchenko, J. Haidenbauer, Exact calculations of a quasibound state in the $\bar{K}\bar{K}N$ system. Phys. Rev. C 92, 044001 (2015)
6. P. Grassberger, W. Sandhas, Systematical treatment of the non-relativistic n-particle scattering problem. Nucl. Phys. B 2, 181 (1967)
7. J. Révai, N.V. Shevchenko, Faddeev calculations of the $\bar{K}NN$ system with chirally-motivated $\bar{K}N$ interaction. II. The $K^-pp$ quasi-bound state. Phys. Rev. C 90, 034004 (2014)
8. K.A. Olive et al. (Particle Data Group), The review of particle physics. Chin. Phys. C 38, 090001 (2014) and 2015 update
9. N.V. Shevchenko, Near-threshold $K^-d$ scattering and properties of kaonic deuterium. Nucl. Phys. A 890–891, 50–61 (2012)
10. M. Sakitt et al., Low-energy $K^-p$ interaction and interpretation of the 1405-MeV $\Sigma^0$ resonance as a $\bar{K}N$ bound state. Phys. Rev. Lett. 21, 29 (1967)
11. J.K. Kim, Low-energy $K^-p$ interaction and interpretation of the 1405-MeV $\Sigma^0$ resonance as a $\bar{K}N$ bound state. Phys. Rev. Lett. 21, 29 (1967)
12. J.K. Kim, Multichannel phase-shift analysis of $\bar{K}N$ interaction in the region 0 to 550 MeV/c. Phys. Rev. Lett. 19, 1074 (1967)
13. W. Kittel, G. Otter, I. Wacek, The $K^-p$ proton charge exchange interactions at low energies and scattering lengths determination. Phys. Lett. 21, 349 (1966)
14. J. Ciborowski et al., Kaon scattering and charged Sigma hyperon production in $K^-p$ interactions below 300 MeV/c. J. Phys. G 8, 13 (1982)
15. D. Evans et al., Charge-exchange scattering in $K^-p$ interactions below 300 MeV/c. J. Phys. G 9, 885 (1983)
16. R.J. Nowak et al., Study of the $\Lambda-N$ system in low-energy $\Lambda-p$ elastic scattering. Phys. Rev. C 51, 38 (1995)
17. F. Eisele et al., Elastic $\Sigma^-p$ scattering at low energies. Phys. Lett. B 37, 885 (1983)
18. R. Engelmann, H. Filthuth, V. Hepp, Inelastic $\Sigma^-p$-interactions at low momenta. Phys. Lett. 21, 587 (1966)
19. V. Hepp, M. Schleich, A new determination of the capture ratio $r_c = \frac{\Sigma^-p\to\Sigma^0n}{(\Sigma^-p\to\Sigma^-n) + (\Sigma^-p\to\Lambda^0n)}$, the $\Lambda^0$-lifetime and the $\Sigma^- - \Lambda^0$ mass difference. Z. Phys. 214, 71 (1968)
20. R.B. Wiringa, V.G.J. Stoks, R. Schiavilla, Accurate nucleon-nucleon potential with charge-independence breaking. Phys. Rev. C 51, 38 (1995)
21. P. Doleschall, Private communication

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