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Kaonic systems

E. Oset[a]

Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigacion de Paterna, Aptdo. 22085, 46071, Valencia, Spain

Abstract. I make a short review of the situation of the kaonic systems, with novel information supporting the two $\Lambda(1405)$ states from the $K^-d \rightarrow n\pi\Sigma$ reaction. A review is made of the $\bar{K}NN$ system with recent calculations converging to smaller bindings and larger widths. Novel systems involving two kaons and one nucleon or three kaons are also reported and finally a short discussion is made of the analogous state DNN for which recent studies find a large binding and a small width.

1 Introduction

Kaonic systems have attracted much attention in the last decade. In particular the interaction of antikaons with nucleons is known to be very attractive. The leading interaction is given by the Weinberg Tomozawa term, which is proportional to the meson energy. This makes it stronger than for pions and can lead to bound systems of kaons and baryons. The simplest of these states are kaonic atoms. Here the Coulomb interaction provides the leading term for attraction, and the strong interaction leads to changes in the energy of the states (shifts) and produces a width due to K^- absorption in the nucleus [1–3]. Yet, the atoms studied in these former works correspond to orbits with l equal or bigger than one, and one can rightly ask where are the states with $l = 0$. The answer to this problem was given in [3] where it was found that, based on potentials derived from chiral unitary theory [4], those states are deeply bound, by 30-40 MeV, but the width is about 100 MeV, which sets clear limits to their experimental observability. One must also quote that there are different claims, with larger bindings and narrower widths, based on phenomenological potentials fitted to data of kaonic atoms [1]. Yet, the fact that K^- in atoms only see the surface of the nucleus implies that atoms only provide information at small nuclear densities, and whatever values one gets at central nuclear densities from these fits is due to assumptions made on the density functional.

At some time it looked like the experiment of [5] for the in-flight (K^-, N) reaction was giving support to the very deep K^--nucleus potential, but in [6] a serious drawback in the experimental set up was shown from the requirement of having, together with the energetic proton, at least one charged particle detected in the decay counter surrounding the target. Indeed, it was found that the shape of the original cross section was appreciably distorted, to the point of invalidating the claims made in the experimental paper on the strength of the kaon nucleus optical.

Advances in light systems, like the $\bar{K}NN$, have converged to small bindings and large widths, in line with the findings in heavier nuclei in [3]. Yet, surprisingly other systems involving kaons have stood a better chance and recently there have been findings of states with $K\bar{K}N$, $KK\bar{K}$ and others which can be associated to known states or are supported by present experiments. Finally, in analogy to the $\bar{K}NN$ one can study the DNN involving mesons with charm. Recent studies indicate that, contrary to the $\bar{K}NN$, that state is bound and narrow providing a challenge for observation in new facilities as JPARC and FAIR.

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[a] e-mail: `oset@ific.uv.es`

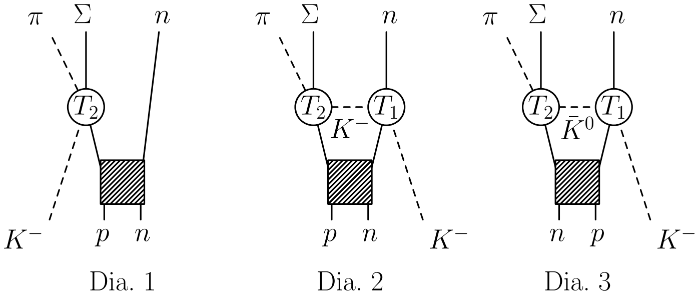

Fig. 1. Diagrams for the calculation of the $K^-d \to \pi\Sigma n$ reaction. T_1 and T_2 denote the scattering amplitudes for $\bar{K}N \to \bar{K}N$ and $\bar{K}N \to \pi\Sigma$, respectively.

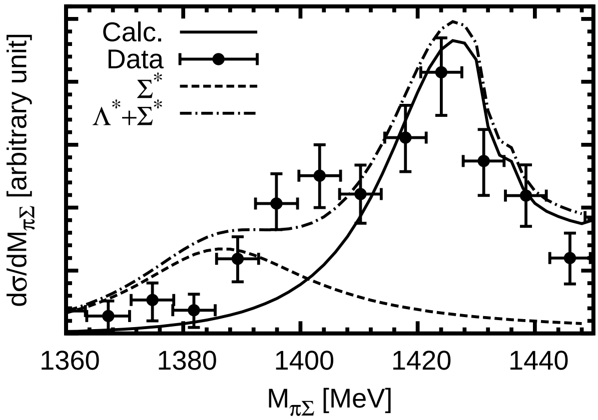

Fig. 2. A possible inference of the $\Sigma(1385)$ resonance to the $\Lambda(1405)$ spectrum of $K^-d \to \pi^+\Sigma^-n$ at 800 MeV/c incident K^- momentum. The $\Sigma(1385)$ spectrum (dashed line) is calculated by the Breit-Wigner amplitude and the phase space factor $|\mathbf{p}_\pi^*||\mathbf{p}_n|$. The dash-dotted lines denotes an incoherent sum of the $\Lambda(1405)$ and $\Sigma(1385)$ spectrum. The height of the $\Sigma(1385)$ spectrum is adjusted so as to reproduce the bump structure around 1390 MeV in the observed spectrum.

2 New developments concerning the two $\Lambda(1405)$ states: The $K^-d \to n\pi\Sigma$ reaction

Ever since it was reported that there were two poles contributing to the $\Lambda(1405)$ excitation [7], it has been reconfirmed by many other works using chiral dynamics (see [8] for a recent review). In [7] it was found that there are two states, one around 1400 MeV and wide and another one around 1420 MeV and narrow. The upper one couples mostly to $\bar{K}N$ while the lower one couples mostly to $\pi\Sigma$. In this sense, depending on which reaction one has and the mechanisms of production, one has different shapes for the resonance peak. If one can ensure that the resonance is formed by the $\bar{K}N$ entrance channel, then we expect a peak around 1420 MeV, relatively narrow. This is what is seen in the reaction $K^-p \to \pi^0\pi^0\Sigma^0$ of [9], studied in [10], and more recently in the $K^-d \to n\pi\Sigma$ reaction [11] studied theoretically in [12]. The mechanisms for the reaction are depicted in Fig. 1. The mechanism of Dia. 1 stands for single scattering which for kaons in flight does not contribute to the $\Lambda(1405)$ production. Dia. 2 is the dominant one for the $\Lambda(1405)$ production, where one has a scattering of the K^- with a neutron, gives it energy and then is left with an energy below threshold, such than in a secondary collision it produces the $\Lambda(1405)$ visible in the $\pi\Sigma$ spectrum. Then one can reproduce the experiment of [11], with a peak around 1420 MeV, as seen in Fig. 2.

The work of [12] has been discussed in [13] for forward neutron angles, questioning the approach of [12]. Yet, in [14] the issue has been clarified, showing that in [13] the NN potential is omitted. In addition the spikes shown in [13], tied to the neglect of the NN potential, disappear in any case when the experimental resolution is considered and then the remaining broader peak is tied to the $\Lambda(1405)$ production both if one uses the approach of [12] or [13].

In a recent paper [15] it is proposed to divide the cross section by the theoretical response with a constant amplitude. This method removes the spikes related to the kinematics of thresholds within a model, but its application to correct the experimental spectrum has problems because the spikes have disappeared in a resolution folded distribution and the division by this theoretical cross section creates the spikes that the method was supposed to remove. The discussion in those papers has served to clarify the situation and lay the grounds for further experiments in JPARC [16].

3 The $\bar{K}NN$ system

This system, with a K^- bound with two nucleons has been thoroughly studied. We can quote here the recent papers of [17–19], where using chiral unitary dynamics for the $\bar{K}N$ system they obtain binding energies for the $\bar{K}NN$ system with total spin $S = 0$ of about 20 MeV or less. The widths are large, of the order of 50 or more. Yet, if one takes into account the K^- absorption by the pair of nucleons one gets another 30 MeV extra width as shown recently in the nonperturbative study of [20].

Alternative studies to the variational calculations of [17] or the Faddeev calculations of [18,19] are done in [21–23] using the fixed center approximation to the Faddeev equations (FCA). One obtains a binding of about 30 MeV and a width of about 50 MeV, which turns out to be 80 MeV when the absorption by two nucleons is included. While there is no discussion that full Faddeev equations should be superior to the Fixed Center approximation, the usual Faddeev equations have a drawback in the uncertainty due to the use of off shell amplitudes in the approach, while the FCA relies upon on shell amplitudes. The question is less than trivial because as we shall discuss in the next section, in the Faddeev equations with a complete theory, there are explicit three body terms than cancel the contribution from the off shell two body amplitudes used as input in the Faddeev equations. In the absence of these terms one has to live with uncertainties that are present in the former approaches. Yet, the similarity with the FCA results, relying only on the on shell two body amplitudes, give us some confidence in those results, within moderate uncertainties, and the shared fact that the width of the $\bar{K}NN$ system is much bigger than the binding. This looks then as a lost case for experimental observation, although claims were done about its observation. We refrain from quoting these works here and lead to reader to papers where these issues are discussed in detail showing that the peaks observed experimentally come from conventional, unavoidable mechanisms, related to the absorption of the kaon by a pair of nucleons [24–27].

The $\bar{K}NN$ state found in all approaches corresponds to total spin $J = 0$. Interestingly, it was also found in [21,22] that a state with $J = 1$, like a K^-d bound state, also appears, with smaller binding but also large width. This state is also found in a more recent work using Faddeev calculations [19], with smaller binding than the one of $J = 0$.

4 Three body systems involving kaons

In this section we simply want to report on the interesting finding of [28,29] studying systems made of two mesons and one baryon, with strangeness S=-1 in [28] and S=0 in [29]. What was found in these references is that the low lying baryon states with $J^P = 1/2^+$, except for the Roper which is a very complex object [30], can be obtained as resonant states of two mesons and one baryon.

A second interesting finding of these works was the cancellation between the contribution from the off shell amplitudes in the Faddeev equations with three body terms stemming from the same chiral Lagrangians. The cancellation goes as that: In Fig. 3 the internal lower line between two t-matrices is off shell, the amplitude can be written as

$$t = t_{on} + \beta(q^2 - M^2) \tag{1}$$

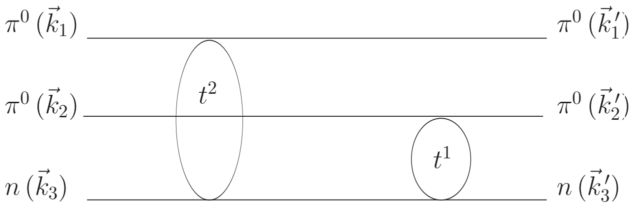

Fig. 3. An example of a simplest possible interaction amongst the three particles, $\pi^0\pi^0 n$. The labels $\mathbf{k}_i$ ($\mathbf{k}_i'$) on the particle lines denote the momenta corresponding to the initial (final) state. The blob stands for the two body scattering matrix.

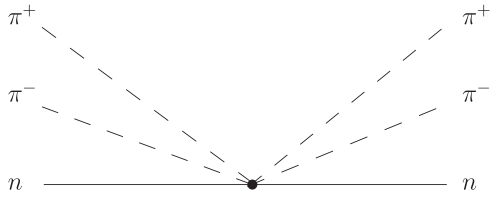

Fig. 4. Source of three-body force from the chiral Lagrangians.

However, the off shell term going as $(q^2 - M^2)$ gets cancelled by the propagator of this line and one gets a diagram topologically equivalent to a three body force. It was shown in [28, 29] that the contribution from this off shell terms gets canceled by the term of Fig. 4 which stems from the same chiral Lagrangian upon expansion of the function $U(\phi) = exp(i\sqrt{2}\phi/f_\pi)$ in the meson fields. This means that one can then ignore the diagrams of Fig. 4 and evaluate only those of the type of Fig. 3, but using only the on shell two body amplitudes. This findings also shows that the contribution from the unphysical off shell part of the amplitudes gets cancelled and the results only depend on physical quantities. This finding also implies that calculations based on pure Faddeev of full amplitudes (containing the off shell part) introduce some spurious contribution. In three body calculations where one can compare with data one reestablishes the equilibrium by introducing empirically three body forces, most of which go into cancelling the spurious contribution of the off shell part of the two body amplitudes. This fact should be kept in mind when discussing the binding obtained with the Faddeev equations for the $\bar{K}NN$ system and the value of the FCA, which relies only upon the on shell two body amplitudes to get a feeling of the uncertainties.

Another of the relevant findings of [29] is that a state made of $K\bar{K}N$ of $J^P = 1/2^+$ is found with energy around 1920 MeV with the $K\bar{K}$ system forming a cluster around the $f_0(980)$ resonance. This finding was actually observed before within a variational calculation in [31]. The interest in this state has increased since it was shown in [32] that this state was an ideal candidate to explain the peak around 1920 MeV observed in the $\gamma p \to K^+\Lambda$ reaction. It has been quite rewarding to see that in a recent work using Bayesian statistics to determine the most probable combinations of resonances needed to describe the $\gamma p \to K^+\Lambda$ reaction [33, 34], a $N^*, J^P = 1/2^+$ state with mass around 1900 MeV is needed to best explain the data.

5 Other systems involving kaons

The dream of having kaons as a glue that binds nucleons together has met with the undesired feature that the widths of the systems are very large. Yet, there are other systems involving kaons that could be investigated and gradually one is finding some of them. For instance, in [35] a Ξ state around 1900 MeV with $J^P = 1/2^+$ is found investigating the $\bar{K}\bar{K}N$ system, where the stable configuration corresponds to a cluster of $\bar{K}N$ and a kaon. Similarly in [36] a resonance made from $K\bar{K}K$ is found which is associated to the known resonance K(1460). So, ultimately the dream of having the kaon glueing elementary particles together is coming true, but in systems quite different than those envisaged originally.

6 The DNN system

The $\bar{K}NN$ system described above had the problem of presenting a width which was much larger than the binding. Intuitively it is easy to understand that. The $\bar{K}N$ couples to give a $\Lambda(1405)$ with about 30-40 MeV binding. Since the $\bar{K}$ can couple to the second nucleon, then the probability of decay is about double and one gets a width of the order of 60 MeV without absorption, which has to be added to it. The binding was found of the order of 20 MeV in the latest studies. The DNN system is the analogous one, substituting a strange quark by a charm quark. The analogies continue because the DN system, together with other coupled channels, develops the $\Lambda_c(1595)$ resonance according to [37,38]. However, unlike the $\Lambda(1405)$, the $\Lambda_c(1595)$ has a width of 2.6 MeV. On the other hand, the potential of the DN interaction goes like the energy of the D, similarly to the one of the $\bar{K}N$ that goes like the energy of the kaon. As a consequence of this, one expects two features: the system DNN should be more bound and should have a smaller width than the $\bar{K}NN$ one. This gives great chances to have a relatively stable DNN state, perfectly observable.

The intuitive conclusions obtained before are fully supported by recent calculations. Two independent methods have been used to determine the properties of this state: a Fixed Center evaluation and a variational calculation [39]. Investigations with the two methods, carried out independently, have converged to the same results, which is the existence of a bound state DNN around 3500 MeV, with a binding of about 200 MeV and a width of about 30-40 MeV. The width is much smaller than the binding in this case, and this makes it a clear case for observation, unlike the $\bar{K}NN$ system. Suggestions are made to look for this state at FAIR using the $\bar{p}\ {}^3He \to \bar{D}DNN$ reaction [39].

7 Conclusions

In this short review on recent developments on kaonic systems I have called the attention to new information on the two $\Lambda(1405)$ states stemming from the reaction $K^- d \to n\pi\Sigma$. Old data had in store the surprise that there was a $\Lambda(1405)$ at about 1420 MeV, as chiral unitary theory was predicting. New experiments along these lines are being proposed for JPARC. I reviewed recent developments concerning the $\bar{K}NN$ system showing that all new calculations have been using the chiral unitary approach as input for $\bar{K}N$ and they find binding energies around 20 MeV. The widths are however larger than that and counting the absorption by two nucleons, which has been evaluated accurately recently, the width of this state is around 80 MeV. I also reported in the existence of a bound state of spin J=1, which is less bound but equally wide.

I also reported on the interesting finding, made possible within a complete chiral theory, that the unphysical contribution from the off shell part of the two body amplitudes in the Faddeev equations is cancelled by other three body terms that stem directly from the same chiral theory. Since this cancellation is not implemented in ordinary Faddeev or variational calculations one had to accept some uncertainties from this source. In this sense, the calculations done for the $\bar{K}NN$ system with the Fixed Center Approximation, which involves only two body on shell amplitudes, plays an important role as a guide on what the uncertainties can be. They are about 10 MeV in the binding, but the relevant remaining feature is that the width is much larger than the binding, making the quest for experimental observation something like mission impossible.

Surprisingly it has been recently found that there are other systems where the kaons play a role glueing other elementary particles together, and I reported on the recently found $\bar{K}KN$, $\bar{K}KN$ and KKK, which can be associated to known resonances or play a role in reactions which are currently being investigated.

Finally, I reported on the DNN system, where two independent methods lead to the conclusion that the state is bound and has a width much smaller than the binding, which should make it a clear case for experimental observation in reactions at JPARC and FAIR.

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References

1. C. J. Batty, E. Friedman and A. Gal, Phys. Rept. **287**, 385 (1997).
2. E. Friedman and A. Gal, Nucl. Phys. A **881**, 150 (2012).
3. S. Hirenzaki, Y. Okumura, H. Toki, E. Oset and A. Ramos, Phys. Rev. C **61**, 055205 (2000).
4. A. Ramos and E. Oset, Nucl. Phys. A **671**, 481 (2000).
5. T. Kishimoto, T. Hayakawa, S. Ajimura, F. Khanam, T. Itabashi, K. Matsuoka, S. Minami and Y. Mitoma *et al.*, Prog. Theor. Phys. **118**, 181 (2007).
6. V. K. Magas, J. Yamagata-Sekihara, S. Hirenzaki, E. Oset and A. Ramos, Phys. Rev. C **81**, 024609 (2010).
7. D. Jido, J. A. Oller, E. Oset, A. Ramos and U. G. Meissner, Nucl. Phys. A **725**, 181 (2003).
8. Y. Ikeda, T. Hyodo and W. Weise, Nucl. Phys. A **881**, 98 (2012).
9. S. Prakhov *et al.* [Crystall Ball Collaboration], Phys. Rev. C **70**, 034605 (2004).
10. V. K. Magas, E. Oset and A. Ramos, Phys. Rev. Lett. **95**, 052301 (2005).
11. O. Braun, H. J. Grimm, V. Hepp, H. Strobele, C. Thol, T. J. Thouw, D. Capps and F. Gandini *et al.*, Nucl. Phys. B **129**, 1 (1977).
12. D. Jido, E. Oset and T. Sekihara, Eur. Phys. J. A **42**, 257 (2009).
13. K. Miyagawa and J. Haidenbauer, Phys. Rev. C **85**, 065201 (2012).
14. D. Jido, E. Oset and T. Sekihara, arXiv:1207.5350 [nucl-th].
15. J. Revai, arXiv:1203.1813 [nucl-th].
16. M. Noumi *et al.*, *Spectroscopic study of hyperon resonances below KN threshold via the* (K^-, n) *reaction on Deuteron* - J-PARC proposal E31 (2009).
17. A. Dote, T. Hyodo and W. Weise, Phys. Rev. C **79**, 014003 (2009).
18. Y. Ikeda, H. Kamano and T. Sato, Prog. Theor. Phys. **124**, 533 (2010).
19. N. Barnea, A. Gal and E. Z. Liverts, Phys. Lett. B **712**, 132 (2012).
20. M. Bayar and E. Oset, arXiv:1207.1661 [hep-ph].
21. M. Bayar, J. Yamagata-Sekihara and E. Oset, Phys. Rev. C **84**, 015209 (2011).
22. E. Oset, D. Jido, T. Sekihara, A. Martinez Torres, K. P. Khemchandani, M. Bayar and J. Yamagata-Sekihara, Nucl. Phys. A **881**, 127 (2012).
23. M. Bayar and E. Oset, Nucl. Phys. A **883**, 57 (2012).
24. E. Oset and H. Toki, Phys. Rev. C **74**, 015207 (2006).
25. V. K. Magas, E. Oset, A. Ramos and H. Toki, Phys. Rev. C **74**, 025206 (2006).
26. E. Oset, V. K. Magas, A. Ramos and H. Toki, nucl-th/0701023.
27. V. K. Magas, E. Oset and A. Ramos, Phys. Rev. C **77**, 065210 (2008).
28. A. Martinez Torres, K. P. Khemchandani and E. Oset, Phys. Rev. C **77**, 042203 (2008).
29. A. Martinez Torres, K. P. Khemchandani and E. Oset, Phys. Rev. C **79**, 065207 (2009).
30. O. Krehl, C. Hanhart, S. Krewald and J. Speth, Phys. Rev. C **62**, 025207 (2000).
31. D. Jido and Y. Kanada-En'yo, Phys. Rev. C **78**, 035203 (2008).
32. A. Martinez Torres, K. P. Khemchandani, U. -G. Meissner and E. Oset, Eur. Phys. J. A **41**, 361 (2009).
33. L. De Cruz, T. Vrancx, P. Vancraeyveld and J. Ryckebusch, Phys. Rev. Lett. **108**, 182002 (2012).
34. L. De Cruz, J. Ryckebusch, T. Vrancx and P. Vancraeyveld, Phys. Rev. C **86**, 015212 (2012).
35. Y. Kanada-En'yo and D. Jido, Phys. Rev. C **78**, 025212 (2008).
36. A. Martinez Torres, D. Jido and Y. Kanada-En'yo, Phys. Rev. C **83**, 065205 (2011).
37. J. Hofmann and M. F. M. Lutz, Nucl. Phys. A **763**, 90 (2005).
38. T. Mizutani and A. Ramos, Phys. Rev. C **74**, 065201 (2006).
39. M. Bayar, C. W. Xiao, T. Hyodo, A. Dote, M. Oka and E. Oset, arXiv:1205.2275 [hep-ph].