Recent developments in chiral dynamics of hadrons and hadrons in a nuclear medium

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In this talk I present recent developments in chiral dynamics of hadrons and hadrons in a medium addressing the following points: interaction of the octet of pseudoscalar mesons with the octet of baryons of the nucleon, showing recent experimental evidence on the existence of two $\Lambda(1405)$ states, the interaction of the octet of pseudoscalar mesons with the decuplet of baryons of the Δ, with particular emphasis on the $\Lambda(1520)$ resonance, dynamically generated by this interaction. Then I review the interaction of kaons in a nuclear medium and briefly discuss the situation around the claims of deeply bound states in nuclei. The large renormalization of the $\Lambda(1520)$ in the nuclear medium is shown as another example of successful application of the chiral unitary techniques.

1. Introduction

Chiral theory has caught up as an important tool to deal with hadron reactions at low and intermediate energies, accounting for the underlying basic QCD dynamics. By introducing chiral Lagrangians where the explicit fields are mesons and baryons, a perturbative expansion in powers of momenta is done, leading to chiral perturbation theory (χPT) which has allowed great progress in hadron physics. A very important development in this direction is done with the introduction of unitarity in coupled channels which has allowed to extend the predictions of chiral theory at higher energies than is possible with chiral perturbation theory. A review of the basic ideas can be found in [1]. One of the important issues of this unitarized theory is that it allows to deal with resonances, some of which appear necessarily as a consequence of the dynamics of the chiral Lagrangians, in a similar way as bound states or resonances appear in potential theory in Quantum Mechanics. We call these resonances dynamically generated and by now about 10-15 percent of the particles in the PDG can qualify for this nature, meaning that the meson- meson cloud, or meson-baryon cloud, becomes the basic part of the wave function overriding the relevance of the primary building blocks: constituent $q\bar{q}$ or three q for the case of mesons or baryons, respectively. I shall mention here some of these cases.

The findings about the nature of some resonances have also consequences in nuclear physics, since basic features associated to the chiral dynamics of the resonances show up in interesting ways in nuclear processes which can then be used to stress the nature of these resonances. I shall also give some example of that in this talk. A more extensive description of the ideas exposed here can be found in [2], but we concentrate here on the recent developments not discussed in [2].

2. The meson baryon interaction

We skip here details on the chiral lagrangians which can be found in [1, 2, 3, 4] and sketchhow unitarity enters the framework. One can find a systematic and easily comprehensible derivation of the ideas of the N/D method applied for the first time to the meson baryon system in [5], which we reproduce here below and which follows closely the similar developments used before in the meson meson interaction [6]. One defines the transition $T-$matrix as $T_{i,j}$ between the coupled channels which couple to certain quantum numbers. For instance in the case of $\bar{K}N$ scattering studied in [5] the channels with zero charge are K^-p, $\bar{K^0}n$, $\pi^0\Sigma^0$,$\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Lambda$, $\eta\Lambda$, $\eta\Sigma^0$, $K^+\Xi^-$, $K^0\Xi^0$. Unitarity in coupled channels is written as

$$ImT_{i,j} = T_{i,l}\rho_l T^*_{l,j} \tag{1}$$

where $\rho_i \equiv 2M_l q_i/(8\pi W)$, with q_i the modulus of the c.m. three–momentum, and the subscripts i and j refer to the physical channels. This equation is most efficiently written in terms of the inverse amplitude as

$$\text{Im } T^{-1}(W)_{ij} = -\rho(W)_i \delta_{ij} \ , \tag{2}$$

The unitarity relation in Eq. (2) gives rise to a cut in the T–matrix of partial wave amplitudes, which is usually called the unitarity or right–hand cut. Hence one can write down a dispersion relation for $T^{-1}(W)$

$$T^{-1}(W)_{ij} = -\delta_{ij}\left\{\widetilde{a}_i(s_0) + \frac{s-s_0}{\pi}\int_{s_i}^{\infty} ds' \frac{\rho(s')_i}{(s'-s)(s'-s_0)}\right\} + \mathcal{T}^{-1}(W)_{ij} \ , \tag{3}$$

where s_i is the value of the s variable at the threshold of channel i and $\mathcal{T}^{-1}(W)_{ij}$ indicates other contributions coming from local and pole terms, as well as crossed channel dynamics but *without* right–hand cut. These extra terms are taken directly from χPT after requiring the *matching* of the general result to the χPT expressions. Notice also that the curled bracket, that we call the $g(s)$ function, is the familiar scalar loop integral.

One can further simplify the notation by employing a matrix formalism. Introducing the matrices $g(s)$ = diag $(g(s)_i)$, T and $\mathcal{T}$, the latter defined in terms of the matrix elements T_{ij} and $\mathcal{T}_{ij}$, the T-matrix can be written as:

$$T(W) = [I - \mathcal{T}(W)\cdot g(s)]^{-1}\cdot \mathcal{T}(W) \ . \tag{4}$$

which can be recast in a more familiar form as

$$T(W) = \mathcal{T}(W) + \mathcal{T}(W) g(s) T(W) \tag{5}$$

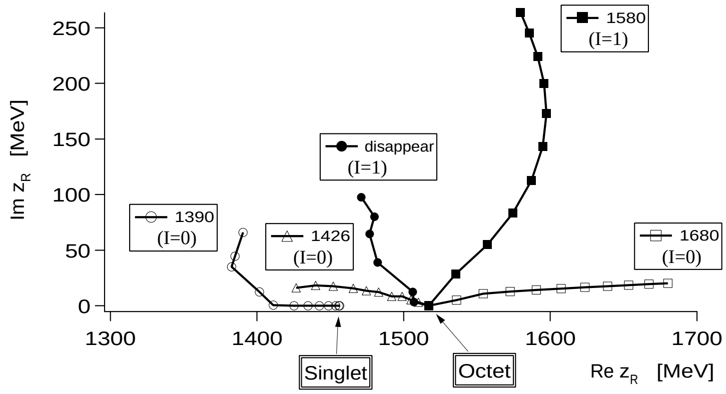

Figure 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking gradually. The symbols correspond to the step size $\delta x = 0.1$ with x running from 0 to 1 . The results are from [8].

Now imagine one is taking the lowest order chiral amplitude for the kernel $\mathcal{T}$ as done in [5]. Then the former equation is nothing but the Bethe Salpeter equation with the kernel taken from the lowest order Lagrangian and factorized on shell, the same approach followed in [7], where different arguments were used to justify the on shell factorization of the kernel.

The on shell factorization of the kernel, justified here with the N/D method, renders the set of coupled Bethe Salpeter integral equations a simple set of algebraic equations.

3. Poles of the T-matrix

The amplitudes of the channels discussed above are extrapolated to the complex second Riemann sheet and we search for poles there. Here I discuss recent finding concerning the two poles corresponding to the $\Lambda(1405)$ resonance. In fig. 1 we can see, from the work of [8], the trajectories of the poles when we start from an SU(3) symmetric situation and go to the real world where this symmetry is broken. This appears because of the different masses of the mesons and the baryon in the study of the interaction of the octet of the pion and the octet of the nucleon respectively. The SU(3) symmetric case corresponds to the poles in the real axis where we have two degenerate octets and a singlet. As soon as SU(3) symmetry starts being broken the degeneracy of the two octets disappears and two branches for I=0 and for I=1 develop which, at the end of the trajectories that represent the real world, correspond to well know resonances like the $\Lambda(1670)$ etc.

The interesting thing to note is that in the region of the $\Lambda(1405)$ there are two poles, one from the original singlet and another one from one of the branches of the original octet. In practice it is impossible to see two peaks in any reaction because the two resonances overlap, but the fact that the two poles couple differently to $\bar{K}N$ and $\pi\Sigma$ (the narrower pole couples strongly to $\bar{K}N$ and the wider one to $\pi\Sigma$) has as a consequence that the

$\Lambda(1405)$ should show up with quite different shapes in different reactions depending on their particular dynamics. This is indeed the case as could be demonstrated recently with the performance of the $K^- p \to \pi^0\pi^0\Sigma^0$ [9] experiment. This reaction has been studied in [10] and the basic mechanism for the reaction is given by fig. 2 left, where we see that it is dominated by the $K^- p \to \pi^0\Sigma^0$ amplitude which has a strong contribution from the narrow pole at higher energies. We should then expect that the peak of the $\Lambda(1405)$ appears at higher energies in this reaction and with a smaller width, and this is the case as one can see in fig. 2 right by comparing with the standard $\Lambda(1405)$ extracted from the $\pi^- p \to K^0\pi\Sigma$ reaction which was studied in [11].

The two experimental figures for the shapes of the $\Lambda(1405)$ in both reactions can be seen in Fig. 2 right, giving a strong support to the existence of the two $\Lambda(1405)$ states.

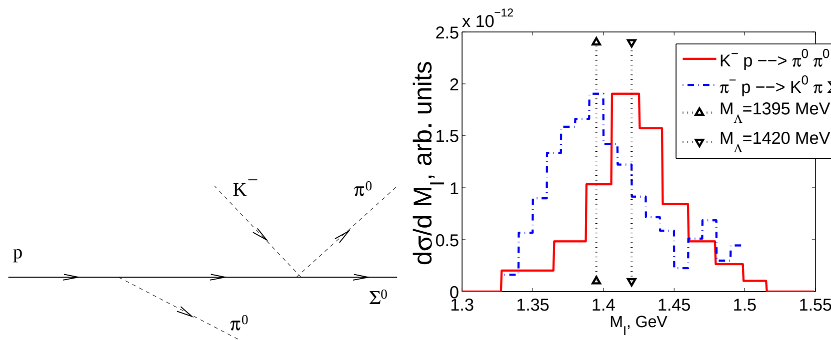

Figure 2. Nucleon pole term for the $K^- p \to \pi^0\Sigma^0$ (left) and two experimental shapes of $\Lambda(1405)$ resonance (right). See text for more details.

4. The interaction of the decuplet of baryons with the octet of mesons

Given the success of the chiral unitary approach in generating dynamically low energy resonances from the interaction of the octets of stable baryons and the pseudoscalar mesons, in [12] the interaction of the decuplet of $3/2^+$ with the octet of pseudoscalar mesons was studied and shown to lead to many states which were associated to experimentally well established $3/2^-$ resonances. One of these would correspond to the $\Lambda(1520)$.

In [13, 14] a refinement of the approach discussed above has been done including the $\bar{K}N$ and $\pi\Sigma$ decay channels of the $\Lambda(1520)$ and finetuning the subtraction constants in the g function, such that a good agreement with the position and width of the $\Lambda(1520)$ is attained. With this new information one can face the study of the reaction $K^- p \to \pi^0\pi^0\Lambda$ by using the mechanisms of $K^- p \to \pi^0\Sigma^{*0} \to \pi^0\pi^0\Lambda$ which provides the dominant contribution to the reaction at energies close to the $\Lambda(1520)$. At higher energies of the experiment of [15] one finds other background mechanisms (dashed line in fig. 3) providing a contribution that helps bring the theory and experiment in good agreement, as we can see in fig. 3. One can see in the figure that up to 575 MeV/c of momentum of the K^- the mechanism based on the strong coupling of the $\Lambda(1520)$ to the $\pi\Sigma(1385)$

channel is largely dominant and provides the right strength of the cross section. Obviously it would be most interesting to investigate the region of lower energies of the K^- in order to see if the predictions done by the theory are accurate. This could be done for a different reaction, the $K^-p \to \pi^+\pi^-\Lambda$ [16], where the cross section is double than for $K^-p \to \pi^0\pi^0\Lambda$. As we can see in fig. 3, the predictions of the theory are in good agreement with the data.

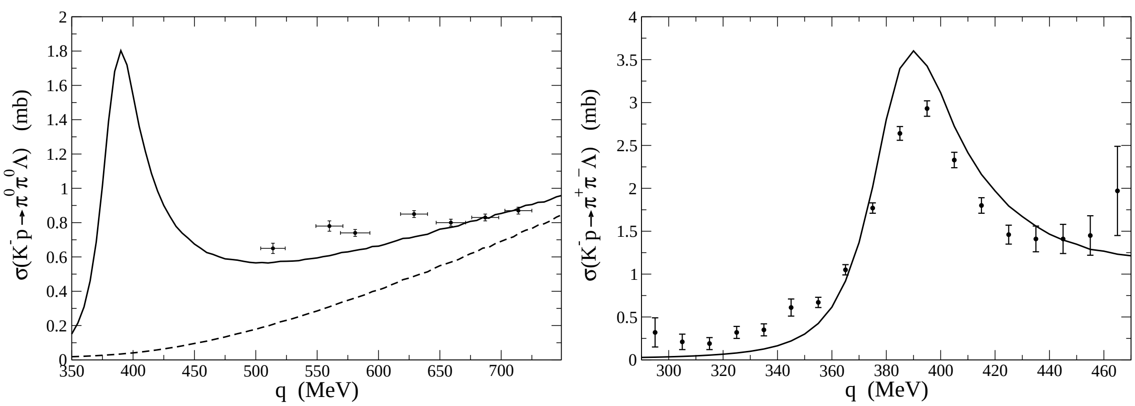

Figure 3. Cross section for the $K^-p \to \pi^0\pi^0\Lambda$ (left) and $K^-p \to \pi^+\pi^-\Lambda$ [16] right.

5. $\bar{K}$ in a nuclear medium

The $\bar{K}$ interaction in a nuclear medium has been the subject of many studies. In [17] a selfconsistent calculation of the $\bar{K}$ nucleus optical potential is done and the results are consistent with data of kaonic atoms as shown in [18]. This potential has a strength of about 50 MeV attraction at normal nuclear matter and an imaginary part of about 50 MeV. This leads to deeply bound states in nuclei of about 30 MeV binding and widths of around 100 MeV. It was hence surprising to find other potentials where, with only three nucleons, the $\bar{K}$ potential reaches a strength of about 650 MeV at the center for the nucleus [19]. A closer inspection shows that the huge results come from several approximations among them the lack of selfconsistency in the calculations that, according to [20], leads to meaningless results, plus the shrinking of the nucleus to attain ten times nuclear matter density at the center of the nucleus. Based on this potential, some peaks seen at KEK in the proton spectra following the absorption of K^- on ^4He were interpreted as a signal of deeply bound kaonic states. Recently, it was shown in [21] that the peaks of the experiments could be easily interpreted in terms of K^- absorption by pairs of nucleons leading to Σp or Λp without further interaction of the baryons with the nucleus. This claim has been recently reinforced by an experiment at FINUDA [22] where the proton spectra is also studied following K^- absorption in different nuclei and the same peaks are seen. An additional measurement of pions in coincidence shows that they come from the decay of the Σ for the peak at lower proton momentum, hence, confirming the claims of [21].

The FINUDA collaboration has another paper [23] in which a wider peak has been seen in the invariant mass of $p\Lambda$ measured back to back following K^- absorption in different nuclei and which was claimed to correspond the a K^-pp bound state. In another recent paper [24] it has been shown that such a peak appears unavoidably as a consequence of the mechanism of K^- absorption by a pair of nucleons going to $p\Lambda$, followed by rescattering of the p or the Λ in the nucleus. Thus, the claims made for deeply bound kaons in nuclei with binding energies of about 200 MeV and narrow widths are unfounded and this was the conclusion of a recent meeting explicitly devoted to this issue in ECT^* Trento [25].

6. $\Lambda(1520)$ in a nuclear medium

Within these techniques there is work done in η selfenergy in the medium, ρ and ϕ renormalization in nuclei and others, but I shall concentrate here on the latest issue which has connections with section 4, where we studied the interaction of the decupled of baryons with the octet of nucleons. The $\Lambda(1520)$ is one of the resonances dynamically generated with the channels $\pi\Sigma(1385)$ and $K\Xi$. Actually, this picture is only qualitative since the $\Lambda(1520)$ couples also to the $\pi\Sigma$ and $\bar{K}N$ channels to which it decays. The study done in [14] including these channels finds that the coupling of the resonance to the $\pi\Sigma(1385)$ is the strongest of all, as if it kept memory of what would happen in a simplified ideal world.

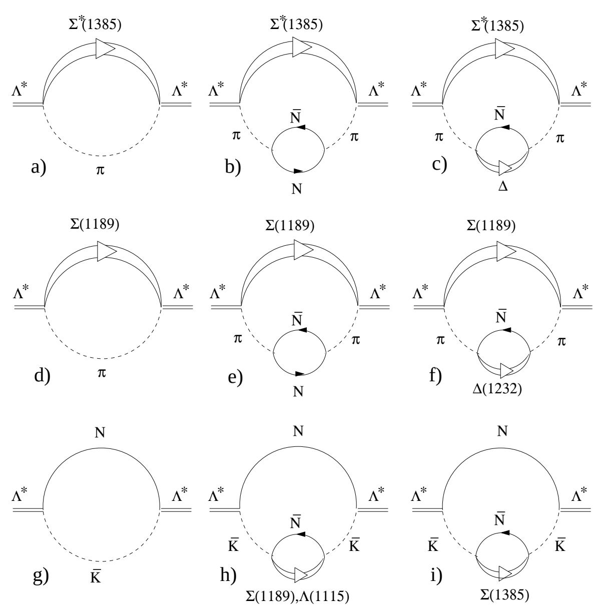

Figure 4. Diagrams for the $\Lambda(1520)$ selfnergy in the nuclear medium

Even if the $\Lambda(1520)$ couples strongly to the $\pi\Sigma(1385)$ channel, it does not decay into this state because it is below the threshold of $\pi\Sigma(1385)$. However, in a nucleus the pion can easily excite a ph which has energy starting from zero. Thus we gain 140 MeV phase space for the decay and this leads to a width in the medium from only this channel which is already bigger than the 14 MeV free width of the $\Lambda(1520)$. This is not the only source of medium modification for the resonance, since the other decay channels are also modified in the medium. A detailed study has been done [26] (see diagrams in fig. 4) and we present the results in fig. 5.

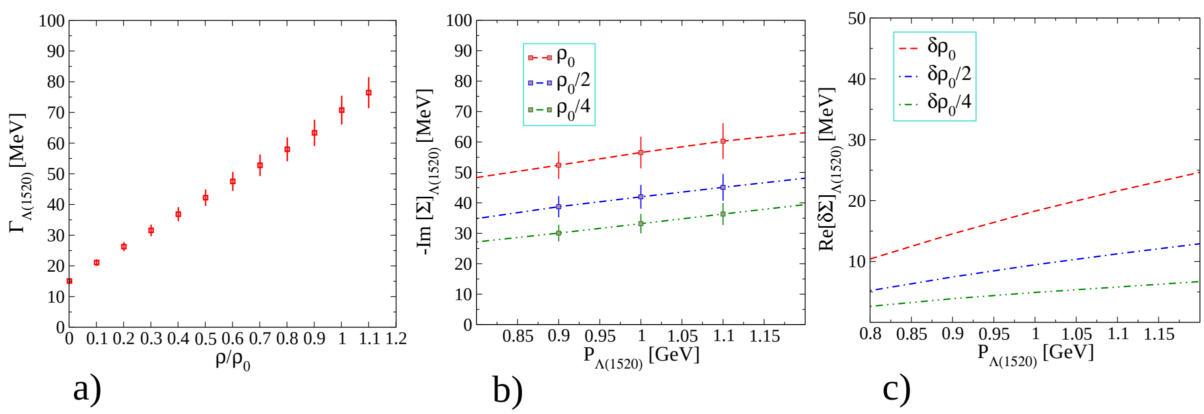

Figure 5. Results for the $\Lambda(1520)$ selfenergy as a function of the nuclear density and $\Lambda(1520)$ momentum.

7. Conclusions

The use of chiral Lagrangians for the meson baryon interaction and the unitary extensions of chiral perturbation theory have allowed to face a large amount of problems which were barred to standard perturbation techniques. It has opened the door to the study of many baryonic resonances which qualify neatly as dynamically generated resonances, or quasibound states of meson baryon. Thanks to this, a quantitative description of the meson baryon interaction at intermediate energies is now possible and with this, an important systematics has been introduced in the many body problem to face issues on the renormalization of hadron properties in the nuclear medium. The constructed scheme is rather powerful and allows to make predictions which consecutive experiments are proving right. Two of these predictions, the two states for the $\Lambda(1405)$, and the nature of the $\Lambda(1520)$ roughly as a quasibound state of $\pi\Sigma(1385)$, have found strong support from two very recent experiments. The spectacular change of the width of the $\Lambda(1520)$ in the medium is partly due to the strong coupling of the resonance to the $\pi\Sigma(1385)$ as predicted by chiral unitary dynamics. Finally, we also discussed that chiral theory, implementing selfconsistency in the many body calculation, leads to a moderate attraction for $\bar{K}$ in nuclei, and that recents claims for deeply bound kaon states, which would require a huge $\bar{K}$ optical potential, were a consequence of an incorrect identification of some peaks for which a natural conventional explanation has been just found.

Altogether, one is seeing through all this work that chiral dynamics is a key ingredient that allows a unified description of much of the hadronic world at low and intermediate energies.

8. Acknowledgments

This work is partly supported by the Spanish CSIC and JSPS collaboration, the DGICYT contract number BFM2003-00856, and the E.U. EURIDICE network contract no. HPRN-CT-2002-00311. This research is part of the EU Integrated Infrastructure Initiative Hadron Physics Project under contract number RII3-CT-2004-506078.

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