MENU 2007
11th International Conference
on Meson-Nucleon Physics and
the Structure of the Nucleon
September10-14, 2007
IKP, Forschungzentrum Jülich, Germany

Dynamically generated resonances in two meson-one baryon systems

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Abstract

We study the systems of two mesons and one baryon with total strangeness $S = -1$ ($\pi\overline{K}N$, $\pi\pi\Sigma$, etc.) by solving Faddeev equations in the coupled channel approach. The calculations have been carried out for $L = 0$, leading to total spin parity $1/2^+$ for the three body system. The study resulted into dynamical generation of many low-lying Σ and Λ resonances which can be associated to those in the Particle Data Book.

1 Introduction

After the finding of a narrow peak in the invariant mass of the K^+n system [1], which was associated to a strangeness +1 pentaquark state, i.e., the θ^+, a series of experimental groups reported findings of the same state but in the pK_S invariant mass (see discussion in [2] for example). Since the K_s is a mixed state of K^0 and $\overline{K}^0$, the pK_S system can possess strangeness +1 or −1. Therefore, the narrow state found in the pK_S system could be, for example, a Σ^{*+} instead of a θ^+. A search for a Σ or Λ resonance in this mass region is thus interesting.

In fact, there exist Λ and Σ resonances in this energy region but with poor or controversial status [3]. Also some of them seem to remain unexplained in terms of two-body dynamics, e.g., a study of the $K^-p \to \pi^0\pi^0\Lambda$ reaction in [4], where the $\Lambda(1520)$ gets dynamically generated and which explains the bulk of the data [5], fails to explain a bump in the $\Lambda(1600)$ region. Additionally, in [6] the excitation of the $\Sigma(1660)$ has been indicated in the data on the $K^-p \to \pi^0\pi^0\Sigma^0$ reaction. These findings naturally demand a study of three-body system(s) such as $\pi\pi\Sigma$, $\pi\pi\Lambda$, $\pi\overline{K}N$, etc.

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2 Formalism

The first striking thought is that adding a π to the $\Lambda(1405)$, which is a resonance in the $\pi\Sigma$ system, one obtains a total mass ~ 1542 MeV. This is exactly the energy region where the narrow state in the pK_S system was found and where the S=-1 resonances are not well understood. The $\Lambda(1405)$ has been studied extensively using chiral dynamics [7–9] where it gets dynamically generated in the $\overline{K}N$ system and its coupled channels and its properties are well reproduced. The idea, thus, is to exploit this knowledge and extend it to a study of the three-body systems formed by adding a pion to all the combinations of 0^- mesons and $1/2^+$ baryons which couple to strangeness -1. For the net charge zero, we end up with 22 coupled channels [10].

The input two-body t-matrices required to solve the Faddeev equations

$$T^i = t^i + t^i G\Big[T^j + T^k\Big], \ \mathrm{i} \neq \mathrm{j} \neq \mathrm{k} = 1,3$$

have been calculated by solving the Bethe-Salpeter equation using the potentials obtained from chiral Lagrangians as in [7,9]. The form of the potentials in this approach is such that it can be divided into an on-shell part, which depends only on the center of mass (C.M) energy of the interacting particles, and an off-shell part, which is inversely proportional to the propagator of the particle. This gives rise to three body forces [10] which have been found, in some approximations, to cancel with those originating directly from the chiral Lagrangian [10]. For a realistic case, the total contribution of three-body forces from all the sources has been found to be about 5% of the total on-shell contribution [10]. Hence, the calculations have been done using on-shell two body t-matrices. In this case, the terms with two successive interaction can be expressed as $t^i g^{ij} t^j$, with

$$g^{ij} = \left(\prod_{r=1}^{D} \frac{N_r}{2E_r}\right) \frac{1}{\sqrt{s} - E_i(\mathbf{k}_i) - E_j(\mathbf{k}_j) - E_k(\mathbf{k}_i + \mathbf{k}_j) + i\epsilon}$$

where $\sqrt{s}$ is the total energy in the global CM system, $E_l = \sqrt{\mathbf{k}_l^2 + m_l^2}$ is the energy of the particle l, N_l is a normalization constant and D is the number of particles propagating between two interactions [10]. These terms correspond to the situation where there are no loops and hence the g^{ij} propagators depend on the on-shell variables only. The terms with three t-matrices involve a loop function of three particle propagators, e.g.

$$\int \frac{d^3q}{(2\pi)^3} t^1(s_{23}) g^{13}(\mathbf{q}) t^3(s_{12}(q)) g^{32}(\mathbf{q}) t^2(s_{13}) \tag{1}$$

where s_{13}, s_{23} are defined in terms of on-shell variables and $s_{12}(q)$ denotes the dependence of the t^3-matrix on the loop variable. Therefore, t^1 and t^2 can be extracted out of the integral, but not t^3. However, if we re-arrange the expression (1) as

$$t^1(s_{23})\left[\int \frac{d^3q}{(2\pi)^3} g^{13}(\mathbf{q})t^3(s_{12}(q))g^{32}(\mathbf{q})[g^{32}]^{-1}[t^3(s_{12})]^{-1}\right]t^3(s_{12})g^{32}t^2(s_{13}) \tag{2}$$

where an identity expression depending on the on-shell variables, i.e., $[g^{32}]^{-1}$ $[t^3(s_{12})]^{-1}t^3(s_{12})g^{32}$, has been introduced, and define

$$G^{132} = \int \frac{d^3q}{(2\pi)^3} g^{13}(\mathbf{q})t^3(s_{12}(q))g^{32}(\mathbf{q})[g^{32}]^{-1}[t^3(s_{12})]^{-1} \tag{3}$$

the equation (1) can be expressed as $t^1(s_{23})G^{132}t^3(s_{12})g^{32}t^2(s_{13})$. Now the $t^3(s_{12})g^{32}t^2(s_{13})$ term depends only on the on-shell variables, the dependence of t^3 and g^{32} on the running variable has been taken care of when defining the G function. With this, the Faddeev equations can be written as [10]

$$T_R^{ij} = t^i g^{ij} t^j + t^i \left[G^{iji}T_R^{ji} + G^{ijk}T_R^{jk}\right] \quad \mathrm{i} \neq \mathrm{j}, \mathrm{j} \neq \mathrm{k} = 1, 3, \tag{4}$$

which are algebraic equations.

3 Results and discussion

We plot the squared $\tilde{T}_R$-matrix as a function of $\sqrt{s}$ and $\sqrt{s_{23}}$ after subtracting the $t^i g^{ij} t^j$ terms ($\tilde{T}_R = \sum_{ij} T_R^{ij}$), which evidently do not have a resonance structure and just provide a background to the amplitudes.

In order to identify the nature of the resulting states, the T-matrix has been projected on the isospin base defined in terms of the total isospin of the three particles, I, and the total isospin of the two mesons, I_m.

In Fig.1 we show our results for the total isospin one, obtained by keeping the two pions in the isospin 2 configuration. We see two peaks: one at $\sqrt{s}$ = 1656 MeV with a width of 30 MeV, which we correlate with the well-established $\Sigma(1660)$ [3], and another at 1630 MeV with a width of 39 MeV [10]. This is the first time when an evidence for the three body structure (two mesons and one baryon) of the $\Sigma(1660)$ has been found. We associate the peak at $\sqrt{s}$ = 1630 MeV with the $\Sigma(1620)$, for which the experimental and partial wave analyzes results are listed separately, with a note saying that its not clear if there are one or more resonances in this energy region.

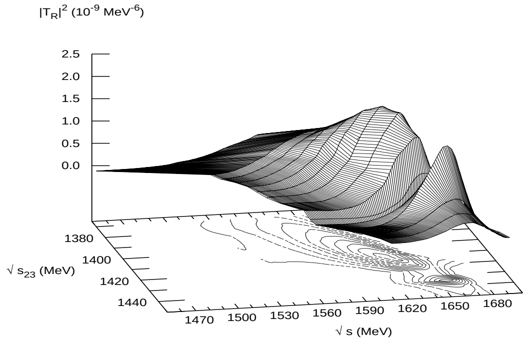

Figure 1: Two resonances in the $\pi\pi\Sigma$ amplitude in $I = 1$, $I_\pi = 2$ configuration.

Our calculations resulted also into dynamical generation of more strangeness = -1 resonances which are not well-understood, for example, $\Sigma(1560)$ with J^π unknown [3] and for which our results predict $J^\pi = 1/2^+$, $\Sigma(1770)$, which is listed as a one star resonance in [3]. Finally, in the isospin zero sector we find evidence for two peaks in $\Lambda(1600)$ region and one corresponding to $\Lambda(1810)$ [10].

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