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New views on the $f_1(1420)$ resonance

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We report on the decay of the $f_1(1285)$ into $\pi a_0(980)$ and $K^*\bar{K}$. We find a shoulder around 1400 MeV, tied to a triangle singularity, for the $\pi a_0(980)$ decay mode, and a peak around 1420 MeV for the $K^*\bar{K}$ mode. Both these features agree with the experimental information on which the $f_1(1420)$ resonance is based. Together with other features we conclude that the $f_1(1420)$ is not a genuine resonance, but the manifestation of the $\pi a_0(980)$ and $K^*\bar{K}$ decay modes of the $f_1(1285)$ at higher energies than the nominal one.

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1. Introduction

The $f_1(1420)$ resonance is catalogued in the Particle data book [1] as an $I^G(J^{PC}) = 0^+(1^{++})$ state and has been observed in over 20 experiments. Its mass is $M = 1426.4 \pm 0.9$ MeV and its width $\Gamma = 54.9 \pm 2.6$ MeV. Its dominant decay mode is $K\bar{K}^*$. In Ref. [2] the decay mode $\pi a_0(980)$ is reported with $\Gamma(\pi a_0(980))/\Gamma(K\bar{K}^* + \text{c.c.}) = 0.04 \pm 0.01 \pm 0.01$. In this latter paper a clean peak is seen for the $f_1(1285)$ in the $\pi a_0(980)$ mode, followed by a broader structure around 1400 MeV with much smaller strength, that is tentatively associated to the $f_1(1420)$, with the statement "The shoulder at 1.4 GeV can be interpreted as an $a_0(980)\pi$ decay mode of the $f_1(1420)$" with no devoted work to support this assertion.

Here we report upon the work [3] which provides a different explanation of the experimental findings, showing that the $K^*\bar{K}$ peak associated to the $f_1(1420)$ is the manifestation of the $K\bar{K}^* +$ c.c. decay mode of the $f_1(1285)$. On the other hand, the broad peak for $\pi a_0(980)$ decay in the region of 1400 MeV is explained as a consequence of a triangle singularity, due to $f_1(1285) \to K^*\bar{K}$, $K^* \to \pi K$, $K\bar{K} \to a_0(980)$. The $K^*\bar{K}$ decay mode of the $f_1(1285)$ appears as "not seen" in the PDG [1]. Indeed the $f_1(1285)$ is 100 MeV below the $K^*\bar{K}$ threshold. However, the $K\bar{K}\pi$ mode is reported with a branching fraction of 9%. These features found an adequate answer in several works [4, 5], where the $f_1(1285)$ was considered as a dynamically generated resonance. This state, together with all the low-lying axial vector resonances, were obtained in Refs. [6, 7] as dynamically generated states from the interaction of pseudoscalar mesons with vector mesons, using a coupled channels unitary scheme with chiral dynamics for the meson interaction [8]. In the particular case of the $f_1(1285)$, the $K\bar{K}^* +$c.c. is the single channel in the coupled channel approach [7]. The work in Refs. [6, 7], using the lowest order chiral Lagrangian, has been extended in Ref. [9] including higher order terms, but in the case of the $f_1(1285)$ the higher order terms were found essentially negligible.

In this picture for the $f_1(1285)$, a good description of the $\pi a_0(980)$ and the isospin-forbidden $\pi f_0(980)$ decay modes were well reproduced [4]. Actually, the $\pi f_0(980)$ decay mode was first predicted in Ref. [4] and corroborated later experimentally by a BESIII experiment [10]. Similarly, in Ref. [5] the $K\bar{K}\pi$ decay mode was studied and also found consistent with experiment [2, 11]. Here we show that, as a consequence of the $K^*\bar{K}$ nature of the $f_1(1285)$, if we excite that state and go to higher energies where the $K^*\bar{K}$ can be produced, the tail of the $f_1(1285)$ propagator, together with the phase space for $K^*\bar{K}$ production, produce a peak around 1420 MeV with a width of about 60 MeV, that explains the experimental features observed for the $f_1(1420)$ resonance.

On the other hand, the triangle diagram with $K^*\bar{K}K$ intermediate states, with π and $f_0(980)$ or $a_0(980)$ external products, develops a singularity at 1420 MeV, which is seen as a peak for $\pi f_0(980)$ or $\pi a_0(980)$ production. This was already suggested in Ref. [12] and shown explicitly in Refs. [13, 14], providing a natural explanation of the COMPASS observation [15] of a peak in the $\pi f_0(980)$ mode around 1420 MeV, which was interpreted as a new resonance, the "$a_1(1420)$", in Ref. [15]. In Refs. [13, 14] the peak was interpreted as a consequence of a triangle singularity associated to the decay mode of the $a_1(1260)$ into $K^*\bar{K}$, followed by $K^* \to K\pi$ and fusion of the $K\bar{K}$ to give the $f_0(980)$. The mechanism to produce the $\pi a_0(980)$ from the decay of the $f_1(1285)$ is identical to the one used in Ref. [14] to produce the $\pi f_0(980)$ from the decay of the $a_1(1260)$. The conclusion of all these observations is that the $f_1(1420)$ is not a genuine resonance, but the manifestation of the $K^*\bar{K}$ and $\pi a_0(980)$ decay modes of the $f_1(1285)$ resonance. This would go in line with the conclusions of Refs. [13, 14] that the "$a_1(1420)$" is not a genuine resonance, but the manifestation of the $\pi f_0(980)$ decay mode of the $a_1(1260)$ resonance.

2. Formalism: The $K^*\bar{K}$ channel

The resonance $f_1(1420)$ is observed in very high energy collisions, which we depict in Fig. 1, where the resonance is observed in the invariant mass of particles 2 and 3.

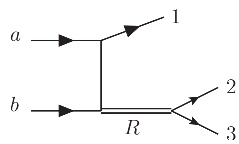

Figure 1: Diagrammatic representation of the process producing the resonance, observed in the decay channel $2+3$.

Let us look at the process depicted in Fig. 1 with 2, 3 being $K^*\bar{K}$, and the resonance R is the $f_1(1285)$. The $K^*\bar{K}$ production begins at a threshold of 1383 MeV, 100 MeV above the nominal mass of the $f_1(1285)$.

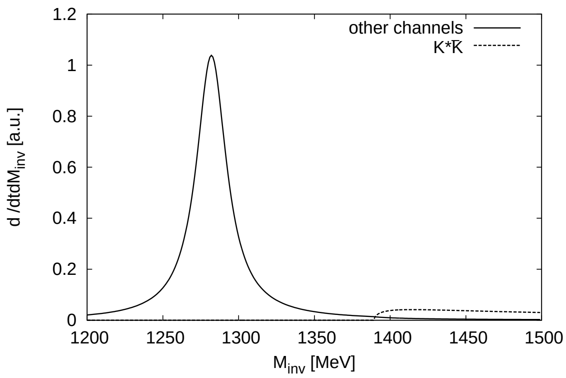

Figure 2: Production of $K^*\bar{K}$ induced by the excitation of the $f_1(1285)$ resonance. Dashed line: production of $f_1(1285)$ through the decay of $f_1(1285)$ into $K^*\bar{K}$. Solid line: through the decay of the $f_1(1285)$ into other channels.

We observe in Fig. 2 the typical threshold production of the $K^*\bar{K}$ channel. However, since the production is driven by the excitation of the $f_1(1285)$, one has two factors competing, a decreasing strength of the resonance as the energy increases, and an increasing phase space for the $K^*\bar{K}$ production, and the product of these two factors confers the cross section a particular shape. However, the K^* is observed throught its $K\pi$ decay and the experimentalist will observe $K\pi\bar{K}$ at the end. This also allows us to go below the threshold of $K^*\bar{K}$ production.

To account for the K^* decay, we look into the diagram of Fig. 3.

In Fig. 4 we plot the results for the mechanism of Fig. 3. Fig. 4 is very intuitive, we see a double peak structure. The first peak accounts for the standard $f_1(1285)$ decay into $K\pi\bar{K}$

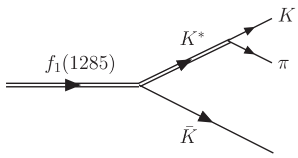

Figure 3: Decay diagram for $f_1(1285) \to K^*\bar{K}$ considering the $K\pi$ decay channel of the K^*.

observed with the shape of the $f_1(1285)$. Yet, what concerns us here is that the same mechanism produces a second peak around 1420 MeV as a consequence of the influence of the tail of the $f_1(1285)$ resonance and the increasing phase space for $K^*\bar{K}$ production. By assuming a smooth background below the second peak, as an experimental analysis would do, we induce that there is a resonant-like structure peaking around 1420 MeV with a width of about 60 MeV, the features observed in experiment when talking about the $f_1(1420)$ resonance. Yet, we have not invoked a new resonance for this structure, which appears naturally and unavoidably from the decay of $f_1(1285)$ into $K^*\bar{K} \to K\pi\bar{K}$. This also explains why the $f_1(1420)$ resonance is seen in the $K^*\bar{K}$ (or $K\pi\bar{K}$) channel alone. In the next section we address the production of the $\pi a_0(980)$ channel.

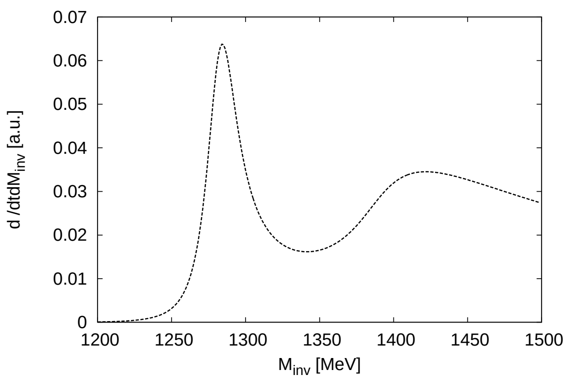

Figure 4: The $K\pi\bar{K}$ production cross section.

3. The $\pi a_0(980)$ decay mode of the $f_1(1285)$

This problem was also addressed in Ref. [4] but at the peak of the $f_1(1285)$. In Ref. [3] it is extended to higher energies. Following Ref. [4] and sticking to the simplified $K^*\bar{K}$ decay of the former section, we look at the diagram of Fig. 5, where we consider the $a_0(980)$ decay into the $\pi^0\eta$ channel.

The diagram of Fig. 5 leads to a singularity for some value of the energy of the incoming $f_1(1285)$ when the particles in the triangle can be placed on shell and the K^* and π^0 momenta are parallel [16]. A modern formulation of the problem, also technically different, is done in Ref. [17].

We show in Fig. 6 the results obtained for the mechanism of Fig 1 with R the $f_1(1285)$ decaying as in Fig. 5.

As we can see in Fig. 6, there is a large strength in the cross section built around 1400 MeV induced by the $f_1(1285)$ excitation, which makes it very distinct from the usual shape of the Breit-

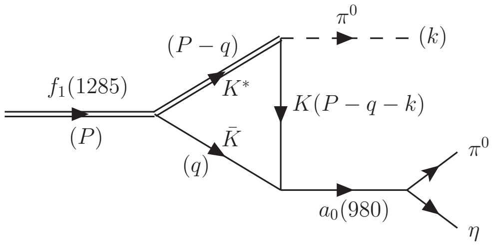

Figure 5: Triangle diagram leading to the production of $\pi a_0(980)$, the latter is observed in $\pi^0\eta$. In brackets the momenta of the particles.

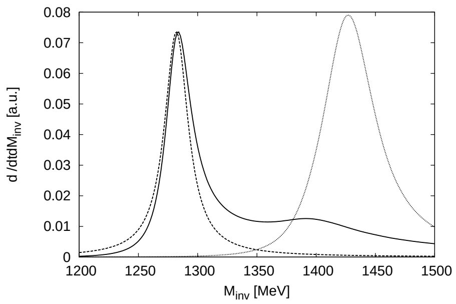

Figure 6: Differential cross section for $\pi a_0(980) \to \pi\pi^0\eta$ production induced by $f_1(1285)$ excitation. Solid line: considering the triangle diagram of Fig. 5. Dashed line: Considering $\Gamma_R = \Gamma_{f_1(1285)} = 24.1$ MeV, $\Gamma_{R,23}$ a constant and normalizing the curves to the peak of the $f_1(1285)$ (this reflects the shape of the modulus square of the $f_1(1285)$ propagator). The dotted curve is what we would expect for $\pi a_0(980) \to \pi\pi^0\eta$ production from $f_1(1420)$ excitation assuming that the production rate of the $f_1(1285)$ and $f_1(1420)$ are the same.

Wigner distribution for the $f_1(1285)$. It is interesting to see that this cross section is remarkably similar to the one found in Ref. [2]. There no explanation was found for this extra strength and it was suggested that it should be the $\pi a_0(980)$ decay mode of the $f_1(1420)$. What we see here is that the peculiar shape of the cross section for this particular channel is a consequence of the triangle diagram of Fig. 5, the mechanism for $\pi a_0(980)$ production from a resonance (the $f_1(1285)$) that is a bound state of $K^*\bar{K}$, or that couples strongly to $K^*\bar{K}$ for the purpose. The unexpected large strength around 1400 MeV comes from a singularity in the triangle diagram softened by the width of the K^* and the tail of the $f_1(1285)$ resonance. From that we can conclude that the strength found in this channel around 1400 MeV is not tied to the $f_1(1420)$ resonance but to the $f_1(1285)$.

This softened singularity, together with the propagator of the $f_1(1285)$, is what gives rise to the broad shoulder of the $f_1(1285) \to \pi a_0(980)$ in Fig. 6.

A more detailed comparison with the results of Ref. [2] is made in Ref. [3]. In Fig. 7 we show our results folded with a resolution of 20 MeV to facilitate comparison with the experimental numbers. We normalize the results approximately to the peak of the experimental distribution. We can see that the agreement with experiment is fair.

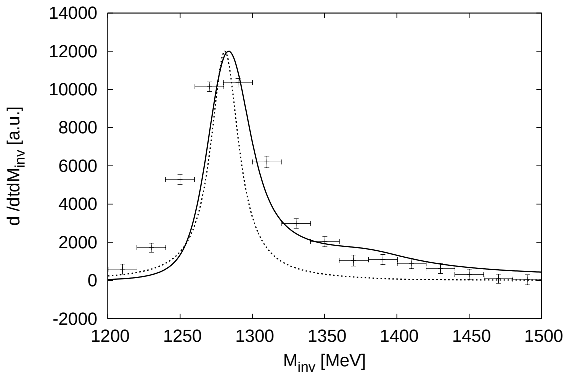

Figure 7: Comparison of the results of Fig. 6, convoluted with a resolution of 20 MeV, with the experimental results of [2].

4. Conclusions

We have carried out a study of the production of the $f_1(1285)$ and decay into $\pi a_0(980)$ and $K^*\bar{K}$ modes. We have studied the cross sections as functions of the $f_1(1285)$ mass, M_{inv}, up to 1500 MeV and we have observed two relevant features:

1) The $K^*\bar{K}$ mode (allowing the $K^* \to K\pi$ decay) has two peaks as a function of M_{inv}, one at the $f_1(1285)$ mass and another one at about 1420 MeV, this latter one with a width of about 60 MeV.

2) The $\pi a_0(980)$ mode has a peak at 1285 MeV and a broad shoulder around 1400 MeV, which comes from a triangle singularity involving $K^*K\bar{K}$ as intermediate states, and tied to the nature of the $f_1(1285)$ as a $K^*\bar{K}$ molecule, a sufficient, although not necessary, condition, since what matters is that the $f_1(1285)$ couples to $K^*\bar{K}$ and this is known experimentally from the $K\pi\bar{K}$ decay mode. The combination of the tail of the $f_1(1285)$ with the increased phase space for the $K^*\bar{K}$ production is the reason for this second peak.

The two features described above are the experimental facts in which the $f_1(1420)$ was accepted as a resonance, but we have shown that they are consequence of the decay modes of the $f_1(1285)$ and one does not have to introduce any new resonance to account for these facts.

Altogether, our study leads us to the unavoidable conclusion that the $f_1(1420)$ is not a resonance but simply the manifestation of the $K^*\bar{K}$ and $\pi a_0(980)$ decay modes of the $f_1(1285)$ around 1420 MeV.

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