Light Meson Spectroscopy from Charm Decays

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ABSTRACT

We discuss recent achievements in light scalar mesons spectroscopy through amplitude analysis of charm particle decay and its consequences. The high statistics clean samples of charmed mesons, in addition to it’s definite $J^P$ and mass, is turning these decays into a new important environment to study light meson physics. We give special attention to the scalar sector favored by a high coupling to charm.

1 Introduction

Most mesons are well understood in the context of the quark model. This is not true just for the scalar sector, that for long has been a source of controversy. For the latest 30 years a great deal of experimental effort have been made but in many cases the experimental results do not converge to compatible outputs. In
production experiments, observing the scalar resonant states is difficult due to a large contribution of the non-resonant background. Moreover, light scalars are too numerous within a relatively short mass interval. The absence of a unique analysis procedure, especially regarding the interference of the background with the resonances results in conflicting measurements. In this sense the wider and lighter the state the worse, and this is the case of the two states $\sigma(500)$ and $\kappa$ that will be discussed here.

The theoretical interpretation of the lightest scalar meson have also been unclear. Many objects – glueballs, $KK$ molecules, multiquark compact states – are expected to populate the area. In a recent review article F. Close and N. A. Törnqvist discuss the scalars from both experimental end theoretical points of view. They suggest that the scalars be organized not in one but two nonets. The “standard” quark model $q\bar{q}$ nonet, distorted by a glueball predicted by lattice QCD, is enough to explain the region above $\sim 1$ GeV. This nonet is composed by $a_0(\sim 1400)$, $f_0(1370)$, $K(1430)$, $f_0(1500)$ and $f_0(1710)$. The states below $\sim 1$GeV – $f_0(980)$, $a_0(980)$ and possibly $\sigma(500)$ and $\kappa$ – by arguments based on QCD attractive forces in S-wave, would also form a nonet. The interpretation of such nonet would be more complex, of the type meson-meson. In the article, they stress the importance of charm decay as “opening up a new experimental window for understanding light meson spectroscopy and specially the controversial scalar meson which are copiously produced in these decays”.

The use of charm decay is an alternative to the traditional production experiments to study lighter resonant particles. It was made possible by the large clean samples of charm now available and which are attributed to mankind effort but also, and more important, by what can be seen as nature’s gifts:

1) Non-leptonic charm decays are preferentially two body or quasi-two body, through the formation of intermediate resonant states. With a small non-resonant (NR) component one avoids having to deal with model dependent amplitudes and its interference with the resonant amplitudes. This feature is particularly important for the wide scalars because their amplitudes and the NR (usually taken as constant) can become very similar. We return to this issue later in the text.

2) Charm couple strongly with scalars. This empirical fact is present in the decays discussed here where the contribution to scalars dominates all
processes.

3) We are dealing with a well defined initial state; (charm meson mass, $M$ and $J^P$)

The first light resonant parameters extracted from charm data use D meson decays to three charged pseudo-scalars. In the following session we summarize the Dalitz plot amplitude formalism used. The parameterization of the overall amplitude consists of a coherent sum of all contributions (NR flat and resonant as relativistic Breit-Wigners modulated by angular momentum conservation functions and form factors) with complex coefficients obtained from the fit. The magnitude of the coefficients are proportional to each relative contribution and the phases accommodate in an effective way the final state interactions. It should be pointed out as the a great pro of these analysis the very good description that such simple model give to the data. Alternative descriptions for the decay amplitude are being tried, for example Focus experiment is using K-matrix to parameterize the light scalars contribution, but we shall not discuss those, still preliminary, results. Also expected for the near future are Focus four-body amplitude analysis.

2 Three body hadronic decay formalism

We describe here the analysis procedure used by the E791 collaboration in their $D^+$ and $D_s^+ \to \pi^+\pi^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$, from which was measured masses and widths of $\sigma(500)$, $f_0(980)$, $f_0(1370)$, $\kappa$ and $K_0^*(1430)$.

The decay of a scalar hadron of mass $M$ into 3 spinless daughter particles is completely specified with two degrees os freedom, conveniently chosen as two Dalitz plot variables, $m_{12}^2$ and $m_{23}^2$. The Dalitz plot density distribution is proportional to the invariant decay amplitude $A$ squared and reflects the dynamics of the decay process. A simple analytical model for $A$ is given by a coherent of all intermediate states contributing, resonant or not:

$$A = a_{NR} e^{i\delta_{NR}} A_{NR} + \sum_{j=1}^{n} a_j e^{i\delta_j} A_j$$

The parameters $a$ give the various relative contributions and the phases $\delta$ are accounts for final state interactions. The non-resonant amplitude $A_{NR}$ is represented by a constant. Which is a reasonable assumption if we imagine that it is dominantly $S$-wave, in any case, the impact of this choice in the results is
reduced due to a small NR contribution observed. The decay through resonant intermediate states, $j$ (that then decay to the observed $k$ and $l$ hadrons), are viewed as s-channel processes where the resonance plays the role of massive propagators, represented by relativistic Breit-Wigner functions, $BW_j$ \[1\]. Momentum dependent form factors, $F_D$ and $F_R$ describe the non-pointlike nature of the $D$ meson and the resonance respectively and depend on the resonance spin, $J$ and the radii of the relevant mesons. The angular momentum conservation is taken care by the function $\mathcal{M}_j^J$. Each resonant amplitude, $A_j$ is written as:

$$A_j = BW_j \times F_D \times F_R \times \mathcal{M}_j^J$$  \[2\]

$$BW_j = \frac{1}{m_{kl}^2 - m_0^2 + im_0 \Gamma_j(m_{kl})}$$  \[3\]

with

$$\Gamma(m_{kl}) = \Gamma_0 \frac{m_0}{m_{kl}} \left( \frac{p^*}{p_0^*} \right)^{2J+1} \frac{F_R^2(p^*)}{F_R^2(p_0^*)}$$  \[4\]

Above $m_{kl}^2$ is the the Dalitz plot variable, i.e. the invariant mass of the two hadrons forming a spin-$J$ resonance. Detailed expression of all the above functions are found in the references \[2\], \[3\], \[4\]. Combinatorics background, detector efficiency and Bose symmetrization are also considered in a maximum likelihood fit to the data to extract the parameters. In most cases the masses, $m_0$, and widths, $\Gamma_0$ of the resonances are fixed by values listed in PDG. Only for new or poorly measure states they are allowed to float in the fit.

\[1\] For the $f_0(980)^\pi^+$ E791 uses a coupled channel Breit-Wigner, following the parameterization used by the WA76 Collaboration \[3\],

$$BW_{f_0(980)} = \frac{1}{m_{kl}^2 - m_0^2 + im_0 (\Gamma_\pi + \Gamma_K)}$$, with

$$\Gamma_\pi = g_\pi \sqrt{m_{kl}^2/4 - m_\pi^2},$$ and

$$\Gamma_K = \frac{g_K}{2} \left( \sqrt{m_{kl}^2/4 - m_{K^+}^2} + \sqrt{m_{kl}^2/4 - m_{K^0}^2} \right)$$.
Figure 1: Dalitz-plot of the individual resonant contributions to the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decay.

Figure 1 shows, as an example, Monte Carlo simulation Dalitz-plot of each individual resonant state that contributes in the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decay. Notice that being coefficients and the individual amplitudes complex quantities, interference effects will take place when all the pieces act together.

The above described produces a quite stringent model and obtaining acceptable fits is usually a difficult task. To access the quality of each fit a fast Monte Carlo (MC) program was developed which produces Dalitz plot event densities accounting for signal and background PDF’s, including detector efficiency and resolution. Comparing the MC density distribution generated using parameters extracted from a given fit with that for the data, it is produced a $\chi^2$ distribution. When comparing two possible models, the best discriminating power test requires ensembles of Monte Carlo “experiments”. In the $\kappa$ discussion below we illustrate the technique.
3 The $f_0$'s resonances

We have chosen to start the results sessions with the $f_0$ because of the extremely clear signal seen in the $D_s^+ \rightarrow \pi^+\pi^-\pi^+$ decay, figure 3. There are dozens of measurements listed in PDG [1] for this state and they converge to a reasonably well defined mass, $980 \pm 10$ MeV but the estimation for width is from 40 to 100 MeV.

For the best E791 fit 5 resonant channels contributes significantly: $\rho^0(770)\pi^+$, $\rho^0(1450)\pi^+$, $f_0(980)\pi^+$, $f_0(1270)\pi^+$, and $f_0(1370)\pi^+$, plus a NR that contributed with a fraction of only 0.5±0.2%. The fit have $\chi^2/\text{dof} = 71.8/68$ with a confidence level of 35%. The dominant contributions comes from $f_0(980)\pi^+$, $56.5 \pm 6.4\%$, and $f_0(1370)\pi^+$, $32.4 \pm 7.9\%$ from which they measure: $m_{f_0(980)} = 977 \pm 3.6$ MeV/c$^2$, $g_\pi = 0.09 \pm 0.01$, $g_K = 0.02 \pm 0.05$, $m_{f_0(1370)} = 1434 \pm 20$ MeV/c$^2$ and $\Gamma_{f_0(1370)} = 172 \pm 33$ MeV/c$^2$. There is no evidence of a third higher mass scalar state, $f_0(1500)$.

Previous production experiments claim a large contribution of the $K\bar{K}$ channel by estimation a large value of the parameter $g_K$ [5, 6]. These results do not agree with the value measured by E791 that, in fact, finds that a simple Breit-Wigner [3] is sufficient to represent the data. From the small but clear preliminary signal BES collaboration measure $m_{f_0} = 0.980 \pm 0.009$ GeV and $\Gamma_{f_0} = 0.045 \pm 0.30$ GeV. In figure 3 we compare various results and conclude that in charm decay the resonance $f_0(980)$ presents a narrower signal.

4 The $\sigma(500)$

The 1999 the Workshop on Hadron Spectroscopy [8] devoted one entire session to the meson $\sigma(500)$, “What do we know about the $\sigma$?”. By that time E791 had not published their observation of the meson $\sigma$ in the decay of $D^+ \rightarrow \pi^+\pi^-\pi^+$. Today charm decay is viewed as a tool for studying the light spectroscopy.

In figure 4 we show the projection of the E791 Dalitz plot where a clear peak at low mass can be seen. The figure compares the best fit achieved with all possible well established resonances available at the time, a) (Fit 1), to their solution including a low mass scalar state, b) (Fit 2). They measured $m_{\sigma} = 478 \pm 29$ MeV/c$^2$ and $\Gamma_{\sigma} = 324 \pm 46$ MeV/c$^2$ and the inclusion of the state took them from an unacceptable solution of $\chi^2/\text{dof} = 254/162$ with a
Figure 2: E791 $D^+_s \to \pi^+\pi^-\pi^+$ Dalitz plot and $m_{\pi^+\pi^-}^2$ projection

confidence level less than 10^{-5} to a very good fit with $\chi^2/dof = 138/162$ and confidence level of 90%. In Fit 1 the NR contribution is dominant with 38% and in Fit 2 following the trend of charm decays it dropped to 7.8% whereas the $\sigma\pi^+$ dominates with 46%. E791 perform a series of alternative fits and tests to be sure that no other model would as well describe the data.

Studying the channel $J/\Psi \to w\pi^+\pi^-$ BES experiment observe a signal of the mesons $\sigma$ and measure their parameters $^{10)}$:

- $m_{\sigma} = 490^{+60}_{-36}$ MeV/c^2
- $\Gamma_{\sigma} = 282^{+77}_{-50}$ MeV/c^2

In figure 5 we show their final fit and scans for the $\sigma$ mass and width measurements.

5 The $\kappa$

As a last result we consider the $\kappa$ resonance observed in E791 Cabibbo favored decay $D^+ \to K^-\pi^+\pi^+$. Despite the large statistics available in this channel, no previous experiment $^{11)}$ $^{12)}$ have been able to provide a convincing explanation for this decay. E687 $^{12)}$ best model for their sample of almost 9000 events have $\chi^2/dof = 87/29$. The solution have the NR contribution dominating with
a fraction of 99%. Large interference pattern is produced with all fractions summing 147%. In contrast to the $\sigma$ where a clear bump is seen in the $m_{\pi^+\pi^-}$ projection, no evidence for a missing piece in the low $m_{K^-\pi^+}$ region can be easily observed (figure 6b). On the other hand the very large statistics and small number of possible intermediate states provide strong evidence of the need for an extra low mass wide resonance contributing for the decay.

The first approach tried by E791 was to include all established states; $\bar{K}^*(892)\pi^+$, $\bar{K}_0^*(1430)\pi^+$, $\bar{K}_2^*(1430)\pi^+$, $\bar{K}^*(1680)\pi^+$ plus a NR (they have studied also the possibility of a non-flat NR contribution without success). In general the result agree with previous studies including the bad quality of the fit. At this point they measured mass and width of the scalar $K_0^*(1430)$ to be $1416\pm27$ and $250\pm21$ MeV/c$^2$ respectively, which agree with PDG values.

Next they include an additional scalar named “$\kappa$” for which they measure respectively mass and width of $797\pm47$ and $410\pm97$ MeV/c$^2$. In the same fit the parameters relative to $K_0^*(1430)$ were measured to be $1459\pm9$ and $175\pm17$ MeV/c$^2$. This new model describes very well the data with a $\chi^2/dof = 46/63$,
confidence level of 95%. The contribution of the new state is dominant with 48±12% of the total fraction and the NR contribution is of 13±7%. The sum of all fractions dropped from 134% in the fit without κ to 88% indicating a smaller degree of interferences.

In the amplitude analysis described here one do not measure directly a Breit-Wigner phase, instead it is assumed and consistency tests have to be performed to verify if alternative models are able to represent the data. This was done for this analysis; a toy-model (consisting of a Breit-Wigner amplitude without a phase variation), a vector and a tensor alternative models were tried, none producing a satisfying solutions. When comparing two possible models $A$ and $B$ the best figure of merit to be used is given by the Neyman-Person lemma: $\Delta w_{A,B} \equiv -2(ln L_A - ln L_B)$, where $L_{A,B}$ are the likelihood for a given set of events calculated with the parameters obtained from fits to the data with
models $A$ and $B$. Ensembles of 1000 Monte Carlo “experiments” were generated with the parameters extracted from fits to the data for the two models $A$ and $B$. For each of such experiments the quantity $\Delta w_{A,B}$ was calculated and plotted in figure 7, where the model with the scalar $\kappa$ is compared with model without it; with the toy-model $\kappa$ or with the vectorial $\kappa$. The discriminating power of the exercise is obvious by the separation of the distributions. The value of $\Delta w_{A,B}$ for the data is signed by the triangle showing the clear preference of the data to the model of the scalar $\kappa$.

6 Conclusion

In conclusion, charm decay is, as said by F.Close and Törnqvist, a new window for studying light mesons. We discussed some of its remarkable contributions. With the already available data sets and the richness of charm decays, we hope to see in the near future confirmations and better measurements for some of the resonances, like the $\kappa$.

References
Figure 6: LEFT: E791 $D^+ \rightarrow K^+\pi^+\pi^+$ Dalitz plot; RIGHT: projections for data (error bars) a) without $\kappa$ b) with $\kappa$

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Figure 7: Comparison of several models to fit E791 $D^+ \to K^\mp \pi^\mp$ data. Histogram of $\Delta w_{A,B}$, described in the text, for ensembles of Monte Carlo “experiments” and the data point, solid triangle.

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