MEASUREMENT OF INCLUSIVE $f_1(1285)$ AND $f_1(1420)$ PRODUCTION IN $Z$ DECAYS WITH THE DELPHI DETECTOR

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Inclusive production of two $(K\bar{K}\pi)^0$ states in the mass region 1.22–1.56 GeV in $Z$ decay at LEP 1 has been observed by the DELPHI Collaboration. The measured masses and widths are $1274\pm4$ and $29\pm12$ MeV for the first peak and $1426\pm4$ and $51\pm14$ MeV for the second. A partial-wave analysis has been performed on the $(K\bar{K}\pi)^0$ spectrum in this mass range; the first peak is consistent with the quantum numbers $I^G(J^PC) = 0^{++}$ and the second with $I^G(J^PC) = 0^+(1^{++})$. These measurements, as well as their total hadronic production rates per hadronic $Z$ decay, are consistent with the mesons of the type $n\bar{n}$, where $n = \{u, d\}$. They are very likely to be the $f_1(1285)$ and the $f_1(1420)$, respectively.

1 Introduction

The inclusive production of mesons has been a subject of long-standing study at LEP as it provides insight into the nature of fragmentation of quarks and gluons to hadrons. For the first time, we present in this paper a study of the inclusive production of two $J^{PC} = 1^{++}$ mesons, the $f_1(1285)$ and the $f_1(1420)$ (i.e. $3P_1$).

There are at least four nonstrange isoscalar mesons $I^G(J^PC) = 0^+(1^{++})$ and $I^G(J^PC) = 0^+(0^{-+})$, known in the mass region between 1.2 and 1.5 GeV, which couple strongly to the decay channel $(K\bar{K}\pi)^0$. They are $f_1(1285)$, $\eta(1295)$, $f_1(1420)$ and $\eta(1440)$, which are mostly $n\bar{n}$ states, where $n = \{u, d\}$. There exist possibly two additional states, $I^G(J^PC) = 0^-(1^{+-})$ $h_1(1380)$ and $I^G(J^PC) = 0^+(1^{++})$ $f_1(1510)$, which may harbor a large $s\bar{s}$ content.

Given this complexity in the $(K\bar{K}\pi)^0$ systems, it is important that one seek answers as to which resonances among these are readily excited in inclusive hadron $Z$ decays.

The DELPHI data for this study is based on the neutral $K\bar{K}\pi$ channel in the reaction $Z \rightarrow (K_\pi K^\pm \pi^\mp) + X^0$. 
2 Experimental Procedure

The analysis presented here is based on a data sample of about 3.3 million hadronic Z decays collected from 1992 to 1995 with the DELPHI detector.

The charged particle tracks have been measured in the 1.2-T magnetic field by a set of tracking detectors. The average momentum resolution for charged particles in hadronic final states, $\Delta p/p$, is usually between 0.001 and 0.01.

A charged particle has been accepted in this analysis—if its momentum $p$ is greater than 100 MeV/c; its momentum error $\Delta p$ is less than $p$; and its impact parameter with respect to the nominal crossing point is within 4 cm in the transverse ($xy$) plane and 4 cm/sin $\theta$ along the beam direction ($z$-axis), $\theta$ being the polar angle of the track.

Hadronic events are then selected by requiring at least 5 charged particles, with at least 3-GeV energy in each hemisphere of the event—defined with respect to the beam direction—and total energy at least 12% of the center-of-mass energy.

After the event selection, in order to ensure a better signal-to-background ratio for the resonances in the $K^\pm K^\mp \pi^\pm$ invariant mass spectra, tighter requirements have been imposed on the track impact parameters, i.e. they have to be within 0.2 cm in the transverse plane and 0.4 cm/sin $\theta$ along the beam direction.

$K^\pm$ identification has been provided by the RICH detectors for particles with momenta above 700 MeV/c, while the ionization loss measured in the TPC has been used for momenta above 100 MeV/c. Its efficiency has been estimated by comparing the experimental data with simulated events generated with JETSET tuned with the DELPHI parameters and passed through the detector simulation program DELSIM.

The $K_s$ candidates are detected by their decay in flight into $\pi^+ \pi^-$. Our selection process consists of taking the $V^0$s passing certain criteria for quality of the reconstruction plus a mass cut given by $0.45 < M(K_s) < 0.55$ GeV.

After all the above cuts, only events with at least one $K_sK^\pm \pi^\mp$ or $K^- K^\mp \pi^+$ combination have been kept in the present analysis, corresponding to a sample of 705 688 events.

3 $K_sK^\pm \pi^\mp$ Mass Spectra

The key to a successful study of the $f_1(1285)$ and $f_1(1420)$—given the enormous background in the $K_s^0 K^\pm \pi^\mp$ mass spectrum in this mass region—is to make a mass cut $M(K_s K^\pm) \leq 1.04$ GeV, as shown in Fig. [1]. Two clear peaks
are seen in this mass region. There are two reasons for this: (1) the decay
mode $a_0(980)^\pm\pi^\mp$ is selected by the mass cut, while the general background
for the $K\bar{K}\pi$ system is reduced by a factor of $\simeq 7$ at 1.42 GeV or more at
higher masses; (2) the interference effect of the two $K^*(892)$ bands on the
Dalitz plot at $M(K\bar{K}\pi) \sim 1.4$ GeV is enhanced, if the $G$-parity is positive.

Figure 1. $M(K^\pm K^{\mp}\pi^\mp)$ distributions from the $Z$ decays with the DELPHI detector at
LEP I—with a mass cut $M(K^\pm K^{\mp}) < 1.04$ GeV. The two solid curves in the upper part
of the histogram describe Breit-Wigner fits over a smooth background (see text). The
lower histogram and the solid curve give the same fits with the background subtracted and
amplified by a factor of two.

In order to measure the resonance parameters for these two states, we
have first generated a Monte Carlo sample, deleting—from the existing MC
tool—all mesons with a major decay mode into $(K\bar{K}\pi)^0$ in the mass region
1.25 to 1.45 GeV, i.e. $f_1(1285)$, $h_1(1380)$ and $f_1(1420)$, which is then passed
through the standard detector simulation program. The smooth curve shown
in Fig. 1 has been obtained by fitting the mass spectrum of the aforementioned
MC sample between 1.15 to 1.65 GeV with a background function

$$f_b(M) = (M - M_0)^{\alpha_1} \exp(\alpha_2 M + \alpha_3 M^2)$$

(1)

where $M$ and $M_0$ are the effective masses of the $(K\bar{K}\pi)^0$ system and its
threshold, respectively, and $\alpha_i$ are the experimental parameters. We have
fitted the $(K\bar{K}\pi)^0$ spectrum adding two $S$-wave Breit-Wigner forms to the
background $f_b(M)$, given by

$$f_r(M) = \Gamma_r^2 \left/ \left[ (M - M_r)^2 + (\Gamma_r/2)^2 \right] \right.,$$

(2)
where $M_r$ and $\Gamma_r$ are the mass and the width to be determined experimentally. The results are shown in Fig. I and also in Table I.

**Table I. Fitted parameters and numbers of events**

| Mass (MeV) | Width (MeV) | Events            |
|------------|-------------|-------------------|
| $1274 \pm 4$ | $29 \pm 12$  | $345 \pm 88$ (stat) $\pm 69$ (sys) |
| $1426 \pm 4$ | $51 \pm 14$  | $790 \pm 119$ (stat) $\pm 110$ (sys) |

The main sources of systematic errors come from the various cuts and selection criteria applied for the $V^0$ reconstruction plus the charged $K$ identification (7%)—on the one hand—and the conditions of the mass-fit procedure—on the other (15%). The systematic errors have been added quadratically and are shown in Table 1.

4 Partial-wave Analysis

There exists a long list of 3-body partial-wave analyses; the reader may consult PDG for earlier references, for example, on $a_1(1260)$, $a_2(1320)$, $K_1(1270/1400)$ or $K_2(1770)$. For the first time, we apply the same technique to a study of the $(K\bar{K}\pi)^0$ system from the inclusive decay of the $Z$ at LEP.

We have chosen to employ the so-called Dalitz plot analysis, integrating over the three Euler angles. The actual fitting of the data is done by using the maximum-likelihood method, in which the normalization integrals are evaluated with the accepted Monte Carlo events, thus taking into account the finite acceptance of the detector and the event selection.

The background under the two $f_1$’s is very large, some $\sim 80\%$. It is assumed that this represents essentially different processes with, for example, different overall multiplicities—so that the background does not interfere with the signals. We assume further that the background itself is a non-interfering superposition of a flat distribution (on the Dalitz plot) and the partial waves $I^{G(J_{PC})} = 0^+(1^{++}) a_0(980)\pi$, $0^+(1^{++}) (K^*(892)\bar{K} + c.c.)$ and $0^-(1^{+-}) (K^*(892)\bar{K} + c.c.)$. We have verified that these amplitudes give a good description of the three background regions for $M(K\bar{K}\pi)$ in $1.22 \rightarrow 1.26$, $1.30 \rightarrow 1.38$ and $1.48 \rightarrow 1.56$ GeV, respectively.

The signal regions, for $M(K\bar{K}\pi)$ in $1.26 \rightarrow 1.30$ and $1.38 \rightarrow 1.48$ GeV, have been fitted with a non-interfering superposition of the partial waves $I^{G(J_{PC})} = 0^+(1^{++})$, $0^+(1^{+-})$ and $0^- (0^{--})$, where the decay chan-
nels \(a_0(980)\pi\) and \(K^*(892)\bar{K} + c.c.\) are allowed to interfere within a given \(J^{PC}\). All other possible partial waves have been found to be negligible in the signal regions. The fit results can be summarized as follows: (1) the maximum likelihood is found to be the same for \(I^G(J^{PC}) = 0^{+}(1^{++})a_0(980)\pi\) and for \(0^{-}(0^{+-})a_0(980)\pi\), i.e. the 1.28- GeV region is equally likely to be the \(f_1(1285)\) or the \(\eta(1295)\); (2) in the 1.4-GeV region, the maximum likelihood is better (by about 14 for \(\Delta \ln L\)) for \(I^G(J^{PC}) = 0^{+}(1^{++})f_1(1420)\) than \(I^G(J^{PC}) = 0^{+}(0^{-+})\eta(1440)\); the \(I^G(J^{PC}) = 0^{+}(1^{+-})h_1(1380)\) is excluded in this analysis (by about 23 for \(\Delta \ln L\)).

It should be emphasized that both the mass-dependent (per 20 MeV) and the mass-independent global fits give compatible results.

5 Discussion and Conclusions

We have measured the production rate \(\langle n \rangle\) per hadronic \(Z\) decay for \(f_1(1285)/\eta(1295)\) and \(f_1(1420)\). We assume for this study that both have spin 1. The results are

\[
\begin{align*}
\langle n \rangle &= 0.132 \pm 0.034 \quad \text{for } f_1(1285) \\
\langle n \rangle &= 0.0512 \pm 0.0078 \quad \text{for } f_1(1420)
\end{align*}
\]

(3)

taking a \(K\bar{K}\pi\) branching ratio of \((9.0 \pm 0.4)\%\) for the \(f_1(1285)\) and \(100\%\) for the \(f_1(1420)\). The production rate per spin state [i.e. divided by \((2J + 1)\)] has been studied in Fig. 2 is given all the available data for those mesons with a ‘triplet’ \(q\bar{q}\) structure, i.e. \(S = 1\) in the spectroscopic notation \(2S+1LJ\).

To this figure we have added our two mesons for comparison. It is seen that both \(f_1(1285)\) and \(f_1(1420)\) come very close to the line corresponding to other mesons whose constituents are thought to be of the type \(n\bar{n}\). This is suggestive of two salient facts: (1) the first peak at 1.28 GeV is very likely to be the \(f_1(1285)\); (2) both \(f_1(1285)\) and \(f_1(1420)\) have little \(s\bar{s}\) content.

We have studied the inclusive production of \(f_1(1285)/\eta(1295)\) and \(f_1(1420)\) in \(Z\) decays at LEP I. The measured masses and widths are 1274 ± 4 and 29 ± 12 MeV for the first peak and 1426 ± 4 and 51 ± 14 MeV for the second one. For the first time, a partial-wave analysis has been carried out on the \((K\bar{K}\pi)^0\) system. The results show that the first peak is equally likely to be the \(f_1(1285)\) or the \(\eta(1295)\), while the second peak is consistent with the \(f_1(1420)\). However, the hadronic production rate of these two states suggests that their quantum numbers are very probably \(I^G(J^{PC}) = 0^{+}(1^{++})\) and that their quark constituents are mainly of the type \(n\bar{n}\), where \(n = \{u, d\}\). Finally, we conclude that the mesons \(\eta(1295)\), \(\eta(1440)\) and \(h_1(1380)\) are less likely to be produced in the inclusive \(Z\) decays compared to \(f_1(1285)\) and \(f_1(1420)\).
Figure 2. Total production rate per spin state and isospin for scalar, vector and tensor mesons as a function of the mass (open symbols). The two solid circles correspond to the $f_1(1285)$ and the $f_1(1420)$.

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