2 Meson Spectroscopy at LEAR with the Crystal Barrel

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2.1 Introduction

The CRYSTAL BARREL Collaboration has reported the discovery of the scalar mesons $a_0(1450)$ [1, 2] and $f_0(1370)$, together with a relatively narrow $f_0(1500)$, decaying into $\pi^0\pi^0$ [3], $\eta\eta$ [4], $\eta\eta'$ [5], K_LK_L [6] and $4\pi^0$ [7]. The $f_0(1500)$ is interpreted as a glueball [8], but its precise $\bar{K}K$ decay rate has still not been measured precisely [6]. Also, a scalar $s\bar{s}$ meson decaying mainly into $\bar{K}K$ is needed to complete the scalar nonet. This has motivated the recent activities of the Zurich group.

The detector, a barrel of CsI(Tl) crystals, a jet drift chamber and a pair of cylindrical proportional chambers surrounding a hydrogen target in a solenoidal magnetic field is described in details in ref. [9]. The wire chambers have recently been replaced by a silicon microstrip vertex detector to trigger on secondary vertices, e.g. $K_S \to \pi^+\pi^-$.

2.2 Data collection

In the last year of LEAR operation we collected annihilations in gaseous hydrogen and in flight up to 1.9 GeV/c. The various target modes and trigger conditions are summarized in table 2.2. Three different targets were used:

1. Liquid hydrogen (LH_2) was used for $\bar{p}p$ annihilation at rest and in flight. The aim in 1996 was to get a reasonable statistics on 4-prong channels.

2. In liquid deuterium (LD_2) annihilation occurs with the proton or the neutron. The $\bar{p}n$-system has the well defined isospin I=1, so that the number of contributing amplitudes is smaller than for $\bar{p}p$ (which has both $I = 0$ and 1).

3. In gaseous hydrogen (GH_2) annihilation also proceeds through atomic P-states while annihilation from atomic S-states dominates in liquid. Since the production of intermediate resonances is driven by the quantum numbers of the initial state, resonances with different spins can be discriminated by changing the gas

pressure. This property led to the discovery of the $f_2(1565)$ by our former ASTERIX collaboration [10]. The present data were collected with a 14 atm target.

production	minimum-bias	all-neutral	2-prong	4-prong	$K_S X$
at rest					
LH_2	1.9 (16.8)	(24.7)	(22.6)	7.1 (10.4)	10.4 (16.9)
LD_2	1.1 (3.2)	(6.0)	(0.5)	(0.5)	6.8 (11.9)
GH_2	3.0 (8.6)	1.2 (18.0)	3.0 (13.1)	5.5 (8.2)	3.0 (6.2)
in flight (LH_2)					
600 MeV/c	(0.7)	0.1 (4.9)	0.7 (2.2)	(1.2)	(1.2)
900 MeV/c		17.9 (17.9)	20.0 (20.0)		
1050 MeV/c		0.7 (0.7)	5.0 (5.0)		
1200 MeV/c	(1.6)	(10.4)	(12.8)		
1350 MeV/c		1.2 (1.2)	8.1 (8.1)		
1525 MeV/c	20.6 (20.6)	10.2 (10.2)	5.2 (5.2)		
1642 MeV/c	0.1 (0.1)	11.1 (11.1)	12.5 (12.5)		
1800 MeV/c		6.8 (6.8)	3.6 (3.6)		
1900 MeV/c	(13.6)	(14.5)	(15.7)		

Table 2.1: Number of events (in millions) collected in 1996. The numbers in brackets give the corresponding sums over all runs since the beginning of the experiment in late 1989. In the $K_S X$ final state X stands for an arbitrary number of particles produced together with one triggered K_S from the microvertex detector.

2.3 Annihilation into $\bar{K}K\pi$

In the scalar nonet the position of the $\bar{u}u + \bar{d}d$ isoscalar meson is already occupied by $f_0(1370)$. The $s\bar{s}$ meson has not been identified yet but is expected around 1500 - 1700 MeV. If $f_0(1500)$ is not $s\bar{s}$ then this state can hardly be $q\bar{q}$ and its most natural interpretation is as a gluonium state [8]. The surprisingly small width (120 MeV) of $f_0(1500)$ - compared to neighbouring scalar mesons - and its strong decay into $4\pi^0$ are indications for its outstanding character. However, a large $\bar{K}K$ decay rate compared to $\pi\pi$ would imply that $f_0(1500)$ is the missing $s\bar{s}$ state in the scalar nonet. A precise measurement of the $\bar{K}K$ decay mode of the $f_0(1500)$ is therefore important.

For the reaction $\bar{p}p \to K_L K_L \pi^0$ 37,400 events were selected [6]. This channel was reconstructed by measuring the $\pi^0 \to 2\gamma$ momentum and the direction of one K_L which interacts hadronically in the electromagnetic calorimeter. Events with two interacting K_L were therefore rejected. The Dalitzplot before correction for the K_L interaction probability is shown in fig. 2.1a. One observes an asymmetry in the event

Figure 2.1: The four $\bar{K}K\pi$ Dalitzplots from Crystal Barrel data in $\bar{p}p$ annihilation at rest in liquid hydrogen. The channels are (a) $K_LK_L\pi^0$, (b) $K_LK^{\pm}\pi^{\mp}$, (c) $K_LK_S\pi^0$ and (d) $K^+K^-\pi^0$. Resonances are marked by arrows. The channel $K^+K^-\pi^0$ (d) allows the production of all $\bar{K}K$ and $K\pi$ resonances.

population below and above the main diagonal in the Dalitzplot. The top region is depleted due to the stronger interaction probability for the second low energy K_L This effect is particularly pronounced in the $K^*(892)$ bands. In ref. [6] these bands were used to extract the momentum dependent K_L interaction probability ($(57 \pm 3)\%$ for 795 MeV/c K_L) and to correct the Dalitz plot.

The $K_LK_L\pi^0$ Dalitzplot is well described by the resonances $K^*(892)$, $K^*(1430)$ in the $I = \frac{1}{2}$ $K\pi$-system and $f_2(1270), a_2(1320)$ and $f_2'(1525)$ which decay to $\bar{K}K$. For the $\bar{K}K$ S-wave three resonances were introduced: The $I= 0$ $f_0(1500)$, $f_0(1370)$ and the $I= 1$ $a_0(1450)$. The partial wave analysis does not allow a determination of the individual intensities due to strong interferences.

A stable result can be achieved by studying the channel $K_LK^{\pm}\pi^{\mp}$ which contains pure $I = 1$ $\bar{K}K$ amplitudes. Its Dalitzplot with 11,400 events (from 8 million 2-prong events) is shown in fig. 2.1b [11]. Here the K_L was not detected. This suppresses background from channels with mesons decaying into photons which can mimic a K_L interaction in the CsI barrel. The discrimination of charged kaons against charged pions was performed by ionization sampling. The acceptance was corrected for interacting K_L. The momentum dependent interaction probability was taken from the $K_L K_L \pi^0$ analysis [6].

The partial wave analysis of the pure sample revealed that the introduction of $a_0(1450)$ at a level of 8% improves the description of the final state significantly. The intensity of $a_0(1450)$ is compatible with the SU(3) flavour prediction from $a_0(1450) \rightarrow \eta\pi^0$ in $\pi^0\pi^0\eta$ [1]. One can now calculate the $a_0(1450)$ contribution to $K_L K_L \pi^0$ and is consequently able to determine the $K\overline{K}$ branching ratio for $f_0(1370)$ and $f_0(1500)$. From their relative couplings to $\bar{K}K$ and $\pi\pi$, of about 20%, one concludes that neither state can be dominantly $\bar{s}s$. This rules out $f_0(1500)$ as $s\bar{s}$ member of the scalar nonet.

We have analyzed auxiliary $\bar{K}K\pi$ channels: fig. 2.1c shows the $K_L K_S \pi^0$ Dalitzplot for which the $K_L K_S$-system has C-parity $C = -1$, in contrast to $K_L K_L (C = +1)$; fig. 2.1d shows the $K^+K^-\pi^0$ Dalitzplot. This last channel provides a consistency check for the other final states, since K^+K^- can have $C = \pm 1$ and $I = 0$ or 1, allowing the production of all resonances. A coupled channel analysis of the four data sets in fig. 2.1 leads to a consistent description.

2.4 Annihilation into $\pi^0\pi^0\eta'$

The $\pi^0\pi^0\eta'$ final state of $p\bar{p}$ annihilation at rest was selected for the two η' decay modes, $\eta' \rightarrow \gamma\gamma$ and $\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$ [12]. Starting from $17 \cdot 10^6$ all-neutral triggered data we selected 3500 (2γ) and 8200 ($\pi^0\pi^0\eta$) background subtracted and acceptance corrected events. The Dalitzplots for both modes are compatible and we obtain the averaged branching ratio:

$$Br(\bar{p}p \rightarrow \pi^0\pi^0\eta') = (3.34 \pm 0.42) \cdot 10^{-3}. \qquad (2.1)$$

The data are dominated by an η' recoiling against the $(\pi\pi)$ S-wave with, in addition, $a_2(1320) \rightarrow \eta'\pi$. A contribution from $a_0(1450) \rightarrow \eta'\pi$ is also required to achieve a satisfactory description of the intensity distribution of the $\pi^0\pi^0\eta'$ events (fig. 2.2a - c). The $a_0(1450)$ mass is, however, not well defined, varying between 1420 MeV and 1500 MeV without any siginificant change in the fit quality.

One can compare the branching ratios for $a_0(1450) \rightarrow \eta\pi$ and $\eta'\pi$ with predictions from SU(3) flavour:

$$\rho(X) = \frac{Br(X \rightarrow \eta\pi)}{Br(X \rightarrow \eta'\pi)} = \frac{q_{\eta\pi}}{q_{\eta'\pi}} \tan^2(\theta_i - \theta_P), \qquad (2.2)$$

where $\theta_i = 35.3°$ is the ideal mixing angle and assuming a pseudoscalar mixing angle $\theta_P = (-17.3 \pm 1.8)°$ [13]. The decay momenta $q_{\eta'\pi}$ and $q_{\eta\pi}$ are phase space factors. From the contribution of $a_0(1450)$ to the $\pi^0\pi^0\eta$ [1] and $\pi^0\pi^0\eta'$ final states we find a ratio $\rho(a_0) = 0.43 \pm 0.19$, which is in agreement with the SU(3) prediction (eqn. 2.2), $\rho(a_0) = 0.37 \pm 0.06$.

We have now signals for $a_0(1450) \to \eta'\pi$ and $K\overline{K}$ which strengthen the evidence for the existence of this isovector meson, first discovered by our collaboration in its $\eta\pi$ decay mode [1].

Figure 2.2: Comparison of the $\eta'\pi^0$ mass projections for data (dots) and fits (histograms) : a) $(\pi\pi)$ S-wave only; b) adding $a_2(1320)$ and c) including $a_0(1450)$ (best fit).

Figure 2.3: The $\omega \to \pi^0\gamma$ signal from the 7-photon final state of $\bar{p}p$ annihilation at rest (left) and the $\pi^0\pi^0\omega$ Dalitzplot (right).

2.5 Annihilation into $\omega\pi^0\pi^0$ and $\omega\pi^0\eta$

From $19 \cdot 10^6$ all neutral events we have extracted about 260'000 $\omega\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma$; $\omega \to \pi^0\gamma \to 3\gamma$) and 50'000 $\omega\eta\pi^0$ ($\eta \to \gamma\gamma$) events [14], a large increase in statistics compared to previous samples [15, 16]. Seven electromagnetic showers were required and a loose cut for momentum and energy conservation was applied. One observes a sharp ω peak in the $\pi^0\gamma$ invariant mass (fig. 2.3) with a mass of (781.9$\pm$0.2) MeV/c^2.

A kinematic fit to the hypotheses $\pi^0\pi^0\pi^0\gamma$, $\omega\pi^0\pi^0$, $\eta\pi^0\pi^0\gamma$ and $\omega\eta\pi^0$ was then performed, discriminating $\omega\pi^0\pi^0$ against $\omega\eta\pi^0$ and suppressing background from other channels. The $\omega\pi^0\pi^0$ Dalitzplot is also shown in fig. 2.3. It can be described by the $(\pi\pi)$ S-wave and $f_2(1270)$ in the $\pi\pi$-system, and $b_1(1235)$ in the $\omega\pi^0$- system. In combination with the final state $K_L K_S \pi^0\pi^0$, which allows the determination of $\phi\sigma$ production (here σ stands for the $(\pi\pi)$ S-wave), one is able to extract the preliminary ratio [17]

$$R = \frac{Br(\bar{p}p \to \phi\sigma)}{Br(\bar{p}p \to \omega\sigma)} = (1.75 \pm 0.25) \cdot 10^{-2}. \tag{2.3}$$

Since ϕ is mainly $s\bar{s}$, the expected production rate of ϕ mesons should be an order of magnitude smaller. This result confirms the earlier observation of abundant ϕ production in $\bar{p}p$ annihilation at rest in other channels which can be interpreted as evidence for a strange component in the nucleon, although less exotic explanations have also been proposed.

2.6 A first glimpse at the 900 MeV/c data

The search for higher mass resonances in $\bar{p}p$-annihilation demands higher $\overline{p}$ momenta. However, the number of initial angular momentum states also increases with momentum, and hence also the number of free fit parameters. Data at 900 MeV/c offer a good compromise for resonances with masses up to 1900 MeV. At 900 MeV/c about 2% of all incoming antiprotons react within the liquid hydrogen target, half of which undergo annihilation.

A preliminary selection of the $3\pi^0$ final state from a subsample has already been performed [18]. The $3\pi^0$ Dalitzplot in fig. 2.4 shows structures from $f_2(1270)$ and $f_0(1500)$. The low mass part of the $(\pi\pi)$ S-wave is shrinked into the central region of the Dalitzplot. A hint for a weak signal from the $f_0(1700)$ resonance, which has been reported by other experiments, is also observed. However, if this state is the predicted $s\bar{s}$ scalar meson, one expects only a weak signal in the $3\pi^0$ channel but a much stronger one in the final states $\bar{K}K\pi$ (e.g. $K^+K^-\pi^0$) and $\eta\eta\pi^0$. These channels are currently being analyzed.

2.7 Conclusions

The Crystal Barrel experiment has discovered several new mesons, one of which, $f_0(1500)$, is most likely the ground state glueball predicted by lattice gauge theories. With $a_0(1450)$ now also observed in $\eta'\pi$ and $K\overline{K}$ the scalar nonet seems in good shape. The last state to be identified in the nonet is the (mainly) $s\bar{s}$ meson predicted in the 1600 - 1700 MeV range. Precise measurements on $\eta\eta$ and $K\overline{K}$ channels from K_S triggered data at higher momenta are expected from the enormous amount of data collected in the last year of data taking at LEAR .

Figure 2.4: The $3\pi^0$ Dalitzplot (from a subsample of annihilation data in flight at 900 MeV/c).

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