2 Meson Spectroscopy at LEAR with the Crystal Barrel

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The Crystal Barrel experiment started data taking in late 1989 and was completed in autumn 1996 with the closure of LEAR. We collected very large samples of $\bar{p}p$ annihilations at low energy. The total number of minimum bias annihilations (i.e. requiring only an incident antiproton) collected at rest in liquid hydrogen is 10^8. Data were also taken in gaseous hydrogen (13 bar), in liquid deuterium and in liquid hydrogen with a multiplicity trigger requiring 0-prong or n-prong with long tracks in the jet drift chamber. Since 0-prong occur with a probability of 4%, the 0-prong data correspond to 6.3×10^8 annihilations. In addition, we collected data with specialized triggers enhancing specific final states. Data were also taken with antiprotons annihilating in flight between 600 and 1900 MeV/c.

The physics emphasis was (i) in the study of the annihilation mechanism and (ii) on a search for new mesons, in particular still missing $q\bar{q}$ states and glueballs. A comprehensive review of all Crystal Barrel results published until the end of 1997 can be found in ref. [1]. In this report we shall describe two important results achieved in 1997, (i) a confirmation of the isovector (isospin 1) scalar meson $a_0(1450)$ discovered earlier by our collaboration and (ii) the evidence for the exotic meson $\hat{\rho}(1405)$ with quantum numbers incompatible with a $q\bar{q}$ state.

2.1 Confirmation of $a_0(1450)$

Crystal Barrel has discovered a scalar ($J^P = 0^+$) meson decaying to $\eta\pi$ in the annihilation channel $\bar{p}p \to \pi^0\pi^0\eta$, with mass 1450 ± 40 MeV and width 270 ±40 MeV [2]. This state was then also observed to decay into $\eta'\pi$ in the annihilation channel $\pi^0\pi^0\eta'$ [3]. The relative branching ratio $\eta'\pi/\eta\pi$ was found to be in good agreement with predictions from SU(3), assuming that $a_0(1450)$ is a quark-antiquark meson. Therefore two isovectors, $a_0(980)$ and $a_0(1450)$, compete for being the π-like $q\bar{q}$ state of the 0^+ $q\bar{q}$ ground state mesons. The $a_0(980)$ is generally believed to be a $K\bar{K}$ molecule and hence $a_0(1450)$ defines the mass scale for the 0^+ $q\bar{q}$ mesons.

According to the quark model nine mesons should build up the 0^+ ground states: three isovectors $a_0(1450)$ (a_0^+, a_0^-, a_0^0), the four well known $K_0^*(1430)$ (K_0^{*+}, K_0^{*-}, K_0^{*0}, $\overline{K_0^{*0}}$) and two isoscalars (isospin 0). Crystal Barrel has established two isoscalars, $f_0(1370)$ and $f_0(1500)$. The $f_0(1500)$ has been discovered by us and has become one of the best established meson resonances. It decays into $\pi^0\pi^0$ [4], $\eta\eta$ [5], $\eta\eta'$ [6], $4\pi^0$ [7] and $K\bar{K}$ [8]. The decay branching ratio of both $f_0(1370)$ and $f_0(1500)$ into $K\bar{K}$ have been observed, but are much too small and incompatible with either state having a large $s\bar{s}$ content [8, 9]. Therefore $f_0(1370)$ and $f_0(1500)$ cannot both belong to the 0^+ nonet while the $s\bar{s}$ meson still remains to be found.

Lattice gauge theories predict the ground state glueball - a 0^+ - state, to lie around 1500 MeV. This and the fact that $f_0(1500)$ is narrow ($\simeq$ 100 MeV) compared to the other 0^+ states led to the conclusion that $f_0(1500)$ is the supernumerary meson in the nonet, most likely the ground state glueball. A detailed discussion can be found in ref. [10].

This conclusion rests on the crucial fact that the $f_0(1500)$ coupling to $K\bar{K}$ is indeed small. The branching ratio to $K\bar{K}$ was determined from a study of the annihilation channel $K_L K_L \pi^0$ [8, 9]. However, $f_0(1370)$, $f_0(1500)$ and $a_0(1450)$ all contribute to this final state and therefore their $K\bar{K}$ branching ratios cannot be determined independently, due to interferences. Nonetheless, the small coupling to $K\bar{K}$ could be derived by fixing the $a_0(1450)$ contribution to about 10%. This number was derived from our rate for $a_0(1450) \to \eta\pi$ [2], using SU(3).

On the other hand, the isoscalar resonances $f_0(1370)$ and $f_0(1500)$ do not contribute to the channel $\bar{p}p \to \pi^\pm K^\mp K_L$. This channel therefore allows a direct measurement of the $a_0(1450)$ contribution to $K\bar{K}\pi$. Crystal Barrel has studied the reaction $\bar{p}p \to \pi^\pm K^\mp K_L$ with a non-interacting K_L in the barrel [11, 12]. This channel is selected from 2-prong data by requiring exactly two clusters in the CsI barrel from $\pi^\pm$ and $K^\mp$. Particle identification is achieved by measuring the ionisation in the drift chamber and a (1C) kinematic fit which ensures momentum and energy conservation. The Dalitz plot (Fig. 2.1) has been corrected for background and acceptance and for the K_L interaction probability.

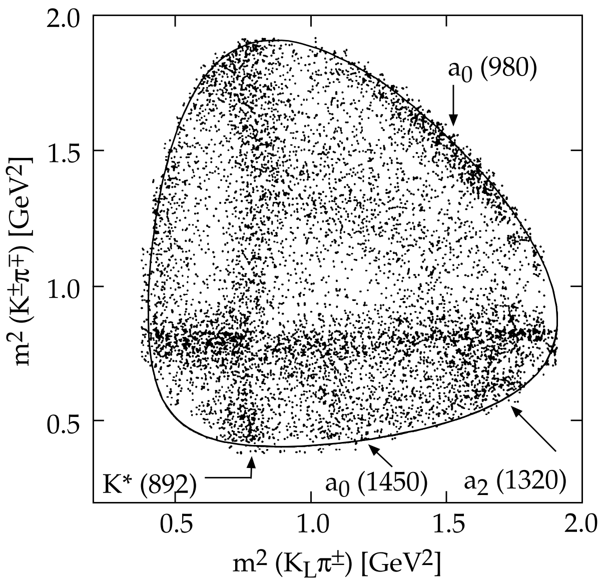

Figure 2.1: $\pi^\pm K^\mp K_L$ Dalitz plot (11,373 events).

The Dalitz plot shows clear signals from $K^*(892) \to K\pi$, $a_2(1320)$ and $a_0(980) \to \eta\pi$. The amplitude analysis did not provide a satisfactory description of the Dalitz plot and the fitted $a_2(1320)$ mass, 1290 MeV, was significantly lower than the accepted well known value (1318 MeV). A substantial improvement in the χ^2 (Fig. 2.2) was obtained when introducing the $a_0(1450) \to K\bar{K}$ with an optimum contribution of (10.8 $\pm$ 2.0) %, in accord with the SU(3) assumptions in ref. [11, 12]. The mass and width are 1480 $\pm$ 30 and 265 $\pm$ 15 MeV, respectively, in agreement with the $\eta\pi$ decay mode [2]. The $a_2(1320)$ mass now becomes compatible with the standard value.

From SU(3) one expects a ratio of branching ratios [10]

$$\frac{\Gamma(a_0^\pm(1450) \to K^\pm K^0)}{\Gamma(a_0^0(1450) \to \eta\pi^0)} = 0.72 \pm 0.03, \tag{2.1}$$

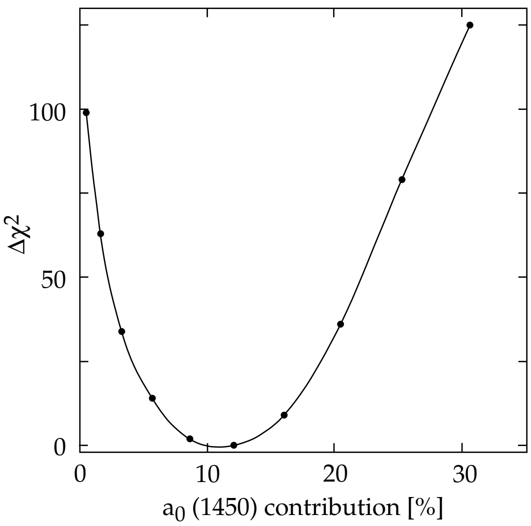

Figure 2.2: χ^2 dependence of the fractional contribution from $a_0(1450)$ to $\pi^\pm K^\mp K_L$.

while Crystal Barrel finds

$$\frac{B(a_0^\pm(1450) \to K^\pm K^0)}{B(a_0^0(1450) \to \eta\pi^0)} = 0.88 \pm 0.23. \tag{2.2}$$

The signals in $K\bar{K}$ and $\eta\pi$ are therefore compatible for a $q\bar{q}$ isovector scalar state. This establishes the existence of $a_0(1450)$ which has now been observed to decay into $\eta\pi$, $\eta'\pi$ and $K\bar{K}$ with consistent rates. Furthermore, its contribution of about 10% to $K\bar{K}\pi$ confirms the small coupling of $f_0(1370)$ and $f_0(1500)$ to $K\bar{K}$ that was predicted from $K_LK_L\pi^0$ data.

2.2 Evidence for $\hat{\rho}(1405)$

Quantum number conservation implies that a meson with quantum numbers $J^{PC} = 1^{-+}$ does not couple to $q\bar{q}$ and therefore the discovery of such a state would prove unambiguously the existence of exotic (non-$q\bar{q}$) mesons. Apart from glueballs, exotic mesons made of $q\bar{q}$ and a valence gluon (the so-called $q\bar{q}g$ hybrids) are also predicted by QCD. According to lattice gauge theories the lightest hybrid is a $J^{PC} = 1^{-+}$ state and lies around 2000 MeV. However, the bag model predicts a 1^{-+} hybrid meson at a much lower mass, around 1400 MeV.

A 1^{-+} hybrid in this mass region would decay to $\eta\pi$ (and $\eta'\pi$), where the two pseudoscalars are in a relative P-wave. This state would be isovector and hence could not be confused with a glueball, which is isoscalar. A candidate, $\hat{\rho}(1405)$, with a mass of 1370 $^{+52}_{-34}$ MeV and a width of 385 $^{+76}_{-112}$ MeV has been reported in the partial wave analysis of $\pi^-p \to \eta\pi^-p$ at 18 GeV [13].

Crystal Barrel has searched for a resonance in the $\eta\pi$ P-wave in $\bar{p}n$ annihilation into $\pi^-\pi^0\eta$, using a liquid deuterium target [14]. Events with a single π^- and $\pi^0\eta \to 4\gamma$ were selected from an 8.1 million 1-prong triggered data sample in liquid deuterium. The single track requirement restricts the spectator proton momentum to less than 200 MeV/c under which protons do not escape from the target. A 3C fit was applied to select $\pi^-\pi^0\eta$ with a missing proton. The missing proton momentum was then limited to 100 MeV/c. This procedure permits the channel $\pi^-\pi^0\eta$ to be treated as quasifree, i.e. insensitive to final state rescattering with the spectator proton.

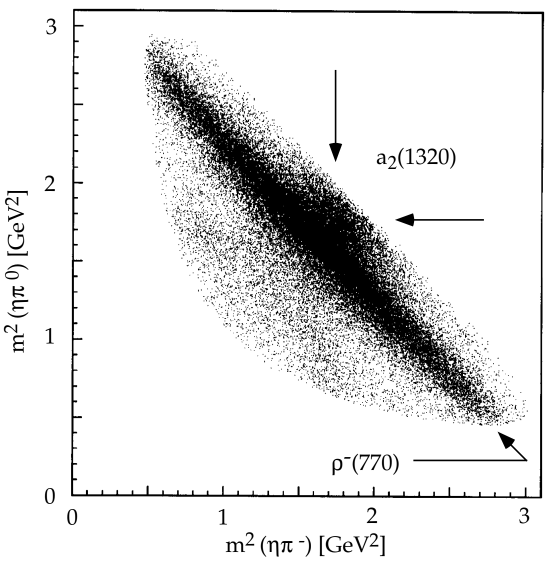

Figure 2.3: Dalitz plot of $\bar{p}n \to \pi^-\pi^0\eta$.

The Dalitz plot from the resulting 52,567 events is shown in Fig. 2.3. Conspicuous is the strong production of ρ^- and the accumulation of events in the $\eta\pi$ mass regions around 1300 MeV but only above the ρ band. This points to the presence of destructive interferences between $a_2(1320)$ and some other amplitude. A partial wave analysis was performed, introducing contributions from $\rho^-(770) \to \pi^-\pi^0$ and $a_2(1320) \to \eta\pi$. Contributions from other $q\bar{q}$ mesons were found to be negligible. The fit could not describe the observed interference pattern in Fig. 2.3. The inclusion of a resonant $\eta\pi$ P-wave led, however, to a good description of the data. The Breit-Wigner mass and width of the 1^{-+} resonance are

$$\hat{\rho}(1405): \; m = 1400 \pm 28, \; \Gamma = 310 \, ^{+71}_{-58} \text{ MeV}. \tag{2.3}$$

The resonance contributes about 11% to the Dalitz plot. It interferes with both $a_2(1320)$ and $\rho^-(770)$. The accumulation of events above the ρ (Fig. 2.3) leads to a forward/backward asymmetry in the $\eta\pi$ rest frame along the $a_2(1320)$ band.

These findings are consistent with the observation of an exotic 1^{-+} resonance in the 1400 MeV mass region. Mass and width are in good agreement with Thompson et al. [13]. However, an adequate fit can also be obtained with a 1 GeV broad enhancement in the $\eta\pi$ P-wave, coupling to the inelastic channel $f_1(1285)\pi$ and generating a distortion around threshold at 1420 MeV. This should be clarified by measuring the branching ratio for $f_1(1285)\pi$ production in deuterium. If not a threshold effect, this meson could be a hybrid but also a four-quark state. A measurement of the partial width into $\eta'\pi$ would help to distinguish between the two alternatives.

We note that another hybrid candidate, $\eta_2(1870)$, with the (non-exotic) quantum numbers $J^{PC} = 2^{-+}$ has been reported earlier by Crystal Barrel [15]. It decays into $\pi^0\pi^0\eta$ and is observed in $\bar{p}p$ annihilation into $3\pi^0\eta$ with 1.9 GeV/c antiprotons. Crystal Barrel finds the dominant decay modes $a_2^0(1320)\pi^0$ and $f_2(1270)\eta$. The ratio of partial widths is is in good agreement with the predicted ratio for a 2^{-+} hybrid meson [16].

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