NEW RESULTS ON MESON SPECTROSCOPY WITH THE CRYSTAL BARREL DETECTOR*

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The results of $\bar{p}p$-annihilation measurements with Crystal Barrel detector are presented. Light meson spectroscopy is stressed. The evidence for exotic states like Glue-Balls or Hybrids is shown.

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1. Introduction

The Crystal Barrel Collaboration [1] at LEAR has taken data on $\bar{p}p(d)$-annihilations at rest and in flight (maximum $\bar{p}$-momentum : 1940 MeV/c) since 1989. A variety of interesting results has shown up. They range from details of the $\bar{p}p(d)$-annihilation mechanism through rare meson (η)-decays to dramatic violations of the OZI-rule. This talk will deal only with results connected to questions of light meson spectroscopy including evidences for exotic states like Glue-Balls or Hybrids. Most of the data is published [2-22]. For a more complete overview see also ref. [23].

2. The Crystal Barrel detector and its performance

The Crystal Barrel (CB) detector [2] is shown in figure 1. It is able to detect neutral (gammas) and charged particles in nearly the full solid angle with good energy and angular resolutions. The short living particles can be well reconstructed. Typical mass resolutions are given in Table I. The values refer to data taken in flight with $20 \leq E_\gamma \leq 1500$MeV. Even better numbers are achieved for data taken at rest. Furthermore, a good $\pi^\pm/K^\pm$-separation via dE/dx and kinematical fitting is achieved, the acceptance -even for data in flight- is rather flat (typical variations $\leq$ several percent over a full Dalitz–Plot) and missing particles, like K^0_L, can be reconstructed

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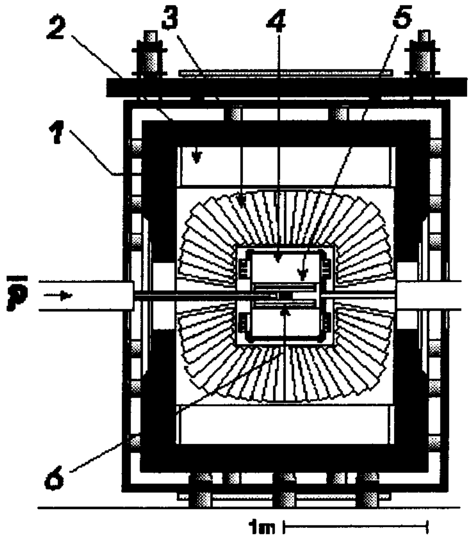

Fig. 1. Crystal Barrel detector (1) Iron-yoke, (2) Cu-coil, (3) Electromagnetic calorimeter consisting of 1380 Cs(Tl) crystals, (4) Cylindrical Jet Drift Chamber with 690 signal wires in 23 layers, (5) Cylindrical Proportional Wire Chambers with 90 wires in the first and 120 wires in the second layer, recently replaced by a cylindrical Si-detector with 1920 strips, (6) Target (Liquid Hydrogen/Deuterium or gaseous Hydrogen)

with high confidence. This excellent performance together with the high quality $\bar{p}$-beam of LEAR has led to data of unparalleled resolution and statistics.

TABLE I

Mass resolutions after kinematic fitting

	mass resolutions (σ) in $\frac{\mathrm{MeV}}{\mathrm{c}^2}$
$\pi^0 \to \gamma\gamma$	11
$\eta \to \gamma\gamma$	16
$\eta \to 3\pi^0(6\gamma)$	9
$\eta \to \pi^+\pi^-\pi^0(2\gamma)$	12
$\eta' \to \pi^0\pi^0\eta(6\gamma)$	8
$\eta' \to \pi^+\pi^-\eta(2\gamma)$	10
$\omega \to \pi^0\gamma(3\gamma)$	20
$\omega \to \pi^+\pi^-\pi^0(2\gamma)$	21

3. Selected results

In the past years about 10^8 $\bar{p}p$ annihilation events have been taken with 200 MeV/c $\bar{p}$-beam momentum. Here the antiproton stops in the Hydrogen (Deuterium) target, and the initial states are atomic states (mainly s- and p-waves, the ratio depending on the pressure of the target). These data are analysed to a great amount, and spin/parity analyses using different formalisms have been performed [2–22]. Recently, about the same amount of data has been taken with antiprotons in flight at 600, 1200 and 1940 MeV/c $\bar{p}$-momentum. Here, the initial states are scattering waves with angular momenta up to 8 $\hbar$. The analysis is more difficult because of the larger number of contributing waves. Most of the data is reconstructed, but only in a few cases a spin/parity analysis was done yet.

3.1. $0^+, 2^+$*-states with I=0,1*

3.1.1. Annihilation at rest

The following reactions were measured and analysed (some of them even in terms of a coupled channel analysis) :

$$\begin{aligned}\bar{p}_{\text{Stop}}p \; &\rightarrow \pi^0\pi^0\pi^0,\ \pi^0\pi^0\eta,\ \eta\eta\pi^0,\ \eta'\eta\pi^0,\ \pi^+\pi^-3\pi^0, \\ &5\pi^0, K_L K_L \pi^0,\ \omega\omega\pi^0,\ \pi^0\eta\omega\end{aligned}$$

As example for the quality of the data the Dalitz plots of the $3\pi^0$ and $2\eta\pi^0$ annihilation channels are shown in Figs 2 and 3.

Clear signals for several states are visible, part of which is already well known ($f_0(975), a_0(980), f_2(1270), a_2(1320)$). In addition, there is clear evidence for a 0^{++}-state ($I = 0$) at 1500 MeV/c^2 decaying into $\pi^0\pi^0$ and $\eta\eta$. Further more, with weaker evidence, an $I = 0$ state at 1370 MeV/c^2 and an $I = 1$ state at 1450 MeV/c^2 are required to fit the data. Combining the results of all analyses, the picture as sketched in Table II evolves, where the resonances contributing to the $\pi\pi$, $\eta\eta$, $\eta\eta'$, 4π, $K\bar{K}$ s- and d-waves are listed.

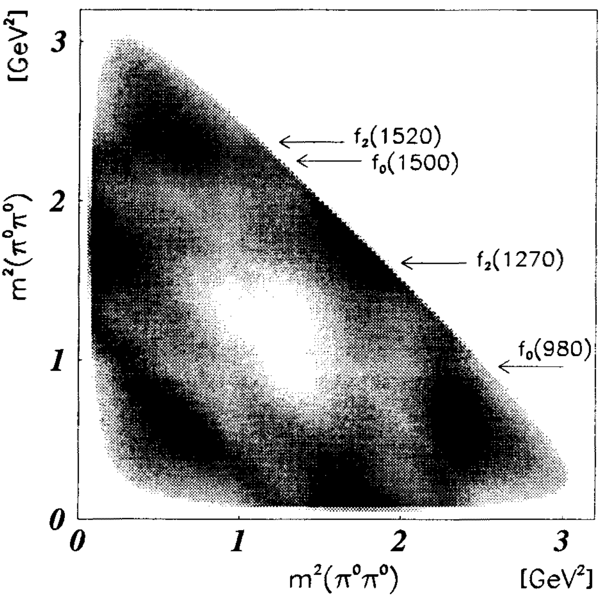

Fig. 2. Dalitz plot of the $3\pi^0$ annihilation channel at rest

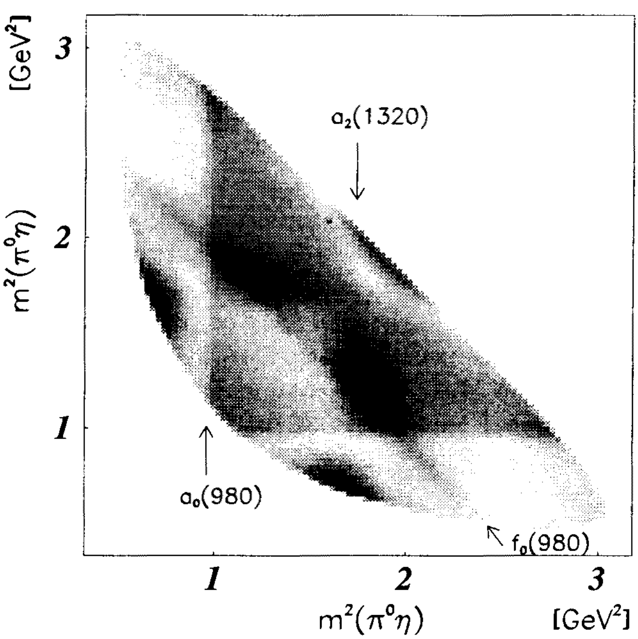

Fig. 3. Dalitz plot of the $2\eta\pi^0$ annihilation channel at rest

TABLE II

Results of CB-analysis at rest in the 0^{++} and 2^{++} section

Resonance	Mass / Width [$\frac{\text{MeV}}{c^2}$]	Decay channels	Remarks
	Isoscalar s-wave states		
$f_0(975)$	$980 \pm 20;\ 50 \pm 20$	$\pi\pi$	known
$f_0(1370)$	$1360 \pm 20;\ 360 \pm 50$	$\pi\pi,\ \eta\eta,\ 4\pi,\ K\bar{K}$	0^{++}-Nonet ?
$f_0(1500)$	$1505 \pm 10;\ 135 \pm 15$	$\pi\pi,\ \eta\eta,\ \eta\eta',\ 4\pi,\ K\bar{K}$	Glue-Ball ?
	Isoscalar d-wave states		
$f_2(1270)$	$1268 \pm 10;\ 180 \pm 20$	$\pi\pi,\ K\bar{K}$	known
$f_2(1565)$	$1550 \pm 20;\ 160 \pm 30$	$\pi\pi$	known (AX)
	Isovector s-wave states		
$a_0(980)$	$985 \pm 5;\ 54 \pm 5$	$\pi\eta,\ K\bar{K}$	known
$a_0(1450)$	$1450 \pm 40;\ 270 \pm 40$	$\pi\eta$	0^{++}-Nonet ?
	Isovector d-wave states		
$a_2(1320)$	$1315 \pm 5;\ 112 \pm 5$	$\pi\eta,\ K\bar{K}$	known

Of particular importance are the yet preliminary branching ratios of the newly found state $f_0(1500)$:

$$BR(f_0(1500)) \rightarrow \pi\pi(3.0) : \eta\eta(0.7) : \eta\eta'(1.0) : K\bar{K}(0.5 - 1.5)$$

They are of great relevance for the nature of this state (Glue-Ball or not; see the discussion in Sec. 4).
With smaller statistics most of the states are also seen in $\bar{p}d$-reactions from CB, but are not discussed here further.

3.1.2. Annihilation in flight

The following in flight reactions were measured by CB at $\bar{p}$-momenta of 600, 1200 and 1940 MeV/c :

$$\begin{aligned}\bar{p}p \;\rightarrow\; & 3\pi^0,\ 2\pi^0\eta,\ 2\eta\pi^0,\ 3\eta,\ 3\pi^0\eta,\ \pi^0\eta\omega,\ \pi^0\omega\omega,\ \pi^+\pi^-\pi^0,\ \pi^+\pi^-\eta, \\ & K^+K^-\pi^0,\ K^+K^-\eta,\ \pi^+\pi^-2\pi^0\eta\end{aligned}$$

The data with the highest statistics were taken at 1940 MeV/c.
As examples for CB-data in flight the Dalitz–Plots of the annihilation channels $\bar{p}(1940\text{MeV/c})\text{p} \rightarrow 2\eta\pi^0$ and $\bar{p}(1940\text{MeV/c})\text{p} \rightarrow \text{K}^+\text{K}^-\pi^0$ are shown in Figs 4 and 5.

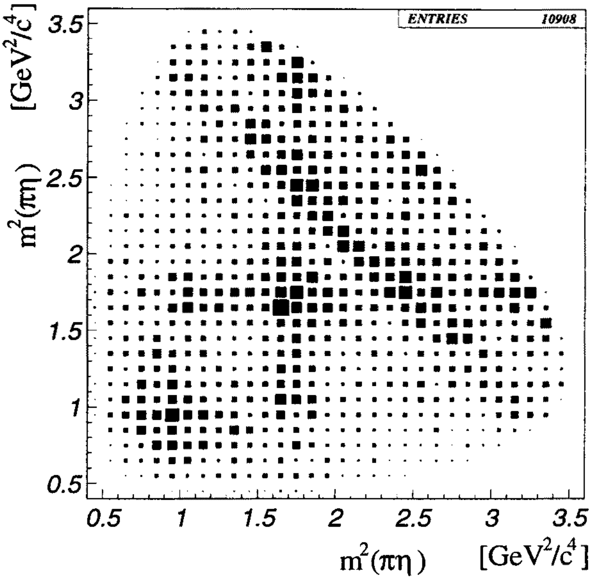

Fig. 4. Dalitz plot of the reaction $\bar{p}$(1940 MeV/c)$p \to 2\eta\pi^0$ [from Ref. [24]

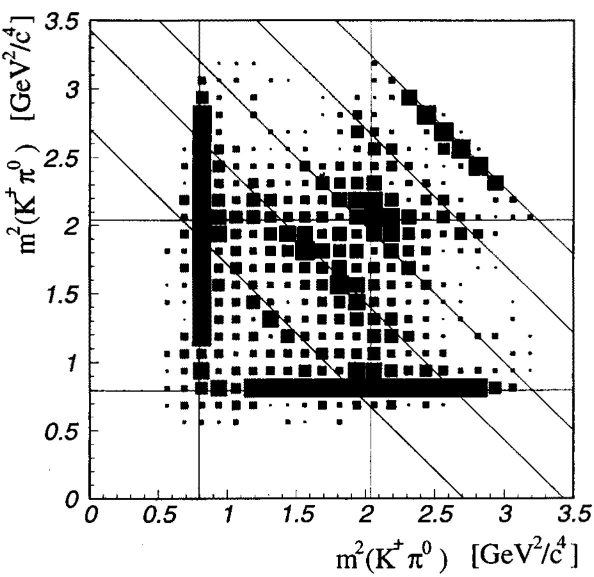

Fig. 5. Dalitz plot of the reaction $\bar{p}$(1940 MeV/c) $p \to K^+K^-\pi^0$ [from Ref. [25]]

It is obvious, that also in these cases the data quality is excellent,although the CB-detector was not optimized for in flight measurements (acceptance hole in forward direction). The resonances found so far in the data are listed in Table III.

TABLE III

Overview on resonant states seen by CB in annihilation in flight

Resonance	Mass / Width [$\frac{\text{MeV}}{c^2}$]	Decay channels	Remarks
		Scalars	
$f_0(975)$		$\pi\pi$	
$a_0(980)$		$\eta\pi$	
$K_0^*(1430)^{2)}$		$K\pi$	not dist. from $K_2^*(1430)$
$f_0(1500)^{1)}$	$1534 \pm 2 \pm 30$; $131 \pm 4 \pm 30$	$\pi\pi$, $\eta\eta$	Glue-Ball ?
		Vectors	
$K^*(892)$		$K\pi$	
$\phi(1020)$		$K\bar{K}$	
		Tensors	
$f_2(1270)$		$\pi\pi$, $K\bar{K}$	
$a_2(1320)$		$\eta\pi$	
$K_2^*(1430)^{2)}$		$K\pi$	not dist. from $K_0^*(1430)$
$f_2(1640)^{1)}$	$1640 \pm 4 \pm 30$; $169 \pm 8 \pm 30$	$\pi^0\pi^0$	I=0, $J^P = 2^{++}$
$a_2(1650)^{1)}$	$1650 \pm 15 \pm 30$; $280 \pm 30 \pm 30$	$\eta\pi$	I=1, $J^P = 2^{++}$
		Pseudo-Tensors	
$\eta_2(1650)^{3)}$	1650 ± 20; 180 ± 50	$a_2(1320)\pi$	Partner of $\pi_2(1670)$?
$\eta_2(1875)^{3)}$	1875 ± 40; 225 ± 50	$f_2(1270)\eta$	?
		Other states seen / No J^P-analysis yet	
$X(1700)^{2)}$		$K\bar{K}$	Member of 0^{++}-nonett ? Glue-Ball ?
$X(1900)^{2)}$		$K\bar{K}$	?
$X(2130)^{1)}$	$2132 \pm 5 \pm 15$; $215 \pm 10 \pm 20$	$\eta\eta$	$0^+, 2^+, 4^+$?

1) Preliminary data from Ref. [24]
2) Preliminary data from ref. [25]
3) From Ref. [21]

Of particular importance is the appearance of the $f_0(1500)$-state, which is seen for the first time also in annihilation in flight. More information about the states marked with a question mark is urgently needed. This is particulary true for the determination of spin and parity of the states at 1700 and 2130 MeV/c^2, which could shed light on the question of the Glue-Ball-Spectrum (see Sec. 4).

3.2. 0^{-+}*-states*

To investigate these states, the channel $\bar{p}_{Rest}p \to \pi^+\pi^-\pi^0\pi^0\eta$ was analyzed. The interest here is in the region around 1400 MeV/c^2, where several signals with different quantum numbers (0^{-+}, 1^{++}) were seen in the past (E/i-puzzle). The Crystal Barrel experiment [20] observes here an 0^--state with a mass of 1409 MeV/c^2 and a width of 86 MeV, which decays into $\eta\pi^0\pi^0$ and $\eta\pi^+\pi^-$. Recently, a narrow peak was seen by CB in the channel $\pi^0\pi^0\eta$ in annihilation reactions in flight, which has to be analysed more in detail.

3.3. Hybrid states

A state of the expected Hybrid spectrum with an exotic quantum number combination $J^{PC} = 1^{-+}(H(1900))$ is supposed to lie around 1.9 $\frac{\text{GeV}}{c^2}$. It is conjectured to decay preferentially into a pair of mesons, one of which is a L=1 state, e.g. $f_1(1285)$ or $b_1(1235)$. Therefore a high statistics run on the channel $\bar{p}(1940\text{MeV}/c)p \to \pi^+\pi^-\pi^0\pi^0\eta$ has been performed by CB, in order to search for the reaction chains

$$\bar{p}p \to H\pi,\ H \to f_1\pi,\ f_1 \to a\pi,\ a \to \eta\pi$$

or

$$\bar{p}p \to H\pi,\ H \to b_1\pi,\ b_1 \to \omega\pi$$

The analysis is not yet finished, but preliminary conclusions can be drawn. There are only weak b_1-signals in the data, but f_1 is clearly visible. The πf_1-mass plot shows a weak signal around 1870 MeV/c^2, which becomes more evident after background subtraction [26]. It seems, that it also shows up in the $4\pi^0\eta$-channel, so that there is hope to find a signal in the expected mass region.

An intensive search for the signal $\hat{\varrho}(1405) \to (\pi^0\eta)_{p-\text{wave}}$, which was seen by the Gams-Collaboration, and was discussed as a good candidate for the Hybrid-ground-state, was performed. Indeed, a $\pi^0\eta$-p-wave was seen in the $\bar{p}_{\text{Stop}}p \to \pi^0\pi^0\eta$-data, but it was broad and non resonant, so that CB has no evidence for the existence of such a state.

4. Discussion of results

The data is of particular interest in two contexts. The first one is the shape of the $(\pi\pi)$-s-wave and the other one is the 0^{++}-nonet / ground state glue-ball problem.

4.1. The $(\pi\pi)$-s-wave

Collecting all results of our coupled channel analysis, the $(\pi\pi)$-s-wave could look as sketched in Fig. 6. A very broad background ($f_0(1300)$), which by itself could be a broad resonance, interferes strongly with states at 975 and 1500 and weaker at 1370 MeV/c^2 (not yet completely clear). If the state at 1700 MeV/c^2 would have spin $\not{0}$, another interference would show up, as indicated in the figure. If confirmed, the $(\pi\pi)$ s-wave would have an unusual shape compared with other waves, *e.g.* $(\pi\pi)$-p/d-waves, which seem to have no broad background and exhibit only well separated resonances. A theoretical explanation of this funny behaviour would be very fundamental for our understanding of non-perturbative QCD-effects.

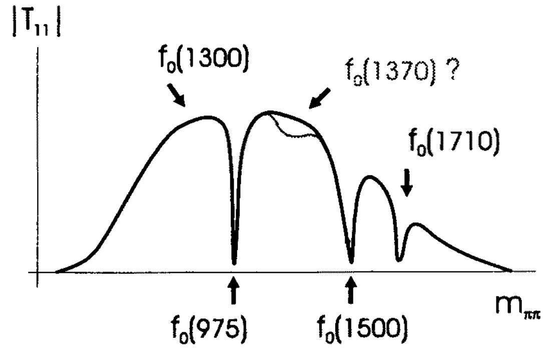

Fig. 6. Educated guess for the $(\pi\pi)$-s-wave amplitude (from Ref. [23] and references there in)

4.2. The 0^{++}-nonet/Glue-Ball-spectrum

Both problems are intimately connected and cannot be solved independently of each other. According to the data, there exist more 0^{++}-states than are needed to fill the 0^{++}-nonet. These are :

$f_0(1370)$, $a_0(1450)$, $f_0(1500)$and$f_J(1700)$, if $J = 0$

As $f_0(975)$ and $a_0(980)$ never were good candidates for the 0^{++}-nonet, they should be replaced by $f_0(1370)$ and $a_0(1450)$. Then, one of the remaining states would be the SU(3)-singulett of the 0^{++}-nonet, the other one could be the glue-ball ground state. It is well possible, that the glue-ball mixes with the $q\bar{q}$-mesons, a scenario, which was quantitatively worked out [27]. It is hoped, that the ongoing experiments and analyses at LEAR and other places will shed still more light on the situation and will help to find an unambiguous solution. The excited states of the glue-ball spectrum probably would have the quantum numbers 0^{-+} and 2^{++} and masses below and above 2 GeV/c^2. Thus, optimists could conclude, that already now three glue-ball candidates ($f_0(1500)$, E/i(1400) and $f_0(2120)$) are known and seen by CB.

5. Conclusions

The excellent performance of LEAR and of the CB-detector has resulted in a set of very accurate and high statistics data on $\bar{p}p$-annihilations with particular relevance for light meson spectroscopy. The new data help to disentangle the nature of 0^{++}-states lying around 1.5 GeV/c^2. Part of them probably belongs to the 0^{++}-nonet, but one of them could be the long expected glue-ball ground state. Signals for higher mass states also show up, but a final interpretation has to wait, until the spin/parity determinations are finished. Even for a Hybrid state weak evidence might exist. The on going measurements and analyses will further help to clear up the situation in the interesting field of light meson spectroscopy.

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