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Search for the isovector member of the scalar nonet

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Abstract. The identification of the isovector member of the scalar nonet plays a fundamental role in fixing the properties of the other members and, therefore, in the possible identification of an extra state as the glueball candidate. After more than 20 years of experiments on this subject the situation has not yet been clarified. A review of the experimental results coming both from $\bar{p}p$ annihilation and the πp reaction is presented in this paper.

1 Introduction

The identification of glueballs is the main goal of light quark spectroscopy. Their existence is one of the foundations of quantum chromodynamics (QCD) as a non-Abelian field theory and their unambiguous detection would provide a striking proof of its validity. This recognition must go through a careful classification of the standard members of the nonet in order to distinguish the outsider.

The identification of the isovector member of the scalar nonet is a very important step in the search for the scalar glueball. The study of its mass and width would provide the natural mass and width scale for the singlet member of the nonet [1,2] and allow us to discriminate among different theoretical models. Moreover its $\bar{\mathrm{K}}\mathrm{K}$ coupling can help to evaluate the extent of the $f_0(1500)$ $\bar{\mathrm{K}}\mathrm{K}$ coupling [3] and compare it with the expectation for a glueball candidate or an ordinary member of the scalar nonet.

2 Theoretical models

With the exception of [4] there is a general consensus [5] that $a_0(980)$ should be excluded as the candidate to fill the isovector place in the scalar nonet. The correct assignment therefore still remains open.

It is natural to expect the 0^{++} isovector state to be close to the 2^{++} $a_2(1320)$ and the 1^{++} $a_1(1260)$. This state should also have a strong coupling to $\bar{\mathrm{K}}\mathrm{K}$ and $\eta\pi$ [6]. This picture was first proposed 30 years ago by Veneziano within the framework of the '*daughter trajectories*' [7].

According to the relativistic quark model by Godfrey and Isgur [8], the isovector scalar was predicted to occur at a lower mass: 1090 MeV (200 MeV below the $^3\mathrm{P}_2$ state $a_2(1320)$) with a large width (about 500 MeV). This would have prevented experimental observation [8,9].

More recently several models have predicted the scalar nonet isovector member at a mass around $1.3\,\mathrm{GeV}/c^2$. In a relativistic quark model with linear confinement and instanton-induced interaction [10] the isovector member of the scalar nonet is predicted at a mass of $1.32\,\mathrm{GeV}/c^2$. This result is confirmed by the quark model calculations based on the Nambu and Jona-Lasinio model in [11]. In [12,13] the $I = 1$ state of the scalar nonet is established to be at a mass of $1.35\,\mathrm{GeV}/c^2$ by the application of the linear mass spectrum on the basis of three mass sum rules. In [12] it is pointed out that a $I = 1$ 0^{++} state must exist at a mass around $1.3\,\mathrm{GeV}/c^2$ in order to belong to the Regge trajectory on which $\rho(1700)$ lies.

3 Experimental results

On the experimental side, the situation, although rich and interesting, is far from being well understood.

The work of Veneziano [7] suggested the investigation of the possible presence of a $I = 1$ 0^{++} state close to the $a_2(1320)$ mass [14]. Unfortunately the analyses performed at that time gave only very limited indications mainly because of the available statistics.

After that, several experiments investigated this problem studying several final states coming from different production mechanisms. Three classes of experiments will be considered: $\bar{\mathrm{p}}\mathrm{p}$ annihilation at rest in a bubble chamber, $\pi\mathrm{p}$ interaction and the new generation of $\bar{\mathrm{p}}\mathrm{p}$ experiments at rest performed at LEAR.

3.1 Bubble chamber experiments

In antiproton–proton annihilation at rest in liquid hydrogen, the presence of an isovector scalar state below $1300\,\mathrm{MeV}/c^2$ was considered possible in $\eta\pi$ and $\bar{\mathrm{K}}\mathrm{K}$ systems [14]. The $\eta\pi$ system was studied by Espigat et al. [15] and by Chung et al. [16] in the channel $\bar{\mathrm{p}}\mathrm{p} \to \eta^0\pi^+\pi^-$. Espigat et al. stated explicitly that their analysis could not

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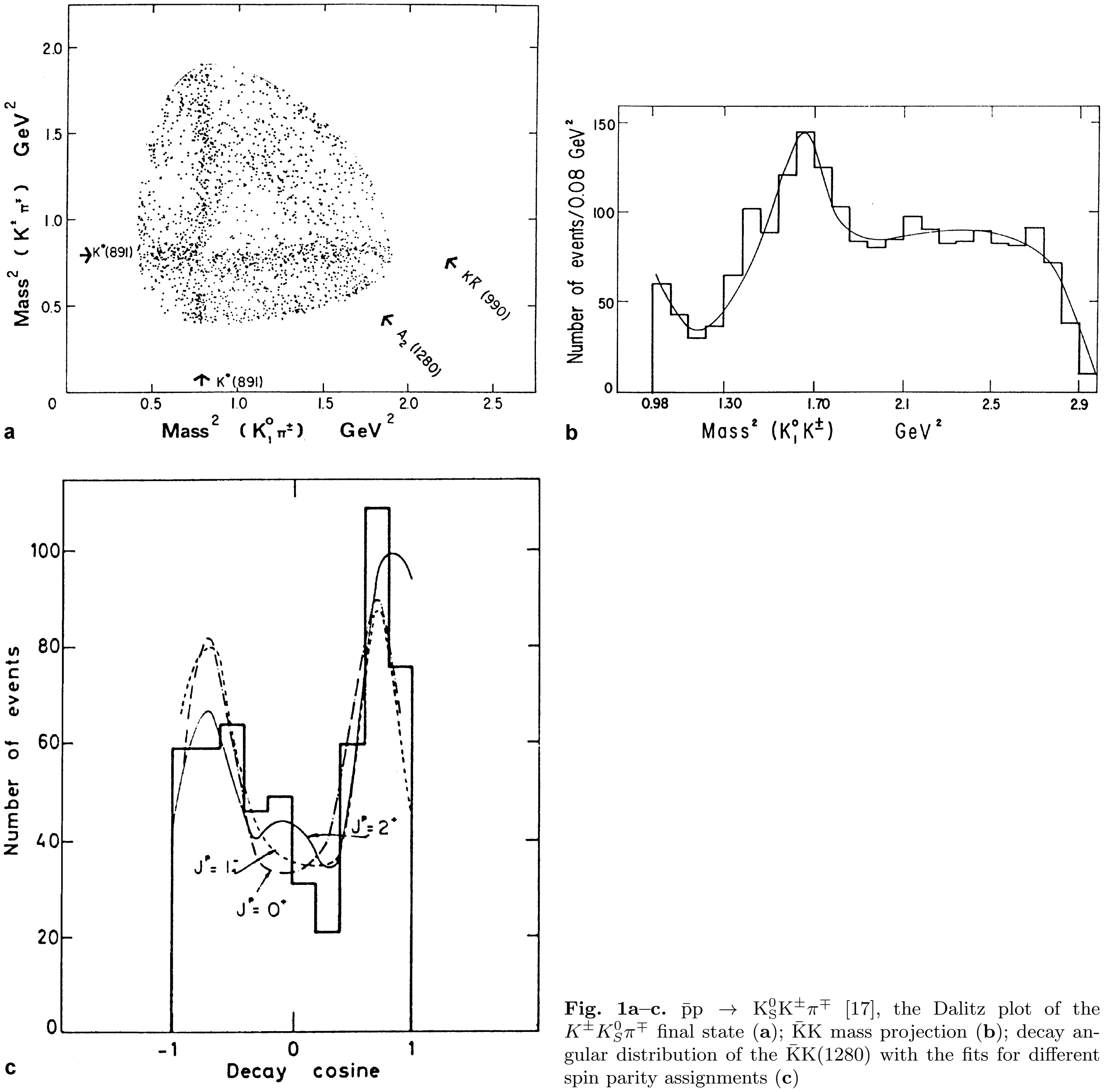

Fig. 1a–c. $\bar{p}p \to K^0_S K^\pm \pi^\mp$ [17], the Dalitz plot of the $K^\pm K^0_S \pi^\mp$ final state (**a**); $\bar{K}K$ mass projection (**b**); decay angular distribution of the $\bar{K}K(1280)$ with the fits for different spin parity assignments (**c**)

distinguish between $J^P = 0^+$ and $J^P = 2^+$. The identification of $J^P = 2^+$ was based on the general assumption that the peak was due to the a_2 but a $J^P = 0^+$ could be equally probable. In the analysis of Chung et al. a good fit was obtained by using the Veneziano dual amplitudes, thus supporting the possible presence of a $J^P = 0^+$ 'daughter' of a_2. Unfortunately the limited statistics and the sizable background in the η peak prevented any further conclusion.

The $K^0_S K^\pm \pi^\mp$ channel is specially valuable. It does not suffer from background contamination and provides the cleanest way to study $I = 1$ scalar resonances since $I = 0$, $J^{PC} = 0^{++}$ states are not present. In the analysis of the $\bar{K}K$ system from $\bar{p}p$ annihilation at rest in the channel $K^\pm K^0_S \pi^\mp$ a structure at 1280 MeV was observed. It was interpreted as due to the a_2 meson [17] even if a 0^+ contribution could not be excluded [14,18]. A notable point is that the peak in the $\bar{K}K$ system was centered at 1280 MeV, clearly below the nominal a_2 mass (see Fig. 1b). This suggested the possible presence of a further structure at a mass lower than the $a_2(1320)$. Here again the statistics allowed us simply to discriminate the 2^+ as the best solution with respect to 0^+ but not to resolve the possible presence of two resonant states (see Fig. 1c).

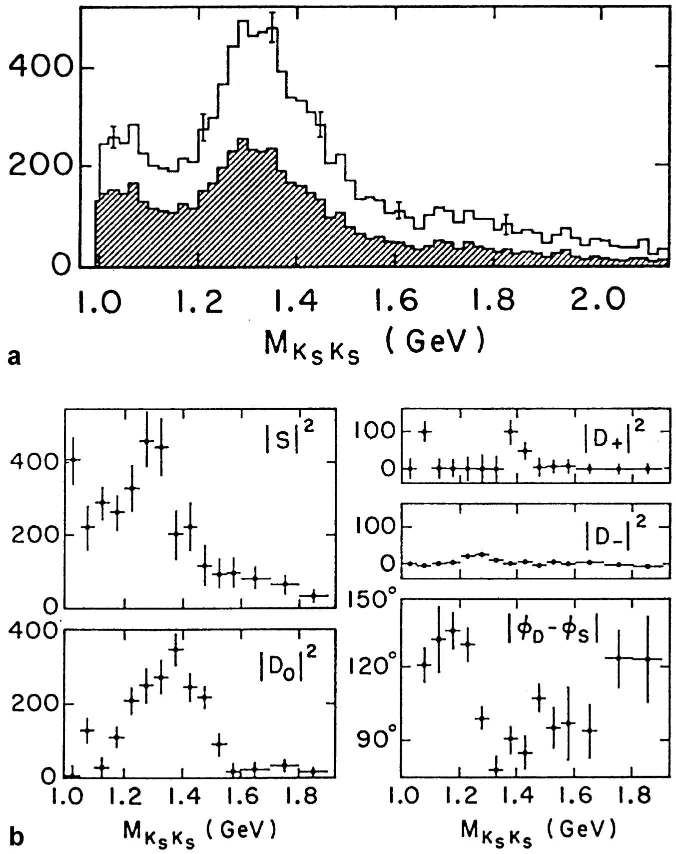

Fig. 2a,b. $\pi^- p \to n K_S^0 K_S^0$ [19] , $K_S^0 K_S^0$ invariant mass distribution (**a**); fitted parameters of the amplitude analysis, for the S- and D-waves and for the relative phase ϕ_{SD} (**b**)

3.2 πp experiments

In several πp experiments evidence was provided for an $I = 1$ $J^{PC} = 0^{++}$ state around 1.3 GeV/c^2.

In 1976 a scalar state at a mass 1255 ± 5 and width 79±10 MeV was reported [19]. The meson was observed in the reaction $\pi^- p \to nK_S^0K_S^0$ at Argonne National Laboratory. The reaction did not allow us to discriminate between $I^G = 0^+$ and $I^G = 1^-$. Nevertheless $I^G = 1^-$ was preferred on the basis of the comparison of the relative phase between the scalar resonance and the $f_2(1270)$ meson.

A further study of the reactions $\pi^- p \to K^- K^+ n$ and $\pi^+ p \to K^- K^+ p$ reported again a peak in the S-wave at 1300 MeV [20] but in this case it was shown that the S-wave was dominantly $I = 0$.

The analysis of 10 GeV/c $\pi^- p \to K^- K_S^0 p$ high statistics data collected at CERN show evidence for a $J^{PC} = 0^{++}$ state with mass 1300 MeV/c^2 and width 250 MeV/c^2 [21,22]. In this case the isospin assignment was unambiguously resolved since the $K^- K_S^0$ channel has $I = 1$. The analysis [22] also included the K^+K^- data of [20].

Nevertheless a new amplitude analysis [23] of the data of [20] disagreed with the results of [22] and, even though not excluding the possibility of an $I = 1$ resonance at around 1300 MeV, interpreted the S-wave enhancement at 1300 Mev as mainly due to a broad (160 MeV) $I = 0$ resonance at a mass 1425 ± 15 MeV which is now commonly identified as $f_0(1370)$ [5].

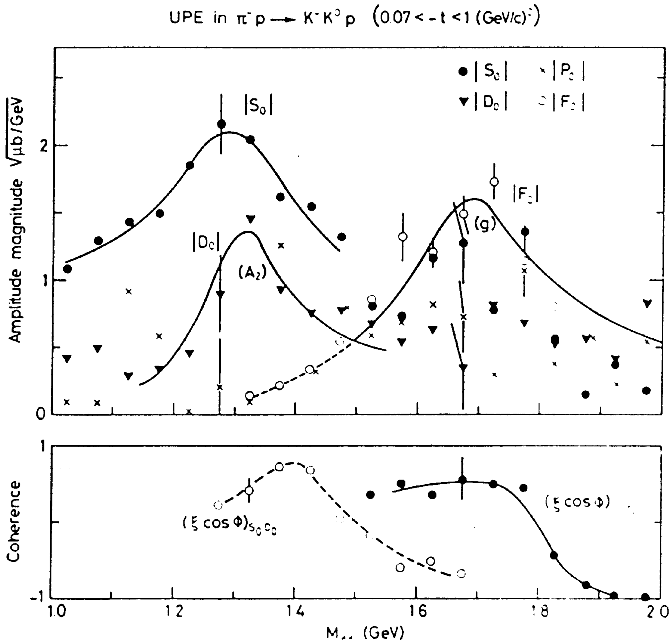

Fig. 3. $\pi^- p \to K^- K_S^0 p$ [21], the amplitudes describing $K^- K_S^0$ production

More recently (1982) the amplitude analysis of the $K_S^0 K_S^0$ performed on a very high statistics data sample collected at Brookhaven National Laboratory in the reaction $\pi^- p \to nK_S^0K_S^0$ at 23 GeV/c showed that $f_0(1370)$ alone was clearly not sufficient to provide a satisfactory description of the S-wave amplitude in the 1300 MeV region [24] (see Fig. 4). An extension of that analysis [25] provided evidence for a $I = 1$ $J^{PC} = 0^{++}$ state whose mass was reported to be 1410 MeV.

A new partial wave analysis performed on GAMS data has shown that also in the $\eta\pi$ system, studied in peripheral collision at 38 GeV/c, a scalar resonance is present at a mass $M = 1308 \pm 6$ MeV and width $\Gamma = 104 \pm 15$ MeV [26]. For this channel, as in the case of $K^- K_S^0$, $I = 0$ resonances are excluded so that the isospin assignment is unambiguous.

In summary the information from πp data is consistent in indicating the presence of an enhancement in the S-wave amplitude at around 1300 MeV. This effect is interpreted as due either to the broad $f_0(1370)$ or to an $I = 1$ resonance. The inconsistencies in its mass and width do not allow for a firm conclusion.

Moreover the S-wave amplitude in πp experiments is intrinsically complicated to study because of difficulties related to the evaluation of the background contribution. Probably for this reason the effect at 1300 MeV tended to be commonly considered as entirely due to $f_0(1370)$ and the results concerning a possible $I = 1$ resonance were mainly forgotten.

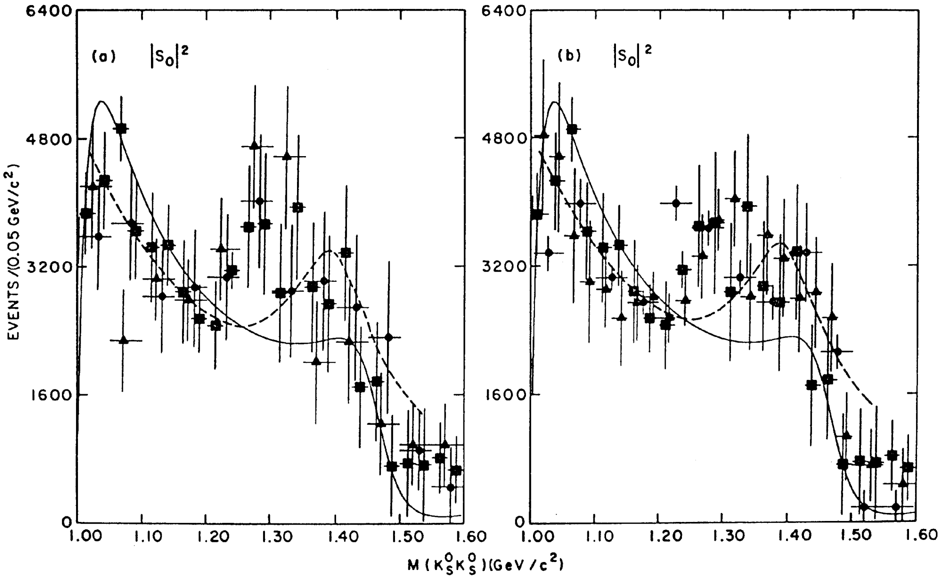

Fig. 4a,b. $\pi^- p \to n K^0_S K^0_S$ [24], comparison of the squared modules for the S-wave solution as a function of the $\bar{K}K$ effective mass, **a**: boxes [24], triangles [34], circles: [35]; **b**: boxes [24], triangles [23], circles: [36]; the solid curve is the fit of [24] data, the dashed curve is the fit of [23] and [37] data, in both cases the fit parameters are the $f_0(980)$ and the $f_0(1370)$ (see [24])

3.3 Antiproton–proton experiments at LEAR

In $\bar{p}p$ annihilation at rest the situation is much simpler but, as pointed out above, bubble chamber experiments lacked the necessary statistics to disentangle a resonant contribution in a mass region where two other important signals ($a_2(1320)$ and $f_0(1300)$) were already present.

With the advent of LEAR at CERN a new generation of experiments was able to collect statistics, on $\bar{p}p$ annihilation, exceeding by orders of magnitude the data collected in bubble chamber experiments. This allowed us to put in evidence structures not accessible with lower statistics.

An $I = 1$ state at a mass of 1450 MeV/c^2 was identified in the analysis of the $\eta\pi\pi$ channel performed on a high statistics data sample from $\bar{p}p$ annihilation at rest in liquid hydrogen collected at CERN by the Crystal Barrel experiment [27]. The analysis required the presence of an $I = 1$ state at a mass of 1450 ± 40 MeV/c^2 and width 270 ± 40 MeV/c^2. The debates on the possible presence of an isovector scalar around 1300 MeV were long forgotten and the $a_0(1450)$ was classified as a new resonance to be confirmed by further experimental evidence.

The same experiment confirmed, essentially, the results in the $\eta\pi\pi$ final state with the study of other channels: $\eta'\pi\pi$ [28], $K^0_L K^\pm \pi^\mp$ [3] and $\eta\pi\pi$ with a gas target at 12 atm [29].

The information coming from the $K^0_L K^\pm \pi^\mp$ channel turned out to be very important since the measurement of the a_0 $\bar{K}K$ coupling allows us to evaluate the $f_0(1500)$ $\bar{K}K$ coupling disentangling the $I = 0$ and $I = 1$ components present in the $K^0_L K^0_L \pi^0$ channel (see [3]). The $\bar{K}K$ mass spectrum of [3] closely resembles that of the bubble chamber [17]. In particular the 'a_2' peak appears shifted to a lower mass as already observed in bubble chamber data. This is interpreted, in the analysis of [3] as due to destructive interference between the $a_0(1450)$ and the $a_2(1320)$.

In summary, the results of [3,27–29] agree in providing a coherent picture of the meson scalar nonet where the $a_0(1450)$ is a standard member and the $f_0(1500)$ is an outsider and a glueball candidate [1–3,30].

The experimental situation became more complicated with the recent results of the analysis of the $K^\pm K^0_S \pi^\mp$ in $\bar{p}p$ annihilation at rest performed at CERN by the Obelix experiment [31]. The channel is the same as in [17] but in this case the fit is performed simultaneously on three data sets coming from different hydrogen target conditions (liquid, gas at NTP, gas at 5 mbar). Each data set is characterized by different initial angular momentum state conditions spanning from S-wave dominance (liquid target) to P-wave dominance (gas target at 5 mbar). This approach provides strong constraints in the spin parity analysis and it is extremely powerful for disentangling nearby resonances featuring different J^{PC}. The Dalitz plots and the $\bar{K}K$ projections for LH_2 (Fig. 7a,d) are quite similar to that of [3, 17] (Figs. 1 and 6 respectively). Again the $\bar{K}K$ mass spectrum exhibits a peak centered at 1290 MeV, about 30 MeV lower than the nominal $a_2(1320)$ mass value. What is peculiar with these data is that the shift disappears as the S-wave contribution decreases (Fig. 7 e,f). This could be the direct indication of the presence of a scalar state produced mainly from the S-wave. The same effect shows up for the $a_0(980)$ as apparent from the Dalitz plot and the $\bar{K}K$ projection at different densities.

The spin parity analysis performed simultaneously on the three data sets confirmed this interpretation [31]. Table 1 shows the expected S- and P-wave contributions as a function of the target density (see [32] and references quoted therein) together with the normalized branching fractions for the two a_0 and the $a_2(1320)$. Both the $a_0(980)$ and the $a_0(1290)$ production frequencies scale with density as the S-wave. In contrast, the $a_2(1320)$ is proportional to the P-wave. This fact is quite natural (scalar states are commonly produced in the S-wave, tensor states mainly come from the P-wave) and makes it relatively easy to disentangle the $a_0(1290)$ and $a_2(1320)$ contributions.

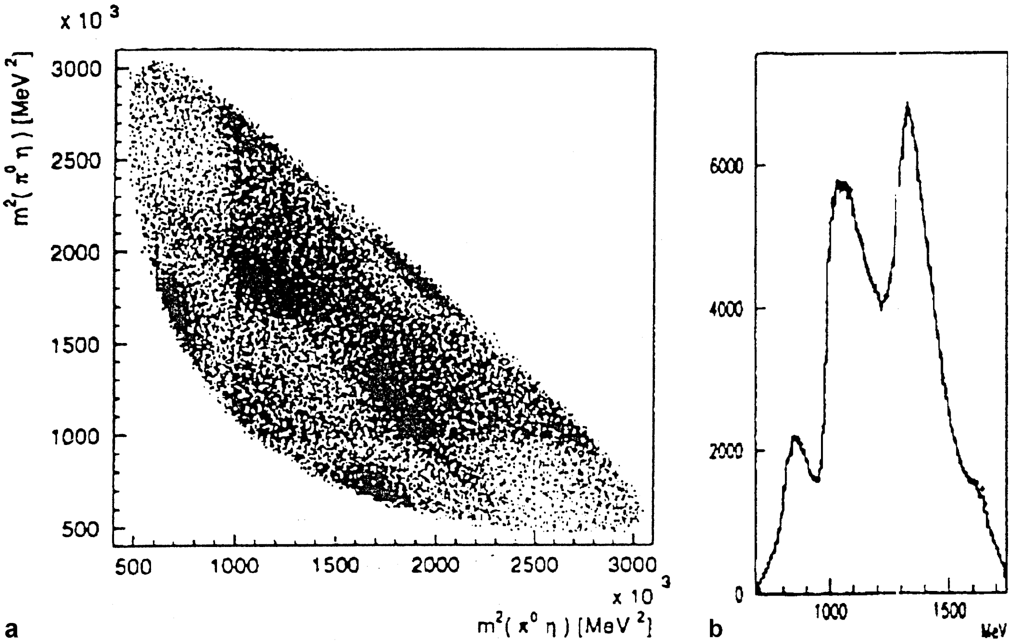

Fig. 5a,b. $\bar{p}p \to \eta\pi^0\pi^0$ [27], the Dalitz plot of the $\eta\pi^0\pi^0$ final state (**a**); $\eta\pi$ mass projection (**b**)

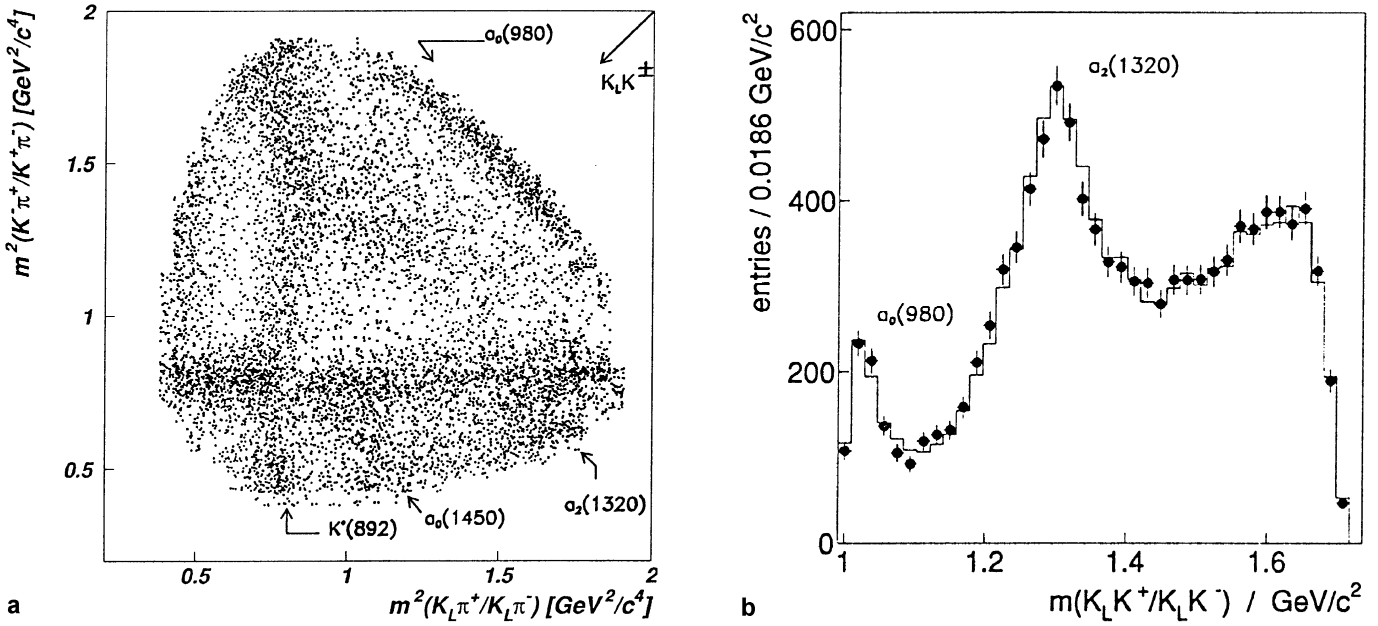

Fig. 6a,b. $\bar{p}p \to K^\pm K^0_L\pi^\mp$ [3], the Dalitz plot of the $K^\pm K^0_L\pi^\mp$ final state (**a**); $\bar{K}K$ mass projection (**b**)

Finally the results of [31] provide evidence for an $I = 1$ state at a mass 1290±10 MeV/c^2 and width 80±5 MeV/c^2, in agreement with the results coming from the πp interaction [19,21,22,25].

The mass and width values differ significantly with respect to the results of [3]. A careful study on the likelihood behavior as a function of the scalar mass and width was performed. The result is shown in Fig. 9. A plateau is present at around 1450 MeV with a large width, but a higher much better defined maximum is present at 1290 MeV. The conclusion of [31] was therefore in favour of the hypothesis of a scalar at 1290 MeV.

A notable point in the analysis of [31] is that, while the $a_0(1290)$ has a branching fraction comparable with that obtained in [3], the $a_2(1320)$ fraction was lower by a huge factor if compared with [3] or if compared with the relative decay widths as reported in the PDG [5].

Several explanations were proposed [31]. Perhaps one of the main reasons for this discrepancy could be the adopted hypotheses for the analysis. In [31], for the first time, the P-wave contribution is not neglected, its fraction being of the order of 12%, in agreement with the expectations of the available models for $\bar{p}p$ annihilation at rest

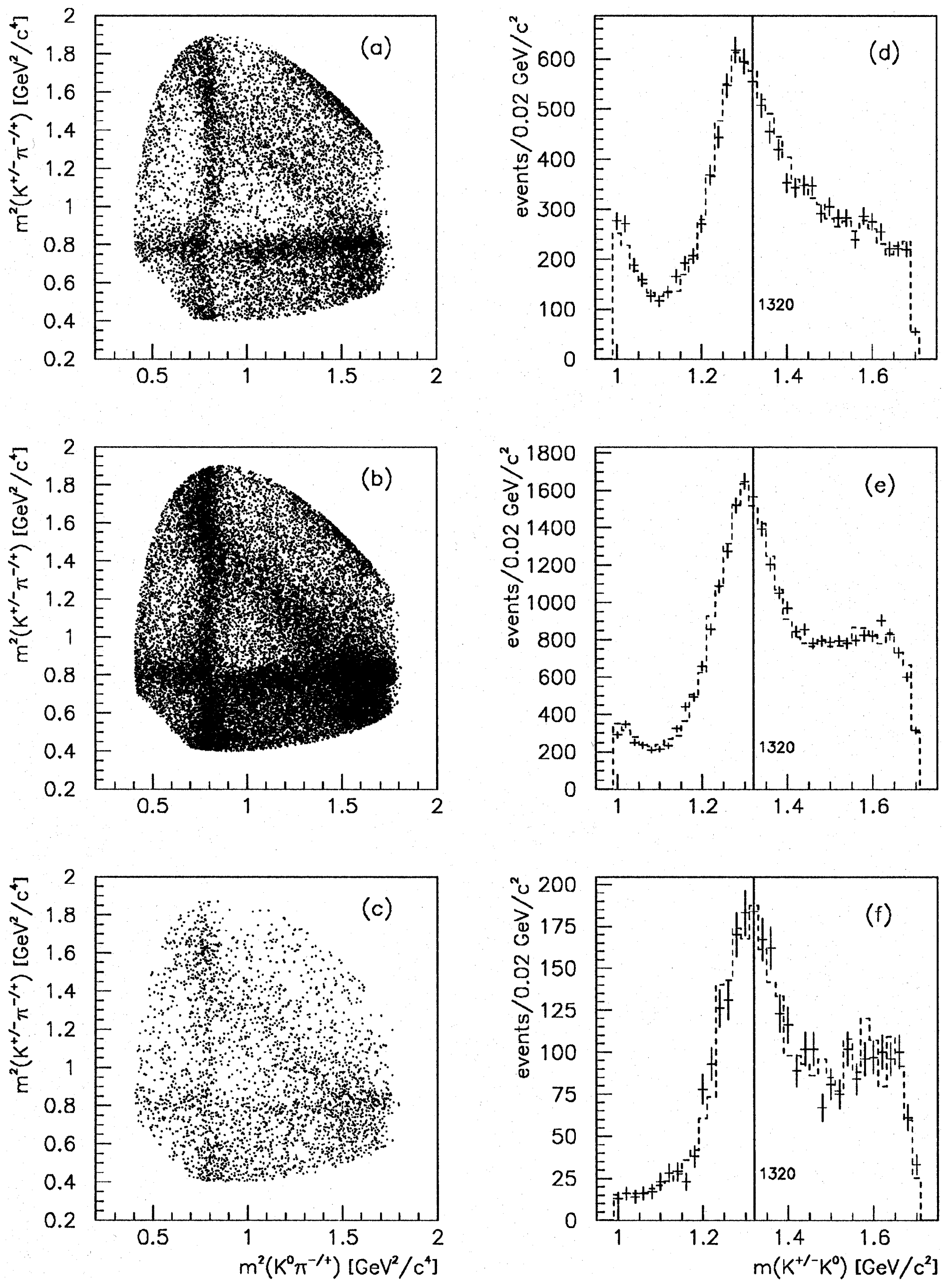

Fig. 7a–f. Dalitz plot of **a** LH_2, **b** NPT, and **c** 5 mbar data; $\bar{K}K$ invariant mass with superimposed the best fit of **d** LH_2, **e** NTP, **f** 5 mbar data

and the indications coming from the experimental results (see [32] and references quoted therein).

Another element could be the fact that the data used to evaluate the $a_2(1320)$ partial width in $\bar{\mathrm{K}}\mathrm{K}$ came from the πp interaction and considered the $a_2(1320)$ as the only resonance present in that mass region while the results of [19,21,22,24,25] indicate that this could not be the case.

Anyway the analysis of [31] showed that the $a_2(1320)$ fraction is only weakly related to that of $a_0(1290)$ since the fit discriminates between the two resonant contributions. Actually, even neglecting totally the $a_0(1290)$, the $a_2(1320)$ remained much lower than the expected value.

Therefore the result on the isovector scalar appear substantially unaffected by this discrepancy on the $a_2(1320)$ branching ratio.

4 Conclusions

Several theoretical models indicate that the isovector member of the scalar nonet should be found at a mass of around 1.3 GeV [7,10–13].

On the experimental side one can try to summarize the situation as follows. The first generation $\bar{\mathrm{p}}$p experiments in the bubble chamber lacked the necessary statistics to draw a definitive conclusion on the subject [14,18].

Among the πp experiments there is clear evidence for a bump in the S-wave at around 1.3 GeV. The questionable point is the isospin of the structure. According to [20, 23] the structure is mainly due to an effect of the $I = 0$ $f_0(1370)$ even if the presence of an $I = 1$ contribution was not excluded [23]. On the other hand several exper-

Table 1. $a_0(980), a_0(1290), a_2(1320)$ contributions from p̄p annihilation at rest at three different target densities (from [31]); the expected S- and P-wave annihilation fractions are also reported (from [32])

Density (ρ_{STP})	Liquid	1	0.05
$a_0(980)$ (%)	4.7 ± 0.6	2.0 ± 0.2	0.6 ± 0.1
$a_0(1290)$ (%)	7.6 ± 0.8	4.4 ± 0.5	2.6 ± 0.8
$a_2(1320)$ (%)	3.3 ± 0.6	9 ± 2	12 ± 2
S-wave contribution (%)	87 ± 4	52 ± 6	20 ± 6
P-wave contribution (%)	13 ± 4	58 ± 6	80 ± 6

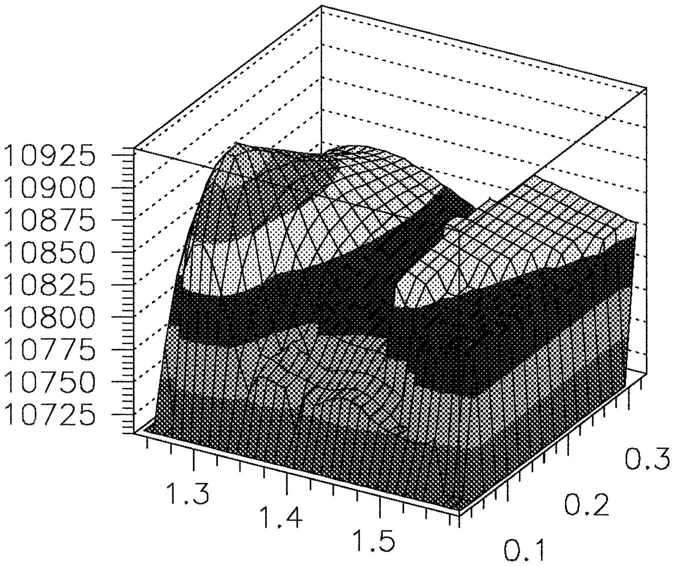

Fig. 8. $\bar{p}p \to K^{\pm}K^0_L\pi^{\mp}$ [31], likelihood as a function of mass and width of a second scalar state

iments from different laboratories (Argonne, CERN and Brookhaven) agree in indicating that a $I = 1$ resonance must be present [19,21,22,25].

With the second generation of p̄p experiments at LEAR, new high statistics data were available in an environment definitely more able, with respect to πp experiments, to study the S-wave structure. These experiments investigated the $\eta\pi\pi$, $\eta'\pi\pi$ and $\bar{K}K\pi$ final states. Both experiments see an isovector scalar state in this mass region but disagree in the determination of its mass and width. The Crystal Barrel experiment identifies this state at a mass of $1450 \pm 40\,\mathrm{MeV}/c^2$ and width $270 \pm 40\,\mathrm{MeV}/c^2$ in the analyses of $\eta\pi\pi$, $\eta'\pi\pi$ and $\bar{K}K\pi$ final states [27,28,3]. In the analysis of the $\eta'\pi\pi$, the final-state mass and width of the a_0 were not determined but assumed to be known from [27]. The decay fractions derived from these data were fully compatible with SU(3) relations. The Obelix experiment obtained a value closer to that of πp experiments: mass $= 1290 \pm 10\,\mathrm{MeV}/c^2$ and width $80 \pm 5\,\mathrm{MeV}/c^2$ from the analysis of the $K^{\pm}K^0_S\pi^{\mp}$ collected under three different initial angular momentum state conditions [31]. The hypothesis of the solution at $1450\,\mathrm{MeV}/c^2$ was tested and rejected (see Fig. 8). It is remarkable that the disagreement is present in the analysis of the channel ($K^{\pm}K^0\pi^{\mp}$) which is by the way perhaps the best environment to study the isovector scalar.

The differences do not appear to depend on the data. The Dalitz plots look quite similar and agree well with those of the bubble chamber (see Figs. 1a,6a,7a. Moreover all three experiments ([17,31,3]) agree in finding the a_2 peak shifted at a mass lower by about 30 MeV with respect to the nominal value. The background sources appear to be well under control: at the level of 2% in the case of the Crystal Barrel experiment (the channel has a missing K_L but all possible background sources are taken into account and rejected); negligible in the case of Obelix (all the particles in the final state are reconstructed and identified and a 5C fit is applied).

The differences should therefore stand in the analysis approach. In the Crystal Barrel analysis [3] the shift in the $\bar{K}K$ mass has been interpreted as due to a destructive interference between the $a_2(1320)$ and a broad higher mass scalar: the $a_0(1450)$. In contrast, the Obelix analysis [31] shows that the mass shift disappears as the P-wave increases and explains it as due to a scalar, produced from S-states, which should be at a mass lower than the $a_2(1320)$: the $a_0(1290)$.

One main difference consist in the approximation concerning the P-wave contribution, of the order of 12%, which has been neglected in the analysis of [3]. This residual P-wave contribution in liquid hydrogen could certainly play a role as shown in [29,31–33] where a P-wave contribution ≥10% is required. Another element is the influence of the other two data samples, present in the Obelix analysis, which allowed a study of the initial state dependence of the produced resonances.

A summary of the experimental situation for the isovector scalar mass and width is reported in Table 2. Several measurements, performed by the Crystal Barrel experiment with p̄p at rest in different final states agree in giving a mass around 1450 MeV and a width of 270 MeV. On the other hand πp experiments mostly agree in putting the mass at around 1300 MeV (with the exception of [25] which reports a mass of 1410 MeV). The width determination is more uncertain. The Obelix experiment analysed $\bar{p}p \to K^{\pm}K^0_S\pi^{\mp}$ finding a mass at 1290 MeV in agreement with the πp results but in disagreement with the Crystal Barrel result on the same channel. The possibility that *two* isovector scalars could be present was not discussed in any of the published papers. The mass and width scan, present in the Obelix paper (see Fig. 8) shows that two solutions are possible but they are considered as alternative ones and finally the low mass one was retained since it had a higher and better defined maximum.

The Crystal Barrel experiment performed a simultaneous analysis of liquid and 12 atm hydrogen data for the channel $\bar{p}p \to \eta\pi^0\pi^0$ showing the need for a P-wave contribution ≥10% in liquid hydrogen also [29]. With these data a scan on the isovector scalar mass (as in [31]) should certainly be very interesting. We will not pass judgement on published experimental results, but it appears that further analysis is necessary to clarify this point.

Table 2. Summary of mass and width results for the isovector scalar obtained by the different experiments

Reaction	Ref.	Mass (MeV/c^2)	Width (MeV/c^2)	Comment
$\pi^- p \to n K_S^0 K_S^0$	[19]	1255 ± 5	79 ± 10	Isospin can be 0
$\pi^- p \to K^- K_S^0 p$	[21,22]	1300	250	Isospin = 1
$\pi^- p \to n K_S^0 K_S^0$	[25]	1410		Isospin can be 0
$\pi^- p \to n \eta \pi^0$	[26]	1308 ± 6	104 ± 15	Isospin = 1
$\bar{p}p \to \eta \pi^0 \pi^0$	[27,29]	1450 ± 40	270 ± 40	
$\bar{p}p \to \eta' \pi^0 \pi^0$	[28]	1450 ± 40	270 ± 40	
$\bar{p}p \to K_L^0 K^\pm \pi^\mp$	[3]	1480 ± 30	265 ± 15	
$\bar{p}p \to K_S^0 K^\pm \pi^\mp$	[31]	1290 ± 10	80 ± 5	

Let us now consider the impact of the two possible solutions on the scalar nonet classification (and especially on the identification of the scalar glueball).

The $\bar{K}K$ coupling is an important issue but in this respect the results can be considered compatible.

This is not the case for the width: in [1] it was pointed out that the $f_0(1500)$ does not fit in the scalar nonet because its width was too narrow compared to the isovector member (assuming the $a_0(1450)$ width). If one takes the $a_0(1290)$ width this conclusion is no longer valid.

Another point concerns the mass predictions of the theoretical models. Most of them agree in indicating 1300 MeV as the expected mass for the isovector scalar and indicate the $f_0(1500)$ as a probably ordinary member of the nonet [10–13].

Nevertheless it is not evident whether these models are sensitive to a mass difference of 150 MeV. At present their capability to help in discriminating between the two currently available experimental solutions is not clear.

In conclusion the present status in the study of the isovector member of the scalar nonet requires both a theoretical and experimental effort in order to reach a clean identification. On the experimental side further analysis is necessary to clarify the observed discrepancies in mass and width. Conversely the theoretical models should give an indication of the accuracy of their mass and width determination so to give a significance to their predictions.

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