A re-analysis of some $\bar{p}p$ and $\bar{p}n$ data, at rest and in flight, obtained in bubble chamber experiments, is presented. The $(\pi^+\pi^-)$ and $(K_SK_S)$ final states for the channels $(2\pi^-\pi^+)$ and $(K_SK_S\pi)$ are investigated. Evidence for a narrow meson resonance structure, cautiously suggested as $f_0(1500)$, is given. In the $(\pi^+\pi^-)$ invariant mass distribution from $\bar{p}n$ annihilations in flight, using the method of difference spectra, a very clear evidence for $\rho^0$, $f_2(1270)$ and $f_0(1500)$ is first time obtained from these data.

This re-analysis suggests that the old bubble chamber data can still provide relevant information on the annihilation process in liquid hydrogen and deuterium, and can elucidate controversial aspects of the annihilation mechanism.

keywords: nucleon-antinucleon annihilations, meson resonance

1 Introduction

In the last time, much of the interest in light quark spectroscopy is dominated by the search for exotic mesons. The theoretical models predict exotic states in the energy range $1.5 - 2$ GeV/$c^2$. The results obtained up to now are rather ambiguous. This is due to the complexity of the meson spectrum, where ground $q\bar{q}$ states overlap in this mass region with radial excitations.

Gray et al. [1], studying the $\bar{p}n$ annihilation in the $3\pi$ final state, have observed a resonance in the $(\pi^+\pi^-)$ invariant mass distribution, with a mass of 1.525 GeV/$c^2$. This state is now considered in Review of Particle Physics [2] as the $f_0(1500)$ resonance. The decay into $K\bar{K}$ final states has not been observed in this experiment.

The possible existence of a resonant structure with a mass in the energy range around 1.6 GeV/$c^2$, in the $\bar{p}p$ annihilation at rest, in the final state $K_SK_S\pi^0$, in the bubble chamber data, has been first considered by Gastaldi [3]. For both states considered here, the suggested quantum numbers are $I = 0$ and $J = (even)^{++}$. The natural question is if the two structures exist and represent the same meson, or a different one.

Scalar and tensorial mesons represent the most controversial sectors of light mesons spectroscopy, where an excess of particle exists in respect to the expectations derived from the naive quark model. These mesons can be produced in $\bar{p}N$ annihilations, in association with a pion.

1 Contribution to the Baryons ’98 Conference
In the present paper we revised systematically some experimental old data obtained in bubble chamber experiments for antiproton - nucleon annihilations, at rest and in flight, for the channels \((3\pi)\) and \((K\bar{K}\pi)\), looking for \((\pi\pi)\) and \((K\bar{K})\) signals. The preliminary results obtained from this analysis are presented.

## 2 Re-analysis of bubble chamber data

### 2.1 The channel \(\bar{p}n \rightarrow 2\pi^{-}\pi^{+}(p)\), at rest and in flight

The \(\bar{p}n\) annihilations were obtained by antiproton deuterium - nucleus interactions in a deuterium bubble chamber. The experimental method selects only the annihilations on neutron, considered quasi-free if the proton is spectator.

For this channel, the data are from references [1] and [4] for annihilations at rest, and from references [3, 5] for the process in flight.

We re-analysed these experimental data, following the method of the so-called "difference spectrum", introduced by Bridges et al. [7]. This method eliminates the combinatorial background in the search of states produced in \(\bar{p}n\) annihilations, for the final states \(\pi^{-}X^{0}(X^{0} \rightarrow \pi^{+}\pi^{-})\) plus neutral. So, the difference between \(\pi^{+}\) and \(\pi^{-}\) spectra is the spectrum of recoiling \(\pi^{-}\), and no background is present in the absence of the interference effects between \(\pi^{-}\) and other charged pions. The interference effects in the low energy range decrease with the increase of the \(X^{0}\) mass, and with the decrease of the \(X^{0}\) width [8].

The BNL group published the partial results in reference [1]: a sample of 2785 events obtained from 70000 \(\bar{p}n\) annihilations at rest, corresponding to proton momentum less than 150 MeV/c. The complete analysis starts from about \(3 \cdot 10^6\) events [4]. The contamination by events in flight and/or \(\pi^{0}\) events has been estimated to be less than 1%. The number of all events with the proton spectator is 5512, and includes the 2785 events from reference [1]. The authors consider a 0.7% contamination of the data by non-spectators.

The invariant mass squared \((\pi\pi)\) distributions recoiling \(\pi^{+}\) and \(\pi^{-}\), as well as the difference spectrum are shown in Figures 1 (a - c). The \(2\pi^{-}\pi^{+}\) data are dominated by \(\rho, f_{2}(1270)\) and \(f_{0}(1500)\) resonances. Large interference effects exist in this channel; the negative values in the difference spectrum at low masses reflect them. Because the presence of the \(\rho\) resonance in the spectrum, there are interferences at nearly all energies [8].

The difference spectrum fits reasonably well a superposition of \(\pi^{-}\rho, \pi^{-}f_{2}(1270)\) and \(\pi^{-}f_{0}(1500)\). We used the Breit - Wigner resonance function, and the results are in reasonably agreement with the polynomial fits of Bridges et al. [6] and Gray et al. [3], as well as with the values of Review of Particle Physics [2], in spite of the simplicity of the fit. The results of the fit are presented in Table. 1.

The \(f_{0}(1500)\) resonance was observed in the invariant mass distribution of \((\pi^{0}\pi^{0})\) in the \(\bar{p}p \rightarrow 3\pi^{0}\) annihilation at rest [3].
For the investigation of annihilations in flight, Bettini and co-workers collected events for the process in the energy range 1 - 1.6 GeV/c, but, in the published paper, only the data at 1.2 GeV/c are given, which represent 818 events from 130000 pictures. The combined contribution of the contamination of the data with events where the proton participates to annihilations, and of the loss of good events, is estimated to be less than 2%. In addition to this, there is an over-all scale error of ±3.5%, obtained combining the systematic error with that of the data. The experimental distribution for proton momentum lower than 150 MeV/c was considered as annihilations with quasi-free neutrons.

The data collected by Tovey [6] represent annihilations for incident antiproton momenta between 0.4 and 0.92 GeV/c. From a total of 150000 photographs, and after the application of all selection criteria, a total of 2038 events were analysed. Figures 1 (d-f) show the same distributions as in Figures 1 (a-c), but for the reaction in flight. The number of events is 818+2038 and represent the combined data from references [5] and [6], to obtain a higher statistics. In the original analysis, no resonance behaviour has been observed by the authors.

In the difference spectrum, structures similar with those corresponding to annihilations at rest are visible, and we used the same fit procedure. The results are also presented in Table 1. In the mass region 1.4 - 1.55 GeV/c², the existence of one more resonance structure is not excluded, but a detailed analysis is not possible, due to the low statistics. For the annihilations in flight, the fit value of the \( \rho \) mass is about 40 MeV lower than the current value. This is, probably, a combined result between the interference effect, the rescattering effects, and the superposition of samples obtained from annihilations in a large interval of proton momentum (0.4 – 1.2 GeV/c). The interference effects were before mentioned. The rescattering effects [10] are present in \( \bar{p}n \) annihilations as interactions of the produced mesons with the "spectator" proton. Due to this rescattering, the apparent mass of the state is situated at lower masses and larger widths. The effect increases with the increase of the spectator proton momentum.

In the analysed sample, the annihilation events produced by antiprotons with different momenta are considered. A comparison between the differences in \( M^2(\pi\pi) \) mass distribution, for extreme cases, at rest and in flight, is shown in Figures 2a and 2b respectively. All spectra are normalised to unity. The difference between the \( (\pi^+\pi^-) \) spectra, at rest and in flight, from Figure 2a, suggests that these spectra are similar, contrary to the spectra \( (\pi^+\pi^-) \), the difference of which is presented in Figure 2b: in the low mass region, an enhancement is present for the annihilation at rest, that disappears for the process in flight, where a large maximum is present at higher masses. This behaviour dominantly affects the mass region of the \( \rho \) meson.

### 2.2 Neutral \((K_SK_S)\) final states in the channel \( \bar{p}N \rightarrow K\bar{K}\pi \)

Conforto et al. [11], and Barash et al [12] have studied the \( \bar{p}\bar{p} \) annihilations at rest in the final states \( K\bar{K}\pi \) at CERN and at BNL. The final states include the three
body particles $K_SK^±\pi^±$ and $K_SK\pi^0$. The reaction with $K_LK_L\pi^0$ final states is not observed in these experiments, because the long $K_L$ lifetime. The combined data from these two experiments correspond to $2.1\cdot10^6$ pp annihilations. Less than 10% of the events are due to the background (one or more $\pi^0$), and contaminations with annihilations in flight.

Bettini et al. [13], have studied the similar annihilations in liquid deuterium in bubble chambers. From a total of $2.22\cdot10^5$ annihilations, the final states studied are: $K_SK^-\pi^0$ (140 events), $K_SK_S\pi^-$ (89 events), and $K.SK^0\pi^-$ (242 events).

The channel $K^+K^-\pi^-$ (84 events) represents a subsample of annihilations in which the proton spectator, with a momentum less than 250 MeV/c, is visible. A similar experiment is cited in reference [1]. The $K^+K^-\pi^-$ sample contains 585 events, and the sample $K_SK^0\pi^-$ 517 events respectively. Details about the experiment are not available.

The Dalitz plots and the invariant squared projections $(K_SK_S)$ and $(K_S\pi)$, of the combined data from $pp \rightarrow K_SK^0\pi^0$ and $pn \rightarrow K_SK_S\pi^-$ respectively, are shown in Figures 3 and 4. The sample $K_SK_S\pi^0$ contains $(182+364)$ events, while $(84+518)$ events correspond to the final state $K_SK^0\pi^-$. Due to the presence of two identical particles in the final state, the Dalitz plot are mirror symmetrised along the $K_SK_S$ diagonal, and contains two entries per event. In both figures, the $K^0\pi$ and $K^-\pi$ bands are recognisable. The non-uniformity of the distribution of events in the $K^*$ bands is visible. This fact could be due to the interference effects, destructive in $K_SK_S\pi^0$, and constructive in $K_SK_S\pi^-$, with diagonal band produced by $K_SK_S$ resonances in the energy range 1.2 - 1.6 GeV/c$^2$, and a dominant $\cos^2(\theta)$ distribution of the $K^*$ decay angle. The $K^*$ resonance is a $K\pi$ effect in the P-wave.

In the $(K_S\pi)$ projection, the prominent structure is the $K^*$ signal.

We have used the fit for the $K^*$ resonance as a test of consistency of adding two different samples of data.

The $(K_SK_S)$ mass squared projections present complex structures. A very weak signal is present at low masses, and corresponds to $K_SK_S$ produced at threshold. The next structures are centred in the 1250 - 1280 MeV/c$^2$ mass region; a very high enhancement is observed at about 1400 MeV/c$^2$, and the last is at 1600 MeV/c$^2$.

For the structure at around 1250 MeV, the assignments suggested were $a_2(1300)$, and $f_2(1270)$ [3, 11].

Between 1400 and 1500 MeV/c$^2$ a dip is present. If it is not due to a negative interference effect, than the 1420 MeV band is too narrow to be associated to the signals produced by $f_0(1370)$ ($\Gamma_{KK} = 118 - 250$ MeV/c$^2$) or $a_0(1450)$ ($\Gamma = 270 \pm 40$ MeV/c$^2$), and, most probably, it is due to the interference between different amplitudes [14].

The last structure present in this distribution, centred at about 1600 MeV, was omitted in all initial analysis [1, 11, 12, 13], and first considered in reference [3]. This signal is not due to reflections in the $K_SK_S$ projection of a $K_S\pi$ low energy S-wave effect. The accumulation of events in the two bands with very low $K_S\pi$ mass at the borders of the Dalitz plot features a sudden variation of density when crossing
the orthogonal $K^*$ band. The density of these low mass $K_S\pi$ bands is higher in the region of the Dalitz plot common with the 1.6 GeV/c$^2$ band, and lower in the high $K_SK_S$ mass corner of the plot: so, the effect of high $K_SK_S$ density superposes and interferes with the $K_S\pi$ S-wave effect.

This enhancement is not a kinematical reflection of the $K^*$ resonance. After removing the events present in the $K^*$ band, comprised between 0.7 and 0.91 GeV/c$^2$, in the $\overline{p}p$ annihilations, about 143 events remain in the energy window corresponding to $f_2(1270)$, 58 events in the region 1400 MeV/c$^2$, and about 76 events in the $X(1540)$ band respectively. For the $\overline{p}n$ annihilations, the number of events that remain in the energetic region of interest are: 75, 89 and 129 respectively.

In the $\overline{p}p$ channel, the approximate production rate of $X(1540)$ events in the $K_SK_S\pi^0$ channels is $0.32\cdot10^{-3}$ of all annihilations.

The distributions of $(K_SK_S)$ invariant mass squared, after the removal of the $K^*$ events, are illustrated in Figures 5, a and b. For these spectra, we performed a fit with three Breit-Wigner functions, excluding the interference effects (the fit being also shown in the figures). The resonance parameters are listed in Table 2.

Another test is to verify if the 1540 MeV mass structures do not belong to the low energy tail of a higher resonance, which decays in $K\overline{K}$. The annihilation $\overline{p}p \rightarrow K_SK_S\pi^0$ in flight has been analysed in references [15, 16] at 0.7 and 1.2 GeV/c respectively.

The signal corresponding to the $X^0(1540)$ state decreases with the increase of the antiproton momentum.

This state is probably dominantly produced from S- and P-waves. With the increase of the energy, the contribution of partial waves with higher angular momentum increases, and the S- and P-waves become marginal, and this explains the decrease of the probability of resonance production.

The final states containing charged particles are also revised. The reactions $\overline{p}p \rightarrow K_SK^\pm\pi^\mp$, with (1897+799) events, $[14, 15]$, $\overline{p}n \rightarrow K^+K^-\pi^-$, (84+585) events $[1, 13]$, and $\overline{p}n \rightarrow K_SK^{0/-}\pi^-/0$ (140+248) events $[13]$, at rest, were considered. In the $(K_SK^\pm)$ effective mass squared distribution, the accumulation of events at around 990 MeV and 1280 MeV is clearly visible. At higher masses, no one structure is visible.

3 Discussion of the results

The bubble chamber data on the following annihilation processes:

$\overline{p}n \rightarrow 2\pi^-\pi^+$ at rest and in flight;

$\overline{p}p \rightarrow K_SK_S\pi^0$, $K_SK^\pm\pi^\mp$ at rest, and

$\overline{p}n \rightarrow K_SK_S\pi^-$, $K_SK^{0/-}\pi^-/0$ at rest

were revised.

In these preliminary results, the $\rho^0$ and $f_2(1270)$ mesons were identified. In the $(\pi\pi)$ distribution for the $(3\pi)$ final states, for annihilations in flight, the existence
of the three resonances: $\rho^0$, $f_2(1270)$ and $X^0(1540)$ is first time put in evidence in the difference spectra.

$X^0(1540)$ was observed in ($K_SK_S$) final states.

Looking at the results obtained from this re-analysis (see Tables 1 and 2 respectively), the resonance parameters for $X^0$ and $X^0'$, obtained in all reactions are consistent, and we think they characterise the same resonance, with mean values: $M = (1541 \pm 6)$ MeV and $\Gamma = (99 \pm 46)$ MeV.

Because it decays into ($\pi^+\pi^-$), ($\pi^0\pi^0$) and ($K_SK_S$), and there is no evidence of a peak in the charged channels, neither in ($\pi^-\pi^-$), nor in ($K_SK^\pm$), the isospin $I = 1$ or 2 are excluded, and consequently $I = 0$, with $J^{PC}$ quantum numbers (even)$^{++}$. The simplest assumption is $0^{++}$ or $2^{++}$.

A detailed spin - parity analysis is necessary to clarify the quantum numbers, but qualitative arguments could be given. In all investigated channels, the production of this resonance is accompanied by the $f_2(1270)$. If $X^0(1540)$ and $f_2(1270)$ have the same spin, there must exist a similarity of the production mechanism. But, looking to the relative BR or production rates, $X^0(1540)$ does not follow the same pattern as $f_2(1270)$, and we cautiously suggest $J^{PC} = 0^{++}$, and in agreement with reference $[2]$, the meson could be $f_0(1500)$.

Due to the interference, most probably with $f_0(1370)$, the mass of the resonance is shifted at higher values $[2]$. If this interpretation is correct, it must appear in other channels. If this supposition is not confirmed, and $J^{PC} = 2^{++}$, the candidate is $f_2(1562)$.

### 4 Summary

In the present paper, some data obtained in bubble chamber experiments have been re-analysed. These experiments collected data about 30 years, in liquid hydrogen and deuterium, in which the initial states are dominantly in S and P - wave.

From the distributions of ($\pi\pi$) and ($K_SK_S$) events from the ($3\pi$) and ($K_SK_S\pi$) channels, we found evidence of a narrow resonance structure, cautiously suggested as $f_0(1500)$, and observed in all investigated channels. The resonance parameters are: $M = (1541 \pm 6)$ MeV and $\Gamma = (99 \pm 46)$ MeV.

In the ($\pi^+\pi^-$) invariant mass distribution obtained from $\bar{p}n$ annihilations in flight, a clear evidence for $\rho^0$, $f_2(1270)$ and $f_0(1500)$ is obtained, using the method of difference spectra.

In spite of the low statistics, the data from bubble chambers have a very good quality: they permit to identify topologically the final channels, all the detectable final states and/or decay channels can be measured with very good precision, and the background removal is allowed. Their re-analysis could still give relevant information and could suggest a new strategy for the present experiments, characterised by a very high statistics.
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Table 1
Results of fits made on different spectra for $2\pi^−\pi^+$ exclusive channels in $\bar{p}n$ annihilations

| Final state $\pi^- X$ | at rest | in flight |
|----------------------|---------|----------|
| ($\rightarrow \pi^+\pi^-$) | $M_X$ (MeV/c$^2$) | $\Gamma_X$ (MeV/c$^2$) | Relative BR(%) | $M_X$ (MeV/c$^2$) | $\Gamma_X$ (MeV/c$^2$) | Relative BR(%) |
| $\pi^- \rho^0$ | $772 \pm 5$ | $149 \pm 19$ | $23.7$ | $727 \pm 7$ | $104 \pm 3$ | $31.1$ |
| $\pi^- f_2$ | $1244 \pm 4$ | $281 \pm 16$ | $71.4$ | $1257 \pm 1$ | $245 \pm 26$ | $57.2$ |
| $\pi^- X^0$ | $1528 \pm 3$ | $69 \pm 9$ | $4.9$ | $1548 \pm 19$ | $111 \pm 6$ | $11.7$ |

Table 2
Results of fits made for the annihilation $\bar{p}N \rightarrow K_S K_S \pi$ at rest

| Final state $\pi X'$ | $\bar{p}p \rightarrow K_S K_S \pi^0$ | $\bar{p}n \rightarrow K_S K_S \pi^-$ |
|----------------------|-----------------|-----------------|
| ($\rightarrow K_S K_S$) | $M_{X'}$ (MeV/c$^2$) | $\Gamma_{X'}$ (MeV/c$^2$) | $M_X$ (MeV/c$^2$) | $\Gamma_X$ (MeV/c$^2$) |
| $\pi (f_2/a_2)$ | $1247 \pm 30$ | $241 \pm 66$ | $1265 \pm 15$ | $155 \pm 22$ |
| $\pi X(1400)$ | $1394 \pm 1$ | $86 \pm 6$ | $1401 \pm 4$ | $43 \pm 20$ |
| $\pi X^0$ | $1543 \pm 5$ | $87 \pm 23$ | $1544 \pm 16$ | $130 \pm 87$ |
Figure Captions

Figure 1
Invariant mass squared spectra ($\pi\pi$) and invariant squared difference spectra for the annihilation $pn \rightarrow \pi^+\pi^-\pi^-$ at rest (Figure 1: a, b and c) and in flight (Figure 1 d, e and f).

(a) and (d) represents the distributions of ($\pi^+\pi^-$) invariant mass squared and (b) and (e) the corresponding distributions for ($\pi^-\pi^-$).

(c) and (f) represent the difference spectra, as explained in the text. The errors in the data are also shown. The fit with three Breit-Wigner functions is superposed to the data.

Figure 2
(a) difference of normalised distributions between the ($\pi^+\pi^-$) invariant squared masses at rest and in flight in the annihilation: $\overline{p}n \rightarrow \pi^+\pi^-\pi^-$. 
(b) the same for ($\pi^-\pi^-$).

Figure 3
Dalitz plot for the annihilation $\overline{p}p \rightarrow K_SK_S\pi^0$ at rest, ($K_SK_S$) and ($K_S\pi^0$) invariant mass squared projections. The combined data from [11][12] are included (535 events). The plot is symmetrised along the $K_SK_S$ diagonal.

Figure 4
Dalitz plot for the annihilation $\overline{p}n \rightarrow K_SK_S\pi^-$ at rest, ($K_SK_S$) and ($K_S\pi^-$) invariant mass squared projections. The combined data from [1][13] are included (605 events). The plot is symmetrised along the $K_SK_S$ diagonal.

Figure 5
$K_SK_S$ invariant mass squared for the annihilations $\overline{p}p \rightarrow K_SK_S\pi^0$ (a), and $\overline{p}n \rightarrow K_SK_S\pi^-$ (b) at rest after the removal of the $K^{*0}$ events. The fit with three Breit-Wigner functions is also shown.
at rest

in flight

a)

d)

b)

e)

c)

f)

Number of events/bin

$M^2 (\pi\pi)$ [GeV/c$^2$]

$M^2 (\pi\pi)$ [GeV/c$^2$]
