Evidence for a Narrow $\pi^+\pi^-$ Peak at 757 MeV/$c^2$ in $\bar{p}n \rightarrow 2\pi^+3\pi^-$ Annihilation at Rest

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Outline

- Introduction: the peak history
- Peak analysis
- Comparison with OBELIX
- Ratio data / phase space
- Peak production
- Interpretation
- Conclusions
Introduction: the peak history (1)

The Rome-Syracuse collaboration (RSC) collected in 1960s about $3.6 \times 10^6 \bar{p}d$ annihilations at rest in the BNL 30” bubble chamber filled with liquid deuterium.

In 1970 the RSC studied the branching ratio of the decays $\omega \rightarrow \pi^+\pi^-$. The analysis measured the upper limit 4.3% at 95% CL. \cite{PRL 25, 1385 (1970)].

**BUT**

there was an unexpected result ....
Introduction: the peak history (2)

The $\pi^+\pi^-$ mass distribution of $1496 \bar{p}d \rightarrow p2\pi^+3\pi^-$ annihilations selected with the cut at 150 MeV/c on the proton momentum showed a peak at about 755 MeV/$c^2$. In the 1970 paper, the distribution was published with bins of 20 MeV/$c^2$. But, the peak was more clear in bins of 10 MeV/$c^2$.

Fig. 1e of PRL 25, 1385 (1970)
Introduction: the peak history (3)

A $\chi^2$ fit made in 1970 found that the peak had significance of about 4.5 standard deviations (SD) and a resolution less than the experimental one. These results and the coincidence of the peak with the $\rho^0$ mass convinced the RSC that the peak was unphysical.

The properties of the $\bar{p}n \to 2\pi^+3\pi^-$ annihilation at rest were not known in 1970. They were understood twenty years after by a reanalysis of the RSC data. [Gaspero, Sov. J. Nucl. Phys. 55, 795 (1992); NP A562, 407 (1993)]. It proved that the reaction is dominated by the channel

$$\bar{p}n \to f_0(1370)\pi^-$$

followed by the $f_0(1370)$ decay into $\rho^0\rho^0$ and $S_wS_w$ where $S_w$ indicates the $I=0$ S-wave $\pi\pi$ interaction,
Introduction: the OBELIX disprove

This analysis was able to describe ten experimental distributions and most of the shape of the $\pi^+\pi^-$ mass, but failed to reproduce the peak at 755 MeV/$c^2$.

BUT

at LEAP ’92 the OBELIX collaboration showed the preliminary data of the analysis of the $\bar{np} \rightarrow 3\pi^+2\pi^-$ annihilation at low momenta. [NP A558, 13c (1993)].

It confirmed the dominance of the $f_0(1370)$ production and that this meson decays into $\rho^0\rho^0$ and $S_wS_w$, BUT DID NOT SEE ANY $\pi^+\pi^-$ PEAK at 755 MeV/$c^2$!
Introduction: Troyan's et al. results

Recently I became aware that a narrow $\pi^+\pi^-$ peak at about $755$ MeV/c$^2$ was seen by Troyan et al. in $np \rightarrow np\pi^+\pi^-$ with neutrons of $5.2$ GeV/c. (Selecting neutrons in the backward hemisphere.)

[Troyan et al. JINR Rapid Commun. No. 5 [91] (1998);
Particle and Nuclei, Letters No. 6 [103], 25 (2000);
Particle and Nuclei, Letters No. 5 [114], 53 (2002);
hep-ex/0405049].

This result has challenged my opinion that the RSC peak was generated by a fluctuation.
Peak analysis: parametrization

The analysis of the RSC $\pi^+\pi^-$ mass distribution has been carried out in the mass interval $600 – 900$ MeV/$c^2$ with the parametrization

$$D(m) = P_3(m-750) + N_p S(m)$$

where $P_3(m-750)$ is a third-degree polynomial and $S(m)$ is the signal parametrization. Three parametrizations have been used:

A) Gaussian with free FWHM;
B) Gaussian with FWHM fixed $30$ MeV/$c^2$. [It is the value reported by the RSC in *PRL* 25, 1385 (1970)];
C) the resolution obtained by the histogram of the error distribution of the Rome subsample. [It is a double Gaussian with FWHM $= 33.6$ MeV/$c^2$.]
Peak analysis: fits

The fits have been made with the $\chi^2$ and with unbinned maximum likelihood. This was possible because the $\pi\pi$ masses of the 1496 events were maintained under the support of punched cards that were copied manually.

The fits with the experimental resolution (B, C, E, and F) have significance between 4.9 and 5.2 SD. These results make very unlikely that the peak was generated by a fluctuation.
Peak analysis: fitted parameters

The mass and the significance found by the fits B, C, E, and F are in agreement. I assume that the best fit is F because it is a maximum likelihood fits and takes into account the tails of the experimental errors.

I estimate the systematic errors to be the mean of the difference between fit F and the other five fits. Then, the results are:

\[ M = 757.4 \pm 2.8 \text{ stat} \pm 1.0 \text{ sys} \text{ MeV/c}^2 \]

\[ \Gamma < 30 \text{ MeV/c}^2 \]

\[ N_p = 224 \pm 43 \text{ stat} \pm 45 \text{ sys} \]
Peak analysis: fit F

Black line: result of fit F

Blue line: polynomial background

Red line: result of the fit published in

*NP A562, 407 (1993)*
Peak analysis: controls

The punched cards contain the information on the photogram number, antiproton number, and laboratory. In addition, the $3\pi$ and $4\pi$ masses, and several other kinematical variables could be obtained by the $10 \pi\pi$ masses. The study of these data has allowed to control that there are not the following systematic errors:

- Event duplication
- Copying errors
- Difference between the 665 events measured at Rome and the 831 events measured at Syracuse.

In particular, the peak is visible in both the Rome and Syracuse data and the separate fits of these subsamples have found peak signals in agreement between the errors.
Comparison with OBELIX: $\pi^+\pi^-$ distributions

The comparison between the RSC $\pi^+\pi^-$ mass distribution (blue histogram) and the OBELIX distribution (black crosses) shows that the two distributions are in agreement below 700 MeV/$c^2$ and above 800 MeV/$c^2$ but differ in the interval 700-800 MeV/$c^2$.

Furthermore, the red line, i.e. the prediction of *NP A562, 407 (1993)* is in disagreement with both distributions in the same interval 700-800 MeV/$c^2$. 

![Graph showing the comparison of RSC, OBELIX, and NP A562 distributions.](image)
Comparison with OBELIX: interpretation

The annihilations

\[ \bar{p}n \rightarrow 2\pi^+ 3\pi^- \quad (1) \]
\[ \bar{n}p \rightarrow 3\pi^+ 2\pi^- \quad (2) \]

are charge conjugate. The neutron is bounded inside the deuteron in reaction (1). The study of the \( \bar{p}d \) capture carried out by the Rome Group proved that the cut at 150 MeV/c on the proton momentum was able to select \( \bar{p}n \) annihilations in S-wave with a small amount (about 5%) of P- and higher-wave annihilations.

[Bizzarri et al., NP B69, 298 (1974); NP B69, 307 (1974)].

On the contrary, reaction (2) is in flight, and it has a non negligible P-wave contribution. Then, the excess of combination in the OBELIX \( \pi^+ \pi^- \) mass distribution at about 700 MeV/c\(^2\) could be explained with a higher \( \rho(770)^0 \) production in P-wave \( \bar{n}p \) annihilations.

But, how one can explain the peak at 757 MeV/c\(^2\)?
Comparison with OBELIX: resolution?

The RSC data were collected in bubble chamber and had FWHM = 33.6 MeV/c². The OBELIX events were generated inside a liquid hydrogen target and the tracks were measured after they had traveled the target and the cryogenic vessel. Then, the OBELIX resolution was probably poorer. What could have happened if the RSC resolution had been 50 MeV/c² FWHM is shown by the green line. It has been obtained by substituting each $\pi^+\pi^-$ mass with a Gaussian having FWHM = 37.0 MeV/c². 

\[(33.6^2 + 37.0^2 = 50.0^2)\]

The peak disappears!
Then, it is reasonable to suppose that the absence of the peak in the OBELIX distribution could be due to the resolution.

But there is another convincing argument: the ratio between the experimental distribution and the phase space (EDPS ratio).

Black: EDPS for fit F
Blue: EDPS for background in fit F
Red: EDPS for the fit shown in NP A562, 407 (1993)

The peak is on the top of the ratio!

Peak with FWHM $\sim 30$ MeV/c$^2$

$F_2(1270)$?

KK threshold
Ratio data / phase space: OBELIX data

The EDPS ratio of the OBELIX data shows also a maximum at about 755 MeV/c² but the distribution is wider. (The phase space is that of the RSC data.)

Black: EDPS for fit F
Blue: EDPS for background in fit F
Red: EDPS for the fit shown in NP A562, 407 (1993)

This EDPS ratio seems to confirm that the peak was not seen in the OBELIX data because its poorer resolution.
Interpretation: quantum numbers

Fit F finds that the peak has a width lower than the experimental resolution $30 \text{ MeV}/c^2$ and has the mass $757.4 \pm 2.8 \text{ MeV}/c^2$.

- It is unlikely that it has spin $J > 1$.
- It cannot be due to the $\omega \rightarrow \pi^+\pi^-$ decay because the $\omega$ mass is $782.6 \text{ MeV}/c^2$.
- It cannot be the $\rho(770)$ because it has width $150.3 \text{ MeV}/c^2$.
- It cannot be due to the $\rho - \omega$ interference because the $\bar{p}n \rightarrow \rho \pi^+2\pi^-$ annihilations are generated in the $^1S_0$ wave, while the $\bar{p}n \rightarrow \omega \pi^+2\pi^-$ annihilations are generated in the $^3S_1$ wave.

Then, the most probable hypothesis is that it is a scalar.
Interpretation: peak production

The knowledge of the ten $\pi\pi$ masses allow to reconstruct the kinematics of each event, i.e. the 3$\pi$ and 4$\pi$ masses, the proton momentum, the angles between the $\pi\pi$ tracks in the 5$\pi$ c.m.s., etc.

The study of the correlation between these kinematical variables and the $\pi^+\pi^-$ masses has found no significant differences between the combinations inside the peak and those in the sidebands. Furthermore, there is no evidence for a double peak production. The result is that the peak is generated in the reaction

$$\bar{p}n \rightarrow P(757)\pi^+2\pi^-$$

where $P(757)$ is the symbol for this state.

The fraction of the peak production in $\bar{p}n \rightarrow 2\pi^+3\pi^-$ is

$$f = \frac{N_p}{1496} = [15.0 \pm 2.0 \text{ (stat)} \pm 3.0 \text{ (sys)}]\%$$
Conclusion

A narrow $\pi^+\pi^-$ peak at about 755 MeV/$c^2$ was observed in 1970 by the Rome-Syracuse collaboration in $\bar{p}n \rightarrow 2\pi^+3\pi^-$ annihilation at rest. The existence of this peak was forgotten for forty years because nobody believed in its existence.

The peak was not seen by the OBELIX collaboration in $\bar{n}p \rightarrow 3\pi^+2\pi^-$ annihilations. Probably this was due to the poorer resolution of the OBELIX data, but this hypothesis needs verification.

A similar peak was observed by Troyan et al in $np \rightarrow np\pi^+\pi^-$. This peak could be generated by a scalar meson.
Backup slides
Results of the $\bar{p}n \rightarrow 2\pi^+3\pi^-$ analysis

The analysis of the $\bar{p}n \rightarrow 2\pi^+3\pi^-$ annihilation reported in *NP A562*, 407 (1973) was done by fitting eleven experimental distributions:

- The three distributions of $\cos \pi \pi$ in the $5\pi$ c.m.s.
- The three distributions of the $2\pi$ masses.
- The three distributions of the $3\pi$ masses.
- The two distributions of the $4\pi$ masses.

The results were:

\[
M_f = 1386 \pm 10_{\text{stat}} \pm 30_{\text{sys}} \text{ MeV}/c^2
\]
\[
\Gamma_f = 310 \pm 17_{\text{stat}} \pm 47_{\text{sys}} \text{ MeV}/c^2
\]

fraction of $\rho^0 \rho^0 = (30.4 \pm 1.5_{\text{stat}} \pm 5.5_{\text{sys}})\%$

relative phase $\rho^0 \rho^0 - S_w S_w = 14^0 \pm 5^0_{\text{stat}} \pm 14^0_{\text{sys}}$

\[
\chi^2/dof = 248.4 / 178 = 1.40
\]

*(Very good for a fit with only four parameters!)*
Phase shifts for $S_w$

The analysis carried out in
*NP A562, 407 (1993)*
used the RPOH4/5
parametrization for
the $S$-wave $\pi^+\pi^-$ interaction.
It was obtained by a
fit of *four*
experimental phase shift analyses.
The peak of *Troyan et al.*

Mass, width and significance estimated in the *four* papers of *Troyan et al.*

<table>
<thead>
<tr>
<th>Paper</th>
<th>Mass</th>
<th>Width</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>759 ± 5</td>
<td>27 ± 16</td>
<td>6.1</td>
</tr>
<tr>
<td>2000</td>
<td>754 ± 4</td>
<td>42 ± 15</td>
<td>8.5</td>
</tr>
<tr>
<td>2002</td>
<td>757 ± 5</td>
<td>51 ± 15</td>
<td>7.8</td>
</tr>
<tr>
<td>2004</td>
<td>762 ± 11</td>
<td>48 ± 33</td>
<td>6.1</td>
</tr>
</tbody>
</table>

The distribution, taken from *hep-ex/0405049* shows the $\pi^+\pi^-$ distribution of the events with the neutron going backwards.
The RSC resolution

Distribution of the $\pi^+\pi^-$ mass errors in the Rome sample.
(The resolution of the Syracuse sample is unknown.)

Red = double Gaussian  Blue = second Gaussian