Search for a narrow state at 1.9 GeV in $3\pi^+2\pi^-\pi^0$ exclusive events in $\bar{n}p$ annihilation

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Abstract

No evidence has been found for a narrow state at 1.911 GeV, recently reported by E687, in an analysis of the $3\pi^+2\pi^-\pi^0$ exclusive events produced in $\bar{n}p$ annihilations in flight.

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In a recent paper [1] the E687 Collaboration reported evidence for a narrow dip in the mass spectrum of the final state $3\pi^+3\pi^-$ produced by diffractive photoproduction. The dip was interpreted as due to the destructive interference of a continuum background with a narrow resonance at $(1.911 \pm 0.04 \pm 0.01)$ GeV with $I^* = (29 \pm 11 \pm 4)$ MeV. The quantum numbers assigned to this state were $J^{PC} = 1^{--}$, $G = +1$ and $I = 1$.

If such a state exists, it could be visible also in other $\bar{n}p$ final states produced in other interactions, like for example $\bar{N}N'$, provided the claimed quantum number can be reached. We performed a series of meson spectroscopy investigations [2–4] with the OBELIX spectrometer installed on the M2-branch of the LEAR complex at CERN. Most of the studies were performed by analysing exclusive final states constituted by $\pi$ and/or $K$ mesons produced in the annihilation of $\bar{p}$ at rest on protons. The upper limit of the invariant mass spectra was $\sim 1.70$ GeV, the maximum allowed by kinematics for a massive object recoiling against a “spectator” pion emitted in a two-body annihilation, according to the isobar model. Some experiments [5–7] were performed also with $\bar{n}'s$ annihilating in flight on protons (the isospin of the reaction being fixed to 1), with momenta from $\sim 50$ MeV/c ($T_{\bar{n},\text{Lab}} = 1.3$ MeV) to 405 MeV/c ($T_{\bar{n},\text{Lab}} = 84$ MeV), and the data analysed in the frame of the isobar model as well. The upper limit of the invariant mass spectra was slightly increased (1.75 GeV).

With $\bar{n}'s$ in flight it could also be possible to study exclusive final states resulting from the decay...
of objects directly formed in the annihilation, in a so narrow mass range (1.88–1.92 GeV) that this possibility was neglected in our previous analyses. However, this range, close to the $N\Lambda^-$ threshold, is exactly the one where E687 reports evidence for a narrow state, and we have searched for a possible confirmation in our data.

We examined the $3\pi^+2\pi^-\pi^0$ exclusive final state in $\bar{n}p$ annihilation. At low energy this final state can be produced only by $3S_1$ and $1P_1$ initial states, and the former allows to form a state with $J^P = 1^-$. The probability of $S$- and $P$-wave annihilations in flight is energy dependent and we referred to the model by Dover and Richard [8] to reproduce the different annihilation probability trends from the two initial states; a proper convolution by the corresponding theoretical distribution was applied to the experimental spectra whenever an hypothesis on the initial state was set. According to the Dover–Richard model, whose validity was confirmed, among others, by our data on selected two-body $\bar{n}p$ annihilations [9–11], the overall fraction of $S$-wave annihilations, integrated over the available $\bar{n}$ momentum range, is $(57 \pm 3)\%$; $3/4$ of them proceed from $3S_1$ initial state, assuming a statistical distribution between the different spin components of $S$-wave. Therefore, the $3S_1$ wave amount should be large enough to allow the observation of the mentioned narrow state. In fact, normalising to the annihilation probability over the two allowed initial states, always assuming a statistical population of $S$- and $P$-wave spin sublevels, about 80% of annihilations into $3\pi^+2\pi^-\pi^0$ must proceed from $3S_1$, while the remainder from $1P_1$.

The OBELIX spectrometer, the $\bar{n}$ beam and the methods and criteria for the analysis of the spectra were described in previous papers [5,6,12]. The $3\pi^+2\pi^-\pi^0$ exclusive events were selected out of the five prong bulk by means of a 1C kinematic fit at 10% C.L., requiring the total energy of the tracked particles to be less than 1.8 GeV. Only events with correctly reconstructed antineutron momentum and a well defined annihilation vertex in the target were retained. A 4C kinematic fit (1% C.L.) was applied as well in order to discard $\bar{n}p \to 3\pi^+2\pi^-$ contaminating events.

The invariant mass resolution for the exclusive $3\pi^+2\pi^-\pi^0$ events was about 6 MeV (RMS), evaluated from the missing mass distribution. The selected sample is affected by a 16% background, coming mainly from reactions with more than one $\pi^0$. We measured that the $\omega\pi^+\pi^+\pi^-$ annihilation channel contributes to the selected sample to a level of 6%; on the contrary, no $\eta\pi^+\pi^+\pi^-$ events are observed.

Fig. 1 shows the distribution of the $6\pi$ exclusive events yield normalised to the total number of events in a given bin of total center of mass energy corresponding to inclusive $2\pi^+\pi^-$ and $3\pi^+2\pi^-$ final states. We consider the inclusive final states distributions as very similar to the $6\pi$ exclusive ones as far as acceptances and geometrical cuts are concerned. They are inherently structureless. The error on each bin of the experimental distribution in Fig. 1 is directly connected to the error on the antineutron momentum measurement, whose details are reported in Ref. [12].

The obtained distribution is flat, with no hint for a narrow structure with parameters as those reported by Ref. [1]. In the hypothesis that the mechanism for the photoproduction of the mentioned narrow state and
the formation of a $1^{-}$ state in $\bar{n}p$ annihilation are the same, we checked the effect of the interference of a resonant state as the one observed in Ref. [1] and a background, supposing it continuum, incoherent and mainly produced with $1^{-}$ quantum numbers.

This is of course a simplification. First of all in $\bar{n}p$ annihilations a different component of the isospin 1 multiplet ($I_3 = +1$) is formed. Other annihilation reactions can occur, producing the same final state, as $\omega(\eta)\pi^+\pi^+\pi^-$; these intermediate states are absent in $3\pi^+3\pi^-$ photoproduction. The removal of $\omega\pi^+\pi^+\pi^-$ events however doesn’t change substantially the shape of the energy spectrum.

Moreover, the background in $\bar{n}p$ data might have a different composition, since it could even proceed by $P$-wave annihilations. To this purpose the spectrum was first fitted by a second order polynomial function weighted by a mixture of $S$- and $P$-wave probability distributions, in order to estimate the trends of six pions incoherent production from the two allowed initial states. We could, therefore, separate the total background into an $S$- and a $P$-wave component. The contribution from $S$-wave was shown to be dominant, as expected (about 90%).

We plotted the expected distribution in case 31% of the exclusive $6\pi$ events were due to a narrow resonance, described by a Breit–Wigner function with $m = 1.911$ GeV and $\Gamma = 29$ MeV, following the method indicated in Ref. [1] (dotted curve in Fig. 1). How this curve has been obtained is explained in detail in Fig. 2.

![Figure 2](image-url)

Fig. 2. Steps to get the curve reported in Fig. 1: a Breit–Wigner amplitude, centered at $m = 1.911$ GeV (dotted line), 29 MeV wide (a), is convoluted with the Dover–Richard’s function for $S$-wave annihilation, and properly normalised (b). As a consequence of the convolution, the position of the peak is slightly shifted as compared to the resonance nominal mass. A fit of the experimental spectrum with polynomial functions weighted by Dover–Richard’s distributions [8] allows to disentangle the contribution of the $S$-wave (dot-dashed curve in (c)) and $P$-wave (solid curve in (c)) part of the continuum background. The dot-dashed curve in (d) shows the coherent sum of the function in (b) and the dot-dashed curve in (c), with phase and relative weight as reported in Ref. [1]. Adding incoherently to this curve the $P$-wave contribution to the continuum background, one gets the solid curve in (d), reported in Fig. 1 in a narrower energy range (up to the dashed vertical line shown in (c) and (d)).
The Breit–Wigner interferes with the $S$-wave part of the background with a relative phase $\phi = 62^\circ$. The Breit–Wigner amplitude must as well be convoluted by the Dover–Richard’s distribution for $S$-wave annihilation, to reproduce correctly in our case the formation of a $1^-$ state as a function of the available energy. The $P$-wave part of the background was then added incoherently to this amplitude.

However, the curve in Fig. 1 does not reproduce the data. A fit with free weights for the resonance signal and the background and their relative phase shows that, again, the $S$-wave term of the total amplitude is dominant, and the maximum contribution from the resonant state is 1.5%: this figure can be understood as an upper limit for its presence in our data. The relative phase between the resonance and the polynomial background is found to be $(189 \pm 24)^\circ$.

Therefore, we cannot confirm that the dip at 1.911 GeV observed by E687 is due to a narrow resonance centered at this energy, if the formation mechanism is the same in photoproduction as well as in $\bar{n}p$ annihilation, and if all the components of the isospin 1 multiplet showed up in a similar way.

If these last hypotheses hold, several explanations can be proposed to justify the disagreement between the two observations. The first is the presence of a possible systematic experimental error on the absolute energy scale. An about 2% error would bring the real value of mass out of our very narrow mass range. Another one is an inadequacy of the analysis method, based on a simple fit by means of a Breit–Wigner function of the observed dip in order to describe the interference phenomenon.

A final remark is that, if the observed dip corresponded to a resonance below $NN$ threshold, it would confirm previous observations of anomalous trends. We remind that the FENICE Experiment [13] reported a dip in the $e^+e^- \rightarrow \text{multihadron}$ cross section, described by the presence of a narrow state at $(1870 \pm 10)$ MeV, with a decay width of $\sim 10$ MeV. Such a state explained also the anomalous trends of the nucleon form factor in the time-like region. An anomalous behavior of the elastic $\bar{n}p$ cross section at low momenta was also recently reported [14]. A possible explanation [15] was the presence of a narrow state below threshold, corresponding to a spin triplet configuration of the $\bar{n}p$ system.

References