ELSEVIER

30 December 1999

PHYSICS LETTERS B

Physics Letters B 471 (1999) 263–270

Study of η and η' production in $\bar{n}p$ annihilations

OBELIX Collaboration

A. Filippi [a,1], M. Agnello [b], E. Botta [a], T. Bressani [a], D. Calvo [a], S. Costa [a], F. D'Isep [a], A. Feliciello [a], F. Iazzi [b], S. Marcello [a], B. Minetti [b], N. Mirfakhraee [a,2], F. Balestra [c], M.P. Bussa [c], L. Busso [c], P. Cerello [c], O. Denisov [c,3], R. Garfagnini [c], A. Grasso [c], A. Maggiora [c], A. Panzarasa [c], D. Panzieri [c,4], F. Tosello [c], A. Bertin [d], M. Bruschi [d], M. Capponi [d], S. De Castro [d], R. Donà [d], D. Galli [d], B. Giacobbe [d], U. Marconi [d], I. Massa [d], M. Piccinini [d], M. Poli [d,5], N. Semprini Cesari [d], R. Spighi [d], V. Vagnoni [d], S. Vecchi [d], M. Villa [d], A. Vitale [d], A. Zoccoli [d], A. Bianconi [e], G. Bonomi [e], E. Lodi Rizzini [e], L. Venturelli [e], A. Zenoni [e], C. Cicalò [f], A. Masoni [f], S. Mauro [f], G. Puddu [f], S. Serci [f], G. Usai [f], O.E. Gorchakov [g], S.N. Prakhov [g], A.M. Rozhdestvensky [g], M.G. Sapozhnikov [g], V.I. Tretyak [g], P. Gianotti [h], C. Guaraldo [h], A. Lanaro [h], V. Lucherini [h], C. Petrascu [h], V. Ableev [i,3], L. Vannucci [i], G. Vedovato [i], G. Bendiscioli [j], V. Filippini [j], A. Fontana [j], P. Montagna [j], A. Rotondi [j], P. Salvini [j], S. Tessaro. [k]

[a] *Dipartimento di Fisica Sperimentale, Università di Torino, and INFN, Sezione di Torino, Torino, Italy*
[b] *Politecnico di Torino and INFN, Sezione di Torino, Torino, Italy*
[c] *Dipartimento di Fisica Generale ''A. Avogadro'', Università di Torino and INFN, Sezione di Torino, Torino, Italy*
[d] *Dipartimento di Fisica, Università di Bologna and INFN, Sezione di Bologna, Bologna, Italy*
[e] *Dipartimento di Chimica e Fisica per l'Ingegneria e per i Materiali, Università di Brescia, Brescia, Italy and INFN, Sezione di Pavia, Pavia, Italy*
[f] *Dipartimento di Fisica, Università di Cagliari and INFN, Sezione di Cagliari, Cagliari, Italy*
[g] *Joint Institute of Nuclear Research, Dubna, Moscow, Russia*
[h] *Laboratori Nazionali di Frascati dell' INFN, Frascati, Italy*
[i] *Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy*
[j] *Dipartimento di Fisica Nucleare e Teorica, Università di Pavia and INFN, Sezione di Pavia, Pavia, Italy*
[k] *Istituto di Fisica, Università di Trieste and INFN, Sezione di Trieste, Trieste, Italy*

Received 16 September 1999; received in revised form 16 November 1999; accepted 22 November 1999
Editor: L. Montanet

[1] Corresponding author. Address: INFN Torino, Via P. Giuria, 1, 10125 Torino, Italy; E-mail: filippi@to.infn.it; fax: + + 39.011.6707325.
[2] On leave of absence from Shahid Beheshty University, Teheran, Iran.
[3] On leave of absence from Joint Institute of Nuclear Research, Dubna, Moscow, Russia.
[4] Dip. di Scienze e Tecnologie Avanzate, Università del Piemonte Orientale ''Amedeo Avogadro'', Italy.
[5] Dipartimento di Energetica ''Sergio Stecco'', Università di Firenze, Firenze, Italy.

PII: S0370-2693(99)01316-7

Abstract

The annihilation fractions and cross sections for the $\bar{n}p$ annihilation reaction in flight ($\sim$ 50–400 MeV$/c$) into $\eta\pi^+$ and $\eta'\pi^+$ final states have been measured. The first ones follow the trend expected for P wave annihilations. From the ratios of the yields an evaluation of the pseudoscalar mixing angle in the standard form is possible. The value found shows that for pseudoscalar meson production from P wave the Quark Line Rule is not grossly violated.

PACS: 13.75.-n; 14.40.Cs
Keywords: Antineutron-proton annihilation in flight; Measured η and η' production; Absolute annihilation frequencies and cross sections; Pseudoscalar physical states mixing angle; OBELIX spectrometer

In this Letter we report on a study of the annihilation reactions

$$\bar{n}p \to \eta\pi^+ \tag{1}$$

and

$$\bar{n}p \to \eta'\pi^+ \tag{2}$$

with incident $\bar{n}$ momentum up to 405 MeV$/c$; the annihilation frequencies and cross sections will be given. From these results an evaluation of the pseudoscalar mixing angle between physical states, in its standard formulation, may be deduced.

Using a quark basis description the physical states in the pseudoscalar nonet may be written as

$$|\eta\rangle = \frac{X_\eta}{\sqrt{2}}|u\bar{u} + d\bar{d}\rangle + Y_\eta|s\bar{s}\rangle\,, \tag{3}$$

$$|\eta'\rangle = \frac{X_{\eta'}}{\sqrt{2}}|u\bar{u} + d\bar{d}\rangle + Y_{\eta'}|s\bar{s}\rangle\,, \tag{4}$$

where $X_\eta^2 + Y_\eta^2 = X_{\eta'}^2 + Y_{\eta'}^2 = 1$, in absence of additional gluonic components. X and Y are related to the pseudoscalar mixing angle by the relationships

$$X_\eta = Y_{\eta'} = \frac{1}{\sqrt{3}}\cos\Theta_{\rm PS} - \sqrt{\frac{2}{3}}\sin\Theta_{\rm PS}\,, \tag{5}$$

$$X_{\eta'} = Y_\eta = -\sqrt{\frac{2}{3}}\cos\Theta_{\rm PS} - \frac{1}{\sqrt{3}}\sin\Theta_{\rm PS}\,, \tag{6}$$

$$\tan\Theta_{\rm PS} = -\frac{\sqrt{2}\,X_\eta + Y_\eta}{X_\eta - \sqrt{2}\,Y_\eta} = \frac{X_{\eta'} - \sqrt{2}\,Y_{\eta'}}{\sqrt{2}\,Y_{\eta'}}\,. \tag{7}$$

Recently it was pointed out that the particle states mixing properties are different from those of the coupling constants [1], which are directly connected to the quark distribution at zero spatial distances, and are in principle momentum dependent [2]. As a consequence, two mixing angles related to the two different decay constants are needed. According to this framework the mixing angle for the singlet components of the coupling constant is $\theta_0 \simeq -4°$, while for the octet ones it is much larger, $\theta_8 \simeq -20°$; this value for θ_8 is consistent with several experimental evaluations of the mixing angle obtained from the ratio of the production yields for the two pseudoscalar mesons.

In this work the basic assumption for the determination of the mixing angle is that the $\mathcal{N}\overline{\mathcal{N}}$ initial states may couple only to the $u\bar{u} + d\bar{d}$ component of η and η' wave functions, and not to the $\bar{s}s$ one. However, sizeable effects on the pseudoscalar mesons production [3] could be given by the presence of a strange quark content in the nucleon wave function, as suggested by Ellis et al. [4]; the $\bar{s}s$ component in the nucleon could explain the abundant ϕ meson production recently measured at LEAR. These effects could be particularly important in η/η' production when the $\mathcal{N}\overline{\mathcal{N}}$ annihilation occurs from spin singlet initial states [5]: yet in $\bar{n}p \to \eta(\eta')\pi^+$ reactions the contributing initial states are only the spin triplet ones $^3P_0$ and $^3P_2$.

Up to now, several experiments have shown that the production rates of η and η' may be accounted for simply by means of the SU(3) Naïve Quark Model, taking possibly into account symmetry breaking effects but without invoking any $s\bar{s}$ component in the nucleon wave function; the measured pseudoscalar mixing angle is in general in good agreement with the value from the Gell-Mann–Okubo linear mass formula, $\Theta_{PS} = -23°$ [6]. Among the experimental observations supporting this fact, the 2γ decays of both η and η', the J/ψ radiative decay and the decay of light mesons, and the ratios of the cross sections for the scattering processes $\pi^+ n \to \eta p, \eta' p$ [7]. All of them show that the yield for the η production is about twice as large as the η' one, after proper phase space corrections. Moreover, several branching ratios for $\bar{p}p$ annihilations at rest into η and η' and neutral mesons have been measured by the Crystal Barrel Collaboration, and among them $\mathrm{BR}(\bar{p}p \to \eta'\pi^0)/\mathrm{BR}(\bar{p}p \to \eta\pi^0) = (0.548 \pm 0.046 \pm 0.014)$, from which the experimental value for the pseudoscalar mixing angle $\Theta_{PS} = -(17.3 \pm 1.8)°$ was derived [8]. The evaluation of the mixing angle however depends on dynamical corrections, related to phase space factors and particle momenta, which can be quite important especially in low energy annihilation processes.

The annihilation fractions and cross sections have been measured by the OBELIX detector, which operated from 1990 to 1996 at LEAR at CERN. The apparatus, whose detailed description may be found elsewhere [9], was endowed with a unique facility for the production of an antineutron beam, from the LEAR $\bar{p}$'s by means of the Charge Exchange reaction $\bar{p}p \to \bar{n}n$. The data used for the present analysis have been collected in three large data takings with $\bar{p}$ momentum of 412 MeV$/c$, producing antineutrons with a continuous momentum distribution ranging from ~ 50 to 405 MeV$/c$. The antineutron beam had an intensity and momentum resolution quite suitable to perform high precision annihilation dynamics and meson spectroscopy studies. Many details about its production and its features may be found in Ref. [10]. The advantages of using the antineutron as a projectile are manyfold [11]. We remind here only the fact that, being the isospin quantum number fixed in the initial state, the number of allowed partial waves is reduced. Moreover, provided the available statistics are enough, the production yields may be sketched as a function of the antineutron momentum, and a more transparent comparison of their trends with the theoretical expectations from specific partial waves may be performed.

For the measurement described in the following information from the OBELIX Time-Of-Flight system (TOF) and the Jet Drift Chamber (JDC) only were employed; the latter device measured the momenta of the particles and was used to determine the event topology: events with three or five tracks only, with well defined annihilation vertices, were selected for the analysis. The TOF system was used to reconstruct, by means of an iterative algorithm, the momentum of each interacting antineutron, and only the events with a physically meaningful $\bar{n}$ momentum value (for $\bar{n}$'s annihilating inside the 25 cm long reaction target) were kept.

In the $\bar{n}p \to \eta\pi^+$ reaction the η meson was observed in its charged decay mode: $\eta \to \pi^+\pi^-\pi^0$ (B.R. $= (23.1 \pm 0.5)\%$). To reduce contaminations from exclusive events $(\bar{n}p \to 2\pi^+\pi^-)$ as well as from events with more than one missing π^0 a selection on the total energy E_{TOT} and on the total measured center of mass momentum p_{TOT} was made, as shown by the lines in Fig. 1a. The $\bar{n}p \to 2\pi^+\pi^-\pi^0$ data sample was then selected out of all three prong events by applying a 1C kinematic fit to test this reaction at 95% C.L., and a 4C one to reject the exclusive hypothesis at 99% C.L. In this reaction the recoiling π^+ is faster (> 700 MeV$/c$) than the pions from η decay, whose momentum doesn't exceed 650 MeV$/c$, being its average value peaked at about 300 MeV$/c$. If one positive pion only is required to be fast, while all the other ones are required to have a momentum lower than 700 MeV$/c$, only 1% of the η signal is lost, while the background is reduced by about 80%.

After this selection, the $(\pi^+\pi^-\pi^0)$ invariant mass distribution of the system recoiling against the fast π^+ has just one entry per event; it is shown, for events without selection on $\bar{n}$ momentum, in Fig. 1b. Different cuts on the measured π^+ momentum, on the kinematic fit χ^2 and on (E_{TOT}, p_{TOT}) were applied in order to check the results' stability and to define systematic effects connected to the selection criteria. They amount to about 5%.

The number of η mesons was evaluated fitting the invariant mass distribution in the η region with a Gaussian plus polynomial contributions; different orders for polynomials were tested, and their choice had no particular effect on the evaluation of the yields, which were always consistent within statistical errors. The background under the η peak amounts to $\sim 55\%$. An average value of different evaluations

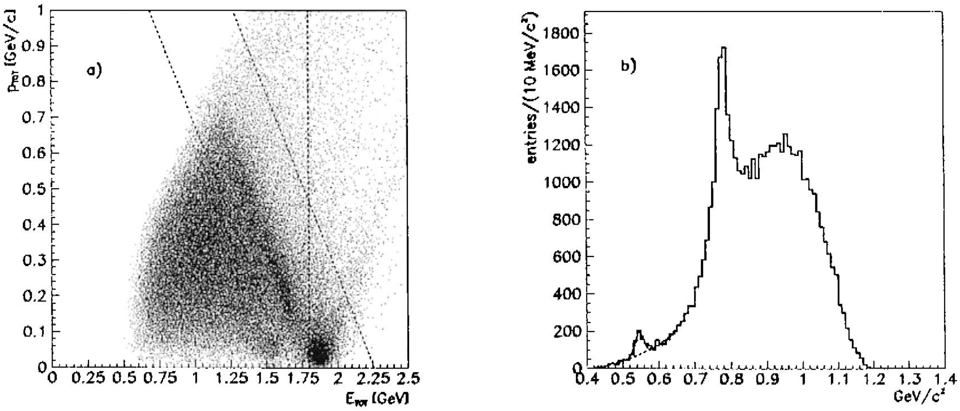

Fig. 1. (a) Total center of mass momentum p_{TOT} vs total energy E_{TOT} scatter plot: the cuts applied to select events with one missing π^0 only are outlined. The total energy was moreover required to be less than 1.8 GeV. (b) Invariant mass distribution for the $(\pi^+\pi^-\pi^0)$ system recoiling against the fast π^+: the η signal has been fitted with a Gaussian plus a third degree polynomial function. The spectrum is not corrected on apparatus acceptance.

is quoted in Table 1 as final result: here the total measured numbers for the full statistics and for three subsamples, selected according to $\bar{n}$ momentum values in the ranges 1) $\sim 50 \leq p_{\bar{n}} \leq 200$ MeV/c, 2) $200 < p_{\bar{n}} \leq 300$ MeV/c, 3) $300 < p_{\bar{n}} \leq 405$ MeV/c, are reported.

The central mass value and the experimental resolution obtained for the η signal are $m_\eta = (546 \pm 1)$ MeV/c^2 and $\sigma_\eta = (12 \pm 1)$ MeV/c^2. The latter is compatible with that obtained by Monte Carlo simulations after event reconstruction through apparatus acceptance.

The detection efficiencies in the different $\bar{n}$ momentum ranges have been determined by means of Monte Carlo simulations based on the GEANT 3.21 package, including hadronic interactions reproduced by the FLUKA code. The Monte Carlo data have been treated as the real ones, submitting them to the same analysis chain. The detection efficiency as well as the geometric acceptance depend on the angular distribution of the emitted particles, which varies according to the quantum numbers of the initial state, due to angular momenta and spins composition and to the effect of centrifugal barriers; moreover, since annihilations occur in flight, some helicity components are missing, namely those with $m = \pm 2$. Since $\bar{n}p \to \eta\pi^+$ annihilations at low energies may only come from $^3P_0$ and $^3P_2$ initial states, the efficiencies have been evaluated in the two hypotheses: they vary of a factor up to 6%, being their difference larger for lower $\bar{n}$ momenta, as shown in Table 1, fourth and fifth column. The final ϵ_η value reported in Table 1, third column, corresponds to their weighted average.

Table 2 gives the total number of $\bar{n}p$ annihilations and of antineutrons for the whole statistics and the three ranges selected according to $\bar{n}$ momentum. The

Table 1
Number n_η of η mesons evaluated from invariant mass spectra, global detection efficiencies and detection efficiencies for events generated in the two initial states $^3P_0$ and $^3P_2$, for antineutron momenta selected in three intervals (total: $\sim 50 \leq p_{\bar{n}} \leq 405$ MeV/c, 1): $\sim 50 \leq p_{\bar{n}} \leq 200$ MeV/c, 2): $200 < p_{\bar{n}} \leq 300$ MeV/c, 3): $300 < p_{\bar{n}} \leq 405$ MeV/c).

$p_{\bar{n}}$ interval	n_η	ϵ_η	$\epsilon_\eta(^3P_0)$	$\epsilon_\eta(^3P_2)$
total	$391 \pm 36_{stat} \pm 19_{sys}$	$0.189 \pm 0.002_{stat}$	0.188 ± 0.002	0.19 ± 0.02
1)	$45 \pm 13_{stat} \pm 2_{sys}$	$0.195 \pm 0.005_{stat}$	0.186 ± 0.005	0.198 ± 0.005
2)	$133 \pm 22_{stat} \pm 7_{sys}$	$0.188 \pm 0.003_{stat}$	0.186 ± 0.003	0.188 ± 0.003
3)	$209 \pm 25_{stat} \pm 17_{sys}$	$0.181 \pm 0.002_{stat}$	0.180 ± 0.002	0.181 ± 0.002

Table 2
Number of annihilations and incoming antineutrons (for which the statistical error is negligible), selected in ranges according to the antineutron momentum value.

$p_{\bar{n}}$ interval	$N_{\rm ANN}$,10^3	$n_{\bar{n}}$,10^6
total	$8516 \pm 40_{\rm stat} \pm 433_{\rm sys}$	$43 \pm 2_{\rm sys}$
1)	$1277 \pm 6_{\rm stat} \pm 65_{\rm sys}$	$6.4 \pm 0.3_{\rm sys}$
2)	$2981 \pm 14_{\rm stat} \pm 152_{\rm sys}$	$14.5 \pm 0.7_{\rm sys}$
3)	$4258 \pm 20_{\rm stat} \pm 217_{\rm sys}$	$21 \pm 1_{\rm sys}$

number of annihilations was determined from the total number of recorded events, selecting those with a fully reconstructed annihilation vertex in the fiducial volume and a correctly evaluated antineutron momentum. A correction by a global annihilation efficiency was then applied to take into account the annihilations into one prong only, which were lost with the strong requirement on vertex topology. The technique used to evaluate the annihilation efficiency is described in Ref. [12]. The measured annihilation frequencies for the $\eta\pi^+$ channel, evaluated by means of the relationship

$$f_\eta(p_{\bar{n}}) = \frac{n_\eta(p_{\bar{n}})}{BR_\eta \cdot \epsilon_\eta(p_{\bar{n}})} \frac{1}{N_{\rm ANN}(p_{\bar{n}})} \qquad (8)$$

(where BR_η is the branching ratio for the decay of the meson in the observed final state) are reported in the second column of Table 3. Previous measurements of $\bar{n}p \to \eta\pi^+$ annihilation frequencies as a function of $\bar{n}$ momentum were performed detecting the $\eta \to \gamma\gamma$ decay channel by the OBELIX electromagnetic calorimeter (BR = (38.8 ± 0.5)%) [12]; the value found for $p_{\bar{n}}$ up to 400 MeV$/c$, $f_{(\eta\to\gamma\gamma)} = (6.4 \pm 1.2_{\rm stat} \pm 0.7_{\rm sys}) \times 10^{-4}$, is in a 2.65σ discrepancy with the present result. A reanalysis of the neutral decay data, with an updated version of the strong interaction simulation and a refined treatment of the trigger efficiency and of all systematic effects reduces this discrepancy to 1.07σ: an updated value, $f_{(\eta\to\gamma\gamma)} = (8.5 \pm 1.6) \times 10^{-4}$, may be quoted [13].

The total number of antineutrons was obtained from the amount of antiprotons entering the production target as counted by the OBELIX online counting system, and from the evaluation of the $\bar{n}$ beam flux, for which a dedicated Monte Carlo had been built. A detailed description of the techniques used to this purpose may be found in Ref. [14]. The annihilation cross sections, evaluated in each $p_{\bar{n}}$ range by means of

$$\sigma_\eta(p_{\bar{n}}) = \frac{1}{\rho N_{\rm AV}\,\Delta z} \frac{n_\eta(p_{\bar{n}})}{BR_\eta\,\epsilon_\eta(p_{\bar{n}})} \frac{1}{N_{\bar{n}}(p_{\bar{n}})} \qquad (9)$$

are reported in Table 3, fifth column. In Eq. (9) ρ is the liquid hydrogen density, $N_{\rm AV}$ the Avogadro number and Δz is the fiducial volume length (24 cm). The errors in the cross sections are dominated by the systematic uncertainty (about 5%) in the counting procedure and related to the fluctuations of the $\bar{p}$'s spot position.

The annihilation frequencies, as well as the cross sections, exhibit a raising trend with $p_{\bar{n}}$ momentum increase. Taking into account the P wave content predicted, as a function of the projectile momentum, by Dover–Richard's model [15,16] (and reported in Table 3, fourth column, after convolution with $\bar{n}$ momentum spectrum) one can derive the values for the elementary branching fractions BR_P for P wave production; they are given in the third column of Table 3. As expected for production from pure P wave, they are constant, within errors. A second

Table 3
Annihilation fractions, elementary branching ratios for P wave annihilations (systematic and statistic error are added in quadrature) and annihilation cross sections for the channel $\bar{n}p \to \eta\pi^+$, for different ranges of antineutron momenta (see in the text). The fourth column reports the P wave content in each $p_{\bar{n}}$ interval obtained by the convolution of the curve from Dover–Richard model and the antineutron momentum spectrum.

$p_{\bar{n}}$ interval	f_η,10^{-4}	BR_P,10^{-3}	P wave (%)	$\sigma(\bar{n}p \to \eta\pi^+)$, mb
total	$10.50 \pm 0.97_{\rm stat} \pm 0.74_{\rm sys}$	1.68 ± 0.15	62.3 ± 0.2	$0.203 \pm 0.019_{\rm stat} \pm 0.014_{\rm sys}$
1)	$7.83 \pm 2.27_{\rm stat} \pm 0.53_{\rm sys}$	2.24 ± 0.88	35.0 ± 0.9	$0.153 \pm 0.044_{\rm stat} \pm 0.010_{\rm sys}$
2)	$10.30 \pm 1.70_{\rm stat} \pm 0.76_{\rm sys}$	1.74 ± 0.31	59.3 ± 0.4	$0.207 \pm 0.034_{\rm stat} \pm 0.015_{\rm sys}$
3)	$11.77 \pm 1.42_{\rm stat} \pm 1.13_{\rm sys}$	1.66 ± 0.26	70.9 ± 0.3	$0.233 \pm 0.028_{\rm stat} \pm 0.022_{\rm sys}$

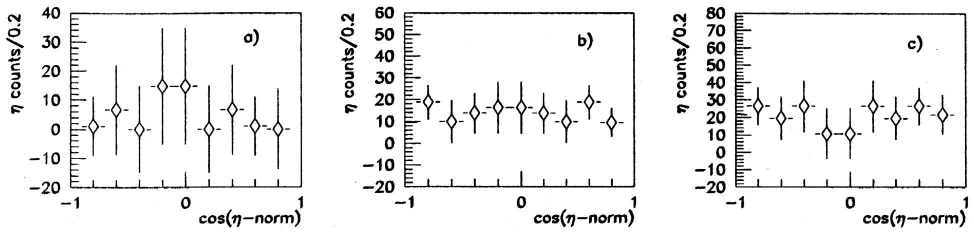

Fig. 2. Distributions of the η decay angle (formed between the η direction and the normal to its decay plane), for events selected in the three intervals chosen for antineutron momentum: (a) $50 < p_{\bar{n}} \leq 200$, (b) $200 < p_{\bar{n}} \leq 300$, (c) $300 < p_{\bar{n}} \leq 405$ MeV$/c$. The plots have already been corrected on apparatus acceptance.

proof of a dominant spin triplet P-wave annihilation is given by the shape of the η decay angular distributions, which are flat, as shown in Fig. 2, as expected for a pseudoscalar particle decay.

The η' meson is observed in its charged decay mode $\eta' \to \pi^+ \pi^- \eta$ (BR $=$ $(43.8 \pm 1.5)\%$), followed by η decay into three pions [17], or η decay in neutral particles only (BR $=$ $(71.4 \pm 0.16)\%$). In the first case a five prong data sample is used. The available statistics does not allow for this channel a selection as a function of the $\bar{n}$ momentum.

The first applied cut requires events with one fast π^+ ($p_{\pi^+} > 600$ MeV$/c$); the momenta of the pions from the η' decay do not exceed 550 MeV$/c$, and their average value is about 190 MeV$/c$. With the five prong data sample (η charged decay) a 1C kinematic fit was applied to test the hypothesis $\bar{n}p \to \pi_f^+ \pi^+ \pi^- \pi^+ \pi^- \pi^0$ at 95% C.L.. The surviving events were then tested against two different kinematic hypotheses: a) a 2C kinematic fit to test the reaction $\bar{n}p \to \pi_f^+ \pi^+ \pi^- \eta$ with $\eta \to \pi^+ \pi^- \pi^0$ at 95% C.L., or b) a 3C kinematic fit to test, requiring however convergence only, the reaction $\bar{n}p \to \pi_f^+ \eta'$, with energy-momentum conservation imposed at both η and η' decay vertices. Fig. 3a, b, and d, e show respectively the $(\pi^+ \pi^- \eta)$ invariant mass and the squared missing mass distribution of the system recoiling against the fast π^+ for the five prong data selected with the described criteria. The systematic uncertainty related to this selection was evaluated to be 4%, by varying the applied cuts.

In the missing η selection mode, a 1C kinematic fit was applied to three prong events to test at 95% C.L. the $\bar{n}p \to \pi_f^+ \pi^+ \pi^- \eta_{\text{miss}}$ hypothesis, and to

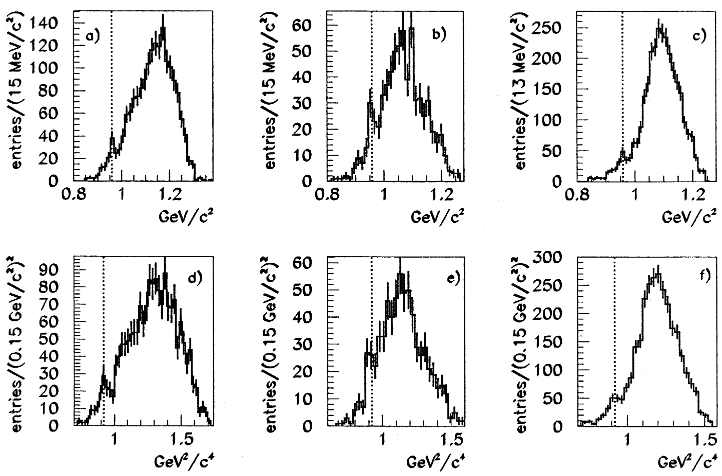

Fig. 3. $(\pi^+ \pi^- \eta)$ invariant mass spectra for data selected by means of (a) 2C fit and (b) 3C fit on the five prong data sample, and (c) 1C fit on the three prong one; (d), (e), (f) are the corresponding missing mass distributions for the system recoiling against the fastest π^+ for the corresponding data samples. The dotted line marks the nominal η' mass. The plots are not corrected on apparatus acceptance.

reject the $\bar{n}p \to \pi_f^+ \pi^+ \pi^- \pi^0$ one at 90% C.L.; the exclusive events were eliminated requiring the total energy to be less than 1.8 GeV. In Fig. 3c and f the $(\pi^+ \pi^- \eta_{\mathrm{miss}})$ invariant mass and missing mass distributions for events selected in this way are shown. The systematic uncertainty of this selection criterion is 7%.

The number of η' was determined by fitting the distributions in Fig. 3a, b, c with a Gaussian plus a linear polynomial function to reproduce the background shape. The mass and experimental resolution of the signal obtained from the five prong sample are $m_{\eta'} = (955 \pm 3)$ MeV$/c^2$ and $\sigma_{\eta'} = (14 \pm 2)$ MeV$/c^2$, while for the η_{miss} selection mode the values $m_{\eta'} = (956 \pm 4)$ MeV$/c^2$ and $\sigma_{\eta'} = (8 \pm 3)$ MeV$/c^2$ were found. Both these σ values are in agreement with the resolutions deduced from Monte Carlo simulations. The evaluated numbers of η' mesons are given in Table 4: a) and b) criteria deliver two consistent η' yields, whose difference may be understood as a systematic uncertainty of the measurement.

The same signature may be given by concurrent decay channels which may be filtered by the selection criteria, such as $\bar{n}p \to \pi^+ \eta'$ followed by η' decay into neutrals $\eta' \to \pi^0 \pi^0 \eta$, whose branching ratio is (20.7 ± 1.3)%, and the subsequent charged decay of η meson ($\eta \to \pi^+ \pi^- \pi^0$ and $\eta \to \pi^+ \pi^- \gamma$, which however occurs just with a branching ratio (4.8 ± 0.1)%). The contamination from this channel, evaluated by means of Monte Carlo simulations, is (0.091 ± 0.021). The number of $\eta' \pi^+$ events got from the three prong data sample after the correction due to contamination is $(28 \pm 13_{\mathrm{stat}} \pm 2_{\mathrm{sys}})$.

The detection efficiencies of the two selection criteria, including the branching fraction for the η decay, are reported in Table 4. The final annihilation frequencies and cross section values have then been determined averaging the absolute yields: for the global annihilation frequency and cross section the two values $f_{\eta'} = (6.63 \pm 2.21_{\mathrm{stat}} \pm 0.03_{\mathrm{sys}}) 10^{-4}$ and $\sigma_{\eta'} = (0.128 \pm 0.043_{\mathrm{stat}} \pm 0.011_{\mathrm{sys}})$ mb are derived.

Table 4
Number of η' mesons evaluated from $(\eta \pi^+ \pi^-)$ invariant mass spectra and corresponding detection efficiencies. They take into account the branching ratio for the η decay into charged (1st row) or neutral (2nd row) particles.

Selection criterion	$n_{\eta'}$	$\epsilon_{\eta'}$
2C or 3C	$19 \pm 9_{\mathrm{stat}} \pm 1_{\mathrm{sys}}$	$0.0072 \pm 0.0004_{\mathrm{stat}}$
1C	$31 \pm 14_{\mathrm{stat}} \pm 2_{\mathrm{sys}}$	$0.0119 \pm 0.0003_{\mathrm{stat}}$

The ratio between the absolute production yields for η' and η, $R = N_{\eta'}/N_{\eta} = (0.63 \pm 0.16_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}})$, can be compared to results obtained in similar reactions [18]. In $\bar{p}p$ annihilations at rest with a recoiling π^0 Backenstoss et al. found $R = (0.37 \pm 0.96)$, Chiba et al. (1.09 ± 0.51), and Crystal Barrel the already mentioned value $R = 0.548 \pm 0.048$ [8]. A comparison may even be possible with the results from the reactions $\pi^- p \to \eta(\eta') n$ at different incident momenta, among which those by Apel et al., $R = (0.59 \pm 0.06)$ at $p_{\mathrm{lab}} = 15$ GeV$/c$, (0.51 ± 0.08) at 20.2 GeV$/c$, (0.52 ± 0.06) at 25 and 40 GeV$/c$ and (0.53 ± 0.03) at 30 GeV$/c$, by Apokin et al. at $p_{\mathrm{lab}} = 39.1$ GeV$/c$, $R = (0.59 \pm 0.07)$, and by Daum et al. at $p_{\mathrm{lab}} = 63$ GeV$/c$, $R = (0.60 \pm 0.18)$.

The pseudoscalar mixing angle is related to R by the relationship:

$$\cot^2(\Theta_{\mathrm{id}} - \Theta_{\mathrm{PS}}) = \frac{X_{\eta'}^2}{X_{\eta}^2} = \frac{\bar{\sigma}(\bar{n}p \to \eta' \pi^+)}{\bar{\sigma}(\bar{n}p \to \eta \pi^+)} = R \frac{F_{\eta}}{F_{\eta'}}. \tag{10}$$

where $\Theta_{\mathrm{id}} = 35.26°$, and the factors F take into account the available phase space for the mesons production and other possible dynamical effects. Different expressions for F may be chosen.

Vandermeulen description [19] is based for instance on the hypothesis that the annihilation process prefers small energy transfers to the outgoing mesons. The dynamical factor is in this case $F_i = q \exp\left\{ A \left[s - (m_{\pi} + m_i)^2 \right]^{1/2} \right\}$ for the production of the i-type meson with m_i mass ($\sqrt{s}$ is the total available energy and q the break-up momentum in the two body i-π^+ system, while A is a constant, fixed to be -1.2 GeV^{-1}). Using this prescription, for which $F_{\eta}/F_{\eta'} \simeq 0.91$, one derives $\Theta_{\mathrm{PS}} = (-17.59° \pm 3.39°_{\mathrm{stat}} \pm 0.82°_{\mathrm{sys}})$.

If the dynamical correction is neglected ($F_{\eta}/F_{\eta'} = 1$), as suggested in Ref. [20], the value $\Theta_{\mathrm{PS}} = (-15.82° \pm 3.44°_{\mathrm{stat}} \pm 0.86°_{\mathrm{sys}})$ is obtained. Other prescriptions, such as the standard factor q^{2l+1} (which however was shown not to be strictly correct for the studied processes [16]), or Maruyama model [21,16], are based in addition on angular momentum values or on several other theory dependent parameters.

The values that we find for Θ_{PS} are in good agreement with the theoretical expectations. Z being the ratio of the matrix element for the production of the $s\bar{s}$ meson versus the production of a non-$s\bar{s}$ one, an upper value for it may be evaluated through the relationship:

$$\frac{\bar{\sigma}_{\eta'}}{\bar{\sigma}_{\eta}} = \left(\frac{|Z| + \cot \delta_{PS}}{1 - |Z| \cot \delta_{PS}} \right)^2 \tag{11}$$

(where $\delta_{PS} = \Theta_{id} - \Theta_{theor}$). One expects $|Z| = 0$ if the Quark Line Rule holds, i.e. in the case the $\bar{s}s$ component of the η and η' wave functions are produced by disconnected quarks diagrams and the $\mathcal{N}\overline{\mathcal{N}}$ system in the initial state doesn't contain a sizeable $\bar{s}s$ component. Having fixed $\delta_{PS} = 58.26°$ (using $\Theta_{PS}^{theor} = -23°$ to get the more conservative evaluation for $|Z|$), and using the value obtained including Vandermeulen phase space factors, $\Theta_{PS} = (-17.59° \pm 3.48°)$, we find $|Z| \leq 0.083$. This shows that the agreement with the quark model expectations is rather good, and a sizeable contribution for $\bar{s}s$ component is not required. Even a mixing of η and η' with a low mass pseudoscalar glueball is not necessary. This experimental observation doesn't conflict with the intrinsic strangeness hypothesis but it strengthens the statement by Dover and Fishbane [22] that the 0^{-+} quantum numbers for a possible $\bar{s}s$ content in the nucleon may be discarded.

In summary, this work presents the first observation of the η' meson performed by the OBELIX Experiment, and the first measurement of the annihilation frequency and cross section for the reaction $\bar{n}p \to \eta'\pi^+$ occurring in flight with $\bar{n}$ momentum up to 405 MeV$/c$. The comparison between this and the cross section for $\bar{n}p \to \eta\pi^+$ annihilation, whose trend as a function of energy follows P wave production, may be used to perform a conventional evaluation of the pseudoscalar mixing angle. The measured values depend rather heavily on the description of the phase space factor, but seem to indicate the absence of a sizeable discrepancy from the expectations of the Quark Line Rule for pseudoscalar meson production from spin triplet initial states.

References

[1] Th. Feldmann et al., Phys. Rev. D 58 (1998) 114006; Phys. Lett. B 449 (1999) 339.
[2] R. Escribano, J.-M. Frère, hep-ph/9901405.
[3] H. Genz et al., Z. Phys. A 335 (1990) 87; H. Genz, Phys. Rev. D 28 (1983) 1094.
[4] J. Ellis, M. Karliner, D. Kharzeev, M. Sapozhnikov, Phys. Lett. B 353 (1995) 319; J. Ellis et al., Phys. Lett. B 217 (1989) 173.
[5] M.G. Sapozhnikhov, JINR preprint, E1-98-341; in: Proc. LEAP'98 Conference, Villasimius, Italy, 1998, Nucl. Phys. A 655 (1999) 151c; J. Ellis, M. Karliner, D.E. Kharzeev, M.G. Sapozhnikov, hep-ph/9909235.
[6] S. Okubo, Phys. Rev. D 16 (1977) 2336.
[7] F. Gilman, R. Kauffman, Phys. Rev. D 36 (1987) 2761.
[8] Crystal Barrel Collaboration, C. Amsler et al., Phys. Lett. B 294 (1992) 451.
[9] OBELIX Collaboration, A. Adamo et al., Sov. J. Nucl. Phys. 55 (1992) 1732.
[10] M. Agnello et al., Nucl. Instr. Methods Phys. Res. A 399 (1997) 11.
[11] F. Iazzi, in: M.C. Birse, G.D. Lafferty, J.A. McGovern (Eds.), Proc. 6th International Conference on Hadron Spectroscopy, Manchester, England, 1995, World Scientific, Singapore, 1996, p. 99.
[12] OBELIX Collaboration, A. Bertin et al., Phys. Lett. B 410 (1997) 344.
[13] OBELIX Collaboration, to be published.
[14] OBELIX Collaboration, A. Filippi et al., Nucl. Phys. A 655 (1999) 453.
[15] C.B. Dover, J.M. Richard, Phys. Rev. C 21 (1990) 1466.
[16] C.B. Dover et al., Prog. Part. Nucl. Phys. 29 (1992) 87.
[17] M. Foster et al., Nucl. Phys. B 6 (1968) 174; M. Cerrada et al., Nucl. Phys. B 126 (1977) 189; P. Weidenauer et al., Z. Phys. C 47 (1990) 353.
[18] G. Backenstoss et al., Nucl. Phys. B 228 (1983) 424; M. Chiba et al., Phys. Rev. D 38 (1988) 2021; W.D. Apel et al., Phys. Lett. B 83 (1979) 131; V.D. Apokin, IFVE-86-240, 1986; C. Daum et al., Z. Phys. C 8 (1981) 95.
[19] J. Vandermeulen, Z. Phys. C 37 (1988) 563.
[20] E. Klempt, Phys. Lett. B 244 (1990) 122; U. Hartmann et al., Z. Phys. A 331 (1998) 217.
[21] M. Maruyama et al., Nucl. Phys. A 472 (1987) 643.
[22] C.B. Dover, P.M. Fishbane, Phys. Rev. Lett. 64 (1990) 3115.