Comment on "Protonium annihilation into $\pi^0\pi^0$ at rest in a liquid hydrogen target"

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We comment on the recent paper published by the Obelix Collaboration on protonium annihilation into $\pi^0\pi^0$ at rest in a liquid hydrogen target [Phys. Rev. D **65**, 012001 (2002)], with particular reference to the discrepancy with the results obtained by the Crystal Barrel Collaboration.

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The Obelix Collaboration has recently published [1] a measurement of the branching ratio for the annihilation reaction $\bar{p}p\rightarrow\pi^0\pi^0$ at rest in a liquid hydrogen target. The value obtained is $BR(\pi^0\pi^0,\mathrm{liq})=(2.8\pm0.1_{\mathrm{stat}}\pm0.4_{\mathrm{syst}})\times10^{-4}$. Their measurement is in general agreement with most measurements made prior to 1989, but is about a factor of two lower than the recent measurements [2,3] of $(6.93\pm0.43)\times10^{-4}$ and $(6.14\pm0.40)\times10^{-4}$ made by us using a high efficiency photon detector with an acceptance of $0.95\times4\pi$. Our mass resolution is typically $\sigma=10$ MeV/c^2 for $\pi^0\rightarrow2\gamma$. The Obelix branching ratio is also 2σ below and the Crystal Barrel value 1.7σ above the result [4] of Devons *et al.* who obtained $(4.8\pm1.0)\times10^{-4}$. In that experiment [4], the direction of photons was determined in spark chambers to within 2° and the photon energies estimated, to an accuracy of a factor of two, from the number of sparks in each shower. A photon detection efficiency of (0.82 ± 0.02) was achieved. The Obelix detector used a sampling electromagnetic calorimeter consisting of alternate layers of lead plates and plastic limited streamer tubes. Only the photon directions from π^0 decay were measured.

Since the $\pi^0\pi^0$ branching ratio is important for determining the fraction of P-state annihilation in $\bar{p}p$ annihilations at rest [5], it is important to try to understand the reason for the discrepancy between the Obelix and Crystal Barrel measurements. In this Comment on the Obelix paper [1] we discuss (i) evidence from the two experiments that their efficiency determination for photon detection is correct, (ii) the comment [1] that the Crystal Barrel experiment gives cross-section measurements for the $\pi^0\pi^0$ final state in flight which are apparently a factor of two larger than earlier work and (iii) the claim [1] that, when interpreted in terms of the atomic cascade, the Obelix measurement of the branching ratio in H_2 gas cannot be too low by a factor of two.

The fact that the $\pi^+\pi^-$ branching ratios obtained by the two experiments [1–3] are in good agreement suggests that the origin of the problem lies in the determination of the

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TABLE I. Detection efficiencies for $\bar{p}p \rightarrow \pi^0\pi^0$ from Obelix and Crystal Barrel.

Obelix	$(6.18\pm0.08)\%$	with kinematical fit $\bar{p}p \rightarrow \pi^0\pi^0$ (2C)	[1]
Crystal Barrel	$(48.8\pm1.0)\%$	with kinematical fit $\bar{p}p \rightarrow 4\gamma$ (4C)	[2]
	$(63.7\pm3.2)\%$	without kinematical fit	[3]

reconstruction efficiency for detecting $\pi^0\pi^0$. Table I compares the detection efficiencies of the two experiments for $\bar{p}p$ annihilation at rest into $\pi^0\pi^0$ in a liquid hydrogen target. Crystal Barrel detects all four photons from π^0 decay in direction and energy, whereas Obelix only detects the directions of the photons. Therefore, the energies of the photons must be reconstructed with a kinematical fit to two π^0. Assuming the Obelix $\pi^0\pi^0$ branching ratio to be right, the Crystal Barrel detection efficiency must be too low by a factor of about two. This cannot be, since the geometrical limit [3] of 66.2% gives a natural upper bound.

In their paper the Obelix Collaboration also report measurements of the branching ratio for the reaction $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$, both with and without the π^0 being detected, and obtain $BR(\pi^+\pi^-\pi^0,\text{liq})=(57.0\pm1.0)\times10^{-3}$ and $BR(\pi^+\pi^-\pi^0{}_{\text{miss}},\text{liq})=(57.3\pm0.4)\times10^{-3}$. They then suggest that the good agreement between these two results shows the reliability of their estimation of the Obelix detector photon efficiency. In a similar measurement we obtained [6] $BR(\pi^+\pi^-\pi^0,\text{liq})=(58.2\pm4.3)\times10^{-3}$. The good agreement with the Obelix results would also confirm the reliability of the photon efficiency determination for the Crystal Barrel detector.

The value of $BR(\pi^0\pi^0,\text{liq})$ was used by us to normalize our other branching ratio measurements [2] for all neutral final states. A large number of two-body annihilation modes were measured using different final states. Table II shows the good agreement of the branching ratios measured for several reactions with different numbers of photons in the final state. In [2] various final states with 4 (or 5) and with 8 (or 9) photons in the final state were measured. On average, the number of events is reduced by 30% due to the four additional photons. This reduction is reproduced by Monte Carlo simulations. The ratio of the predicted reduction to the observed value is (0.988 ± 0.015). This comparison shows how well the photon efficiency of the Crystal Barrel detector is understood. There is certainly no room for an error as large as 100%.

Using the measured $BR(\pi^0\pi^0,\text{liq})$ to normalize the branching ratio [2] for the $\omega\omega$ final state gives $BR(\omega\omega,\text{liq})=(3.32\pm0.34)\%$ which has also been used to normalize most Crystal Barrel analyses of 3 pseudoscalar data e.g. $\bar{p}p \rightarrow 3\pi^0$ [7], $2\pi^0\eta$ [8] etc. More recently the $\bar{p}p \rightarrow \omega_1\omega_2$ branching ratio has been measured [9] by us with $\omega_1 \rightarrow \pi^+\pi^-\pi^0$, $\omega_2 \rightarrow \pi^0\gamma$. We obtain $BR(\omega\omega,\text{liq})=(3.15\pm0.25)\%$ in agreement with our earlier result, giving confidence in our measured $BR(\pi^0\pi^0,\text{liq})$.

Further support for the efficiency determination for the Crystal Barrel detector can be made by a comparison of branching ratio measurements both for all neutral and for final states involving charged particles. These include measurements by the Obelix Collaboration [10] for the reaction $\bar{p}p \rightarrow K_S^0K_L^0$; $K_S^0 \rightarrow \pi^+\pi^-$ at three target densities, $0.005\rho_{\text{STP}}$, ρ_{STP} and liquid, where ρ_{STP} is the density of H_2

TABLE II. Two-body branching ratios from Crystal Barrel measured with a liquid hydrogen target. The zero-prong data have a common systematic uncertainty of about 4.2% as discussed in [2]. This error is not included in the table.

Reaction	Decay	N_γ	Branching ratio	Ref.	Comment
$\pi^0\eta$	$\eta \rightarrow \gamma\gamma$	4	$(2.09\pm0.22)\times10^{-4}$	[2]	zero-prong
	$\eta \rightarrow \gamma\gamma$	4	$(2.50\pm0.30)\times10^{-4}$	[3]	minimum-bias
	$\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$	8	$(2.21\pm0.44)\times10^{-4}$	[2]	zero-prong
$\eta_1\eta_2$	$\eta_1 \rightarrow \gamma\gamma,\ \eta_2 \rightarrow \gamma\gamma$	4	$(1.61\pm0.03)\times10^{-4}$	[2]	zero-prong
	$\eta_1 \rightarrow \gamma\gamma,\ \eta_2 \rightarrow 3\pi^0 \rightarrow 6\gamma$	8	$(1.66\pm0.04)\times10^{-4}$	[2]	zero-prong
$\pi^0\eta'$	$\eta' \rightarrow \gamma\gamma$	4	$(1.09\pm0.08)\times10^{-4}$	[2]	zero-prong
	$\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma,\ \eta \rightarrow \gamma\gamma$	8	$(1.27\pm0.07)\times10^{-4}$	[2]	zero-prong
$\eta\eta'$	$\eta \rightarrow \gamma\gamma,\ \eta' \rightarrow \gamma\gamma$	4	$(1.82\pm0.18)\times10^{-4}$	[2]	zero-prong
	$\eta \rightarrow 3\pi^0,\ \eta' \rightarrow \gamma\gamma$	8	$(2.37\pm0.16)\times10^{-4}$	[2]	zero-prong
$\omega_1\omega_2$	$\omega_1 \rightarrow \pi^0\gamma,\ \omega_2 \rightarrow \pi^0\gamma$	6	$(3.32\pm0.34)\times10^{-2}$	[2]	zero-prong
	$\omega_1 \rightarrow \pi^0\gamma,\ \omega_2 \rightarrow \pi^+\pi^-\pi^0$	5	$(3.23\pm0.25)\times10^{-2}$	[9]	
$\eta\omega$	$\eta \rightarrow \gamma\gamma,\ \omega \rightarrow \pi^0\gamma$	5	$(1.48\pm0.72)\times10^{-2}$	[2]	zero-prong
	$\eta \rightarrow 3\pi^0 \rightarrow 6\gamma,\ \omega \rightarrow \pi^0\gamma$	9	$(1.45\pm0.01)\times10^{-2}$	[2]	zero-prong
$\eta'\omega$	$\eta \rightarrow \gamma\gamma,\ \omega \rightarrow \pi^0\gamma$	5	$(0.76\pm0.03)\times10^{-2}$	[2]	zero-prong
	$\eta \rightarrow 3\pi^0 \rightarrow 6\gamma,\ \omega \rightarrow \pi^0\gamma$	9	$(0.81\pm0.03)\times10^{-2}$	[2]	zero-prong

gas at STP (standard temperature and pressure). The latter value $BR(K_S^0K_L^0,\text{liq})=(7.8\pm0.7\pm0.3)\times10^{-4}$ is in good agreement with those measured [3,11] by us, $BR(K_S^0K_L^0,\text{liq})=(9.0\pm0.6)\times10^{-4}$ and $BR(K_S^0K_L^0,\text{liq})=(8.6\pm1.0)\times10^{-4}$, for the same reaction but with $K_S^0\to\pi^0\pi^0$.

In their paper the Obelix Collaboration point out that cross section measurements for the final state $\pi^0\pi^0$ measured in flight with the Crystal Barrel detector over the momentum range from 600 to 1940 MeV/c [12,13] are about a factor of two larger than those measured by Dulude *et al.* [14]. However a partial wave analysis of the reactions $\bar{p}p\to\pi^+\pi^-,\pi^0\pi^0,\eta\eta$ and $\eta\eta'$, [12,15] clearly shows that the normalization of the data of Dulude *et al.* [14] is inconsistent with the $\pi^+\pi^-$ data as well as the Crystal Barrel $\pi^0\pi^0$ data. If the Crystal Barrel data for $\pi^0\pi^0$ are given a floating overall normalization in the analysis of all the in-flight data, including polarization data for $\bar{p}p\to\pi^+\pi^-$, then a multiplication factor of 0.989 ± 0.023 is obtained [12]. This agreement with the other in-flight results supports the validity of the efficiency determination for the detection of all neutral final states in the Crystal Barrel detector.

The Obelix Collaboration has also measured [16] the $\pi^0\pi^0$ branching ratio with a gaseous H_2 target at STP. They suggest that a mis-evaluation of the $\pi^0\pi^0$ reconstruction efficiency by a factor greater than two would also be reflected in this measurement and would give a branching ratio value which is incompatible with the measurement of the $\pi^+\pi^-$ branching ratio in coincidence with $\bar{p}p$ L x-rays, $BR(\pi^+\pi^-)_X$, made by the Asterix experiment [17]. However, as shown below, their Eq. (16) is derived using a classical model neglecting the effect of the *enhancement factors* [5] which take into account the deviation of the population of the hyper-fine levels from a statistical distribution in the presence of Stark mixing. Following the model of Batty [5] then

$$BR(\pi^+\pi^-)_X=\frac{1}{12}B(\pi^+\pi^-,{}^3P_0)+\frac{5}{12}B(\pi^+\pi^-,{}^3P_2) \tag{1}$$

and

$$BR(\pi^0\pi^0,\rho)=\frac{1}{2}f_P(\rho)\left[\frac{1}{12}E({}^3P_0,\rho)B(\pi^+\pi^-,{}^3P_0)+\frac{5}{12}E({}^3P_2,\rho)B(\pi^+\pi^-,{}^3P_2)\right] \tag{2}$$

where $BR(\pi^0\pi^0,\rho)$ is the branching ratio, $E({}^{2S+1}L_J,\rho)$ are the enhancement factors, $B(\pi^+\pi^-,{}^{2S+1}L_J)$ are the partial branching ratios and $f_P(\rho)$ is the fraction of P-state annihilation at target density ρ.

The analysis of Batty [5] gives values for $B(\pi^+\pi^-,{}^3P_2)$ which are consistent with zero, and then

$$BR(\pi^0\pi^0,\rho)=\frac{1}{2}f_P(\rho)E({}^3P_0,\rho)BR(\pi^+\pi^-)_X \tag{3}$$

which differs from Eq. (16) of the Obelix paper [1] by the factor $E({}^3P_0,\rho)$ which at a gas density ρ_{STP} is predicted [5] by a cascade calculation to have values in the range 1.21 to 1.29. Taking a value of $E({}^3P_0,\rho_{\text{STP}})=1.25$ and repeating the calculation of the Obelix group [1] gives $f_{\text{P}}(\rho_{\text{STP}})=(85\pm9)\%$. While somewhat high compared with the best fit value [3] of $(61\pm4)\%$, this is within the physically acceptable range. It is also uncertain if, as assumed by the Obelix group, the branching ratio measured at a density ρ_{STP} should be low by the same factor as that measured in liquid H_2. For example the fit to $\pi^0\pi^0$ measurements obtained in the analysis made by us [3] would indicate that the measured $BR(\pi^0\pi^0,\rho_{\text{STP}})$ is too low by a factor ≈1.4.

While the Obelix measurement agrees with some earlier data [18,19] where only 2 or 3 photons were observed, it should be noted that Obelix, Crystal Barrel and the work of Devons *et al.* [4] are the only experiments to measure all 4 photons and to reconstruct $2\pi^0$ events fully.

To summarize, there is a large body of evidence that the photon efficiency determination for the Crystal Barrel detector is reliable and that the branching ratios measured with a variety of different final states are consistent. The Crystal Barrel in-flight measurements for the $\pi^0\pi^0$ final state [12,13] are consistent with measurements for charged channels, as shown by a partial wave analysis [12,15] indicating a normalization problem with the data of Dulude *et al.* [14], although no explanation has been found for this discrepancy. Finally the argument in terms of the atomic cascade that the Obelix measurements of the branching ratio in H_2 gas cannot be too low by a factor of two has been shown to be modified when enhancement factors [5] for the hyperfine levels are taken into account.

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