First Observations of Pontecorvo Reactions With a Recoiling Neutron

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Abstract

We report the first observations of Pontecorvo reactions of the type $\bar{p}d \rightarrow Xn$. We fully reconstruct the outgoing meson and, for antiprotons stopped in liquid deuterium, we measure:

$$BR(\bar{p}d \rightarrow \pi^0 n) = (7.03 \pm 0.72) \times 10^{-6},$$
$$BR(\bar{p}d \rightarrow \eta n) = (3.19 \pm 0.48) \times 10^{-6},$$
$$BR(\bar{p}d \rightarrow \omega n) = (22.8 \pm 4.1) \times 10^{-6},$$
$$BR(\bar{p}d \rightarrow \eta' n) \leq 14 \times 10^{-6} \text{ (at 95\% confidence level).}$$

Assuming charge independence, our result for $\bar{p}d \rightarrow \pi^0 n$ is compatible with measurements of the only other observed Pontecorvo reaction $\bar{p}d \rightarrow \pi^- p$. The experimental ratios between the above branching ratios are in fair agreement with both the statistical model and dynamical two-step models (assuming $N\bar{N}$ annihilation into two mesons, with subsequent absorption of one meson on the remaining nucleon). This agreement suggests that there may be appreciable rates for Pontecorvo reactions producing final state mesons with masses above 1 GeV.

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1 Introduction

In 1956, a few months after the discovery of the antiproton, B. Pontecorvo [1] suggested the existence and pointed out the interest of antinucleon annihilations in nuclei leading to final particle configurations not attainable with free nucleons. Examples are the annihilation on the deuteron leading to one meson and one nucleon or the annihilation on a ^{3}He nucleus leading to two nucleons. At present, the main theoretical interest in these Pontecorvo reactions is found in their sensitivity to small internucleon distances where quark degrees of freedom may play an important role. Experimentally there is little information on the subject, with the only previously observed reaction being $\bar{p}d \rightarrow \pi^- p$ [2-5]. In this paper we present the first observations of Pontecorvo reactions where the recoiling nucleon is a neutron. With stopped antiprotons we observe the reactions $\bar{p}d \rightarrow \pi^0 n$, $\bar{p}d \rightarrow \eta n$, $\bar{p}d \rightarrow \omega n$ and $\bar{p}d \rightarrow \eta' n$. In each case we fully reconstruct the outgoing meson and measure the branching ratio for the reaction.

2 Apparatus and Data

The data presented here were obtained by the Crystal Barrel Collaboration at the CERN Low Energy Antiproton Ring (LEAR). The Crystal Barrel detector is a multipurpose magnetic spectrometer situated at an external beam line of LEAR. The detector contains a cryogenic target (this time filled with liquid deuterium), surrounded by two cylindrical proportional wire chambers (PWCs). These PWCs (which cover 99% and 97% of the solid angle for annihilations at rest in the centre of the target) are surrounded in turn by a cylindrical jet drift chamber (JDC) with 23 radial layers. This assembly is positioned inside a close-fitting electromagnetic calorimeter constructed in the shape of a barrel. The calorimeter is made of 1380 CsI crystals, each 16 radiation lengths in depth, pointing to the centre of the target. It covers 97% of the solid angle seen from the target centre. The calorimeter achieves an energy resolution of 2.5% (rms) at 1 GeV, and a spatial resolution of 25 mrad (rms) for isolated photons. The detector sits in a solenoidal magnet providing a uniform axial field. More complete details of the detector are given in ref. [6].

With an incident antiproton beam of 200 MeV/c momentum, stopping near the centre of the target, we have collected data for $\bar{p}d$ annihilations under two trigger conditions. We have 1.574 million open-trigger events (where data were collected whenever an antiproton entered the target), and 3.953 million all-neutral trigger events where, in addition to an incident antiproton, we required that there have been no signals in the PWC's and inner layers of the JDC. After event reconstruction we searched for the Pontecorvo reactions in the all-neutral data set. We obtained branching ratios by normalizing the all-neutral data set to the open-trigger data, using reactions visible in both (e.g. $\bar{p}d \rightarrow \pi^0\pi^0 n$). This method of branching ratio determination has also been used in a previous paper where more details are given [7].

3 Results

After reconstructing events from the all-neutral data set we remove all which are found to contain charged tracks. These can occur, despite the trigger, because of slight PWC and JDC inefficiencies, decays of long-lived neutrals (e.g. K_s^0), etc. We next group the data by the number of signals (Particle Energy Depositions: PED’s[1]) found in the calorimeter. These are not necessarily photons; they could be neutrons interacting in the crystals.

For the reactions studied here we find, as will be described later, that the neutron has a high probability of not being observed in our detector. We therefore set out to measure events with two or three PED’s but no signal for the neutron. Since most PED’s are photons, we may expect that the two-PED data sample contains signals for the Pontecorvo reactions $\bar{p}d \to \pi^0 n$, $\bar{p}d \to \eta n$ and $\bar{p}d \to \eta' n$, while the Pontecorvo reaction $\bar{p}d \to \omega n$ should contribute to the three-PED sample. The meson decays leading to these signals are, respectively, π^0, η, $\eta' \to 2\gamma$ and $\omega \to \pi^0\gamma \to 3\gamma$. Their decay branching ratios BR_d [8] are listed in the last column of Table 1.

From the measured individual photon momenta $\vec{p}_i$ one can calculate their total momentum magnitude $p_{tot} = \left|\sum_{i=1}^{N} \vec{p}_i\right|$ and their total invariant mass $m_{N\gamma} = \sqrt{\left(\sum_{i=1}^{N} E_i\right)^2 - p_{tot}^2}$. We set c = 1, thus $E_i = |\vec{p}_i|$; we have N = 2 or 3. Assuming that the recoiling undetected particle is a neutron with momentum magnitude $p_n = p_{tot}$, we calculate the total energy of the event $E_{tot} = \sum_{i=1}^{N} E_i + \sqrt{p_n^2 + m_n^2}$, m_n being the neutron mass. The equation $E_{tot} = m_d + m_{\bar{p}}$, with m_d and $m_{\bar{p}}$ being respectively the deuteron and antiproton mass, expresses energy conservation in the annihilation and corresponds to a line in a p_{tot} vs. $m_{N\gamma}$ plot that we shall call the "neutron recoil line".

In order to obtain clear two-dimensional scatterplots of measured events, we select (only for Fig. 1) events around the neutron recoil line, i.e., with $|E_{tot} - (m_d + m_{\bar{p}})| < 300$ MeV. Fig. 1a shows a scatterplot (p_{tot} vs. $m_{2\gamma}$) of the selected events from the two-PED sample and Fig. 1b presents the projection of the scatterplot on the $m_{2\gamma}$ axis. We observe the expected signals for the Pontecorvo reactions $\bar{p}d \to \pi^0 n$, $\bar{p}d \to \eta n$, $\bar{p}d \to \eta' n$ and an enhanced occurrence of events at $p_{tot} \le 200$ MeV. The latter is to be expected due to various kinds of background annihilation processes in which most of the available energy of $2m_p$ is concentrated in two photons of comparable energy and opposite direction. An example of such a process is $\bar{p}d \to \pi^0\pi^0 n$ with a spectator (i.e., low-momentum) neutron, and with both π^0’s decaying very asymmetrically so that two low-energy photons remain undetected. One can prove that N-PED events originating from N'-photon final states with N' > N populate the region of the scatterplot between the origin of the coordinate system and the neutron recoil line. On the other hand, events with interacting neutrons (depositing energy

1. A PED is a cluster of crystals in which at least 20 MeV has been deposited, with the central crystal receiving more energy than any of its eight immediate neighbours (and more than 4 MeV).

anywhere in the barrel of crystals, not necessarily in the original direction of neutron flight) populate the complementary region of the scatterplot. Due to the imperfect experimental angle-energy resolution, such events may also appear anywhere in the band of selected events. Furthermore, neutron interactions occurring in conjunction with losses of photons, electromagnetic shower fluctuations (so called "split-offs" which may be suppressed, but never totally eliminated, in the analysis), and pile-up may contribute to the observed background inside and around the band.

The background is much more pronounced in the three-PED sample of selected events shown in the scatterplot of Fig. 1 c, with its $m_{3\gamma}$-projection shown in Fig. 1 d. The peak near $p_{tot} = 0$ was cut out to permit an adequate presentation of the interesting part of the band. In this scatterplot one can discern one end of a strong "satellite" band which appears at lower values of p_{tot} (for given $m_{3\gamma}$) than those of the neutron recoil line. This band corresponds to annihilations with a spectator neutron and where the three detected photons are recoiling against an undetected particle (or several of them) of small mass, such as a π^0. One can also see that the experimentally observed neutron recoil "line" is actually narrower than the band of selected events. However, even inside that "line", the $\bar{p}d \rightarrow \omega n$ signal appears on a strong background of events presumably due to channels such as $\bar{p}d \rightarrow \pi^0\pi^0 n$ with one undetected low-energy photon but with a (non-spectator) neutron of large momentum.

The subsequent analysis is illustrated by the example $\bar{p}d \rightarrow \pi^0 n$. We select events with $| m_{2\gamma} - m_{\pi^0} | < 60$ MeV, m_{π^0} being the π^0 rest mass, and plot in Fig. 2a their momentum distribution in the region of 1246 MeV, where we expect a signal for the $\bar{p}d \rightarrow \pi^0 n$ reaction. A clear signal is seen. The solid curve shown is a fit of the expected signal shape to the data. This shape is found by the Monte Carlo (MC) simulation of the reaction, using GEANT [9], where we include all detector effects and analyse the MC data in the same way as real data. The resulting shape of the MC signal is taken and fitted to the data together with a parametrisation of the background which is assumed to be a linear function of p_{tot}. Apart from the background, the only free parameter in the fit of the shape is its area, which yields the signal strength. We find $N_{ev} = 677 \pm 36$ events. The error includes the statistical error on the signal and uncertainties in estimating the signal (the shape of the background and the effect of varying the width of the mass selection cut). Using the same MC events we can determine the efficiency ε_γ for observing the reaction $\bar{p}d \rightarrow \pi^0 n$ regardless of what happens to the neutron. We find ε_γ to be 0.794 (note that this does not include the probability ε_0 of not observing the neutron, which is estimated separately below). For the reaction $\bar{p}d \rightarrow \eta n$ the analysis proceeds along similar lines, resulting in the fit of Fig. 2b with $N_{ev} = 115 \pm 14$.

The signal for the reaction $\bar{p}d \rightarrow \eta' n$ is analysed in a different way. First, we find that about 25% of the events in the peak region above $p_{tot} = 850$ MeV/c are characterized by having an angle close to 180° between the two photons. Such events are even more frequent in the neighbourhood of the peak region in the two-dimensional p_{tot} vs. $p_{2\gamma}$ plot (Fig. 1a) where they constitute about 50%

of all events. They are easily eliminated by a tight cut on cos $\Theta_{\gamma\gamma}$ ($\Theta_{\gamma\gamma}$ being the angle between the two photons) close to -1, without noticeably affecting the acceptance for genuine photons from the η'-decay. In this way, 7 out of 29 events are eliminated from the peak region and do not appear in the histogram of Fig. 2c. From the study of the two-dimensional neighbourhood around the peak region we also conclude that the latter must still be contaminated by about 7 events due to other sources of background, leaving 15 ± 6 genuine events. The solid curve in Fig. 2c represents the expected MC signal normalized to the remaining total number of 15 events in the peak region. Also in the case of the reaction $\bar{p}d \to \omega n$, the relatively large background has to be estimated as a function of both p_{tot} and $m_{3\gamma}$. As expected from Fig. 1c, the background is peaked at the position of the neutron recoil line. The best estimate of its integral over the region $| m_{3\gamma} - m_{\omega} | < 60$ MeV as a function of p_{tot} is shown by the dotted line in Fig. 2d where the full line again represents the sum of the estimated background and the MC signal normalized in such a way that the sum best fits the total measured spectrum of events. This procedure yields 148 ± 22 events ascribable to the reaction $\bar{p}d \to \omega n$.

For the four detected reactions, the resulting numbers of events N_{ev} with their estimated errors are summarized in Table 1 .

From past experience we believe that the most serious systematic error of the MC simulation stems from uncertainties in the calculation of the probability for the neutron not being detected: it is notoriously difficult to accurately simulate the low-energy hadronic processes in a complicated experimental apparatus. For this reason we have tried to obtain experimental information on the problem by examining the reaction $\bar{p}d \to 3\pi^0 n$ in both six- and seven-PED samples. This is a reaction with a relatively large branching ratio so that it yields a high statistics sample. Furthermore, since there are more than two particles in the final state, the neutron momentum varies over a wide range. Fig. 3 presents (as a function of the neutron momentum) the ratio *r* of events observed in seven-PED to the sum of events in six- or seven-PED data. In the seven-PED sample, we search for three π^0 by kinematically fitting any six photons to the hypothesis $\bar{p}d \to 3\pi^0 n$. The fit returns the direction of the neutron. If the calculated neutron direction does not point to the seventh PED (within 0.2 rad), we omit the event from the seven PED sample. We see that above p_n = 600 MeV/c the ratio *r* is consistent with having a constant value of $r = 0.387 \pm 0.008$. Within errors, this value is in agreement with the value of *r* obtained by investigating the reactions $\bar{p}d \to \pi^0 n$ and $\bar{p}d \to \eta n$. In these reactions, the signal strength in the three-PED sample, with the third PED near the expected neutron direction (where we find it in most cases), is compared to the sum of itself and the signal strength in the two-PED sample. The result is shown in Fig. 3 by the last two entries (circled points), leading to an average value of $r = 0.408 \pm 0.029$.

In spite of the larger statistical error of this latter value, we weight the two independent determinations of *r* equally, obtaining $r = 0.398$. We consider that this averaging procedure is justified since the reactions $\bar{p}d \to \pi^0 n$ and $\bar{p}d \to \eta n$ yield *r* in a more relevant region of neutron momenta than the reaction $\bar{p}d \rightarrow 3\pi^0 n$ does.

We have searched for events with more than three PEDs resulting from the reaction $\bar{p}d \rightarrow 3\pi^0 n$ and can put an upper limit of 0.02 on their relative occurrence. However, this number could be larger at the higher neutron momenta relevant for the Pontecorvo reactions. As the best estimate of the probability for the neutron not being detected we take ε_0 = 1 - r - 0.02 = 0.58 for all four Pontecorvo reactions. We feel that a standard deviation $\Delta\varepsilon_0$ = 0.04 represents a conservative estimate of the combined statistical and systematic uncertainties of the efficiency ε_0, covering also its potential variation with neutron momentum in the relevant range.

We determine the number of $\bar{p}d$ annihilations giving rise to the observed Pontecorvo events by exploiting for normalization the more frequent reactions $\bar{p}d \rightarrow 2\pi^0 n$, $\bar{p}d \rightarrow 3\pi^0 n$, $\bar{p}d \rightarrow 2\pi^0 \eta n$ observable both in the all-neutral and the open-trigger data. The results are presented in Table 2. Within statistical errors, the ratios of event numbers in the two data sets are independent of the reaction observed, the mean ratio being 123.5 ± 2.5. We multiply this ratio by the number of antiprotons, $N_{\bar{p}}$ =1.792 x 10^6 counted during the live time of the open-trigger data-taking run and correct by a factor of 0.956 ± 0.025 for antiprotons lost due to interactions in the beam counters and material in front of the target. In this way we obtain the final number of annihilations in deuterium that must have led to the observed Pontecorvo reactions N_{an} = (211.6 ± 6.8) x 10^6. The stated error arises from the quadratic combination of the two individual errors given above. Note, however, that in the determination of N_{an} we assume equal analysis efficiency for all-neutral and open-trigger data as well as the absence of any correction due to the contamination by in-flight annihilations of the observed Pontecorvo reactions. The absence of such a correction is equivalent to assuming that the branching ratios for Pontecorvo reactions are equal at rest and at finite antiproton momenta ≤ 200 MeV/c.

The branching ratios of the Pontecorvo reactions are obtained from N_{an} and the numbers listed in Table 1 through the relation:

$$BR(\bar{p}d \rightarrow Xn) = N_{ev}/(\varepsilon_\gamma \varepsilon_o BR_d N_{an}). \qquad \text{Eq. (1)}$$

The results are:

$$BR(\bar{p}d \rightarrow \pi^0 n) = (7.03 \pm 0.72) \times 10^{-6},$$
$$BR(\bar{p}d \rightarrow \eta n) = (3.19 \pm 0.48) \times 10^{-6},$$
$$BR(\bar{p}d \rightarrow \omega n) = (22.8 \pm 4.1) \times 10^{-6},$$
$$BR(\bar{p}d \rightarrow \eta' n) = (8.2 \pm 3.4) \times 10^{-6}.$$

The errors of the branching ratios result from standard propagation of errors in the quantities on the right hand side of Eq. (1) as quoted either here or in ref. [8]. The value of $BR(\bar{p}d \rightarrow \eta' n)$ deviates only by a little more than two standard deviations from zero, and one cannot exclude the possibility that the signal is at least partly due to some additional, poorly understood background. Adopting this more conservative point of view would lead to an upper limit at a 95% confidence level of

$$BR(\bar{p}d \rightarrow \eta' n) \leq 14 \times 10^{-6}.$$

By invoking the principle of charge independence, we can relate our result for $\bar{p}d \rightarrow \pi^0 n$ to that for the other measured Pontecorvo reaction $\bar{p}d \rightarrow \pi^- p$. The predicted result is $(\bar{p}d \rightarrow \pi^- p)/(\bar{p}d \rightarrow \pi^0 n) = 2$. By doubling our branching ratio, we obtain:

$$BR(\bar{p}d \rightarrow \pi^- p) = (1.41 \pm 0.14) \times 10^{-5}.$$

This number can be directly compared to the results of refs. [2] and [3] whose authors have also measured annihilations in liquid deuterium. The error given in ref. [3] is purely statistical; the systematic error (mainly due to uncertainty about the background) is estimated to be about 20% [3a]. The error given in ref. [2] is also purely statistical but so large that the systematic uncertainty is presumably negligible. The results of refs. [4] and [5] have been obtained in gaseous deuterium (at NTP). Adding the systematic and statistical errors in quadrature, one arrives at the following branching ratios for the Pontecorvo reaction $\bar{p}d \rightarrow \pi^- p$ (in units of 10^{-5}):

0.9 ± 0.4	[2]
2.8 ± 0.6	[3,3a]
1.41 ± 0.14	this work, assuming charge independence
1.4 ± 0.7	[4]
1.20 ± 0.27	[5]

The two direct experiments in liquid deuterium are not in very good agreement with each other, but our value is not in disagreement with their weighted mean of 1.5 ± 0.3. The weighted mean of the two experiments in gaseous deuterium is 1.23 ± 0.25 which also agrees with our value. Therefore, at the present level of experimental accuracy, we see no indication for either charge-independence violation or a substantial difference between the branching ratios for Pontecorvo reactions in liquid and gaseous deuterium.

4 Comparison of Results to Theoretical Predictions

While Pontecorvo reactions may be intriguing, they are very difficult to calculate from "first principles". Indeed, Cugnon and Vandermeulen [10] assume that they are as complicated as processes such as the formation and decay of compound nuclei and therefore accessible only through a statistical approach. The latter is not intended to make detailed predictions about particular reactions (beyond an order-of-magnitude estimate), its strength being in a rough, but simple and coherent, description of many reactions at many different incident energies. Thus, ref. [10] makes no explicit predictions about the Pontecorvo reactions that we have measured. However, in the spirit of the statistical model, one would expect the reactions producing the heavier mesons η, ω and η' to be slightly suppressed when compared to those producing π^0 due to the smaller available phase space, which is proportional to p_n. On the other hand, the yield of ω–mesons should be favoured by a factor of 3 when compared to that of π^0-mesons due to the spin factor 2S+1. The production of a π^0 should be more probable than that of either an η or an η' because the latter contain strangeness; in fact, ref. [10] estimates that $s\bar{s}$-pair production is hindered by about a factor of 5 relative to $u\bar{u}$- or $d\bar{d}$-pair production. Taking this and the phase space difference into account, [BR(ηn) + BR(η'n)]/BR(π^0n) should be about 1.1. The ratio BR(ηn)/ BR(η'n) should depend mainly on the relative $s\bar{s}$ content of the mesons η and η' as determined by the pseudoscalar mixing angle θ_{PS}. With any reasonable value of θ_{PS}, the strangeness content of the η'-meson should be comparable to or larger than that for the η-meson; therefore, BR(ηn)/ BR(η'n) should be comparable to or larger than 1. Considering the sizeable experimental errors, especially on the η' production, these statistical predictions are not in violent disagreement with the experimental ratios of branching ratios as presented in Table 3 (some of the errors of branching ratios cancel in their ratios). The statistical model does not even attempt a quantitative prediction of absolute branching ratios: ref. [10] uses the known BR(π^-p) to extract the probability of "B=1 fireball"-formation, i.e., the overall probability that any Pontecorvo reaction occurs in $\bar{p}$d annihilation.

At the other extreme of the theoretical spectrum, several authors [11-17] have tried to make quantitative predictions about absolute branching ratios on the basis of dynamical models assuming two mesons plus one nucleon as an intermediate state before the absorption of one of these mesons by the nucleon to yield the final state of the Pontecorvo reaction. Most of them come to the conclusion that their quantitative results on absolute branching ratios are very uncertain because of poorly known meson-nucleon form factors far away from the mass-shell, badly known deuteron wave functions at small neutron-proton distances, etc.[1]

Just as in the statistical model, it stands to reason that also in dynamical models the ratios of branching ratios should be less plagued by uncertainties than the absolute values. Indeed, recently Kondratyuk and Sapozhnikov [15], and Kudryavtsev and Tarasov [17] have ventured quantitative predictions of some of these ratios, among others those of interest to us. They are reproduced in Table 3 . The results of ref. [15] are quoted for two choices of form factors, monopole and dipole, assuming an incoherent sum of contributions from the π- and the ρ-meson in the intermediate state; those of ref. [17] are given for the preferred deuteron wave function but for a range of dipole form factors corresponding to the possible values of an interference contribution with unknown phase. We see that the latitude provided by experimental errors and by uncertain meson-nucleon form factors is sufficient to accommodate the experimentally observed ratios of branching ratios.

Recently, Kaidalov [18] has advocated Reggeon exchanges as the proper model for calculating Pontecorvo reactions. Specific predictions do not include the channels measured here but, in general, they tend to be intermediate between those of the meson-exchange models and those of the statistical model of ref. [10].

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1. The usual assumption of dominant annihilation from $p\bar{p}$ S-states which is justified on the average [19] may be even more doubtful for Pontecorvo reactions than it is - a priori - for any specific annihilation channel. As noticed by Bizzarri et al. [20], the high momentum components of the deuteron wave function enhance annihilations in $\bar{p}$-nucleon P-states even if the antiproton is in an atomic S-state of the $\bar{p}$d system. Naively, one should expect this phenomenon to be particularly important for Pontecorvo reactions which depend on the high momentum components of the deuteron wave function in order to proceed.

5 Summary

Using data from the Crystal Barrel detector we have performed the first measurement of Pontecorvo reactions of the type $\bar{p}d \rightarrow$ (meson + neutron). This increases the number of observed Pontecorvo reactions from one to five.

At present, theory seems unable to predict the absolute branching ratios of Pontecorvo reactions to better than an order of magnitude. However, both the statistical model and the dynamical models lead to semiquantitative agreement with experiment in the relative branching ratios of Pontecorvo reactions with different mesons accompanying the neutron in the final state.

The extent of agreement between experiment and theory enables us to predict rather safely that Pontecorvo reactions of the type $\bar{p}d \rightarrow Xn$, with X being a meson heavier than 1 GeV/c^2 should have a substantial yield, especially if the meson has spin 2 (see also ref. [15]). However, since such mesons tend to have large widths and since the recoil neutron momentum decreases with increasing meson mass, it is likely to become increasingly difficult to separate quasi-free and Pontecorvo reactions; this may create additional difficulties for theoretical predictions, especially since the heavier mesons decay mainly into light quasistable mesons which may form baryonic resonances with the nucleon in the final state.

On the other hand, Pontecorvo reactions with a recoiling nucleon are apparently not well suited to discriminate between different theoretical models. For this purpose, the best possibility seems to be offered by hyperon-production reactions like $\bar{p}d \rightarrow K^0\Lambda$ or $\bar{p}d \rightarrow \Sigma^- K^+$. For those the statistical model predicts much higher branching ratios than dynamical models. The predictions of the two extreme models [10] and [12] are in the ratio 20:1 for the first of the above reactions and 2000:1 for the second one. At least the first reaction should be measurable at LEAR even if the pessimistic prediction of ref. [12] is correct.

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Table 1: Pontecorvo reactions $\bar{p}d \to X$ + neutron. The number of observed events at the calculated momentum is listed with the efficiencies for reconstruction of the neutral meson (ε_γ) and for non-detection of the neutron (ε_0). The branching ratios BR_d [8] for meson decay into two or three photons are also given.

X	$p_{tot}=p_n$(MeV/c)	N_{ev}	ε_γ	ε_0	BR_d
π^0	1246	677 ± 36	0.794 ± 0.033	0.58 ± 0.04	0.988
η	1183	115 ± 14	0.754 ± 0.031	0.58 ± 0.04	0.389 ± 0.005
ω	1111	148 ± 22	0.629 ± 0.026	0.58 ± 0.04	0.084 ± 0.005
η'	1040	15 ± 6	0.677 ± 0.028	0.58 ± 0.04	0.022 ± 0.002

Table 2: Trigger and running time enhancement. The number of observed events in the open-trigger data is compared to the number of events seen in the all-neutral data set.

Channel	N_{ev} (open trigger)	N_{ev} (all neutral)	Ratio (neutral/open trigger)
$2\pi^0 n$	405	50868	125.6 ± 6.3
$3\pi^0 n$	1572	192983	122.8 ± 3.1
$2\pi^0 \eta n$	415	51449	124.0 ± 6.1
Sum	2392	295300	123.5 ± 2.5

Table 3: Final results and a comparison of ratios of branching ratios for Pontecorvo reactions with different theoretical predictions.

X	$BR(\bar{p}d \to Xn)$ (10^{-6})	$BR(Xn)/BR(\pi^0 n)$ experiment	$BR(Xn)/BR(\pi^0 n)$ ref. [15] (monopole form f.)	$BR(Xn)/BR(\pi^0 n)$ ref. [15] (dipole form f.)	$BR(Xn)/BR(\pi^0 n)$ ref. [17]
π^0	7.03 ± 0.72	1	1	1	1
η	3.19 ± 0.48	0.45 ± 0.07	0.12	0.72	0.7 ± 0.3
ω	22.8 ± 4.1	3.3 ± 0.6	3.0	6.5	11^{+9}_{-6}
η'	< 14	≤ 2.0	0.8	1.3	-

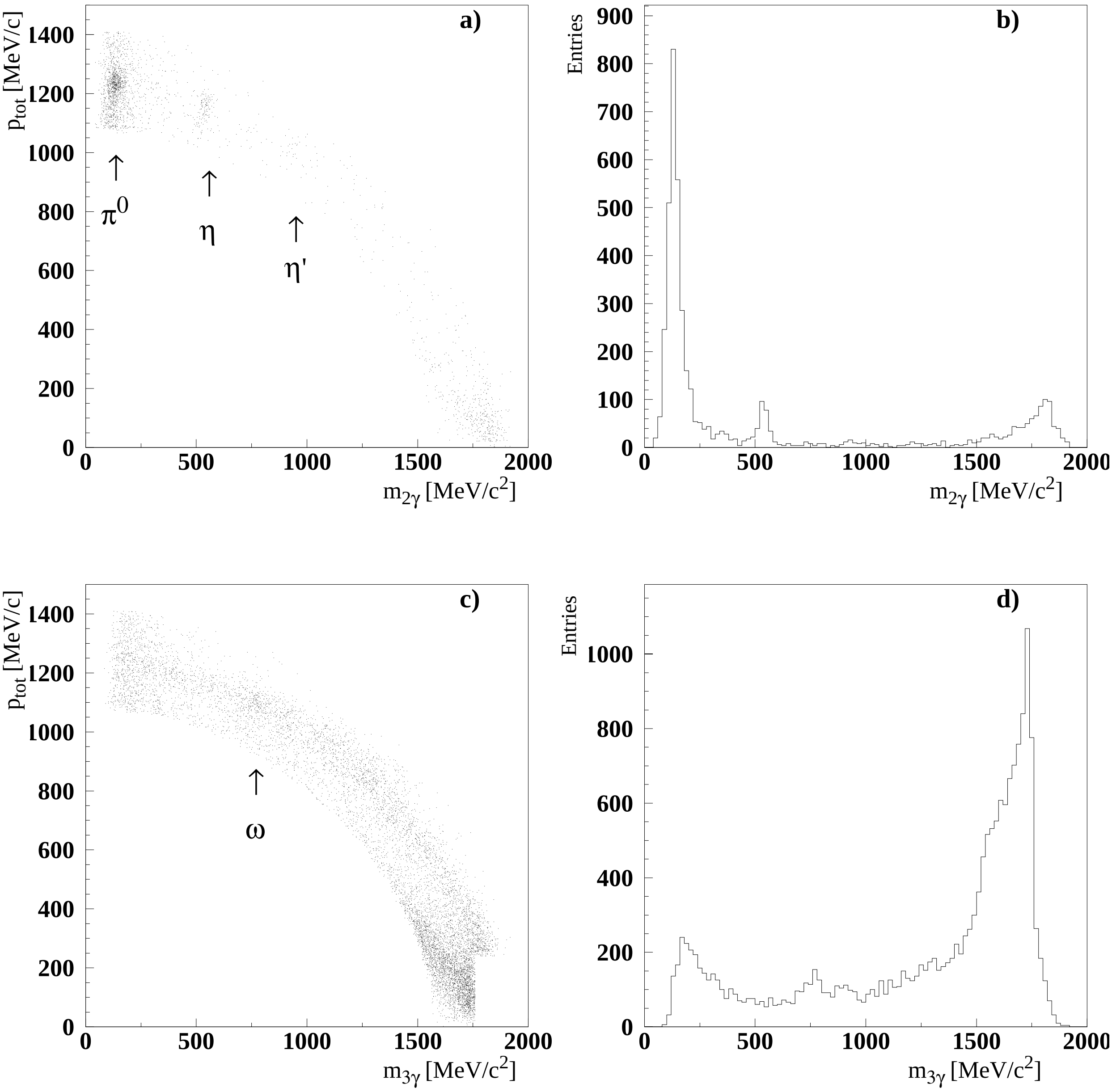

Figure 1: **Scatterplots of p_{tot} vs. $m_{N\gamma}$ with a cut of ±300 MeV on the total energy together with their projections on the $m_{N\gamma}$ axis. N = 2 in a) and b), N = 3 in c) and d).**

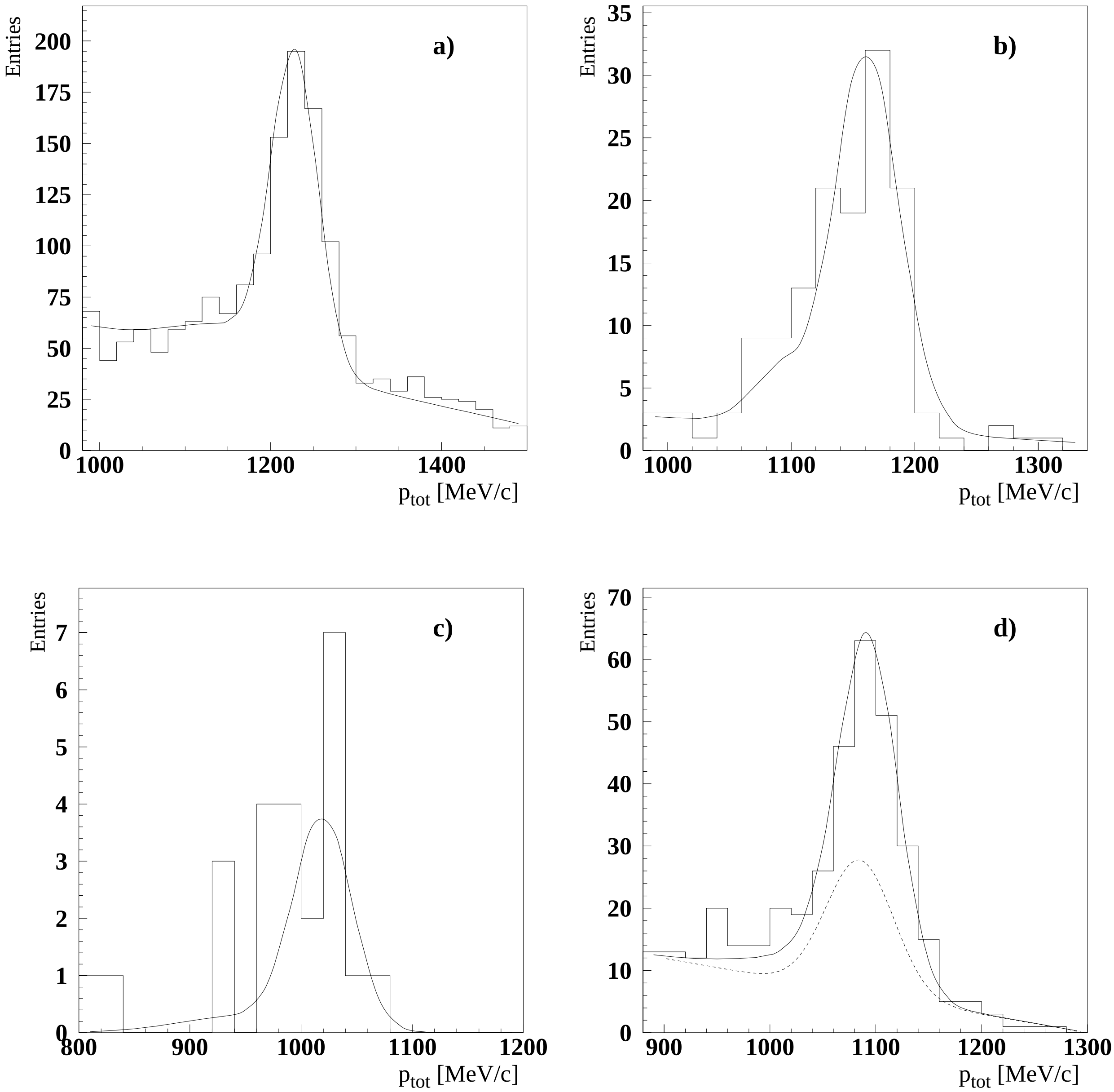

Figure 2: **a) p_{tot}-spectrum for two photon events with invariant mass compatible with a π^0. b) The same for events with mass compatible with an η, c) - for events with mass compatible with an η', and d) - for three photon events with invariant mass compatible with an ω. The curves are described in the text.**

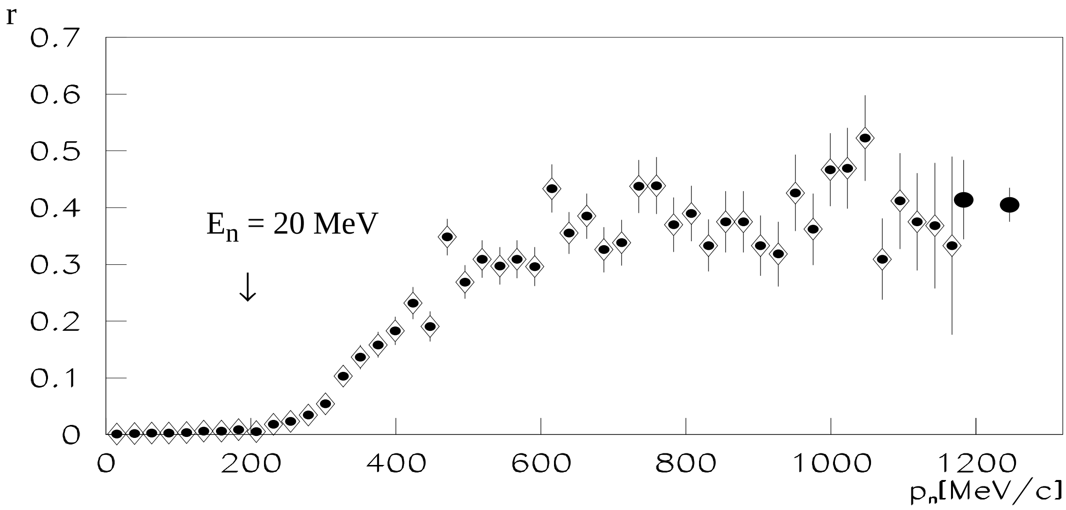

Figure 3: **Efficiency r for single-PED detection of neutrons from the reaction $\bar{p}d \to 3\pi^0 n$ (diamond symbols) and from the Pontecorvo reactions $\bar{p}d \to Xn$ ($X = \pi^0, \eta$) (circled symbols).**