Observation of the decay $\tau\to\rho\pi\pi\nu_\tau$

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An analysis of the decay $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ has been performed with the ARGUS detector at the DORIS II storage ring. From a study of the two pion subsystems we have found first evidence for the decays $\tau^- \to \rho^0\pi^-\pi^0\nu_\tau$, $\tau^- \to \rho^-\pi^+\pi^-\nu_\tau$, and $\tau^- \to \rho^+\pi^-\pi^-\nu_\tau$ with relative contributions to the decay $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ of 0.30 ± 0.04, 0.26 ± 0.05, and 0.10 ± 0.03, respectively. The fraction of the subchannel $\tau^- \to \omega\pi^-\nu_\tau$ has been determined to be 0.33 ± 0.05. The production of ρ mesons is enhanced by a factor of 1.9 ± 0.3 over that of ω mesons. We conclude that in more than 81% (95% CL) of all $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ decays either a ρ or ω meson is produced.

The decay mode $\tau^- \to \pi^-\pi^-\pi^+\pi^9\nu_\tau$ [#1] is well established and has a branching ratio of $4.4 \pm 1.6\%$ [1]. The only known subchannel is due do the decay $\tau^- \to \omega\pi^-\nu_\tau$ [#2]. This decay mode was discovered in 1987 [2] and contributes $(32 \pm 5)\%$ to the decay rate of $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$.

We have studied the decay $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ in order to look for subchannels containing a ρ meson. The observation of such decay modes can shed some light on the mechanism of hadronic τ decays. If the four-pion final state is produced via an intermediate resonance with two-body decays to $\omega\pi$, $a_1^-\pi^0$, and $a_1^0\pi^-$, one would expect ρ production from the a_1 decay. In addition, neglecting any possible interference between the various decay channels, the different ρ-isospin states are expected to be produced with equal rates.

The measurement was performed with the ARGUS detector at the DORIS II storage ring. The detector is a 4π spectrometer described in detail in ref. [3]. The analyzed event sample was collected at centre-of-mass energies between 9.4 GeV and 10.6 GeV and corresponds to an integrated luminosity of 264 pb^{-1}.

We search for τ-pairs events with the following combinations of τ-decay modes:

$$e^+e^- \longrightarrow \tau^+\tau^- \longrightarrow \pi^-\pi^-\pi^+\pi^0\nu_\tau$$
$$\hookrightarrow e^+\nu_e\bar{\nu}_\tau,\ \mu^+\nu_\mu\bar{\nu}_\tau,\ \pi^+ n\gamma\bar{\nu}_\tau \text{ or } K^+ n\gamma\bar{\nu}_\tau\ (0 \leqslant n \leqslant 2)\ .$$

The events were preselected by requiring exactly four charged tracks with a summed charge of zero. In addition, each track must have a transverse momentum of $p_T > 0.06$ GeV/c and point to the main vertex. Since the τ-lepton pairs are produced back-to-back with large momenta, their decay products typically point into opposite hemispheres. This characteristic one-versus-three topology of the charged particles was selected by requiring

$$\cos(\boldsymbol{p}_1, \boldsymbol{p}_i) < 0 \quad (i = 2, 3, 4)$$

and

$$\cos\left(\boldsymbol{p}_1, \sum_{i=2}^{4} \boldsymbol{p}_i\right) < -0.5\ ,$$

where $\boldsymbol{p}_1$ denotes the momentum of the charged particle on the one-prong side and $\boldsymbol{p}_i$ ($i = 2, 3, 4$) are the

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[#1] References in this paper to a specific charged state are to be interpreted as also implying the charge conjugate state.
[#2] References to production rates of the ω meson are to be interpreted as implying the product of the rates with the branching ratio BR($\omega \to \pi^+\pi^-\pi^0$).

particle momenta on the three-prong side. Contributions from radiative QED processes were reduced by rejecting events with a secondary vertex consistent with a converted photon. To suppress background from QED processes, two-photon reactions, and from hadronic processes, we apply the following cut [4]:

$$\left|\sum_{i=1}^{n} \boldsymbol{p}_{\mathrm{T}_i}\right| > 8\ \mathrm{GeV}/c\left(\sum_{i=1}^{n} \frac{|\boldsymbol{p}_i c|}{E_{\mathrm{CMS}}} - 0.7\right)^2 + 0.2\ \mathrm{GeV}/c\,.$$

Here, $\boldsymbol{p}_i$ denotes the momentum and $\boldsymbol{p}_{\mathrm{T}_i}$ the transverse momentum of the ith particle. Note that the sum includes all charged particles and all photons found in an event. Energy clusters in the calorimeter of more than 80 MeV with no associated track were accepted as photon candidates. The number of photons in an event was restricted to be 2, 3 or 4.

In the events we are searching for, photons on the three-prong side must originate from the decay $\pi^0 \to \gamma\gamma$. Therefore, such events were only accepted if they contained exactly two photons on the three-prong side fulfilling the condition

$$\cos(\boldsymbol{p}_1, \boldsymbol{p}_{\gamma_i}) < 0 \quad (i=1,2)\,.$$

In addition, the two-photon system must have an invariant mass within $\pm 100\ \mathrm{MeV}/c^2$ of the nominal π^0 mass [1] and yield a $\chi^2 < 9$ when kinematically constrained to the π^0 mass.

With these cuts the data sample of about two million events is reduced to 1817 events. In a subset of 1594 events the four-pion system on the three-prong side, formed by three charged pions assigned to the tracks and by the π^0 candidate, has an invariant mass of less than $1.8\ \mathrm{GeV}/c^2$, consistent with a four-pion final state originating from the decay $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$. However, the remaining 223 events with an invariant mass $m_{4\pi}$ larger than the τ-lepton mass indicate that our data sample still contains considerable background, even at lower invariant four-pion masses. To suppress this background, we use the fact that in τ decays the four-pion system is strongly boosted in the lab frame resulting in a correlation between the invariant mass $m_{4\pi}$ and the observed momentum of the four-pion system. Fig. 1 shows the invariant mass $m_{4\pi}$ versus the momentum $p_{4\pi}$ of the four-pion system for the data. The cut

$$p_{4\pi} > 6 m_{4\pi} c - 6\ \mathrm{GeV}/c\,,$$

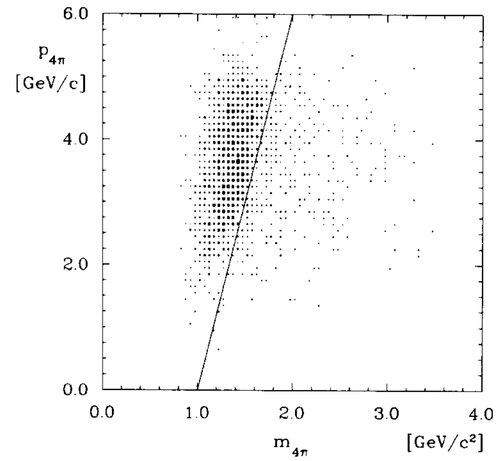

Fig. 1. Momentum distribution of the four-pion system versus its invariant mass. The line corresponds to the cut described in the text. Events below the line were rejected.

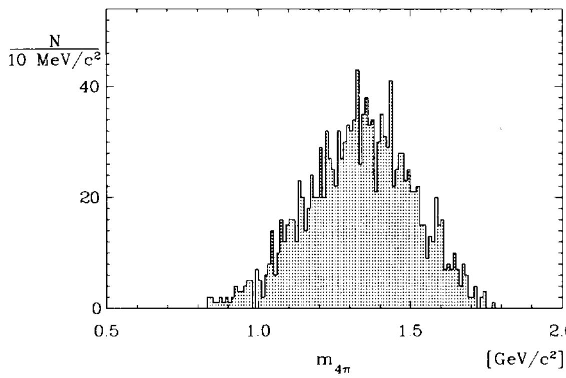

Fig. 2. Distribution of the invariant mass of the four-pion system, obtained from the final data sample.

indicated by the solid line in fig. 1, removes those events which are kinematically incompatible with $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ decays. After this cut there remain 1462 events with the $m_{4\pi}$ spectrum shown in fig. 2.

The main background in our final data sample originates from the reaction $e^+e^- \to q\bar{q} \to$ hadrons and from direct Υ decays. A Monte Carlo study [4] based on the Lund 6.2/6.3 program version [5] yields 73 ± 13 background events. Possible background from the two-photon reactions $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-\pi^0$ and $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$ was studied by Monte Carlo simulations. The estimated contribution from these processes is small and amounts to 16 ± 6 events.

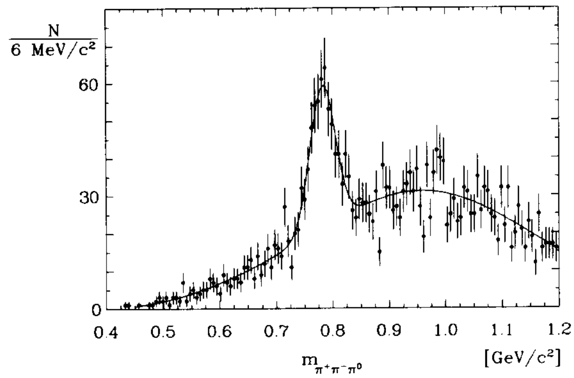

Fig. 3. Distribution of the invariant mass of the $\pi^+\pi^-\pi^0$ subsystem. The curve shows the result of the fit described in the text.

Furthermore, the applied selection criteria remove radiative Bhabha events from the data sample completely. Correcting for these background contributions, we obtain 374 ± 14 τ-pair events in our data sample.

In order to extract the fractions of events in which different subchannels occur, we first determine the number of $\tau\rightarrow\omega\pi^-\nu_\tau$ events contributing to the four-pion final state. The invariant $\pi^+\pi^-\pi^0$ mass distribution, plotted in fig. 3, shows a clear signal at the mass of the ω meson with a width compatible to our experimental mass resolution of about 20 MeV/c^2. Fitting the spectrum with a gaussian for the signal and a smooth background function and correcting for inefficiencies in the ω reconstruction results in

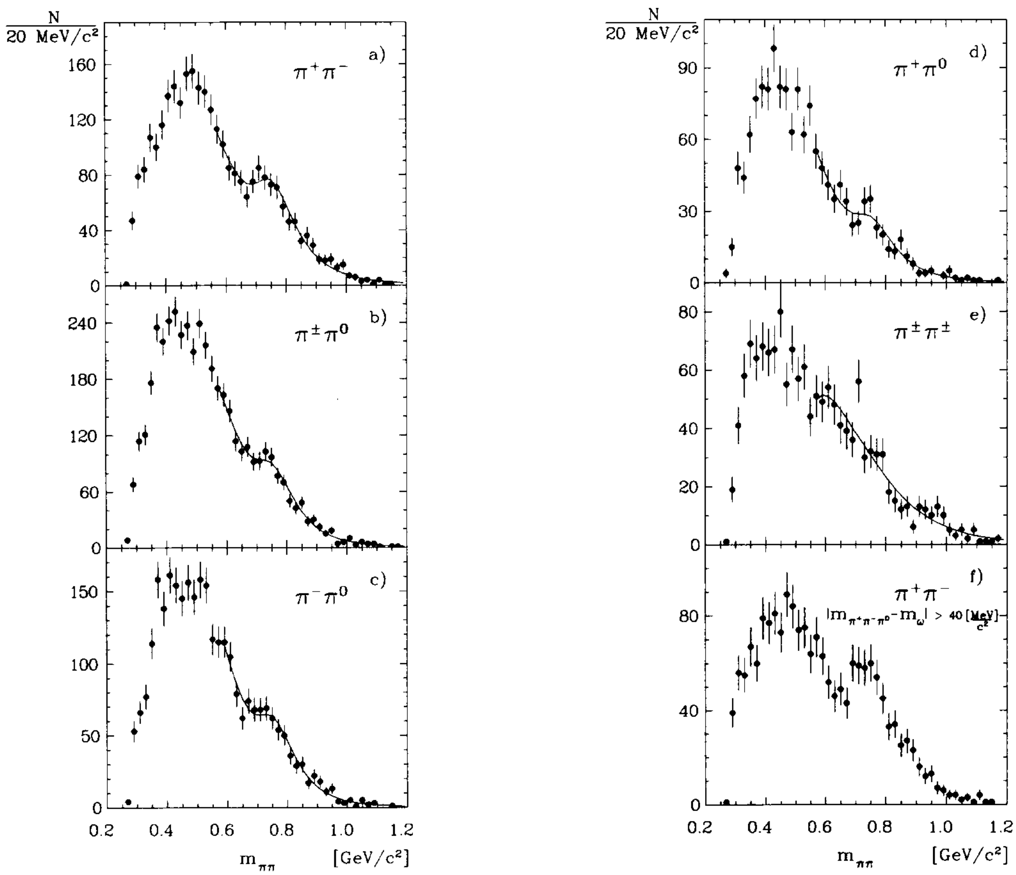

Fig. 4. Distribution of the invariant mass of the two-pion subsystem. (a) $\pi^+\pi^-$, (b) $\pi^\pm\pi^0$, (c) $\pi^-\pi^0$, (d) $\pi^+\pi^0$, (e) $\pi^\pm\pi^\pm$, (f) $\pi^+\pi^-$ with the ω-contribution removed (see text). The curves show the results of the fits described in the text.

$458 \pm 48 \pm 36$ signal events.

To study subchannels containing ρ mesons, we analyze the effective mass spectra of the two-pion subsystems formed from the four-pion final state. The measured invariant $\pi^+\pi^-$ mass spectrum of fig. 4a shows a clear enhancement at the ρ^0 mass. Also, in the invariant mass spectrum of the combinations of a charged pion, $\pi^\pm$, with a π^0, a structure at the ρ mass is observed (fig. 4b). The latter can be analyzed in terms of $\pi^-\pi^0$ and $\pi^+\pi^0$ combinations which have the same and the opposite charge as the decaying τ^- lepton. The corresponding spectra are shown in figs. 4c and 4d. In both spectra a ρ contribution is present. However, no such enhancement is observed in the invariant mass spectrum of like-sign pion pairs, $\pi^\pm\pi^\pm$, of fig. 4e.

To enhance possible ρ signals in our event sample, we remove contributions from $\tau^-\to\omega\pi^-\nu_\tau$ decays. We exclude those events where at least one of the two $\pi^-\pi^+\pi^0$ combinations forms an invariant mass compatible with the ω mass within ± 40 MeV/c^2. For the remaining events the invariant $m_{\pi^+\pi^-}$ spectrum is shown in fig. 4f and contains a prominent ρ^0 signal. The same behaviour is found for the $\pi^+\pi^0$ and $\pi^-\pi^0$ mass spectra. Only a slight increase in significance is obtained for the ρ^+ signal of the $\pi^+\pi^-$ mass spectrum, since only a few events contribute to this channel.

Since our data sample contains some background, it is possible that part of the observed ρ production is not due to τ decays. To investigate this background we analyzed events with $m_{4\pi} > 2$ GeV/c^2 selected from the data sample obtained before the cut on the mass–momentum correlation of the four-pion subsystem was applied. Assuming that the production of ρ mesons in hadronic events is independent of the $m_{4\pi}$ mass we estimate that our final event sample contains 33 ± 8 events with a ρ^0 from background processes. The number of charged ρ mesons due to the hadronic background was determined to be 19 ± 10 (ρ^-: 13 ± 8, ρ^+: 6 ± 4). No ω signal was found in the background events.

It is also possible that in a fraction of the τ decays two ρ mesons are produced. Then the number of charged and neutral ρ mesons, determined in this analysis, would be correlated. From fig. 5, where the invariant mass of the $\pi^+\pi^-$ pairs is plotted versus the invariant mass of the remaining $\pi^-\pi^0$ pair, it is obvious that there is no indication for the decay $\tau^-\to\rho^-\rho^0\nu_\tau$. Thus, we conclude that not more than one ρ meson is produced in a specific event.

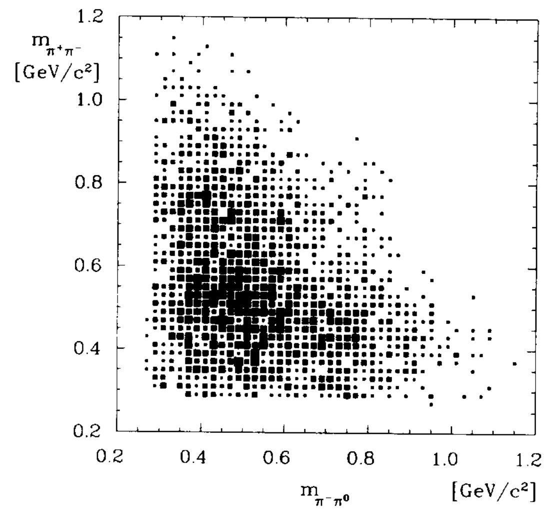

Fig. 5. Invariant mass of the $\pi^+\pi^-$ subsystem versus the mass of the remaining $\pi^-\pi^0$ subsystem (two entries per event).

For events with low $m_{4\pi}$ mass values, the available phase space for ρ meson production is restricted which leads to a distorted lineshape of the ρ signal. Since fig. 2 contains many entries at low $m_{4\pi}$ mass values, we fit the $\pi^+\pi^-$ mass spectrum with a ρ-lineshape derived from a sample of three-prong events where no photons are recorded on the three-prong side. These events are known [6] to be dominated by the decay $a_1^-\to\rho^0\pi^-$ (for more details see ref. [4]). In addition, the fit region was restricted to the interval 0.55 GeV/$c^2 \leqslant m_{\pi^+\pi^-} \leqslant 1.2$ GeV/c^2. The fit results are summarized in table 1.

From Monte Carlo studies it is known that the shape of the invariant $\pi^\pm\pi^\pm$ mass spectrum is identical to the spectrum formed by $\pi^+\pi^0$ combinations in case of absence of a ρ^+ signal. The fit to the $m_{\pi^+\pi^0}$ spectrum yields a ρ^+ signal of four standard deviations, whereas no enhancement at the ρ mass is observed in the $m_{\pi^\pm\pi^\pm}$ spectrum. We take this result as evidence for ρ^+ production in the decay $\tau^-\to\pi^-\pi^-\pi^+\pi^0\nu_\tau$.

Correcting for the specific detection efficiencies of the decay channels involved, we compute the fraction of events containing one of the resonances ρ^0, ρ^+, ρ^-, ω. These values are listed in table 2. Note that

Table 1
Results of the fits to the invariant $\pi\pi$ mass spectra. N denotes the fitted number of events, N_{corr} is the number of events after background subtraction.

	N	N_{corr}
ρ^0	426 ± 50	393 ± 51
$\rho^\pm$	494 ± 80	475 ± 80
ω	458 ± 60	458 ± 60
total		1326 ± 112
ρ^-	382 ± 65	370 ± 72
ρ^+	148 ± 37	142 ± 41
$\pi^\pm\pi^\pm$	19 ± 28	

Table 2
Fraction of resonances produced in the decay $\tau^-\to\pi^-\pi^-\pi^+\pi^0\nu_\tau$.

ρ^0	$0.30\pm0.04\pm0.02$
$\rho^\pm$	$0.33\pm0.06\pm0.01$
ρ^-	$0.26\pm0.05\pm0.01$
ρ^+	$0.10\pm0.03\pm0.004$
$\rho^0+\rho^\pm$	$0.64\pm0.07\pm0.03$
ω	$0.33\pm0.04\pm0.02$

the detection efficiencies are flat over the kinematically allowed range of $m_{4\pi}$. From the sum of the ρ and ω relative production rates we calculate a lower limit of 0.81 (95% CL) for the probability that at least one of these resonances is produced in the decay $\tau^-\to\pi^-\pi^-\pi^+\pi^0\nu_\tau$. As already mentioned, one would expect equal rates of ρ^0, ρ^-, and ρ^+, if the ρ production results from the decay $\tau^-\to a_1\pi\nu_\tau$. Since the production of ρ^+ mesons is small compared to that of ρ^- and ρ^0, the a_1 decay mode cannot contribute dominantly to the four-pion final state. Neglecting any possible interferences in the $a_1\pi$ system, we obtain an upper limit of 44% (95% CL) on the a_1 contribution to the $\pi^-\pi^-\pi^+\pi^0\nu_\tau$ final state. From table 2 one can infer that ρ meson production is enhanced by a factor of 1.9 ± 0.3 over that of ω mesons, whereas charged and neutral ρ mesons are produced with approximately equal abundancies. The fraction of $\tau^-\to\pi^-\pi^-\pi^+\pi^0\nu_\tau$ events which proceed via the decay mode $\tau^-\to\omega\pi^-\nu_\tau$ is also shown in table 2. This value is in good agreement with our previous result of 0.32 ± 0.05 [2].

Here we only give the relative fractions of the various decay channels contributing to the decay $\tau^-\to\pi^-\pi^-\pi^+\pi^0\nu_\tau$, since any branching ratio derived from this analysis depends on the one-prong branching ratios. The so-called τ decay problem [7,8], referring to the discrepancy between the measured inclusive and exclusive τ branching ratios, is not as yet solved (see refs. [9,10]).

In conclusion, we have observed for the first time ρ production in the decay $\tau^-\to\pi^-\pi^-\pi^+\pi^0\nu_\tau$. All isospin states of the ρ meson contribute to this decay channel. No evidence for the decay $\tau\to\rho^-\rho^0\nu_\tau$ has been found. In more than 81% (95% CL) of all decays $\tau^-\to\pi^-\pi^-\pi^+\pi^0\nu_\tau$ either a ρ or ω is produced. The measured abundancies of ρ^-, ρ^0, and ρ^+ indicate that the ρ production cannot emerge entirely from a possible decay $\tau^-\to a_1\pi^-\nu_\tau$.

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