SEARCH FOR EXOTIC TAU DECAYS

CRYSTAL BALL Collaboration

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The Crystal Ball detector at the Doris II storage ring at DESY was used to search for the exotic decay processes $\tau\to e\gamma$, $\tau\to e\pi^0$, and $\tau\to e\eta$. No signal was observed. We obtained the following 90% CL upper limits on the branching fractions: $B(\tau\to e\gamma)<2.0\times10^{-4}$, $B(\tau\to e\pi^0)<1.4\times10^{-4}$, $B(\tau\to e\eta)<2.4\times10^{-4}$.

For footnote see next page

1. Introduction

The standard model of electroweak and strong interactions has been very succesful phenomenologically. However, it has some theoretically unsatisfactory features which seem to point to new physics at energies beyond the range of present accelerators. One of the most unsatisfactory features is the large number of arbitrary parameters: quark and lepton masses, mixing angles, W mass, Weinberg angle, etc., none of which is predicted within the standard model.

In extensions of the standard model it can happen that some of the familiar conserved quantum numbers are no longer strictly conserved. See for instance ref. [1] and references therein for the case of the electron or muon quantum number. In particular composite and technicolor models predict flavor changing neutral currents which give rise to decays violating quark and lepton family conservation. Examples of such decays are neutrino-less tau decays such as $\tau\to e\gamma$, $\tau\to e\pi^0$, and $\tau\to e\eta$. Even without a definite model, it is still possible to estimate effects at and below the electroweak energy scale [2–7]. It is thus possible that upper limits on a branching ratio can yield information on the scale at which the new physics begins to play a significant role.

For the above-mentioned tau decays such calculations have only been carried out or suggested for the decay $\tau\to e\gamma$ [2–7]. We know of no theoretical analysis for the decays $\tau\to e\pi^0$ or $\tau\to e\eta$. Nor have these decays received much experimental attention, in spite of the fact that they are quite similar to decays like K^0, D^0, $B^0\to e\mu$, which have been extensively studied [1].

Upper limits for the decays $\tau\to e\gamma$ and $\tau\to e\pi^0$ have been previously determined by the MARK II group [8]. Because of the excellent detection properties of the Crystal Ball for the electromagnetically showering particles, we have been able to improve these limits considerably. We have also determined the first upper limit for the decay $\tau\to e\eta$.

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2. Data sample and detector

The data used for this analysis were collected at the DORIS II storage ring from 1982 to 1986 on the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ and on the continuum near these resonances. The integrated luminosity, calculated using the number of large angle Bhabha events, was found to be 260 pb^{-1}. The corresponding number of produced $\tau^+\tau^-$ events from continuum $e^+e^-\to\tau^+\tau^-$ and from $\tau^+\tau^-$ decays of the Υ states is $(265\pm9)\times10^3$.

The Crystal Ball detector has been described extensively elsewhere [9] and its properties will be only briefly summarized here. It is a non-magnetic calorimeter designed to measure precisely the energies and directions of electromagnetically showering particles. The main part of the detector consists of a spherical shell of 672 NaI(Tl) crystals covering 93% of 4π. The length of each crystal corresponds to about 16 radiation lengths and to about 1 nuclear absorption length.

For electromagnetically showering particles the energy resolution is given by $\sigma_E/E=(2.7\pm0.2)\%/(E/\mathrm{GeV})^{1/4}$. The angular resolution in θ, the polar angle of a particle with respect to the beam axis, is $\sigma_\theta=2°$–

$3°$, slightly depending on energy. An additional 5% of 4π is covered by endcaps, consisting of 40 NaI(Tl) crystals; however, these endcaps do not allow an accurate measurement of the energy and direction of a particle and are therefore only used to veto events.

Proportional tube chambers surrounding the beam pipe detect charged particles. Depending on the run period, the chambers consisted of three or four double layers of tubes. The outer layer covers about 78% of 4π solid angle. Charge division readout allows a determination of the z-position (the direction along the beam pipe).

Photons, electrons and positrons yield a rather symmetric lateral energy deposition pattern with typically 70% of the energy in one crystal and about 98% within a group of 13 contiguous crystals. Muons and charged hadronic particles which did not undergo a strong interaction deposit energy by ionization only. Minimum ionizing particles deposit typically about 200 MeV in one or two crystals; we will refer to such particles as MIPs, i.e. minimum ionizing particles. If a hadron interacts strongly while traversing the ball the deposited energy is much higher and the pattern of the hadronic shower is very irregular.

3. Analysis

We search for $\tau^+\tau^-$ events where one tau decays to a single charged particle (called the tag) plus neutrinos and the second tau decays to the channel of interest ($e\gamma$, $e\pi^0$ or $e\eta$). The search for $\tau\to e\gamma$, $\tau\to e\pi^0$, and $\tau\to e\eta$ proceeds via reconstruction of the invariant mass of the electron-neutral system. For the latter two decays the π^0 and the η are first reconstructed from their two decay photons. The method used to achieve this depends on whether the two photons have a large enough opening angle to give two well-separated clusters of energy depositions. If this is the case, the invariant mass of the neutral particle is calculated directly from the measured energy and directions of the two photons. We will refer to such neutrals as "open" neutrals. If the individual showers overlap, they form a more or less elliptical lateral energy deposition distribution in a number of contiguous crystals. Such a distribution can be distinguished from the circular distribution of a single photon. A study of the second moment of such energy deposition patterns with Monte Carlo techniques has produced an algorithm [10,11] which determines the invariant mass and the direction cosines of the parent π^0 or η. A π^0 or η identified in this fashion will be referred to as a "merged" π^0 or η. Combining both methods for the reconstruction of the invariant mass we are able to identify, albeit with an efficiency which decreases towards high energies, π^0's with energies up to about 2.5 GeV and η's with energies up to the maximum available energy.

Obviously the degree of overlap of the two photon showers depends on the invariant mass and the boost of the parent particle. Because of this we expect to find few π^0's with two well-separated photons in the decay $\tau\to e\pi^0$. We have therefore looked only for merged π^0's. However in the $\tau\to e\eta$ analysis we searched for both open and merged η's.

4. Event selection

We start by selecting events with exactly two charged particles having an opening angle larger than $90°$. A charged particle is identified by a track in the tube chambers which is correlated with an energy deposition in the calorimeter. At least one of the charged particles is required to be an electron [#1], as identified by its typical electromagnetic shower. No cuts are made on the energy deposition pattern of the other charged particle which is the tagging particle. Hence it can be an electromagnetically showering particle (electron), a minimum ionizing particle (muon or charged pion) or a particle producing some irregular pattern such as a strongly interacting hadron. A charged ρ-meson from the decay $\tau^\pm\to\rho^\pm\nu$, highly boosted such that the energy patterns of the π^0 and charged π overlap, also gives a contribution to the tag.

In addition, we require the total measured energy of the event to be between 0.8 and 1.75 times the beam energy, the lower limit to reject beam–gas events and the upper limit to reduce the QED Bhabha background. Furthermore, in the searches for a γ, a merged π^0 and a merged η, we require exactly one neutral energy deposition with a minimum energy of 250, 500 and 2500 MeV, respectively, the latter two values being energies below which the photons seldom

[#1] Throughout the paper, the term electron is used to refer to both the electron and the positron.

merge. In the search for an open η we require exactly two energy depositions each having an energy greater than 30 MeV. These cut-off energies were determined using Monte Carlo simulations. In order to ensure an accurate energy measurement, we require all the particles to be well within the main ball ($|\cos\theta|<0.85$), i.e. away from the edges near the beam-pipe holes. From the neutral energy depositions we reconstruct the π^0 and η as described above.

The next step is to select those events in which the neutral particle has a direction within 90° of the electron direction, and in which the sum of the electron and the neutral particle energies is approximately the beam energy, $0.84<(E_e+E_{\text{neutral}})/E_{\text{beam}}<1.02$.

The remaining sample of events with only one neutral energy deposition is still heavily contaminated by radiative Bhabha events. Guided by Monte Carlo studies, we were able to reduce this background by requiring (a) a minimum angle of 35° between the electron and the neutral particle; (b) a maximum energy for tagging particle of 55% of the beam energy; and (c) that the transverse energy ($E_t=E\sin\theta$) of the neutral particle be greater than 20% of the beam energy and that the transverse energy of the electron and the neutral particle satisfy the relation $E_t(\text{electron})+0.78E_t(\text{neutral})>0.6E_{\text{beam}}$.

Finally, to reject the events which had other particles besides the three particles of interest, we required less than 250 MeV energy deposited in the endcaps. For the same reason we required the total energy measured in the main ball minus the sum of the energies of the three particles of interest to be less than 6% of the energy in the main ball.

5. Results

We will first consider the case where the tagging particle can be any charged particle and where the π^0 and η are reconstructed from photons with overlapping (merged) energy depositions. Fig. 1 shows the invariant mass plots of eγ, $e\pi^0$ and eη, respectively. The superimposed gaussian curves represent fits to the signals obtained from Monte Carlo simulation for a branching ratio of 5×10^{-4}. From these simulations we derived detection efficiencies, i.e. the fraction of $\tau^+\tau^-$ events detected when one τ decays via the known modes and the other decays via the mode

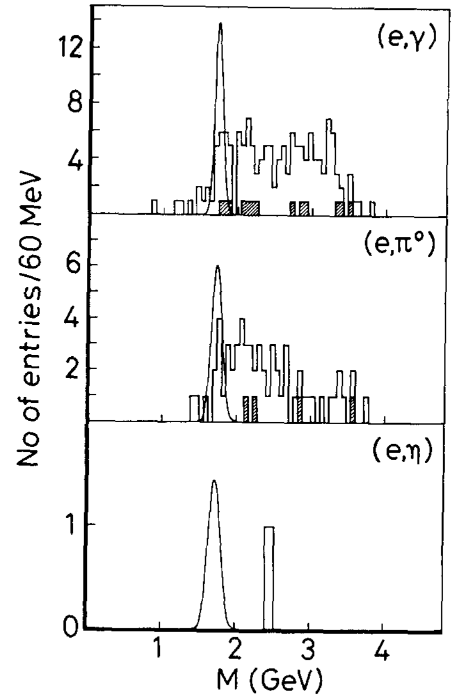

Fig. 1. Invariant mass plots of the eγ, $e\pi^0$ and eη, respectively. The histograms represent the data when the tagging particle is any charged particle; the cross-hatched area represents the events when the tagging particle is minimum ionizing. The superimposed gaussian curves represent the fits to the signals resulting from Monte Carlo simulation of $\tau\to e\gamma$, $\tau\to e\pi^0$ and $\tau\to e\eta$, respectively, for a branching ratio of 5×10^{-4}.

being searched for. Efficiencies of 12.5%, 6.7% and 0.9% were found for $\tau\to e\gamma$, $\tau\to e\pi^0$, and $\tau\to e\eta\to e\gamma\gamma$, respectively. No significant signal consistent with our resolution is observed in any of the decay channels. The $\tau\to e\eta$ plot contains only two entries, both significantly higher in mass than the expected signal.

For the decays $\tau\to e\gamma$ and $\tau\to e\pi^0$ there is a significant background, which is mainly due to radiative Bhabha events. In order to reduce the background we now examine the subsample of those events where the tagging particle is minimum ionizing, the MIP-tagged events. This results is reduced efficiencies: 6.4% and 3.1% for $\tau\to e\gamma$ and $\tau\to e\pi^0$, respectively. The resulting mass plots are shown cross-hatched in fig. 1. The background is essentially gone; in the signal region only three events survive the cuts the $\tau\to e\gamma$ analysis and none in the $\tau\to e\pi^0$ analysis.

We now turn to the case where the η is reconstructed from two well-separated photons. In order to reduce the background as much as possible we also require a MIP-tag. This results in zero events. The Monte Carlo simulation gives an efficiency of 0.9%. Since merged-η and open-η are mutually exclusive categories, the two samples may be simply combined. The result is zero events in the signal region and an efficiency of 1.8%.

The branching ratio, B, is calculated from the number of observed decays, N_0, by $B=N_0/F$, $F=\epsilon N_\tau$, where ϵ is the detection efficiency and N_τ is the number of τ leptons produced in the experiment. An uncertainty in N_τ of 3.5% arises from uncertainties in the luminosity, the cross section for $e^+e^-\to\tau^+\tau^-$ and the branching ratios of the Υ resonances to $\tau^+\tau^-$. Two sources contribute to the uncertainty in ϵ: The tracking efficiency of charged particles in the tube chambers is uncertain to 10%. Limited Monte Carlo statistics contribute uncertainties of 7.3% and 9.9% for $\tau\to e\gamma$ and $\tau\to e\pi^0$, respectively, when using "any tag"; 10.2% and 14.6% for $\tau\to e\gamma$ and $\tau\to e\pi^0$, respectively, when requiring a MIP-tag; and 15.6% for the combined $\tau\to e\eta$ analysis. For the MIP-tag samples there is an additional 10% systematic uncertainty from the Monte Carlo simulation of the calorimeter response. By comparison with the above, all other sources of error are found to be insignificant. The errors are added in quadrature to obtain the uncertainty, σ_F, on F for each decay sample.

Since no significant signals are observed, we compute upper limits on the branching ratio for each decay mode. By definition the 90% confidence level upper limit is that value of B such that the probability of observing $N>N_0$ events is 90%, i.e.

$$0.90=\sum_{N=N_0+1}^{\infty} P_B(N)=1-\sum_{N=0}^{N_0} P_B(N)\,, \qquad (1)$$

where $P_B(N)$ is the probability of observing N events for a branching ratio B. Convoluting the gaussian distribution reflecting the uncertainty on F with the poissonian distribution on the number of events in the signal region, N, gives

$$P_B(N)=\int_0^{\infty} \frac{\exp(-BF')(BF')^N}{N!}\frac{1}{\sqrt{2\pi}\,\sigma_F} \times\exp\left(\frac{-(F-F')^2}{2\sigma_F^2}\right)\mathrm{d}F'\,. \qquad (2)$$

Table 1
90% CL upper limits on the branching ratios of the specified decay channels.

Decay mode	Branching ratio upper limit	
	this experiment	MARK II [8]
$\tau\to e\gamma$	2.0×10^{-4}	6.4×10^{-4}
$\tau\to e\pi^0$	1.4×10^{-4}	$21\ \times10^{-4}$
$\tau\to e\eta$	2.4×10^{-4}	–

Eqs. (1) and (2) are easily solved by Monte Carlo techniques. The upper limits resulting from the MIP-tag eγ and $e\pi^0$ samples and the combined eη sample are shown in table 1.

If there is background, as is the case for the eγ and $e\pi^0$ decay modes when not requiring a MIP-tag, we must in addition perform a convolution with the number of background events expected in the signal region. Assuming a flat background, one arrives at the values 2.1×10^{-4} and 1.9×10^{-4} for $\tau\to e\gamma$ and $\tau\to e\pi^0$, respectively. These values are somewhat higher than those found using the MIP-tag.

6. Discussion

The decays $\tau\to e\gamma$, $\tau\to e\pi^0$, and $\tau\to e\eta$ violate lepton family number conservation, and the upper limits on their branching ratios can be used to set limits on models which predict such violations [2–7]. As an example we cite the work of Buchmüller and Wyler [7] who have considered an effective lagrangian

$$\mathscr{L}_{\mathrm{eff}}=\mathscr{L}_0+\frac{1}{\Lambda^2}\mathscr{L}_2+\dots\,,$$

where $\mathscr{L}_0$ is the standard model lagrangian and $\mathscr{L}_2$ is a low-energy approximation of the lagrangian of the new interactions. The parameter Λ gives the scale of the new interactions. Using our upper limit on the branching ratio of $\tau\to e\gamma$ we find the corresponding lower limit on Λ to be 80 TeV.

Our best values for the branching ratio upper limits are those shown in table 1. They represent an improvement over previous determinations, which are also shown for comparison. Ours is the first determination for $\tau\to e\eta$.

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