THE MICHEL PARAMETER FOR THE DECAY $\tau \to e\nu\bar{\nu}$

CRYSTAL BALL Collaboration

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The Crystal Ball detector at the Doris II storage ring at DESY has been used to study the electron energy spectrum of the decay $\tau \to e\nu\bar{\nu}$. In the standard model the Lorentz structure of the decay matrix element is of the well known V−A type, resulting in a Michel parameter of $\rho = 0.75$. Our spectrum is found to be consistent with this value. A fit yields the value of $0.64 \pm 0.06 \pm 0.07$.

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1. Introduction

Since the discovery of the τ lepton [1] in $e^+e^- \to \tau^+\tau^-$ [2], a large number of groups at various laboratories have investigated its properties [3]. All evidence available to date supports the validity of the standard model and the treatment of the τ lepton as the sequential partner of the muon and electron.

In the standard model the W-boson couples only to left-handed fermions. Consequently, the Lorentz structure of the matrix elements for the decays $\mu \to e\nu\bar{\nu}$, $\tau \to \mu\nu\bar{\nu}$ is of the well known V−A type. The Lorentz structure of the vertices of the above decays is therefore central to the standard model; a deviation from the V−A structure would severely challenge the standard model. The V−A character of the $eW\nu_e$ and $\mu W\nu_\mu$ vertices is very well established, but that of the $\tau W\nu_\tau$ vertex is much less well tested.

Leptonic charged weak interactions at low energies ($\ll M_W c^2$) can be described by a four-fermion interaction hamiltonian. In the case of the decay $\tau \to e\nu\bar{\nu}$, the general form of this hamiltonian density is [4,5]

$$\mathscr{H} = \sum_i [C_i(\bar{e}\Gamma_i\nu_e)(\bar{\nu}_\tau\Gamma^i\tau) + C_i'(\bar{e}\Gamma_i\nu_e)(\bar{\nu}_\tau\Gamma^i\gamma_5\tau) + \text{h.c.}] , \quad (1)$$

where Γ_i stands for the scalar, pseudo-scalar, vector, axial-vector and tensor operators constructed from the Dirac matrices, i.e.

$$\Gamma_S = 1, \quad \Gamma_P = i\gamma_5, \quad \Gamma_V = \gamma_\mu, \quad \Gamma_A = \gamma_\mu\gamma_5 , \quad \Gamma_T = \sigma_{\mu\nu}/\sqrt{2} , \quad (2)$$

with $\sigma_{\mu\nu} = \frac{1}{2}i[\gamma_\mu, \gamma_\nu]$. One obtains a hamiltonian with only left-handed currents by setting $C_S = C_S' = C_P = C_P' = C_T = C_T' = 0$ and $C_V = -C_V' = C_A = -C_A' = G$, where G is a constant determined by the strength of the interaction.

The hamiltonian determines the electron energy spectrum for the decay $\tau \to e\nu\bar{\nu}$. In the τ rest frame it is given by [4,5]

$$\frac{dN}{dx} = \frac{m_\tau^5 G^2}{16\pi^3} x^2[1 - x + \tfrac{2}{9}\rho(\tfrac{4}{3}x - 1)] , \quad (3)$$

where $x = 2E_e/m_\tau$ and ρ is the Michel parameter [4]. The Michel parameter is a function of the above ten couplings C_i and C_i'. With the above values for the V−A interaction, $\rho = 0.75$ [5].

A measurement yielding $\rho = 0.75$ does not prove the V−A character of the $\tau W\nu_\tau$ vertex, since this value could also result from a conspiracy of, e.g. scalar, pseudo-scalar and tensor contributions. On the other hand a deviation from 0.75 would clearly be in disagreement with the standard model. There are however, several extensions of the standard model which do predict deviations [6].

Table 1 lists the published results of measurements of the Michel parameter for the decays $\tau \to e\nu\bar{\nu}$ and $\tau \to \mu\nu\bar{\nu}$. The experimental errors are large compared to the error of such measurements for muon decay ($\rho_\mu = 0.7518 \pm 0.0026$ [10]).

Furthermore, as has been noted [6,11], the measurements from the decay to an electron all seem to lie below, while those from the decay to a muon seem to lie above the expected value.

Clearly more accurate measurements of the Michel parameter in τ decay are needed. We report here a new, more precise measurement of the Michel parameter for the decay $\tau \to e\nu\bar{\nu}$.

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Table 1
Existing measurements of the Michel parameter in τ decays. When two errors are given the first one is statistical and the second systematic. The errors given in the bottom line are the statistical and systematic errors added in quadrature. CLEO only gives a systematic error for their combined number

Reference	$\tau\to e\nu\bar{\nu}$	$\tau\to \mu\nu\bar{\nu}$	Average
DELCO [7]	$0.72\pm0.10\pm0.11$	-	$0.72\pm0.10\pm0.11$
CLEO [8]	0.60 ± 0.13	0.81 ± 0.13	$0.71\pm0.09\pm0.03$
MAC [9]	$0.62\pm0.17\pm0.14$	$0.89\pm0.14\pm0.08$	$0.79\pm0.10\pm0.10$
average	0.65 ± 0.09	0.84 ± 0.11	0.73 ± 0.07

2. Data sample and detector

The data used in this analysis were collected at the DORIS II storage ring from 1982 to 1986 on the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ resonances and in the nearby continuum. The integrated luminosity used is 216 pb^{-1}, calculated from the number of large-angle Bhabha events. 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 $(221\pm7)\times10^3$.

The Crystal Ball detector has been described in detail elsewhere [12,13] 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 sr. The length of each crystal corresponds to about 16 radiation lengths and to about 1 nuclear interaction length. An additional 5% of the solid angle is covered by endcaps, consisting of 40 NaI(Tl) crystals; these endcaps however, do not allow as accurate a measurement of the energy and direction of a particle and are only used to veto events.

For electromagnetically showering particles measurement of energy and direction is made using 13 contiguous crystals in the main detector. This procedure yields an energy resolution given by $\sigma_E/E=(2.7\pm0.2)\%/(E/\text{GeV})^{1/4}$. For such particles the angular resolution in the polar angle [#1] with respect to the beam axis is $\sigma_\theta=1°-2°$, for energies above 0.5 GeV. The better resolution is achieved as the energy increases.

Photons, electrons and positrons yield a rather symmetric lateral energy deposition pattern with typically 70% of the energy in one crystal and about 98% with 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. If an energetic hadron interacts strongly while traversing the ball, the deposited energy is in general much larger than 200 MeV and the pattern of the hadronic shower is very irregular compared to that of an electromagnetic shower.

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 sr. Charge division readout allows a determination of the z-position to $\pm1.5\%$ of the length of the tube, i.e. from ±9.8 mm for the inner layer to ±5.5 mm for the outer layer.

3. Event selection

We search for $\tau^+\tau^-$ events where one τ decays to an electron [#2] plus neutrinos and the other to a muon or a charged hadron (π or K) plus neutrino(s).

We select events having exactly two charged particles with an opening angle larger than 73°. A charged particle is identified by a track in the tube chambers

[#1] The z axis is in the direction of the e^+ beam, the origin is at the center of the overlapping beam bunches, and θ is the angle with respect to the z axis.

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

which is correlated with an energy deposition in the calorimeter. One of the charged particles is required to be an electron as identified by its typical electromagnetic shower pattern [13]. For the other charged particle we require an energy deposition and pattern consistent with that of a minimum ionizing particle. We restrict the acceptance of the electron (e) and minimum ionizing particle (mip) to $|\cos\theta_e| < 0.7$ and $|\cos\theta_{mip}| < 0.8$, respectively. This restriction reduces background from beam gas events, radiative Bhabha events and events due to the process $e^+e^- \to e^+e^-\mu^+\mu^-$ where the e^+ or e^- and one of the muons disappear in the beam pipe. It also rejects some of the $e^+e^- \to \mu^+\mu^-\gamma$ events. The latter kind of events gives a background to our sample because the detector cannot separate a muon and a nearby photon. The angle between the direction of an energetic muon and a bremsstrahlung photon, for a photon having an energy larger than 1 GeV, is practically always smaller than 2°. This is an angle our detector cannot resolve. Such a $\mu\gamma$ pair produces an electromagnetic shower having an associated track in the tube chambers and thus fakes an electron.

We allow at most two additional energy depositions, each less than 75 MeV, in the main detector ($|\cos\theta| < 0.9$). This cut rejects events with two charged and additional neutral particles, e.g. τ decays to multiple hadrons or low multiplicity hadronic events. Not allowing any small neutral energy deposition at all would reject good events which contain soft radiative photons. It would also reduce the efficiency because of the presence of low energy beam-related background.

In order to reduce contamination due to beam–gas and beam–wall events we cut on the z-position of the vertex, requiring $|z_{vertex}| < 4.3$ cm. In addition, we require the energy of the electron to be larger than $0.25 \times E_{beam}$ and to be less than $0.95 \times E_{beam}$. The upper limit serves to reject (radiative) Bhabha events. The lower limit selects against $\mu^+\mu^-\gamma$ and beam gas events and contamination due to charged pions which have interacted strongly in the NaI crystals. Such pions, originating from the decay $\tau \to \pi\nu$, can interact via $\pi^\pm + \text{nucleon} \to \pi^0 + \text{nucleon}$, resulting in two photons. When both the photons have a small angle with respect to the original charged-pion direction, the resulting shower can be symmetrical enough to pass the electron identification requirements. In addition the lower electron energy requirement ensures a well-defined trigger efficiency.

The sample selected with the above cuts still shows a large enhancement of events with an angle of nearly 180° between the electron and the minimum ionizing particle directions. This indicates the presence of a considerable background from $e^+e^- \to \mu^+\mu^-\gamma$, a contamination which is also confirmed by Monte Carlo studies. To further reduce this background, we require the cosine of the angle between the minimum ionizing particle and the electromagnetic shower to be greater than -0.98.

All the above cut values are motivated by Monte Carlo simulation studies. Events are generated for the processes of interest and for the possible sources of background. The most important event generators used are the ones for the processes $e^+e^- \to \tau^+\tau^-(\gamma) \to$ standard decay modes [14] and for $e^+e^- \to \mu^+\mu^-(\gamma)$ [15]. The former generator includes QED corrections up to $O(\alpha^3)$ and effects due to spin correlations between the τ's. The generated events are passed through a complete detector simulation including the following features: (a) Electromagnetically showering particles are simulated by the program EGS 3 [16]. (b) Hadronic interactions in the detector are simulated by an improved version of the GHEISHA 6 program [17]. (c) Extra energy deposited in the crystals by beam-related background is taken into account by adding special background events to Monte Carlo events. These background events are obtained by triggering on one in every 10^7 beam crossings, with no other condition imposed. (d) Events are reconstructed using our standard software and subjected to the same cuts as the data.

4. Corrections and background

The Michel parameter is determined by the shape of the electron energy spectrum. Corrections to the observed spectrum to be described below are calculated using the Monte Carlo simulation programs discussed above.

An important feature of the electron identification is the typical electromagnetic shower pattern [13]. The electron detection efficiency due to the various cuts on the energy deposition pattern, is slightly energy dependent. Over the full energy range from

$0.25 \times E_{beam}$ to $0.95 \times E_{beam}$ the efficiency increases from 72% to 88%. It is also necessary to take into account effects related to the energy measurement of electromagnetically showering particles in our detector, namely the NaI energy response function [13,18] and the lateral energy leakage, i.e. energy deposited outside the region of 13 contiguous crystals. Combining these two effects with the pattern cut efficiency curve results in a slowly varying correction curve increasing towards medium energies, flat however within 10%. Not applying the above corrections would increase the measured value of the Michel parameter by 5%

Further corrections to the observed spectrum are needed because of the cut on the angel between the electron and the minimum ionizing particle, and because of the angular acceptance of the electron. The first cut biases our sample to lower electron energies, because high energy decay particles tend to occur at smaller angles with respect to the τ direction. This results in angles between the two charged particles close to 180°, which are rejected. If uncorrected, this effect would reduce our value of the Michel parameter by 10%. The cut on the angular acceptance of the electron also biases our electron energy distribution. A τ produced at a small angle will be detected only if the decay angle of the electron is sufficiently large; thus lower energy electrons are preferentially detected. This effect is partially cancelled by τ's produced at angles greater than the cut angle, for which lower energy electrons are preferentially lost. However, this compensation is not perfect since the cross section is larger at smaller production angles. If uncorrected, this effect would reduce the value of the Michel parameter by another 5%. It has been checked that these corrections do not depend significantly on the ρ value assumed in the Monte Carlo generator.

QED radiative corrections have the largest influence on the spectrum. A radiated photon takes energy away from the τ or electron, thereby making the electron spectrum softer. This results in an apparent reduction of the Michel parameter. We determine a correction function using a Monte Carlo program [14] for $e^+e^- \to \tau^+\tau^-(\gamma) \to$ standard decay modes. Account is taken of the fact that $\tau^+\tau^-$ events in our data sample produced by direct Υ decays are not affected by initial state radiation. The program does not include bremsstrahlung from the final state electron which can have a significant effect on the electron spectrum [19]. In our experiment however, this effect is negligible because the angle between the photon and the electron is in general very small compared to the resolution of our calorimeter. Furthermore, the energy of the bremsstrahlung photons decreases with larger emission angles. Cuts on the energy of detected bremsstrahlung photons also influence the observed electron energy spectrum: e.g. an upper limit on the energy of such bremsstrahlung photons makes the electron spectrum slightly harder with respect to the QED uncorrected spectrum. Therefore the cut on neutral energy depositions, described in the previous section, must be taken into account in the calculation of the QED correction. Without this correction, the value of the Michel parameter would be reduced by 27%.

It should be noted that, although they were discussed separately, all corrections to the spectrum, apart from the ones related to the energy measurement and the electron identification requirements, are determined simultaneously. This procedure is adopted to take into account correlations between the corrections.

Monte Carlo simulation reveals remaining backgrounds from $\tau \to \pi\nu$, $\tau \to \rho\nu$ and $e^+e^- \to e^+e^-\mu^+\mu^-$ [20]. The background from $\tau \to \pi\nu$ and $e^+e^- \to e^+e^-\mu^+\mu^-$ have already been discussed. The decay of a charged ρ meson can fake an electron when the pion and the photons from $\rho \to \pi\pi^0 \to \pi\gamma\gamma$ overlap in the detector. The latter, however, can only happen for highly energetic ρ mesons ($E_\rho > 3$ GeV). In the selected event sample there is a contribution of about 2% from these τ decay modes and a 3% contribution due to the process $e^+e^- \to e^+e^-\mu^+\mu^-$. The influence of this background on the shape of the spectrum is marginal.

A more significant background comes from $e^+e^- \to \mu^+\mu^-\gamma$. Its contribution was determined from Monte Carlo simulation [15] to be 4%. Using this same Monte Carlo program we also made an estimate of the extra background in our sample due to the process $e^+e^- \to \mu^+\mu^-\gamma\gamma$, where one of the photons comes from the electron or positron. The total background due to these muon channels is then 5.5%. A curve fitted to the spectrum of these Monte Carlo events, subjected to the same cuts as the data, is subtracted from the data. Not subtracting this background would result in a 7% increase in the value of the Michel parameter.

The uncorrected and the fully corrected spectra are both shown in fig. 1. They contain 2753 and 2464 events, respectively.

The overall efficiency for detecting $\tau^+\tau^-$ events with one electron and one muon or charged hadron (π or K) using the cuts described above, is $(11.7\pm0.2\pm2.1)$%. The systematic error is rather large. This is due to the hard cuts on the pattern of energy deposition of the minimum ionizing particle and large uncertainties in the tube chamber efficiency. It should be noted that these uncertainties are independent of the electron energy and thus do not affect the determination of the Michel parameter. Monte Carlo simulation shows that contamination from other τ decay modes is negligible small. This detection efficiency, combined with the known branching ratios [10] for the tagging particles, the size of the analyzed $\tau^+\tau^-$ sample, and the number of events in the background corrected spectrum, yields a branching ratio for $\tau\to e\nu\bar{\nu}$ of$(16.3\pm0.3\pm3.2)$% . The errors are statistical and systematic, respectively. Our value is in good agreement with the known branching ratio [10].

5. Results

We make a χ^2 fit to the corrected spectrum with the expected distribution in the laboratory frame given, for $x\geqslant(1-\beta)/2$, by [21]

$$\frac{dN}{dx}=A_{\rm exp}\frac{2}{\beta}\left[1-\frac{4x^2}{(1+\beta)^3}(3+3\beta-4x)-\tfrac{2}{9}\rho\left(1-\frac{4x^2}{(1+\beta)^3}(9+9\beta-16x)\right)\right], \qquad (4)$$

where $x=E_e/E_{\rm beam}$, $\beta=\sqrt{1-(m_\tau/E_{\rm beam})^2}$, and the τ-neutrino mass is assumed to be zero. A non-zero value for the τ-neutrino mass of the order of the present upper limit (35 MeV at 95% confidence level [22]), does not change the spectrum significantly [21]. The constant $A_{\rm exp}$ is determined by normalizing the total number of events in the spectrum. Thus the fit has only one parameter, the Michel parameter ρ.

We first test the hypotheses of V−A, V or A, and V+A by fixing the value of ρ to 0.75, 0.375, and 0, respectively, and calculating the χ^2 of expression (4) with the corrected spectrum. The curve corresponding to a V−A interaction is shown in fig. 2. The resulting χ^2 values are given in table 2. Pure V−A is consistent with the data, with a confidence level (CL)

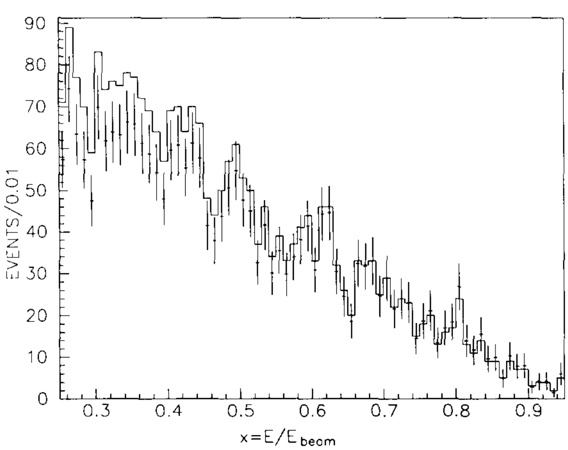

Fig. 1. The electron energy spectrum from the decay $\tau\to e\nu\bar{\nu}$. The uncorrected and corrected electron energy spectra are represented by the histogram and the crosses, respectively. The errors given are statistical only.

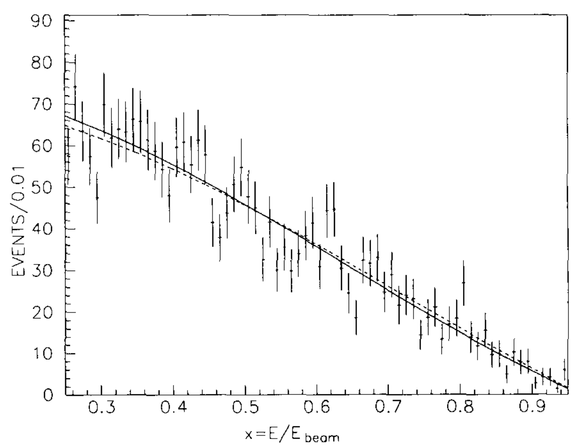

Fig. 2. The corrected electron energy spectrum from the decay $\tau\to e\nu\bar{\nu}$. The dashed line represents the expected curve with a Michel parameter of 0.75. The solid curve represents the fit to the spectrum which yielded a Michel parameter of 0.64 ± 0.06, see also table 2. The figure and fit include statistical errors only.

Table 2
Fits to the electron energy spectrum of fig. 2. The error on the Michel parameter ρ from the last fit is statistical only.

Interaction	ρ	χ^2/DOF	CL (%)
V−A	0.75	78.8/66	13
V or A	0.375	96.8/66	1
V+A	0.0	205.0/66	<0.001
free	0.64 ± 0.06	76.5/65	16

of 13%; V or A are marginally consistent, while V+A is clearly rejected. We also minimize the χ^2 with ρ as a free parameter; the result is shown in table 2 and fig. 2.

Our data were taken at beam energies varying between 4.7 GeV and 5.3 GeV. For practical reasons, in eq. (4) β is calculated using the average beam energy, i.e. the beam energy weighted with number of $\tau^+\tau^-$ pairs produced at each energy. The error introduced by this procedure is negligible. The corrections previously described are obtained from a Monte Carlo event sample with a corresponding mixture of beam energies. As an additional check the data sample has been split into subsamples taken near $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ energies respectively. Consistent results for the Michel parameter are obtained.

To check the influence of the cut on the angle between the electron candidate and the minimum ionizing particle directions, we remove this cut. After subtraction of the increased background (25%) due to $e^+e^- \to \mu^+\mu^-\gamma$, we fit the resulting spectrum. We obtain, in good agreement with the previous fit result, $\rho = 0.64 \pm 0.05$ (statistical error only) at a confidence level of 1.8%. Although this statistical error is slightly smaller then that obtained above, the systematic error is much larger, which is presumably the reason for the poorer confidence level.

In order to check the correction functions, we apply them to the spectrum from a fully simulated $e^+e^- \to \tau^+\tau^-(\gamma)$ Monte Carlo sample subjected to the same cuts as the data. A fit to this spectrum with eq. (4) yields, within statistical error, the expected value for the Michel parameter. It should be noted that all the efficiency and energy corrections are obtained from independent Monte Carlo samples.

We find the following contributions to the systematic error on the measurement of ρ: (a) 0.01 due to uncertainties in the trigger efficiency, (b) 0.03 due to uncertainties in the efficiency of the electron identification and the energy correction function needed to take into account the NaI response and the lateral energy leakage, (c) 0.03 due to uncertainties in the angle between the minimum ionizing particle and the electron directions, (d) 0.03 due to uncertainties in the QED correction, (e) 0.02 due to uncertainties in background from other τ decays and radiative Bhabha events, (f) 0.03 due to uncertainty in the $\mu\mu\gamma\gamma$ background, (g) 0.03 due to variations in the free fit results when varying the fit interval and bin size within reasonable limits. Except for the case of (g), all systematic errors have been determined using Monte Carlo simulation. Adding the above errors in quadrature gives a yields systematic error of 0.07.

6. Conclusions

The electron spectrum is consistent with a pure V−A interaction, at a confidence level of 13%. Fitting the energy spectrum with a freely varying Michel parameter yields

$$\rho = 0.64 \pm 0.06 \pm 0.07 \qquad (5)$$

(the errors are statistical and systematic respectively) at the somewhat higher confidence level of 16%. Combining this result with previous measurements of ρ from $\tau \to e\nu\bar{\nu}$ (see table 1), we obtain a weighted average value of $\rho = 0.64 \pm 0.06$, where the error has been obtained by adding in quadrature the statistical and systematic errors (where available). This value is about two standard deviations away from the V−A value of 0.75. If the measurements from $\tau \to \mu\nu\bar{\nu}$ are also included, a value of $\rho = 0.70 \pm 0.05$ is obtained in a good agreement with the V−A value. It is curious, that the four values from $\tau \to e\nu\bar{\nu}$ all lie below the V−A value while the two values from $\tau \to \mu\nu\bar{\nu}$ both lie above 0.75. However, with a 1.6% probability of occurrence this can only be regarded as a coincidence.

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