Z. Phys. C – Particles and Fields 33, 7–12 (1986)

Zeitschrift für Physik C Particles and Fields

Measurement of Tau Decays into Three Charged Pions

ARGUS Collaboration

H. Albrecht, U. Binder, P. Böckmann, R. Gläser, G. Harder, I. Lembke-Koppitz, A. Philipp, W. Schmidt-Parzefall, H. Schröder, H.D. Schulz, R. Wurth, A. Yagil [1]
DESY, D-2000 Hamburg, Federal Republic of Germany

J.P. Donker, A. Drescher, D. Kamp, U. Matthiesen, H. Scheck, B. Spaan, J. Spengler, D. Wegener
Institut für Physik, Universität, D-4600 Dortmund [2], Federal Republic of Germany

J.C. Gabriel, K.R. Schubert, J. Stiewe, K. Strahl, R. Waldi, S. Weseler
Institut für Hochenergiephysik, Universität, D-6900 Heidelberg [2], Federal Republic of Germany

K.W. Edwards [3], W.R. Frisken [4], C. Fukunaga [5], D.J. Gilkinson [6], D.M. Gingrich [6], M. Goddard [3], H. Kapitza [3], P.C.H. Kim [6], R. Kutschke [6], D.B. MacFarlane [6], J.A. McKenna [6], K.W. McLean [7], A.W. Nilsson [7], R.S. Orr [6], P. Padley [6], P.M. Patel [7], J.D. Prentice [6], H.C.J. Seywerd [6], T.-S. Yoon [6], J.C. Yun [3]
Institute of Particle Physics [8], Canada

R. Ammar, D. Coppage, R. Davis, S. Kanekal, N. Kwak
University of Kansas [9], Lawrence, KS 66044, USA

G. Kernel, M. Pleško
J. Stefan Institute and Department of Physics, University, YU-61000 Ljubljana [10], Yugoslavia

K. Jönsson
Institute of Physics, University, S-22362 Lund [11], Sweden

A. Babaev, M. Danilov, A. Golutvin, I. Gorelov, V. Lubimov, V. Matveev, V. Nagovitsin, V. Ryltsov, A. Semenov, V. Shevchenko, V. Soloshenko, V. Tchistilin, I. Tichomirov, Yu. Zaitsev
Institute of Theoretical and Experimental Physics, SU-117259 Moscow, USSR

R. Childers, C.W. Darden, Y. Oku
University of South Carolina [12], Columbia, SC 29208 USA

H. Gennow
University of Stockholm, S-11346 Stockholm, Sweden

Received 30 June 1986

[1] Weizmann Institute of Science, Rehovot, Israel
[2] Supported by the Bundesministerium für Forschung und Technologie, FRG
[3] Carleton University, Ottawa, Canada
[4] York University, Downsview, Canada
[5] Now at the University of Tokyo, Tokyo, Japan
[6] University of Toronto, Toronto, Canada
[7] McGill University, Montreal, Canada
[8] Supported by the Natural Sciences and Engineering Research Council, Canada
[9] Supported by the U.S. National Science Foundation, USA
[10] Supported in part by the Internationales Büro KfA, Jülich and DESY, Hamburg, FRG
[11] Supported by the Swedish Research Council, Sweden
[12] Supported by the U.S. Department of Energy, under contract DE-AS09-80ER10690, USA

Abstract. We report a study of the decay $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ using the ARGUS detector at the DORIS II storage ring. Tau pairs were produced by e^+e^- annihilation at centre-of-mass energies near 10 GeV. We have observed about 1,700 events, corresponding to a branching ratio for $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ of $(5.6 \pm 0.7)\%$. The dominant mode for this decay is observed to be $\rho^0 \pi^-$ in a $J^P = 1^+$ spin state. The $\rho^0 \pi^-$ mass spectrum shows a broad enhancement near $1.10\,\mathrm{GeV/c^2}$, which has the properties expected for the A_1.

1. Introduction

The study of the decay $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$* is of special interest for several reasons. First, the weak axial-vector hadronic current can be investigated under very clean conditions and, in particular, the axial-vector spectral function $\rho_t(q^2)$ extracted. Second, isospin relates this channel to the decay $\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$, which is expected to represent a significant part of the one-prong decay rate of the tau, but which is not yet well measured. In view of the apparent discrepancy between the measured inclusive one-prong branching ratio of the tau and the sum of measured exclusive one-prong decays [1], improved measurements of the $3\pi\nu_\tau$ decay mode may lead to better understanding. In this paper, we present the results of an analysis of the decay $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ at centre-of-mass energies ranging from 9.4 to 10.6 GeV. The data were obtained using the ARGUS detector at the electron-positron storage ring DORIS II at DESY. The event sample corresponds to an integrated luminosity of about $80\,\mathrm{pb}^{-1}$. Part of this data has already been used to set a limit on the tau neutrino mass [2].

2. Apparatus and Event Selection

ARGUS is a solenoidal magnetic spectrometer consisting of a cylindrical drift chamber with 5,940 sense wires arranged in 36 layers [3], a time-of-flight (TOF) system with 64 scintillators in the barrel region and with 48 scintillators in each endcap [4], a shower detection system with 1,280 lead-scintillator sandwich counters in the barrel region and 240 in each endcap [5], and a muon identification system with 1,744 proportional counter tubes [6]. The drift chamber provides, in addition to position measurements, a 5% RMS determination of the mean dE/dx loss for traversing charged particles. From this information, in combination with TOF, a likelihood ratio [7] is constructed, which describes the relative probability for each of the possible particle assignments. If the reconstruction procedure requires a specific particle type, then all tracks for which this probability exceeds 5% are considered acceptable candidates. The well-segmented shower counters, located inside the magnet coil, provide good separation and energy resolution over more than 96% of 4π for photons of energy as low as 50 MeV. Further details of the detector performance and trigger conditions are given in [3–8].

Tau pairs were studied in the 1–3 prong decay topology resulting from the reaction:

$$e^+e^- \to \tau^+\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$$
$$\hookrightarrow e^+\nu_e\bar{\nu}_\tau,\ \mu^+\nu_\mu\bar{\nu}_\tau,\ \pi^+\bar{\nu}_\tau,\ K^+\bar{\nu}_\tau \text{ or } \rho^+\bar{\nu}_\tau.$$

The selection criteria used were as follows:

- exactly four charged particles with a total charge of zero originating from the interaction point
- the scalar momentum sum $\sum_1^4 |p_i| \geqq 2.7\,\mathrm{GeV/c}$, in order to suppress beam-gas and 2-photon backgrounds
- the scalar momentum sum $\sum_1^4 |p_i| \leqq 0.92\sqrt{s}$, thereby suppressing events from exclusive resonance decays, such as $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to l^+l^-$
- a hemisphere cut, requiring opening angles of more than 90° between particle 1 from the one-prong tau decay and particles $i = 2, 3, 4$ from the three-prong decay, and less than 90° between each pair of particles on the three-prong side
- a requirement that the polar angle of the one-prong tau decay satisfy the condition $|\cos\theta_1| \leqq 0.75$, ensuring good momentum resolution and trigger conditions
- either no photons with $E_\gamma \geqq 50$ MeV in the shower counters, for an efficient suppression of the $\pi^-\pi^+\pi^-\pi^0\nu_\tau$ mode, or exactly one reconstructed π^0, which in combination with the single prong forms a ρ^+ candidate with mass between 0.57 and 1.07 GeV/c^2, momentum larger than 0.9 GeV/c and an opening angle between the π^+ and π^0 of less than 90°
- opening angles of more than 7.25° between opposite-charge particles on the three-prong side, to reject radiative Bhabha and $\mu\mu\gamma$ events with a converted photon
- the energy deposited in the electromagnetic calorimeter by particle 1 as well as the sum of that deposited by particles 2 to 4 should be less than 4 GeV, to provide further suppression of radiative Bhabha events

* References in this paper to a specific charged state are to be interpreted as also implying the charge conjugate state

● agreement with the pion hypothesis from time-of-flight and dE/dx measurements for all three particles $i=2, 3, 4$ and with either the electron, muon, pion or kaon hypothesis for particle 1.

A total of 1,725 events passed these selection criteria. In determining the branching ratio for $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$, we have excluded the ρ^+-channel from the one-prong tau decays and have used only a subsample of 683 events collected on the $\Upsilon(2S)$ resonance at $\sqrt{s}=10.023$ GeV. This data subset corresponds to an integrated luminosity of $(38.8 \pm 1.2)\,\mathrm{pb}^{-1}$, and was collected under stable trigger conditions. Due to noise in the shower counters, the requirement that there be no photons in the event removes contamination from $\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ decays, but also rejects some events in the signal channel, $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$. On the $\Upsilon(2S)$, the fraction of signal events lost can be determined experimentally.

Figure 1 shows the azimuthal angular distribution of the single particle on the one-prong side for these 683 events. The DORIS II beams are strongly polarized at the $\Upsilon(2S)$, therefore $\mu\mu$ and $\tau\tau$ events show a pronounced modulation with $\cos 2\phi$. The amplitude of this modulation is apparently reduced for taus (solid curve) in comparison with muons (dashed curve) [9], since the taus are not directly observed, and the final state cannot be completely reconstructed due to the missing neutrino.

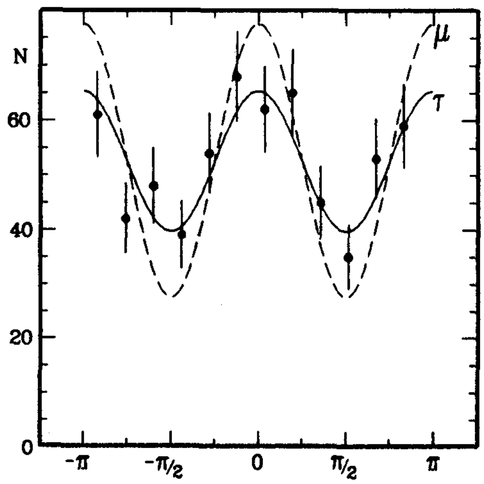

Fig. 1. Azimuthal angular distribution of the single track on the one-prong side for tau decays on the $\Upsilon(2S)$. The solid curve is a fit to the data with $A+B\cos 2\phi$, where A and B are free parameters. The dashed line corresponds to muon pair events on the $\Upsilon(2S)$ [8]

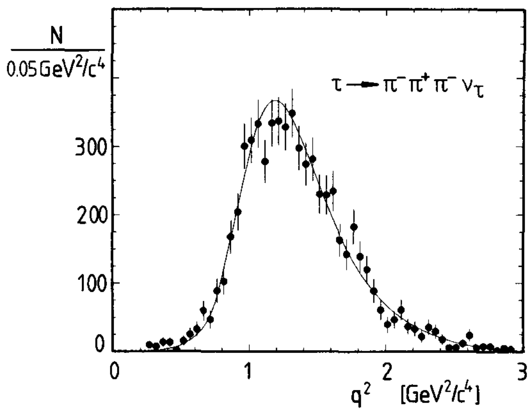

Fig. 2. Acceptance-corrected distribution of the momentum transfer squared, q^2, for the decay $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$. The solid curve is the best fit using a model in [12]

3. Acceptance and Background Calculations

The acceptance for $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ was determined by a Monte Carlo simulation of the detector [10]:

$$\eta = \eta_{\text{selection}} \times \eta_{\text{trigger}} \times \eta_\gamma$$

where $\eta_{\text{selection}}$ is the efficiency for event reconstruction and selection criteria, η_{trigger} is the trigger efficiency and η_γ describes the losses from the requirement of no photons due to noise in the shower counters. The Monte Carlo event generator included the effects of initial-state QED radiation and used previously reported measurements of the branching ratios for one-prong tau decays [11]. Distributions on the three-prong side were described using the form in [12], fitted to the observed distribution as described below. The generated 3π mass distribution, shown by the solid line in Fig. 2, gives a good description of the experimental data. As a result of this Monte Carlo calculation, we found $\eta_{\text{selection}}=0.422 \pm 0.022$ and $\eta_{\text{trigger}}=0.910 \pm 0.036$. A scan of exclusive leptonic decays of $\Upsilon(2S) \to \Upsilon(1S)\pi^-\pi^+$, $\Upsilon(1S) \to l^+ l^-$ was used to determine that $\eta_\gamma = 0.725 \pm 0.055$. Thus, the total acceptance was found to be $\eta = 0.278 \pm 0.028$.

A Monte Carlo simulation was also used to estimate the contamination in the sample from other tau decay channels. The 683 events are estimated to contain a total of 90 ± 25 background events. The most important contributions are 56 ± 9 events from decays of $\tau^+ \to \rho^+ \bar{\nu}_\tau$ on the one-prong side and $\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ on the three-prong side where in both cases the π^0 was not found in the detector, and 22^{+23}_{-17} events from decays $\tau \to KK\pi\nu_\tau$ and $\tau \to K\pi\pi\nu_\tau$, where the kaons were misidentified [13]. The number of events from the decay channel $\tau^- \to K^{*-}\nu_\tau$ was found to be 5 ± 2 from the data itself. The background from radiative Bhabha and $\mu\mu\gamma$ events and from two-photon processes was found to be negligible. By extrapolation from the number of events with a three pion mass above m_τ, assuming a background level constant with $m_{3\pi}$, the number of multihadron events in the sample was estimated to be 7 ± 3.

4. Results

4.1. Branching Ratio

Combining the measured number of events above background (593 ± 36) with the luminosity, detection efficiency (η), and theoretical cross section, including the effects of initial-state radiative corrections and the contribution from $\Upsilon(2S) \to \tau^+\tau^-$ decay [14], and using the recently measured branching ratios for one-prong tau decays [11], we find that $Br(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau) = (5.6 \pm 0.7)\%$, where statistical and systematic errors have been added in quadrature.

Our result is in a good agreement with the recently published measurement of $(5 \pm 1)\%$ for $Br(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau)$ from DELCO [15] and with the older measurement of $(5.4 \pm 1.7)\%$ for $Br(\tau^- \to \rho^0\pi^-\nu_\tau)$ from PLUTO [16]. However, it is somewhat smaller than the result from the MAC collaboration [17], who determined the fraction of all three-prong τ decays unaccompanied by π^0's (For a direct comparison, this result has to be adjusted downward by about 0.7% [11] for the contribution from τ decays with kaons).

4.2. 3π Final State Analysis

The 3π system in tau decay is produced through the axial-vector current and may have $J^P = 0^-$ or 1^+. There are some theoretical arguments [18] which suggest that this decay is dominated by the A_1 ($J^P = 1^+$):

$$\tau^- \to A_1^- \nu_\tau$$
$$\quad \hookrightarrow \rho^0 \pi^-$$
$$\qquad \hookrightarrow \pi^- \pi^+.$$

The dominance of the $\rho^0\pi$ mode can be established from a study of the two pion invariant mass distribution. The distribution of $\pi^+\pi^-$ and $\pi^\mp\pi^\mp$ masses are shown in Fig. 3. Assuming that the shape of the non-resonant $\pi^+\pi^-$ distribution is the same as that for $\pi^\mp\pi^\mp$, we estimate that the non-$\rho^0\pi^-$ resonance contribution to the $(3\pi)^\pm$ final state is less than 10% at the 95% CL. The ρ^0 signal is perfectly described by a relativistic p-wave Breit-Wigner, using the current average values for the mass and width [19].

As a check of the A_1 hypothesis, we have used a simple model [20] which assumes that the weak

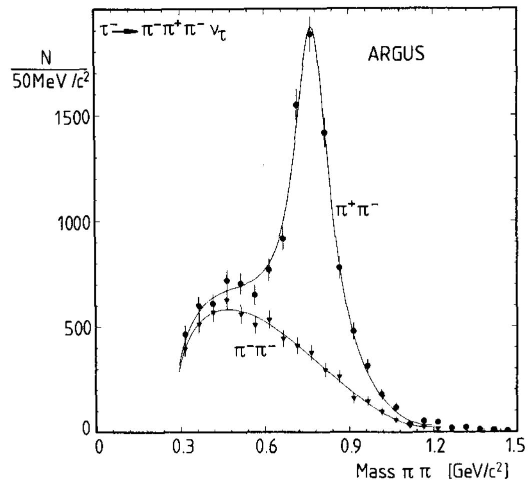

Fig. 3. Acceptance-corrected distribution of the $\pi^+\pi^-$ invariant mass from the decay $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ (2 entries per event). The corresponding distribution for $\pi^-\pi^-$ combinations is shown by the triangles. The solid line is the result of a fit to the $\pi^+\pi^-$ distribution using a relativistic p-wave Breit.Wigner multiplied by a polynomial with coefficients determined from a fit to the $\pi^-\pi^-$ distribution

axial-vector current couples to only one 3π resonance and that this resonance decays only into $\rho^0\pi^-$. Under these two assumptions, we are able to determine the spin, parity, mass and width of the resonance. We consider three possible $\rho^0\pi^-$ waves: s-wave ($J^P = 1^+$), p-wave ($J^P = 0^-$) and d-wave ($J^P = 1^+$). In Figs. 4a–c are shown the Dalitz plot densities for three intervals of 3π mass, where $s_1 = (p_{\pi^+} + p_{\pi_2^-})^2 = m^2_{\pi^+\pi_2^-}$ and $s_2 = (p_{\pi^+} + p_{\pi_1^-})^2 = m^2_{\pi^+\pi_1^-}$. In Figs. 4d, e and f are shown the projections of these densities in the ρ^0-bands with $0.5\ \mathrm{GeV}^2/c^4 \leqq s_{1,2} \leqq 0.7\ \mathrm{GeV}^2/c^4$, together with the expectations for the three waves. The result of a combined fit to these projections of the data is given in Table 1. We conclude that the 1^+ s-wave is strongly favoured, consistent with the A_1 assignment. The mass and width have been determined by a fit [12, 21] to the observed mass distribution shown as a solid line in Fig. 2. Assuming that the s-wave is the only contributing wave, we obtain a mass of $(1{,}046 \pm 11)\ \mathrm{MeV/c^2}$ and a width $\Gamma = (521 \pm 27)\ \mathrm{MeV/c^2}$. In addition to the mass spectrum $dN/dM_{3\pi}$, we show in Fig. 5 the spectral density $\rho_t(q^2)$, defined by [22]:

$$\frac{d\Gamma_{3\pi\nu}(q^2)}{dq^2} = \frac{G_F^2 \cos^2\Theta_c}{16\pi m_\tau^3} \cdot (m_\tau^2 - q^2)^2 \{(m_\tau^2 + 2q^2)\,\rho_t(q^2) + m_\tau^2\,\rho_l(q^2)\}$$

where ρ_t and ρ_l are the transverse and longitudinal components of the spectral density and $q^2 = m_{3\pi}^2$. The contrtibution of $\rho_l(q^2)$, which is of order m_π^2/q^2 under

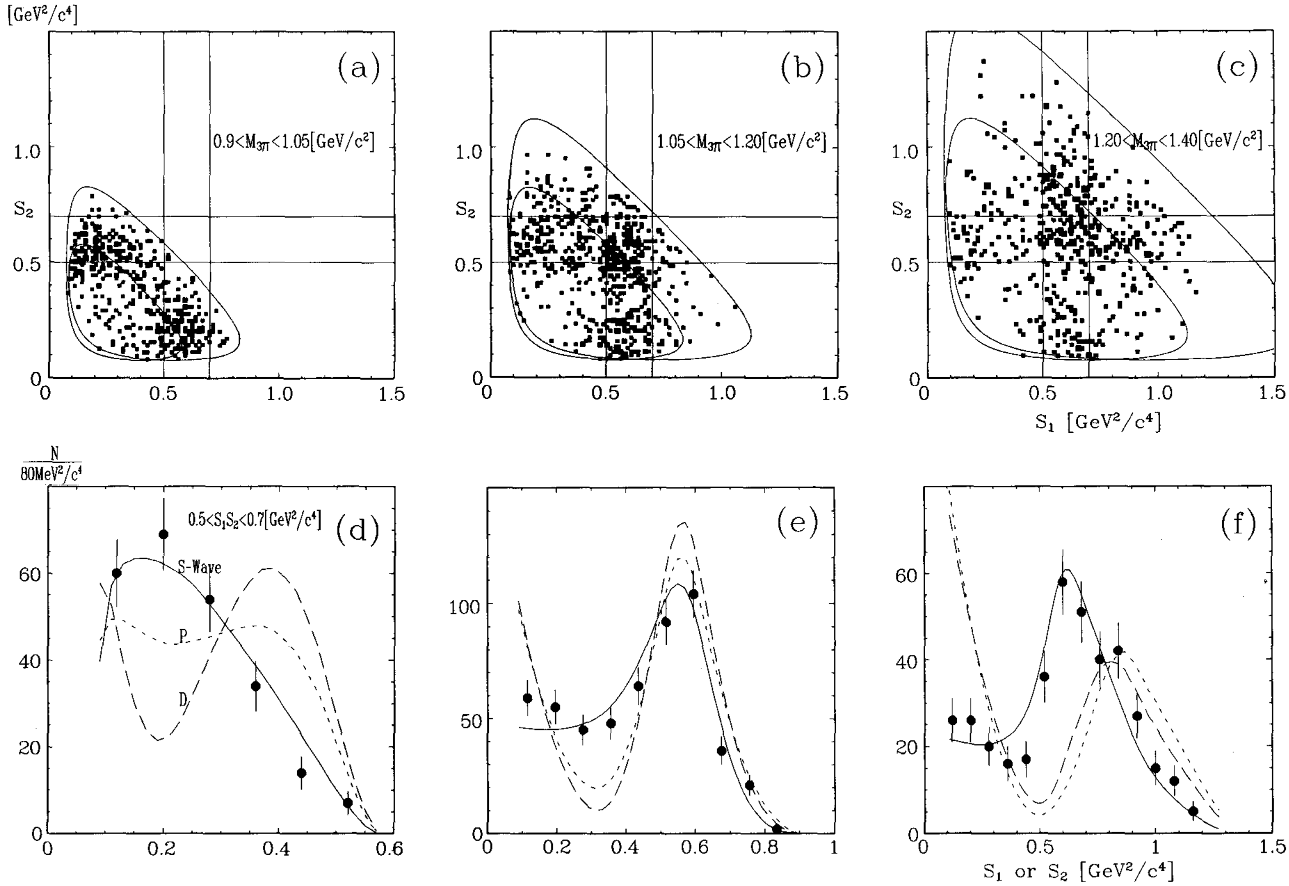

Fig. 4a–f. Dalitz plot densities for three intervals of the 3π mass from the decay $\tau^-\to\pi^-\pi^+\pi^-\nu_\tau$: **a** $0.9\leqq M_{3\pi}\leqq 1.05$ GeV/c², **b** $1.05\leqq M_{3\pi}\leqq 1.20$ GeV/c² and **c** $1.20\leqq M_{3\pi}\leqq 1.40$ GeV/c². The corresponding projections of these densities in the ρ^0-bands with $0.5\leqq s_{1,2}\leqq 0.7$ GeV²/c⁴ are shown in **d**, **e** and **f**, together with the expectations for *s*-wave (solid line), *p*-wave (dotted line) and *d*-wave (dashed line)

Table 1. Result of a fit of projected Dalitz plot densities with different spin assumptions

J^P	l	χ^2/DF
0^-	1	460/27
1^+	0	35/27
1^+	2	406/27

the assumption of PCAC, has been neglected. The solid curve in Fig. 5 is the result of the one-resonance fit transformed into the spectral density representation.

The fitted values for the mass and width are in disagreement with the results of π^-p experiments [23], but the mass value is consistent with a measurement from a K^-p experiment [24]. The A_1 parameters are also in a good agreement with those determined by DELCO [15]. Both e^+e^- experiments find a larger width in comparison with all of the hadronic experiments. This may indicate that there are small contributions from higher mass 0^- and 1^+ resonances in the $\tau\to 3\pi\nu_\tau$ data. A determination of the level of such contributions would require greater statistics and a complete partial wave analysis.

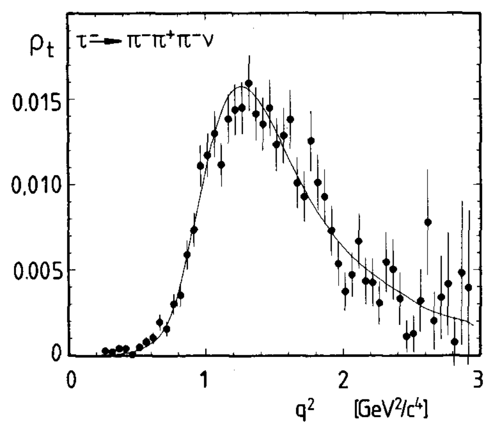

Fig. 5. Distribution of the axial-vector spectral density $\rho_t(q^2)$ determined for the decay $\tau^-\to\pi^-\pi^+\pi^-\nu_\tau$, under the assumption that $\rho_l(q^2)=0$ [22]. The solid curve shows the best fit to the q^2 distribution transformed into the spectral density representation

5. Conclusion

In conclusion, we have determined the branching ratio for $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ to be $(5.6 \pm 0.7)\%$, where statistical and systematic errors have been added in quadrature. This value is in good agreement with prevous measurements and thus the discrepancy between inclusive and exclusive branching ratios for one-prong tau decays remains. The 3π final state is dominated by the $\rho^0 \pi^-$ mode in an s-wave with $J^P = 1^+$, and can be well described by a single resonance of mass $(1,046 \pm 11)$ MeV/c^2 and width $\Gamma = (521 \pm 27)$ MeV/C^2, based on the form of the mass distribution suggested by Kühn and Wagner [12]. Considerable systematic uncertainty in the mass and width values exists due to dependence on the parametrization of the mass distribution. This in fact is probably the origin of the discrepancy with results from hadronic experiments for the mass and width. The observation of $\rho\pi$ dominance and the spin-parity analysis are however consistent with the A_1 assignment to this resonance seen in $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ decays.

Acknowledgements. It is a pleasure to thank E. Michel, W. Reinsch, Dr. K. Rauschnabel, Mrs. U. Djuanda and Mrs. E. Konrad for their competent technical help in running the experiment and processing the data. We thank Dr. H. Nesemann, B. Sarau and the DORIS group for the good operation of the storage ring. The visiting groups wish to thank the DESY directorate for the support and kind hospitality extended to them.

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21. Explicitly, the following expression was used for the $\pi^- \pi^+ \pi^-$ hadronic current:
$$J_\mu = G(q^2)\left[\left(q_{1\mu} - q_{+\mu} - \frac{q(q_1 - q_+)}{q^2} q_\mu\right) B(s_2) + 1 \leftrightarrow 2\right]$$
where:
$$s_{1,2} = (q_{2,1} + q_+)^2,$$
$$B(s_i) = [s_i - m_\rho^2 + i m_\rho \Gamma_\rho]^{-1}$$
and $G(q^2)$ was taken as a Breit-Wigner folded with fixed width with the detector resolution
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Note added in proof. If a width varying with m_A, is used for the fit to Fig. 2 the mass obtained will shift upward by 150–200 MeV/c^2, in reasonable agreement with the result from the hadron scattering, where a variable width is also used.
We wish to thank M. Bowler for bringing this point to our attention.