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TWO CURRENT EXPERIMENTAL PROBLEMS IN HEAVY LEPTON PHYSICS: τ DECAY MODES AND CLOSE MASS PAIRS*

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1. INTRODUCTION

Most of this talk, presented at the 1987 Topical Seminar on Heavy Flavors, is devoted to the problem of understanding present measurements of the decay modes of the tau lepton. This occupies Sections 2-9. In Section 10 I review the present negative results of searches for close-mass lepton pairs.

2. THE τ DECAY MODES PROBLEM

There is a problem in understanding the decay modes of the τ which is best explained by starting with the data in Tables 1a and 1b. These tables respectively summarized branching fraction measurement of 1-charged-particle decay modes such as

$$\begin{aligned} \tau^- &\rightarrow e^- + \bar{\nu}_e + \nu_\tau \\ \tau^- &\rightarrow \pi^- + \nu_\tau \\ \tau^- &\rightarrow K^- + \nu_\tau \\ \tau^- &\rightarrow \pi^- + \pi^0 + \pi^0 + \nu_\tau \end{aligned} \tag{2.1}$$

and of 3-charged-particle decay modes such as

$$\begin{aligned} \tau^- &\rightarrow \pi^- + \pi^+ + \pi^- + \nu_\tau \\ \tau^- &\rightarrow \pi^- + \pi^+ + \pi^- + \pi^0 + \nu_\tau \\ \tau^- &\rightarrow K^- + \pi^+ + \pi^- + \nu_\tau \quad . \end{aligned} \tag{2.2}$$

The meaning of the term formal average will be discussed in connection with Table 2. In addition to measurements of the branching fractions for single modes, exclusive measurements, there are the inclusive measurements: the B_1 branching fraction summing over all 1-charged-particle modes and the B_3 branching fraction summing over all 3-charged-particle modes.

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Table 1a. Summary of measured branching fractions for modes with 1-charged-particle in percent. Values are from Tables 2, 3, 4, 5 and 9 of this paper, Refs. 4 and 5.

Type of Measurement	Row	Decay Mode	Branching Fraction (%)	Reference
Exclusive Measurements of Modes with 0 or 1 π^0	A	$e^-\bar{\nu}_e\nu_\tau$	17.7 ± 0.4	Table 3
	B	$\mu^-\bar{\nu}_\mu\nu_\tau$	17.6 ± 0.4	Table 3
	C	$\pi^-\nu_\tau$	10.9 ± 0.6	Table 4
	D	$\rho^-\nu_\tau$	22.7 ± 1.0	Table 5
	E	$K^-\nu_\tau$	0.7 ± 0.2	Ref. 4
	F	$K^{*-}\nu_\tau$	1.4 ± 0.1	Ref. 4
Sum of rows A-F Called $B_{1\,e\mu\pi\rho K}$	G		71.0 ± 1.3	
Exclusive Measurements of Modes with > 1 π^0 or with η's Called $B_{1\,\mathrm{mult\,neut}}$	H	$\pi^- n\pi^0\nu_\tau,\ n > 1$ $\pi^- n\eta\nu_\tau,\ n > 0$ $\pi^- m\pi^0 n\eta\nu_\tau,\ m+n > 1$ $K^- n\pi^0\nu_\tau,\ n > 1$ $\vdots \quad \vdots$	8. to 16.	Table 10 and Section 4
Sum of rows G-H	I		79. to 87.	
Inclusive Measurement B_1	J	All modes with 1-charged-particles	86.5 ± 0.03	Table 2

Table 1b. Summary of measured branching fractions for modes with 3 or 5-charged-particles in percent. Values are from Tables 6 or 7 of this paper or Ref. 4.

Type of Measurement	Row	Decay Mode	Branching Fraction (%)	Reference
Exclusive Measurement	K	$\pi^-\pi^+\pi^-\nu_\tau$	6.6 ± 0.4	Ref. 4
	L	$\pi^-\pi^+\pi^- n\pi^0\nu_\tau,\ n \geq 1$	5.0 ± 0.5	Ref. 4
	M	3-charged-particles with at least 1 $K^\pm$	0.4 ± 0.2	Ref. 5
Sum of rows K-M	N		12.0 ± 0.7	
Inclusive Measurement B_3	O	All modes with 3-charged-particles	13.4 ± 0.3	Table 2
Inclusive Measurement B_5	P	All modes with 5-charged-particles	0.11 ± 0.03	Ref. 5

The problem, first discussed by Gilman[1,2] and others[3] is that we do not understand quantitatively how the exclusive 1-charge-particle branching fraction *as measured* sum to B_1. Denoting the branching fraction for the i^{th} 1-charged-particle mode by B_{1i}, the definition of B_1 is

$$B_1 = \sum_i B_{1i} \quad . \tag{2.3}$$

However B_1 and the various B_{1i}'s are mostly measured by different methods and often in different experiments. Therefore the quantitative realization of Eq. (2.3) is not obvious.

As shown in Table 1a the B_{1i} measurements fall into two classes. One class, the decay modes in rows A-F, have either 0 or 1 π^0, no other neutral mesons, and hence have 0 or 2γ's in the final state. They are easy to distinguish and the B_{1i}'s are well measured. Their sum in row G is called $B_{1\,e\mu\pi\rho K}$. The other class, lumped together in row H, consists of modes such as

$$\tau^- \rightarrow \pi^- + n\pi^0 + \nu_\tau \ , \quad n > 1 \tag{2.4a}$$

$$\tau^- \rightarrow \pi^- + n\eta + \nu_\tau \ , \quad n > 0 \tag{2.4b}$$

$$\tau^- \rightarrow \pi^- + m\pi^0 + n\eta + \nu_\tau \ , \quad m + n > 1 \quad , \tag{2.4c}$$

or other modes which can lead to more than 2γ's in the final state. For brevity I call these *multiple neutral meson* modes with total branching fraction $B_{1\,\text{mult neut}}$, although the class includes the mode in Eq. (2.4b) with one y. This class would include unknown neutral mesons which decay to two or more γ's.

From Table 1a there are three possible ways in which $B_1 = \sum_i B_{1i}$ can be satisfied, and these possibilities are not mutually exclusive.

Possibility I: The obvious possibility is to take $B_{1\,\text{mult neut}} \approx 15\%$ in row H. As discussed in Section 4, the measurement of $B_{1\,\text{mult neut}}$ are poor and at first sight would appear to allow this value. But deeper examination of the measurement complicate this assumption, and the imposition of conventional theory argues strongly, Section 5, against such a large value. $B_{1\,\text{mult neut}} \approx 10\%$ seems more likely. If the latter is true, then two other possibilities must be considered.

Possibility II: The partial sum $B_{1\,e\mu\pi\rho K}$ in row G of Table 1a is larger by three or four times the given error because one or more of the branching fraction in rows A-D are larger than given in the table.

Possibility III: B_1 is smaller than the value in Table 1a, row J.

Although the use of conventional theory sharpens the puzzle my approach in studying this problem and in this talk is to first proceed experimentally as far as possible. In the next section I consider Possibilities II and III by reviewing the branching fraction measurements used in Table 1a.

Before moving on, I comment on B_3 in Table 1b. There is no problem here, the sum of the exclusive modes, row N, agree with B_3 in row O. However this must happen because $B(\pi^-\pi^+\pi^-\nu_\tau)$ and $B(\pi^-\pi^+\pi^- n\pi^0\nu_\tau)$ are measured by finding the events which contribute to B_3, and then dividing the events into those without or with γ's.

3. B_1 and $B_{1\,e\mu\pi\rho K}$

The average values used in Table 1a come mainly from Tables 2-5 and 9 which are based on a review article by Gan and I[4]. A few values come from Barish and Stroynouski[5], a slightly earlier review article. The individual measurements used in Tables 2-5 and 9 meet three criteria:

a. The statistical and systematic errors must each be smaller than a constant given in the table heading. This constant is chosen to be 5 to 10 times the smallest error in the table, thus eliminating the generally very old measurements with relatively very large errors.

b. The measurement must be described in a cataloged preprint, journal article, or a Ph.D. thesis authored by some of those who performed the measurement. This allows everyone to determine how a measurement was made and the errors estimated.

c. Measurements said to be superseded by the authors are not used.

In each of these tables I combine in quadrature the statistical and systematic error, to give a combined, ϵ_i, for each measurement, v_i the average of all the measurements, v_1 is

$$v = \sum_i w_i v_i \Big/ \sum_i w_i \tag{3.1}$$

where $w_i = \epsilon_i^{-2}$. This conventional method for obtaining a weighted average is not a satisfactory method: combining two different kinds of errors in quadrature is not justified unless the systematic error is gaussian. But we have no better method short of equisitely careful studies of each measurement to set up a uniform system of error estimation. Therefore I am resigned to this method, but I call the result a *formal* average.

Table 2. τ topological branching fractions in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 2.0\%$, (b) the measurement is described in a preprint, journal article, or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

B_1		B_3		Experimental Group	Reference
Measurement	Combined Error	Measurement	Combined Error		
84.0	± 2.0	15.0	± 2.0	CELLO	H. J. Behrend *et al.* Phys. Lett. **B114**, 282 (1982)
$86.0 \pm 2.0 \pm 1.0$	± 2.2	14.0	± 2.2	MARK II	C. A. Blocker *et al.* Phys. Rev. Lett. **49**, 1369 (1982)
85.2	± 1.7	$14.8 \pm 0.9 \pm 1.5$	± 1.7	TPC	H. Aihara *et al.* Phys. Rev. **D30**, 2436 (1984)
$84.7 \pm 1.1^{+1.6}_{-1.3}$	$^{+1.9}_{-1.7}$	$15.3 \pm 1.1^{+1.3}_{-1.6}$	$^{+1.7}_{-1.9}$	TASSO	M. Althoff *et al.* Z. Phys. **C26**, 521 (1985)
86.7	± 0.7	$13.3 \pm 0.3 \pm 0.6$	± 0.7	MAC	E. Fernandez *et al.* Phys. Rev. Lett. **54**, 1624 (1985)
$86.9 \pm 0.2 \pm 0.3$	± 0.4	$13.0 \pm 0.2 \pm 0.3$	± 0.4	HRS	C. A. Akerlof *et al.* Phys. Rev. Lett. **55**, 570 (1985)
$86.1 \pm 0.5 \pm 0.9$	± 1.0	$13.6 \pm 0.5 \pm 0.8$	± 0.9	JADE	W. Bartel *et al.* Phys. Lett. **161B**, 188 (1985)
$87.9 \pm 0.5 \pm 1.2$	± 1.3	$12.1 \pm 0.5 \pm 1.2$	± 1.3	DELCO	W. Ruckstuhl *et al.* Phys. Rev. Lett. **56**, 2132 (1986)
		$12.8 \pm 1.0 \pm 0.7$	± 1.2	MARK II	P. R. Burchat *et al.* Phys. Rev. **D35**, 27 (1987)
$84.7 \pm 0.8 \pm 0.6$	± 1.0	$15.1 \pm 0.8 \pm 0.6$	± 1.0	TPC	H. Aihara *et al.* Phys. Rev. **D35**, 1553 (1987)
86.5	± 0.3	13.4	± 0.3		Formal Average

Table 3. τ leptonic branching fractions in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 3.0\%$, (b) the measurement is described in a preprint, journal article, or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Use $e-\mu$ Universality	$B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$		$B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)$		Experimental Group	Reference
	Measurement	Combined Error	Measurement	Combined Error		
No			15.0	±3.0	PLUTO	J. Burmester *et al.* Phys. Lett. **68B**, 297 (1977)
No	16.0	±1.3			DELCO	W. Bacino *et al* Phys. Rev. Lett. **41**, 13 (1978)
No			$17.8\pm2.0\pm1.8$	±2.7	PLUTO	Ch. Berger *et al.* Phys. Lett. **99B**, 489 (1981)
Yes	$17.6\pm0.6\pm1.0$	±1.3	$17.1\pm0.6\pm1.0$	±1.3	MARK II	C. A. Blocker *et al.* Phys. Lett. **109B**, 119 (1982)
No	$18.3\pm2.4\pm1.9$	±3.1	$17.6\pm2.6\pm2.1$	±3.3	CELLO	H. J. Behrend *et al.* Phys. Lett. **127B**, 270 (1983)
No	$20.4\pm3.0^{+1.4}_{-0.9}$	$^{+3.3}_{-3.1}$	$12.9\pm1.7^{+0.7}_{-0.5}$	±1.8	TASSO	M. Althoff *et al.* Z. Phys. **C26**, 521 (1985)
No	$18.2\pm0.7\pm0.5$	±0.9	$18.0\pm1.0\pm0.6$	±1.2	MARK III	R.M.Baltrusaitis *et al.* Phys. Rev. Lett. **55**, 1842 (1985)
No	$17.4\pm0.8\pm0.5$	±0.9	$17.7\pm0.8\pm0.5$	±0.9	MAC	W. W. Ash *et al.* Phys. Rev. Lett. **55**, 2118 (1985)
Yes*	17.8	±0.5	17.3	±0.5	MAC	Same data as above
No			$17.4\pm0.6\pm0.8$	±1.0	MARK J	B. Adeva *et al.* Phys. Lett. **179B**, 177 (1980)
No	$17.0\pm0.7\pm0.9$	±1.1	$18.8\pm0.8\pm0.7$	±1.1	JADE	W. Bartel *et al.* Phys. Lett. **182B**, 216 (1986)
No	$18.4\pm1.2\pm1.0$	±1.6	$17.7\pm1.2\pm0.7$	±1.4	TPC	H. Aihara *et al.* Phys. Rev. **D35**, 1553 (1987)
No	$19.1\pm0.8\pm1.1$	±1.4	$18.3\pm0.9\pm0.8$	±1.2	MARK II	P. R. Burchat *et al.* Phys. Rev. **D35**, 27 (1987)
	17.7	±0.4	17.6	±0.4		Formal Average

*Not included in formal average.

Table 4. $\tau^- \rightarrow \pi^- \nu_\tau$ branching ratio in percent. The standard error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 3.0\%$, (b) the measurement is described in a preprint, journal article, or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Measurement	Combined Error	Experimental Group	Reference
$9.0 \pm 2.9 \pm 2.5$	± 3.8	PLUTO	G. Alexander *et al.* Phys Lett. **78B**, 162 (1978)
$11.7 \pm 0.4 \pm 1.8$	± 1.8	MARK II	C. A. Blocker *et al.* Phys. Lett. **109B**, 119 (1982)
$9.9 \pm 1.7 \pm 1.3$	± 2.1	CELLO	H. J. Behrend *et al.* Phys. Lett. **127B**, 270 (1983)
$11.8 \pm 0.6 \pm 1.1$	± 1.3	JADE	W. Bartel *et al.* Phys. Lett. **182B**, 216 (1986)
$10.7 \pm 0.5 \pm 0.8$	± 0.9	MAC	W. T. Ford *et al.* Phys. Rev. **D35**, 408 (1987)
$10.1 \pm 1.1 \pm 1.4$	± 1.8	MARK II	P. R. Burchat *et al.* Phys. Rev. **D35**, 27 (1987)
10.9	± 0.6		Formal Average

Table 5. $\tau^- \rightarrow \rho^- \nu_\tau$ branching ratio in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 3.0\%$, (b) the measurement is described in a preprint, journal article, or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Measurement	Combined Error	Experimental Group	Reference
$22.1 \pm 1.9 \pm 1.6$	± 2.5	CELLO	H. J. Behrend *et al.* Z. Phys. **C23**, 103 (1984)
$22.3 \pm 0.6 \pm 1.4$	± 1.5	MARK II	J. M. Yelton *et al.* Phys. Rev. Lett. **56**, 812 (1986)
$22.3 \pm 1.3 \pm 1.6$	± 2.1	MARK III	J. Alder *et al.* SLAC-PUB-4205 (1986)
$25.8 \pm 1.7 \pm 2.5$ *	± 3.0	MARK II	P. R. Burchat *et al.* Phys. Rev. **D35**, 27 (1987)
22.7	± 1.0		Formal Average

*All $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ included in $\tau^- \rightarrow \rho^- \nu_\tau$.

The error, ϵ, of the average v is obtained conventionally in a suspect method

$$\epsilon = v \left[\sum_i \left(\frac{v_i}{\epsilon_i} \right)^2 \right]^{-1/2} . \tag{3.2}$$

Where all v_i are close to v, as is the case in these tables,

$$\epsilon \approx \left(\sum_i \epsilon_i^{-2} \right)^{-1/2} . \tag{3.3}$$

This assumes the systematic errors of the different individual measurements are random with respect to each other. Suppose that every measurement included a systematic error $\epsilon_{\rm same}$ due to the same uncertainty in knowing the full set of τ branching fractions used in computing detector efficiencies. Then a better error estimate would be

$$\epsilon \approx \left[\left(\sum_i \epsilon_i'^{-2} \right)^{-1} + \epsilon_{\rm same}^2 \right]^{1/2} \tag{3.4}$$

where

$$\epsilon_i'^2 = \epsilon_i^2 - \epsilon_{\rm same}^2 \quad .$$

I now return to the possible explanations listed at the end of Section 2. and first consider Possibility III that B_1 is smaller than its formal average in Table 2, say about 80% rather than 86.5%. The statistical errors on many of the individual measurement are less than 1%, hence a 5% or 6% error in B_1 would have to come from a large $\epsilon_{\rm same}$. I have not been able to find any reason[6] for a large $\epsilon_{\rm same}$ in B_1. Therefore the problem cannot be completely solved by Possibility III. Incidentally the error of $\pm 0.3\%$ on B_1, Table 2, is probably too good to be true, it probably should lie between 0.5% and 0.8%.

Next consider Possibility II that the sum of the branching fractions, $B_{1\,e\mu\pi\rho K}$, for

$$\begin{aligned} \tau^- &\rightarrow e^- + \bar{\nu}_e + \nu_\tau \\ \tau^- &\rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau \\ \tau^- &\rightarrow \pi^- + \nu_\tau \\ \tau^- &\rightarrow \rho^- + \nu_\tau \quad , \end{aligned} \tag{3.5}$$

Tables 3-5, augmented by 2.1% for K decay modes, is greater than 71.0% by about 5%. This might occur because most methods used for measuring individual branching fractions use different event selection criteria than the methods used to measure B_1 and B_3. Could there be inefficiencies in selecting the individual decay modes which are not properly accounted for in calculations of detection acceptance? Or could there be a substantial $\epsilon_{\rm same}$ for some of the modes in Eq. (3.4)?

P. Burchat[7] examined the former question experimentally by requiring that all events counted in B_1 be allotted to some 1-charge-particle mode, thus building in

$$B_1 = \sum_i B_{1i} \quad .$$

Table 6 gives the results. $B(e^-\bar{\nu}_e\nu_\tau)$, $B(\mu^-\bar{\nu}_\mu\nu_\tau)$, and $B(\rho^-\nu_\tau)$ are larger than the corresponding formal average, $B(\pi^-\nu_\tau)$ is smaller, giving a net increase of 4.3% in $B_{1\,e\mu\pi\rho}$. This is attractive because it allows a small and more comfortable value of $B_{1\,\rm mult\,neut}$. But I cannot select the measurements of a single experiment against the measurements of all the other experiments listed in Tables 3-5, unless a substantial $\epsilon_{\rm same}$ is found in the latter. None have so for been pointed out.

Table 6. τ branching fractions in percent from Ref. 7 using an analysis method in which all observed τ decays must be allotted to one at the modes listed here. These measurements are compared with the formal averages from Table 1.

Row	Mode	Measured Branching Fraction (%)	Formal Average Branching Fraction (%)
A	$e^- \bar{\nu}_e \nu_\tau$	$19.1 \pm 0.8 \pm 11$	17.7 ± 0.4
B	$\mu^- \bar{\nu}_\mu \nu_\tau$	$18.3 \pm 0.9 \pm 0.8$	17.6 ± 0.4
C	$\pi^- \nu_\tau$	$10.0 \pm 1.1 \pm 1.4$	10.9 ± 0.6
D	$\pi^- \pi^0 \nu_\tau$	$25.8 \pm 1.7 \pm 2.5$	22.7 ± 1.0
E	Sum of rows A-D called $B_{1\, e\mu\pi\rho}$	73.2	68.9
F	$\pi^- n\pi^0 \nu_\tau,\ n \geq 1$	$12.0 \pm 1.4 \pm 2.5$	
G	Sum of rows E and F	85.2	
H	$\pi^- \pi^+ \pi^- \nu_\tau$	$6.7 \pm 0.8 \pm 0.9$	6.6 ± 0.4
I	$\pi^- \pi^+ \pi^- n\pi^0 \nu_\tau,\ n \geq 1$	$6.1 \pm 0.8 \pm 0.9$	5.0 ± 0.5
J	Sum of rows H and I	12.8	11.6
K	Modes containing $\geq 1\, K^\pm$	2.0 *	
L	Sum of rows G, J and K	100.0	

* Fixed in analysis from other experiments.

Another way to measure $B(e^- \bar{\nu}_e \nu_\tau)$ is to measure the τ lifetime, τ_τ, assume $\mu - \tau$ universally and use

$$\tau_\tau = \left(\frac{m_\mu}{m_\tau}\right)^5 \tau_\mu\, B(e^- \, \bar{\nu}_e \, \nu_\tau) \tag{3.6}$$

$$\tau_\tau = 16.03 \times 10^{-13}\, B(e^- \, \bar{\nu}_e \, \nu_\tau) \text{ s} \quad .$$

The formal average value for τ_τ, Table 7, is

$$\tau_\tau = (3.07 \pm 0.10) \times 10^{-13} \text{ s} \tag{3.7a}$$

yielding

$$B(e^- \, \bar{\nu}_e \, \nu_\tau) = (19.2 \pm 0.6)\% \quad . \tag{3.7b}$$

The formal average for the direct measurement of $B(e^- \bar{\nu}_e \nu_\tau)$ is 17.7 ± 0.4 from Table 2, two standard deviations smaller. No conclusion can be drawn from a two standard deviation difference. Furthermore the error on τ_τ of 0.1×10^{-13} s is probably too small given the systematic error problems in measuring τ_τ; an error of 0.2×10^{-13} s is more appropriate.

Table 7. τ lifetime in units of 10^{-13} s. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are $\leq 0.40 \times 10^{-13}$ s, (b) the measurement is described in a preprint, journal article, or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Lifetime	Errors combined in quadrature	Experimental Group	Reference
$2.86 \pm 0.16 \pm 0.25$	± 0.30	MARK II	J. Jaros, SLAC Report 281 (1984)
$3.15 \pm 0.36 \pm 0.40$	± 0.54	MAC	E. Fernandez *et al.* Phys. Rev. Lett. **54**, 1624 (1985)
3.09	± 0.19	MAC	H. R. Band *et al.* Phys. Rev. Lett. **59**, 415 (1987)
$3.02 \pm 0.15 \pm 0.08$	± 0.17	HRS	S. Abachi *et al.* ANL-HEP-PR-87-1 (1987)
$3.25 \pm 0.14 \pm 0.18$	± 0.23	CLEO	C. Bebek *et al.* Phys. Rev. **D36**, 690 (1987)
3.07	± 0.10		Formal Average

Returning to Possibility II of Section 2, one cannot simply increase $B_{1\,e\mu\pi\rho K}$, one must explain how so many measurements of the various B_{1i}'s turned out to be too small. Furthermore, there are theoretical constraints[1] on the ratios of the various B_{1i}'s in $B_{1\,e\mu\pi\rho K}$, so that drastically increasing a single B_{1i} strains error limits if the theory is accepted.

Thus I am not able to settle Possibility II of Section 2, that $B_{1\,e\mu\pi\rho K}$ should be larger. Therefore I turn to Possibility I that $B_{1\,\mathrm{mult\,neut}} \approx 15\%$. I discuss in Section 4 direct measurements of $B_{1\,\mathrm{mult\,neut}}$, and in Section 5 constraints on $B_{1\,\mathrm{mult\,neut}}$ from conventional theory and other data.

4. $B_{1\,\text{mult neut}}$: DIRECT MEASUREMENT

In the past the G-parity forbidden decay mode

$$\tau^- \rightarrow \pi^- + \eta + \nu_\tau \tag{4.1}$$

has been ignored, but Derrick *et al.*[8] has compelled attention. Measurements are given in Table 8. The weight of evidence is that $B(\pi^-\eta\nu_\tau) < 1\%$ and I shall not specifically consider this mode. Events from it can be counted, but not correctly, in the more general measurement discussed next.

Table 8. Branching fraction in percent for $\tau^- \rightarrow \pi^-\eta\nu_\tau$ from catalogued preprints or journal articles authored by the experimenters.

Branching Fraction (%)	Experimental Group	Reference
5.1 ± 1.5	HRS	M. Derrick *et al.*, Phys. Lett. **B189**, 260 (1987)
< 2.5 at 90% CL	MARK III	D. Coffman *et al.*, SLAC-PUB-4314 (1987), submitted to Phys. Rev.
< 1.3 at 95% CL	ARGUS	H. Albrecht*et al.*, submitted to Phys. Lett.
< 1.0 at 95% CL	MARK II	K. K. Gan *et al.*, SLAC-PUB-4365 (1987), submitted to Phys. Lett.

The experimental signature

$$\tau^- \rightarrow X^- + n\gamma + \text{missing energy}\ , \quad n > 2 \tag{4.2}$$

with $X^- = \pi^-$ or K^- can come from several classes of decay modes.

(a) Modes containing a π^- and several π^0's:

$$\tau^- \rightarrow \pi^- + 2\pi^0 + \nu_\tau \tag{4.3a}$$

$$\tau^- \rightarrow \pi^- + 3\pi^0 + \nu_\tau \tag{4.3b}$$

$$\tau^- \rightarrow \pi^- + 4\pi^0 + \nu_\tau \tag{4.3c}$$

$$\tau^- \rightarrow \pi^- + 5\pi^0 + \nu_\tau \tag{4.3d}$$

(b) Modes containing a π^- and at least one η:

$$\tau^- \rightarrow \pi^- + \eta + \nu_\tau \tag{4.4a}$$

$$\tau^- \rightarrow \pi^- + \eta + \pi^0 + \nu_\tau \tag{4.4b}$$

$$\tau^- \rightarrow \pi^- + \eta + 2\pi^0 + \nu_\tau \tag{4.4c}$$

$$\tau^- \rightarrow \pi^- + 2\eta + \nu_\tau \tag{4.4d}$$

$$\tau^- \rightarrow \pi^- + 2\eta + \pi^0 + \nu_\tau \tag{4.4e}$$

(c) The modes in Eqs. (4.3) and (4.4) can contain a K^- instead of a π^-, but there are expected to be Cabibbo suppressed.

(d) Beyond the π^0 and η, the only known neutral meson with major branching fractions to all γ final states is the η' with mass 958 MeV/c. This relatively large mass argues against substantial τ decay modes containing the η'.

(e) There remains the possibility of unknown, small mass, neutral mesons with all γ final states. Such mesons could contribute to the process in Eq. (4.2).

Published experiments, Table 9, have not been able to sort thru this multitude of decay modes. The best that has been done is to measure $B(\pi^- 2\pi^0 \nu_\tau)$, to get some idea of the size of $B(\pi^- 3\pi^0 \nu_\tau)$, and to roughly measure $B_{1\,\mathrm{mult\,neut}}$. As shown in Table 9, the measurements of $B_{1\,\mathrm{mult\,neut}}$ have used different assumptions as to which modes in Eqs. (4.3) and (4.4) to include. The detector efficiency and hence the value of $B_{1\,\mathrm{mult\,neut}}$ depends on these assumptions.

Rows D and E of Table 9, two analyses of the same set of events[9], illustrate the experimental problems. The events are τ decay candidates with one decay of the form

$$\tau^- \rightarrow X^- + n\gamma\text{'s} + \text{missing energy}\ , \quad n \geq 3\ . \tag{4.5}$$

In row D all such decays are assumed to come from

$$\tau^- \rightarrow \pi^- + 2\pi^0 + \nu_\tau \tag{4.6a}$$

or

$$\tau^- \rightarrow \pi^- + 3\pi^0 + \nu_\tau \tag{4.6b}$$

The fit is poor, $\chi^2 = 6.9$ for four degrees of freedom. The inclusion of another source of the decays in Eq. (4.5) improves the fit. The final states $\pi^- 4\pi^0 \nu_\tau$ or $\pi^- 5\pi^0 \nu_\tau$ or $\pi^- \pi^0 \eta \nu_\tau$

Table 9. Branching fractions $B(\pi^- 2\pi^0 \nu_\tau)$, $B(\pi^- 3\pi^0 \nu_\tau)$, and $B_{1\,\mathrm{mult\,neut}}$ in percent according to different assumptions as to modes included. The mode description uses a π^-, but the measured events may include those with a K^- instead of a π^-. The first error is statistical, the second systematic.

Row	Modes Assumed	$B(\pi^- 2\pi^0 \nu_\tau)$ (%)	$B(\pi^- 3\pi^0 \nu_\tau)$ (%)	$B_{1\,\mathrm{mult\,neut}}$ (%)	Experimental Group	Reference
A	$\pi^- 2\pi^0 \nu_\tau$ $\pi^- 3\pi^0 \nu_\tau$	$6.0 \pm 3.0 \pm 1.8$	$3.0 \pm 2.2 \pm 1.5$	9.0	CELLO	H. J. Behrend *et al.*, Z. Phys. **23**, 103 (1984)
B	$\pi^- 2\pi^0 \nu_\tau$ $\pi^- 3\pi^0 \nu_\tau$ $\pi^- \pi^0 \eta \nu_\tau$			$13.9 \pm 2.0^{+1.9}_{-2.1}$	TPC	H. Aihara *et al.*, Phys. Rev. Lett. **57**, 1836 (1986)
C	$\pi^- 2\pi^0 \nu_\tau$ $\pi^- 3\pi^0 \nu_\tau$			$12.0 \pm 1.4 \pm 2.5$	MARK II	R. R. Burchat *et al.*, Phys. Rev. **D35**, 27 (1987)
D	$\pi^- 2\pi^0 \nu_\tau$ $\pi^- 3\pi^0 \nu_\tau$	6.7 ± 0.5	2.2 ± 0.4	8.9	MARK II	K. K. Gan *et al.*, Phys. Rev. Lett. **59**, 411 (1987)
E	$\pi^- 2\pi^0 \nu_\tau$ $\pi^- 3\pi^0 \nu_\tau$ $\pi^- \pi^0 \eta \nu_\tau$	$6.2 \pm 0.6 \pm 1.2$	$0.0^{+1.4+1.1}_{-0.0-0.0}$	10.4	MARK II	Same data as above
F	$\pi^- 2\pi^0 \nu_\tau$ $\pi^- 3\pi^0 \nu_\tau$	$8.7 \pm 0.4 \pm 1.1$			MAC	H. R. Band *et al.*, SLAC-PUB-4333 (1987), submitted to Phys. Lett.

or more complicated states improve the fit. There was no way from the data to choose one additional final state over another. The mode

$$\tau^- \;\rightarrow\; \pi^- + \pi^0 + \eta + \nu_\tau \tag{4.7}$$

was picked as an example, giving the results in row E with $B(\pi^- \pi^0 \eta \nu_\tau) = (4.2^{+0.7}_{-1.2} \pm 1.6)\%$. A choice of some other additional final state would have given a corresponding size B for that state.

Returning to Table 9, it is pointless to calculate a formal average for $B_{1\,\mathrm{mult\,neut}}$. All I can do is conclude:

(a) $B_{1\,\mathrm{mult\,neut}}$ is in the range of 8 to 16%, and use this in Tables 1 and 10.

(b) If $B_{1\,\mathrm{mult\,neut}}$ is more than a few percent larger than 8%, there must be modes contributing to it other than $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^- 3\pi^0 \nu_\tau$.

5. $B_{1\,\mathrm{mult\,neut}}$: THEORY AND OTHER DATA

The conventional theoretical concepts of conserved vector current and strong isospin conservation have been used by Gilman[1,2] to calculate or set upper limits on the branching fractions of multiple neutral meson modes. The conserved vector current concept allows the calculation of

$$\tau^- \to \nu_\tau + a + b + c + \ldots \tag{5.1a}$$

from the cross section for

$$e^+e^- \to a + b + c + \ldots \tag{5.1b}$$

if $a + b + c + \ldots$ is a vector spin state. A value of $B(e^- \bar{\nu}_e \nu_\tau)$ must also be used. Strong isospin conservation allows setting a limit on the branching fraction of a multiple neutral meson mode using a better measured multiple charged pion mode. The small branching fraction

$$B_5 = 0.11 \pm 0.03 \tag{5.2}$$

is very useful.

Table 10 summarizes the results. If all the modes contributing to $B_{1\,\mathrm{mult\,neut}}$ are in Table 10, then

$$B_{1\,\mathrm{mult\,neut}} \leq 9.8\% \quad . \tag{5.3}$$

Comparing Tables 9 and 10:

a. The values of $B(\pi^- 2\pi^0 \nu_\tau)$ are consistent.

b. The values of $B(\pi^- 3\pi^0 \nu_\tau)$ are consistent.

c. The theoretical value of $B_{1\,\mathrm{mult\,neut}} \leq 9.8\%$ fall within the range of 8% to 16% from the direct measurements of Table 9.

d. If the measured value of $B_{1\,\mathrm{mult\,neut}}$ is nearer to 16% than 10%, we do not know what modes contribute to the excess.

Table 10. Constraints on branching fractions of multiple neutral meson modes from conventional theory and other data. CVC means conserved vector current, SI means strong isospin, B_e means $B(e^-\bar{\nu}_e\nu_\tau)$. Based on Refs. 1 and 2 unless noted.

Decay Mode	Branching Fraction (%)	Method
$\pi^- + 2\pi^0 + \nu_\tau$	$\leq 6.6 \pm 0.4$	SI, $B(\pi^-\pi^+\pi^-\nu_\tau) = 6.6 \pm 0.4$
$\pi^- + 3\pi^0 + \nu_\tau$	1.0	CVC, $B_e = 18.\%$
$\pi^- + n\pi^0 + \nu_\tau,\ n > 3$	≤ 0.3	SI, $B_5 = 0.11\%$
$K^- + n\pi^0 + \nu_\tau,\ n > 1$	≤ 0.4	$\sin^2\theta_{\text{Cabibbo}} \times$ (modes with π^-)
$\pi^- + \eta + \nu_\tau$	0.0	Ref. 10
$\pi^- + \eta + \pi^0 + \nu_\tau$	≤ 0.2	CVC, $B_e = 18.\%$
$\pi^- + \eta + 2\pi^0 + \nu_\tau$	≤ 0.3	SI, $\eta \to \pi^+\pi^-\pi^0$, $B_{5+\gamma\text{'s}}$
$\pi^- + 2\eta + n\pi^0 + \nu_\tau,\ n = 1, 2$	≤ 1.0	$\eta \to \pi^+\pi^-\pi^0$, B_5
Sum	≤ 9.8	

6. SUMMARY OF τ DECAY MODES PROBLEM

In Table 11 I summarize the discussions in Sections 2, 4 and 5 on the branching fractions for the 1-charged-particle decay modes. Recall that $B_{1\,e\mu\pi\rho K}$ is the sum of the branching fractions for

$$\begin{aligned} \tau^- &\to e^- + \bar{\nu}_e + \nu_\tau \\ \tau^- &\to \mu^- + \bar{\nu}_\mu + \nu_\tau \\ \tau^- &\to \pi^-\ \nu_\tau \\ \tau^- &\to \rho^-\ \nu_\tau \\ \tau^- &\to K^-\ \nu_\tau \\ \tau^- &\to K^{*-}\ \nu_\tau \quad , \end{aligned} \tag{6.1}$$

and $B_{1\,\text{mult neut}}$ is the sum of all other 1-charged-particle decay modes.

Table 11. Summary of 1-charged-particle branching fractions in percent.

Decay Mode Catagory	Branching Fraction (%) and Origin	
$B_{1\,e\mu\pi\rho K}$	71.0 ± 1.3 from measurement	
$B_{1\,\text{mult neut}}$	8 to 16 from measurement	≤ 9.8 from theory and other data
$B_{1\,e\mu\pi\rho K} + B_{1\,\text{mult neut}}$	79. to 87.	$\leq 80.8 \pm 1.3$
B_1	86.5 ± 0.3 from measurement	

I use the measured value of $B_{1\,e\mu\pi\rho K}$ in Table 11, because while conventional theory agrees with these measurements it adds no further overall constraint on $B_{1\,e\mu\pi\rho K}$. Conventional theory and other data does fix the ratio[1]

$$r = B_{1\,e\mu\pi\rho K}/B(e^- \bar{\nu}_e \nu_\tau) \tag{6.2}$$

but not $B(e^-\bar{\nu}_e\nu_\tau)$ itself. Thus according to conventional theory an increase of $\delta B(e^-\bar{\nu}_e\nu_\tau)$ would require

$$\delta B_{1\,e\mu\pi\rho K} = r\,\delta B(e^- \bar{\nu}_e \nu_\tau) \quad . \tag{6.3}$$

Returning to Table 11, I present the sum $B_{1\,e\mu\pi\rho K}+B_{1\,\mathrm{mult\,neut}}$ for two choices of $B_{1\,\mathrm{mult\,neut}}$: the direct measurements from Section 4 or the theoretical constraint from Section 5. In the latter choice

$$B_{1\,e\mu\pi\rho K} + B_{1\,\mathrm{mult\,neut}} \leq 80.8 \pm 1.3 \tag{6.4}$$

presenting the clearest difference from

$$B_1 = 86.5 \pm 0.3 \quad . \tag{6.5}$$

At the end of Section 2 I listed three possibilities:

Possibility I: $B_{1\,\mathrm{mult\,neut}}$ is about 15% not 8% or 10%.

Possibility II: $B_{1\,e\mu\pi\rho K}$ is larger than 71%.

Possibility III: B_1 is smaller than 86.5%.

In Section 3 I stated the Possibility III was unlikely. Published measurement do not discriminate between Possibilities I and II or a combination of these possibilities. Statistical and systematic errors are too large. Our direct knowledge of $B_{1\,\mathrm{mult\,neut}}$ and the decay modes it includes is too scanty. If Possibility I is too bear most of the burden of closing the gap between the values in Eqs. (6.4) and (6.5), there must be an error in Table 10 or in our understanding of the multiple neutral meson decay modes. References 1 and 4 present some further speculate thoughts, but I have nothing further to add. We are in a difficult situation where the limitations of published measurements present us from deciding whether Table 11 represents simply an unfortunate concatenation of experimental errors or unknown physics.

7. CLOSE–MASS LEPTON PAIRS

In 1986 I pointed out[11] that searches at e^+e^- or $\bar{p}p$ colliders for new lepton pairs, $L^- - L^0$, did not exclude the situation where the L^0 mass, m_0, is close to the L^- mass, m_-. Specifically new pairs with

$$\delta = m_- - m_0 \lesssim 3 \text{ GeV/c}^2 \tag{7.1}$$

would have been missed in e^+e^- searches because of the small visible energy. The L^0 is assumed to be stable. A similar situation occurs in searches for other types of pairs of weakly interacting particles, supersymmetric for example, when the mass difference is small.

Stoker and I[12] have searched for close mass pairs using 29 GeV e^+e^- annihilation data required by the Mark II collaboration at PEP. We consider three types of decay signatures:

(a) $L^- \to L^0 + e^- + \bar{\nu}_e$

(b) $L^- \to L^0 + \mu^- + \bar{\nu}_\mu$

(c) $L^- \to L^0+$ 3-or-more-charged particles, γ's allowed.

The searched used three event signatures: $a+b$, $a+c$ and $b+c$. These signatures were selected to separate the sought signal from backgrounds from the two-virtual-photon processes

$$\begin{aligned} e^+e^- &\to (e^+ + e^-) + e^+ + e^- \\ e^+e^- &\to (e^+ + e^-) + \mu^+ + \mu^- \\ e^+e^- &\to (e^+ + e^-) + \pi^+ + \pi^- \quad . \end{aligned} \tag{7.2}$$

Here (e^+e^-) means the e^+e^- pair is not detected because the particles are emitted at angles close to the beam line. The sought signal was separated from the

$$e^+e^- \to \tau^+ + \tau^- \tag{7.3}$$

background by imposing criteria described in Ref. 11. For the signature $a+b$, $e\mu$ events, a large acollinearily angle was required, specifically $\theta_{\text{acol}} > 25°$. For the signatures $a+c$ and $b+c$ the lepton had to be separated by at least 90° from all other charged particles and photons. The events were further divided into two classes depending on the number of charged particles opposite the lepton, 3 or > 3, and into two further classes depending on whether $m_{\text{inv}} < 2.5$ GeV/c^2 or $m_{\text{inv}} > 2.5$ GeV/c^2. Here m_{inv} is the invariant mass of all charged particles and photons excluding the isolated lepton. Events from τ pairs would fall mostly in the classes: $e - \mu$, $\theta_{\rm acol} < 25°$; e vs 3, $m_{\rm inv} < 2.5$ GeV/c^2; and μ vs 3, $m_{\rm inv} < 2.5$ GeV/c^2.

No evidence for close-mass pairs was found, the excluded region in terms of m_- and δ is given in Figure 1. In this Mark II data the lower limit on δ was set by the need to identify an e or μ to obtain decay signature a or b. We are using the decay signatures:

(d) $L^- \to L^0 + \rho^-$

(e) $L^- \to L^0 +$ 1-charged-particle

and the event signature $d + e$ to study smaller values of δ.

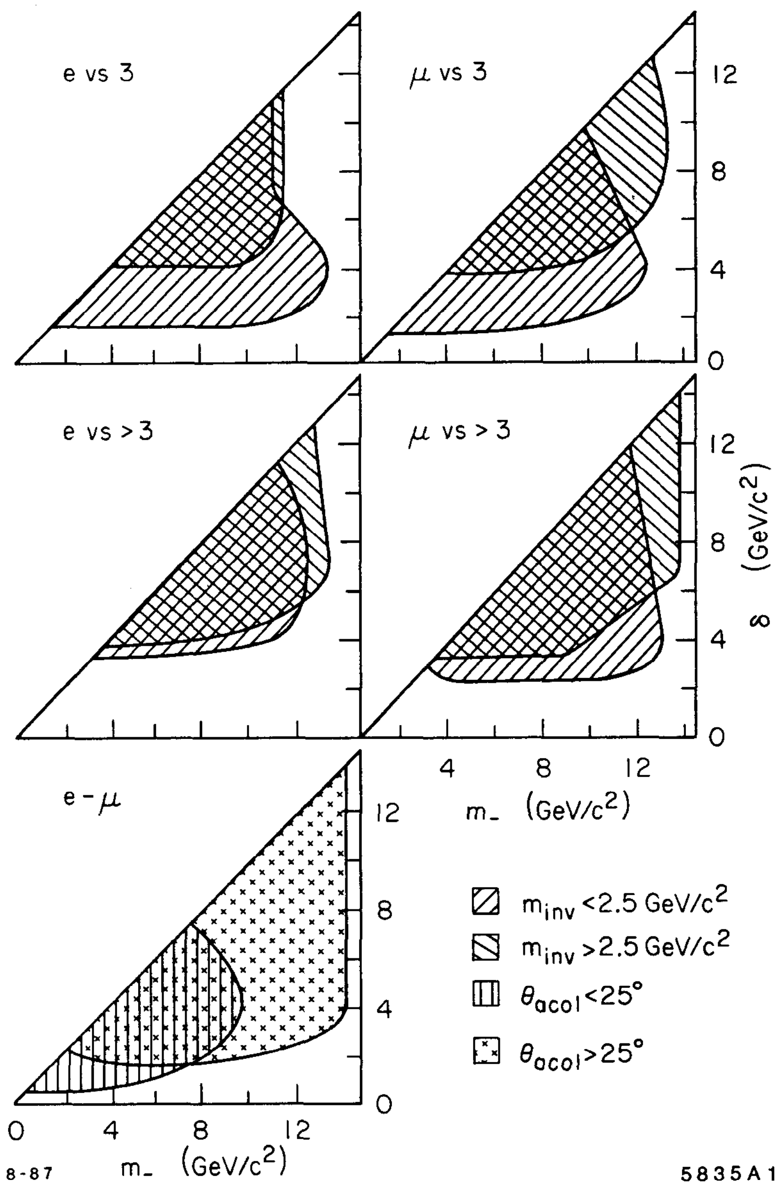

Figure 1. L^-, L^0 pairs within the hatched regions are excluded with greater than 2σ confidence. From e^+e^- annihilation data[12] at $E_{\rm tot} = 29$ GeV. See text for signature descriptions.

The TPC collaboration[13] is using the decay signatures:

(f) $L^- \to L^0 + e^- + \bar{\nu}_e$

(g) $L^- \to L^0 +$ 1-charged-particle-not-an e

and the event signature $f + g$ to search to small values of δ. This can be done because the TPC detectors permits electron identification down to momenta of several hundred MeV/c.

Barnett and Haber[14] have analyzed the data used by Albajar *et al.*[15] to set a lower limit of $m_- > 41$ GeV/c^2. This limit was based on searching for the process

$$\begin{aligned} \bar{p} + p &\to W^- + \text{hadrons} \\ W^- &\to L^- + \bar{L}^0 \\ L^- &\to L^0 + \text{3-or-more-charged-particles}\,, \quad \gamma\text{'s allowed} \end{aligned} \tag{7.4}$$

Figure 2 is my transcription of Barnett and Haber's result[14]. The excluded region in $m_- - \delta$ space is relatively small because a large δ is needed to separate the sought signal in Eq. (7.4) from backgrounds.

Raby and West[16] have discussed a dark matter interpretation of the L^0 in a close-mass pair.

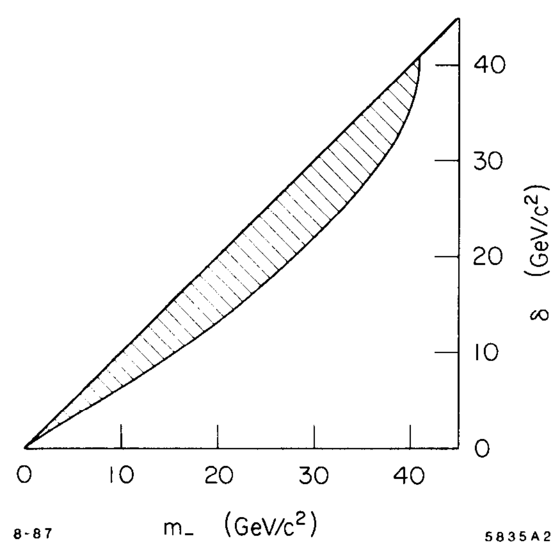

Figure 2. L^-, L^0 pairs within the hatched regions are excluded[14]. From $\bar{p}p$ collision data[15] at $E_{\text{tot}} = 630$ GeV.

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