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**BEYOND THE TAU:  
OTHER DIRECTIONS IN TAU PHYSICS\***

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**ABSTRACT**

This paper calls attention to four topics in tau lepton physics which are outside our present areas of tau physics research:  $\tau^+\tau^-$  atoms,  $\tau^-$  nucleus atoms, photoproduction of  $\tau$ 's, and heavy ion production of  $\tau$ 's.

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## A. Introduction

This paper is based on a talk delivered at the *Second Workshop on Tau Lepton Physics* held at The Ohio State University, September 8-11, 1992. In that talk I called attention to four out-of-the-way topics in tau physics:  $\tau^+\tau^-$  atoms,  $\tau^-$ -nucleus atoms, photoproduction of  $\tau$ 's, and heavy ion production of  $\tau$ 's; and these are the areas covered in this paper. Two other topics from that talk will not be discussed in this paper: future searches for heavy leptons and speculations on missing modes in tau decay (Perl 1992).

## B. The $\tau^-\tau^+$ Atom

### B.1 Introduction

In the early years of the discovery of the  $\tau$  there was some discussion of the physics of an atom that would consist of the Coulombic bound state of a  $\tau^+$  and a  $\tau^-$  (Moffat 1975, Avilez *et al.* 1978, Avilez *et al.* 1979), an entity analagous to the  $e^+e^-$  atom positronium (Rich 1978). The  $\tau^+\tau^-$  atom can be made in  $e^+e^-$  annihilation just below  $\tau$  pair threshold.

$$e^+ + e^- \rightarrow \tau^+\tau^- \text{ atom} , \quad (1)$$

hence the tau-charm factory offers the best route for making these atoms as discussed in Sec. B.5.

### B.2 Static Properties

The energy levels of the  $\tau^+\tau^-$  atom are shown in Fig. 1 where the atomic spectroscopy notation

$$\tau^{2S+1}L_J$$

is used. Here  $n$  is the principle quantum number;  $S$  is the total spin quantum number and is 0 or 1,  $L$  is the orbital angular momentum quantum number with  $L = S, P, D \dots$  for  $L = 0, 1, 2 \dots$  and  $J$  is the total angular momentum quantum number. Ignoring fine structure, the energy levels are given by

$$E_n = -\frac{m_\tau c^2 \alpha^2}{4n^2} = -\frac{23.7 \text{ keV}}{n^2} \quad (2)$$

The 4 in the denominator comes from the usual 2 in the denominator and and  $m_{\text{reduced}}(\tau^+\tau^- \text{ atom}) = m_\tau/2$  in the numerator. I use  $m_\tau = 1777 \text{ MeV}/c^2$ .

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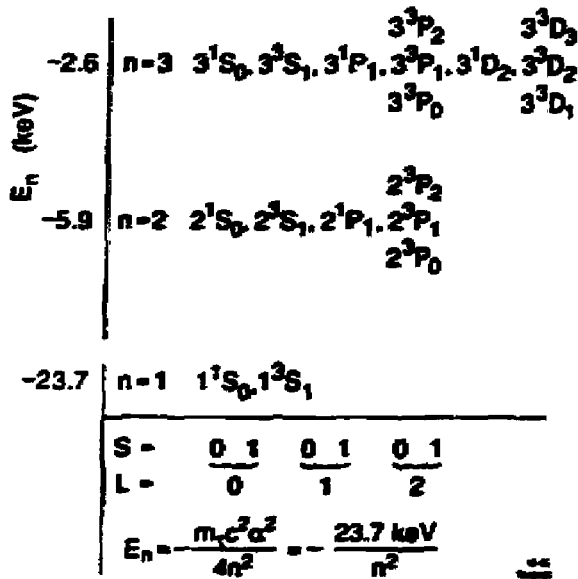


Figure 1

The Bohr radius is given by

$$a_0 = \frac{2\hbar^2}{m_e e^2} = 3.04 \times 10^{-12} \text{ cm} \quad (3)$$

which is three orders of magnitude smaller than the Bohr radius for hydrogen of  $5.29 \times 10^{-9} \text{ cm}$ .

The  $n = 1, 2$  wave functions are given by

$$\psi_{nl} = R_{nl}(r) Y_{lm}(\theta, \phi) \quad (4a)$$

where  $Y_{lm}$  is a normalized spherical harmonic and

$$\begin{aligned} R_{10} &= \frac{1}{a_0^{3/2}} 2 e^{-r/a_0} \\ R_{20} &= \frac{1}{a_0^{3/2}} \frac{1}{\sqrt{2}} \left(1 - \frac{r}{2a_0}\right) e^{-r/2a_0} \\ R_{21} &= \frac{1}{a_0^{3/2}} \frac{1}{\sqrt{6}} \frac{r}{2a_0} e^{-r/2a_0} \end{aligned} \quad (4b)$$

### B.3 Charge Conjugation Rules for Production and Decay

Charge conjugation,  $C$ , imposes selection rules on the production and decay of the  $\tau^+\tau^-$  atom

$$C\psi(\tau^+\tau^- \text{ atom}, n, S, L) = (-1)^{S+L}\psi(\tau^+\tau^- \text{ atom}, n, S, L) \quad (5)$$

and for a state of  $N$  photons

$$C\psi(N \text{ photons}) = (-1)^N\psi(N \text{ photons}) \quad (6)$$

Therefore in production

$$e^+ + e^- \rightarrow \gamma_{\text{virtual}} \rightarrow \tau^+\tau^- \text{ atom} \quad (7a)$$

the atom must be produced in a state with

$$S + L = \text{odd number} \quad (7b)$$

The decay

$$\tau^+\tau^- \text{ atom} \rightarrow \gamma + \gamma \quad (8a)$$

requires

$$S + L = \text{even number} \quad (8b)$$

and the decay

$$\tau^+\tau^- \text{ atom} \rightarrow \gamma + \gamma + \gamma \quad (9a)$$

requires

$$S + L = \text{odd number} \quad (9b)$$

### B.4 Decay channels of the $\tau^+\tau^-$ atom

Next I discuss the decay of the  $\tau^+\tau^-$  atom. There are two classes of decay channel. In the first class the  $\tau^+$  or  $\tau^-$  decay through the weak interaction in the normal way and the atomic state disappears. The decay width is

$$\Gamma(\text{atom. } \tau \text{ decay}) = 2\hbar/\tau_{\text{lifetime}} = 4.4 \times 10^{-3} \text{ eV} \quad (10a)$$

where the 2 occurs because the decay of either  $\tau$  breaks up the atomic state. I have used the  $\tau$  lifetime (Trischuk 1992) of

$$T_\tau = (2.96 \pm 0.03) \times 10^{-13} \text{ s} \quad (10b)$$

In the second class of decay channels the  $\tau^+$  and  $\tau^-$  annihilate. The annihilation

requires that the atomic wave function  $\psi(r)$  be unequal to 0 at  $r = 0$

$$\psi(0) \neq 0$$

Here  $r$  is the distance between the  $\tau^+$  and  $\tau^-$ . Therefore in lowest order annihilation only occurs in  $L = 0$  states, that is,  $S$  states. This is illustrated in Eq. 4b. There are five annihilation channels:

$$\tau^+\tau^- \text{ atom} \rightarrow \gamma + \gamma \quad (11a)$$

$$\tau^+\tau^- \text{ atom} \rightarrow \gamma + \gamma + \gamma \quad (11b)$$

$$\tau^+\tau^- \text{ atom} \rightarrow e^+ + e^- \quad (11c)$$

$$\tau^+\tau^- \text{ atom} \rightarrow \mu^+ + \mu^- \quad (11d)$$

$$\tau^+\tau^- \text{ atom} \rightarrow \text{hadrons} \quad (11e)$$

The annihilation channel

$$\tau^+\tau^- \text{ atom} \rightarrow \gamma + \gamma \quad (12a)$$

is even under charge conjugation, therefore

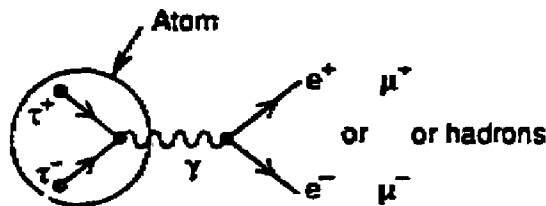
$$\text{atomic state} = n \ ^1S_0 \quad (12b)$$

The decay width is

$$\begin{aligned} \Gamma(\text{atom} \rightarrow 2\gamma) &= \frac{\alpha^5 m_\tau c^2}{2n^3} \\ &= \frac{1.8 \times 10^{-2} \text{ eV}}{n^3} \end{aligned} \quad (12c)$$

The four other annihilation channels have odd charge conjugation, therefore

$$\text{atomic state} = n \ ^3S_1 \quad (13)$$



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Figure 2

The channel

$$\tau^+\tau^-\text{ atom} \rightarrow \gamma + \gamma + \gamma \quad (14a)$$

has the width

$$\begin{aligned} \Gamma(\text{atom} \rightarrow 3\gamma) &= \frac{2(\pi^2 - 9)\alpha^5 m_\tau c^2}{9\pi n^3} \\ &= \frac{1.7 \times 10^{-5} \text{ eV}}{n^3} \end{aligned} \quad (14b)$$

The two channels, Fig. 2,

$$\tau^+\tau^-\text{ atom} \rightarrow e^+ + e^- \quad (15a)$$

$$\tau^+\tau^-\text{ atom} \rightarrow \mu^+ + \mu^- \quad (15b)$$

have the same width

$$\begin{aligned} \Gamma(\text{atom} \rightarrow e^+e^-) = \Gamma(\text{atom} \rightarrow \mu^+\mu^-) &= \frac{\alpha^5 m_\tau c^2}{6n^3} \\ &\approx \frac{6.1 \times 10^{-3} \text{ eV}}{n^3} \end{aligned} \quad (15c)$$

when we neglect the masses of the  $e$  and  $\mu$ . Finally there is the channel, Fig. 2,

$$\tau^+\tau^-\text{ atom} \rightarrow \text{hadrons} \quad (16a)$$

The width cannot be calculated from first principles, however from colliding beams  $e^+e^-$  annihilation data at  $E_{tot} \sim 2m_\tau$  we know

$$\sigma(e^+ + e^- \rightarrow \text{hadrons}) \approx 2\sigma(e^+ + e^- \rightarrow \mu^+ + \mu^-) \quad (16b)$$

Therefore

$$\Gamma(\text{atom} \rightarrow \text{hadrons}) \approx 2 \Gamma_{\mu\mu} \quad (16c)$$

Collecting all this together, for  $n^1S_0$  states

$$\begin{aligned} \Gamma_{tot}(n^1S_0) &= \Gamma(\text{atom}, \tau \text{ decay}) + \Gamma(\text{atom} \rightarrow 3\gamma) \\ &= \left( 4.4 \times 10^{-3} + \frac{3.7 \times 10^{-2}}{n^3} \right) \text{ eV} \end{aligned} \quad (17)$$

For the  $n^3S_1$  states we can neglect  $\Gamma(\text{atom} \rightarrow 3\gamma)$ , Eq. 14b, and set

$$\begin{aligned} \Gamma_{tot}(n^3S_1) &\approx \Gamma(\text{atom}, \tau \text{ decay}) + 4\Gamma(\text{atom} \rightarrow e^+e^-) \\ &\approx \left( 4.4 \times 10^{-3} + \frac{2.44 \times 10^{-2}}{n^3} \right) \text{ eV} \end{aligned} \quad (18)$$

Table I gives the widths and lifetimes for various  $S$  states.

Table I. Widths and lifetimes of  ${}^3S_1$  states of the  $\tau^+\tau^-$  atom due to  $\tau$  decay and  $\tau^+\tau^-$  annihilations.

$n$	Width (eV)	Lifetimes (s)
1	$29 \times 10^{-3}$	$2.3 \times 10^{-14}$
2	$7.5 \times 10^{-2}$	$8.8 \times 10^{-14}$
3	$5.3 \times 10^{-3}$	$12 \times 10^{-14}$
4	$4.8 \times 10^{-3}$	$14 \times 10^{-14}$

I remind the reader that in addition to the decays which destroy the  $\tau^+\tau^-$  atom there are electromagnetic decays within the atom from an upper level to a lower level (Sec. B6)

$$\psi(\tau^+\tau^- \text{ atom}, n') \rightarrow \psi(\tau^+\tau^- \text{ atom}, n) + \gamma, \quad n' > n \quad (19)$$

### B.5 Production of the $\tau^+\tau^-$ Atom

As noted in Sec. B.1 the production process

$$e^+ + e^- \rightarrow \gamma_{\text{virtual}} \rightarrow \tau^+\tau^- \text{ atom} \quad (20)$$

requires  $S + L = \text{odd number}$ . Furthermore, the produced state must have  $\psi(0) \neq 0$  and hence  $L = 0$ . Therefore,  $S = 1$  and the produced state must be  $n {}^3S_1$ .

The production cross section for the process in Eq. 20 is

$$\sigma(e^+e^- \rightarrow \tau^+\tau^- \text{ atom}) = \frac{3\pi(\hbar c)^2}{4m_\tau^2} \frac{\Gamma_{ee} \Gamma_{tot}}{(E_{tot} - 2m_\tau)^2 + \Gamma_{tot}^2/4} \quad (21)$$

Here  $\Gamma_{ee}$  means  $\Gamma(\text{atom} \rightarrow e^+e^-)$  and is given by Eq. 15c.  $\Gamma_{tot}$  is given by Eq. 18. Thus the production cross section is given by the Breit-Wigner equation with full width at half-height of  $\Gamma_{tot}$  and peak cross section

$$\sigma(e^+e^- \rightarrow \tau^+\tau^- \text{ atom, peak}) = \frac{3\pi(\hbar c)^2}{m_\tau^2} \frac{\Gamma_{ee}}{\Gamma_{tot}} \quad (22)$$

As an example consider  $\tau^+\tau^-$  atom production into the ground state  $1 {}^3S_1$ . Then

$$\Gamma_{ee} = 6.1 \times 10^{-3} \text{ eV} \quad (23a)$$

$$\Gamma_{tot} \approx 2.9 \times 10^{-2} \text{ eV} \quad (23b)$$

$$\Gamma_{ee}/\Gamma_{tot} = 0.21 \quad (23c)$$

and

$$\sigma(e^+e^- \rightarrow \tau^+\tau^- \text{ atom, peak}) \approx 2.4 \times 10^{-28} \text{ cm}^2 \quad (24)$$

This is a large cross section, but the energy spread of the  $e^+$  and  $e^-$  beams,  $\Delta E$ , is much larger than  $\Gamma_{tot}$ . Thus in a tau-charm factory we expect

$$\Delta E \sim 1 \text{ MeV} \quad (F.25)$$

and the effective cross section is

$$\begin{aligned} \sigma(e^+e^- \rightarrow \tau^+\tau^- \text{ atom, effective}) &\sim \\ 2.4 \times 10^{-28} \text{ cm} \times \frac{2.9 \times 10^{-2}}{10^6} &\sim 10^{-35} \text{ cm}^2 \end{aligned} \quad (26)$$

Therefore for a tau-charm factory luminosity of  $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  we expect

$$\tau^+\tau^- \text{ atoms produced per sec.} \sim 10^{-2} \quad (27)$$

### B.6 Detecting $\tau^+\tau^-$ Atoms?

Equation 27 shows that  $\tau^+\tau^-$  atoms can be produced at a reasonable rate at a tau-charm factory. However, we don't know how to detect  $\tau^+\tau^-$  atoms in the ground state. One difficulty, Table I, is the small width,  $2.9 \times 10^{-2} \text{ eV}$ , compared to the 1 MeV energy spread of the beams. The other difficulty is the short lifetime,  $2.3 \times 10^{-14} \text{ s}$ .

Another approach discussed by Moffat (1975) and Avilez *et al.* (1979) is to look for atoms produced in an excited state and look for photons produced in the transition to the ground state. First, suppose  $\tau^+\tau^-$  atoms are produced in the  $2^3S_1$  state. This is a metastable state and will decay by annihilation

$$\tau^+\tau^- \text{ atom} \rightarrow e^+ + e^-, \mu^+ + \mu^-, \text{ hadrons} \quad (28)$$

before it decays to an  $n = 1$ ,  $S$  state of the atom. The next possibility is to produce the  $\tau^+\tau^-$  atom in the  $3^3S_1$  state (Avilez *et al.* 1979) and look for the x-ray photon emitted in the transition

$$3^3S_1 \rightarrow 2^3P_J + \gamma, \quad E_\gamma = 3.3 \text{ kev} \quad (29)$$

where  $J = 0, 1, 2$ .  $E_\gamma$  is the energy of the x-ray.



The width for  $r^+r^-$  atom decay from the atomic state  $a$  to the atomic state  $b$  is

$$\Gamma_{ab} = \frac{4c^2 w^2 \hbar}{m_r c^3} f_{ab} \quad (30)$$

where

$$E_\gamma = \hbar w$$

and  $f_{ab}$  is the oscillator strength, a number of order 0.1 or less. For our purpose it is useful to rewrite Eq. 30 as

$$\Gamma_{ab} = \frac{4\alpha E_\gamma^2}{m_r c^2} f_{ab} \quad (31)$$

and to use Eq. 2 to obtain

$$\Gamma_{ab} = \frac{\alpha^5 m_r c^2}{4} \left[ \frac{1}{n_b^2} - \frac{1}{n_a^2} \right]^2 f_{ab} \quad (32)$$

If  $a$  is an  $n \ ^3S_1$  state, then comparing Eq. 32 with Eq. 15c and then Eq. 18

$$\Gamma_{ab} < \Gamma_{tot}(n \ ^3S_1) \quad (33)$$

Hence in  $r^+r^-$  atoms an  $n \ ^3S_1$  state is more likely to decay by annihilation than make an x-ray transition to a lower atomic state.

For example, in the specific case of Eq. 29

$$f_{ab} = 0.42 \quad (34)$$

from Table 45 of Condon and Shortley (1959). Hence from Eq. 32

$$\Gamma(3 \ ^3S_1 \rightarrow 2 \ ^3P_J) = 7.4 \times 10^{-6} \text{ eV} \quad (35)$$

and from Table I

$$\Gamma_{tot}(3 \ ^3S_1) = 5.3 \times 10^{-3} \quad (36)$$

Dividing Eq. 35 by Eq. 36

$$\frac{\text{Probability}(3 \ ^3S_1 \rightarrow 2 \ ^3P_J)}{\text{Probability}(3 \ ^3S_1 \text{ annihilation})} = 1.4 \times 10^{-3} \quad (37)$$

Therefore, if we made  $r^+r^-$  atoms in the  $3 \ ^3S_1$  state only  $1.4 \times 10^{-3}$  of them will make an x-ray transition before decaying. Furthermore, the production rate in Eq. 27

is reduced because for the  $3 \ ^3S_1$  state

$$\sigma(e^+e^- \rightarrow \tau^+\tau^- \text{ atom, effective}) \sim 3 \times 10^{-27} \quad (38)$$

For a luminosity of  $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ , there will be about  $4 \times 10^{-7}$  transitions per second of the form

$$3 \ ^3S_1 \rightarrow 2 \ ^3P_J + \gamma ,$$

a rate much too small to detect.

Finally, as pointed out by Avilez *et al.* (1979) the transition

$$2 \ ^3P_J \rightarrow 1 \ ^3S_1 + \gamma , E_\gamma = 17.6 \text{ keV} \quad (39)$$

has the much more favorable ratio

$$\frac{\text{Probability } (2 \ ^3P_J \rightarrow 1 \ ^3S_1)}{\text{Probability } (2 \ ^3P_J \text{ annihilation})} = 0.16 \quad (40)$$

But  $2 \ ^3P_J$  states cannot be produced directly by

$$e^+ + e^- \rightarrow \tau^+\tau^- \text{ atom}$$

as discussed in Sec. B5.

Summarizing, with a tau-charm factory we can make  $\tau^+\tau^-$  atoms but we don't know how to detect their production. Beyond that problem, is the yet deeper question of what physics we can do with  $\tau^+\tau^-$  atoms.

## C. The $\tau^-$ -Nucleus Atom

### C.1 Static Properties

The  $\tau^-$ -Nucleus atom in analogy to the  $\mu^-$ -Nucleus atom consists of a  $\tau^-$  and  $Z - 1$   $e^-$ 's around a nucleus of charge  $Z$  and atomic number  $A$ . In the  $\tau - N$  atom the reduced mass of the  $\tau$  is

$$m = \frac{m_\tau m_N}{m_\tau + m_N} \quad (41)$$

and ignoring the fine structure and effects of the non-zero nuclear radius, the  $n^{\text{th}}$  energy level is

$$\begin{aligned} E_n &= -\frac{m_e c^2 \alpha^2 Z^2}{2n^2} \left( \frac{m_N}{m_\tau + m_N} \right) \\ &= -\frac{47.4 Z^2}{n^2} \left( \frac{m_N}{m_\tau + m_N} \right) \text{ keV} \end{aligned} \quad (42)$$

The Bohr radius is given by

$$a_0 = \frac{\hbar^2}{m_r e^2} \left( \frac{m_r + m_N}{m_N} \right) \\ = 1.52 \times 10^{-12} \left( \frac{m_r + m_N}{m_N} \right) \quad (43)$$

The average value of the radius of the  $\tau^-$  orbit is

$$\bar{r} = \frac{a_0}{2Z} [3n^2 - \ell(\ell + 1)] \quad (44)$$

ignoring the effect of the non-zero nuclear radius. Thus for  $Z \geq 4$  and small  $n$ ,  $\bar{r}$  is of the order of  $10^{-13}$  cm or less. Then particularly for  $S$  states, the  $\tau^-$  is inside the nucleus part of the time. This effect reduces the magnitude of  $E_n$ . This is illustrated in Table II taken from Strobel and Wills (1983) who limit their calculations to  $Z \leq 12$ .

Table II. Energy levels of the 1S and 2P states of a  $\tau^-$  nucleus atom in keV.  $E_p$  is for a point nucleus and  $E_{ex}$  is for an extended size nucleus. The proton is always taken as a point. These calculations are from Strobel and Wills (1983) and are corrected for the  $\tau$  mass of  $1777 \text{ MeV}/c^2$ .

Nucleus	1S		2P	
	$E_p$	$E_{ex}$	$E_p$	$E_{ex}$
$^1_1\text{H}$	-16.3	-16.3	-4.1	-4.1
$^4_2\text{He}$	-128	-118	-32	-32
$^9_4\text{Be}$	-625	-474	-156	-155
$^{24}_{12}\text{Mg}$	-6310	-2940	-1580	-1460

### C.2 Atomic Transitions

Table III, also from Strobel and Wills (1983) gives the energy of the emitted x-ray and the lifetime for the transition

$$2P \rightarrow 1S + \gamma \quad (45)$$

We see that the lifetime of the 2P-1S transition is much shorter than the  $\tau$  lifetime of  $3.0 \times 10^{-13}$  s, Eq. 10b. Therefore, once the  $\tau^-$  is in the 2P state, the  $\tau^-$  will make the transition to the 1S state before it decays. Of course, the experimental question is how to get the  $\tau^-$  into that state or other low lying states.

Table III. Transition energy and lifetime for  $2P \rightarrow 1S$  in a  $\tau^-$ -nucleus atom. From Strobel and Wills (1983) corrected for  $\tau$  mass of  $1777 \text{ MeV}/c^2$ .

Nucleus	$E(2P \rightarrow 1S)$ keV	Lifetime ( $2P \rightarrow 1S$ ) s
${}^1_1\text{H}$	12.2	$5.0 \times 10^{-14}$
${}^4_2\text{He}$	66	$2.1 \times 10^{-15}$
${}^9_4\text{Be}$	319	$2.3 \times 10^{-16}$
${}^{24}_{12}\text{Mg}$	1460	$2.6 \times 10^{-17}$

### C.3 $\tau^-$ Capture in the Nucleus

An interesting result of the  $\tau^-$  orbit passing through the nucleus is that the  $\tau^-$  can interact with the protons in the nucleus

$$\tau^- + p \rightarrow \nu_\tau + n \quad (46)$$

in analogy to  $e^-$  and  $\mu^-$  capture. Ching and Oset (1991) have studied the process for heavy nuclei where the capture rate is greatest. They find for  ${}^{208}_{82}\text{Pb}$  the following captive rates

$$\begin{aligned} \Gamma(\tau \text{ capture from } 1S) &= 2.5 \times 10^9 \text{ s}^{-1} \\ \Gamma(\tau \text{ capture from } 2S) &= 2.3 \times 10^9 \text{ s}^{-1} \\ \Gamma(\tau \text{ capture from } 2P) &= 5.2 \times 10^9 \text{ s}^{-1} \end{aligned} \quad (47)$$

However from Eq. 10b

$$\Gamma(\tau \text{ decay}) = 1/T_\tau = 3.4 \times 10^{12} \text{ s}^{-1}$$

Therefore, even in the best case in Eq. 47 there is only a  $10^{-3}$  chance that a  $\tau$  will be captured with  $\tau^- + p \rightarrow \nu_\tau + n$  compared to the chance that the  $\tau^-$  decays.

Morley (1992) has given an interesting discussion of the  $\tau^- - U$  atom. He discusses in some detail the process of the  $\tau^-$  slowing down in solid uranium, the  $\tau^-$  being captured in a high atomic orbit, and then cascading down to a low orbit.

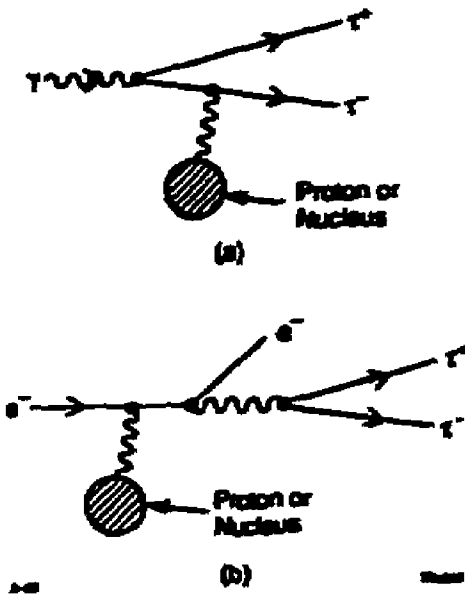


Figure 3

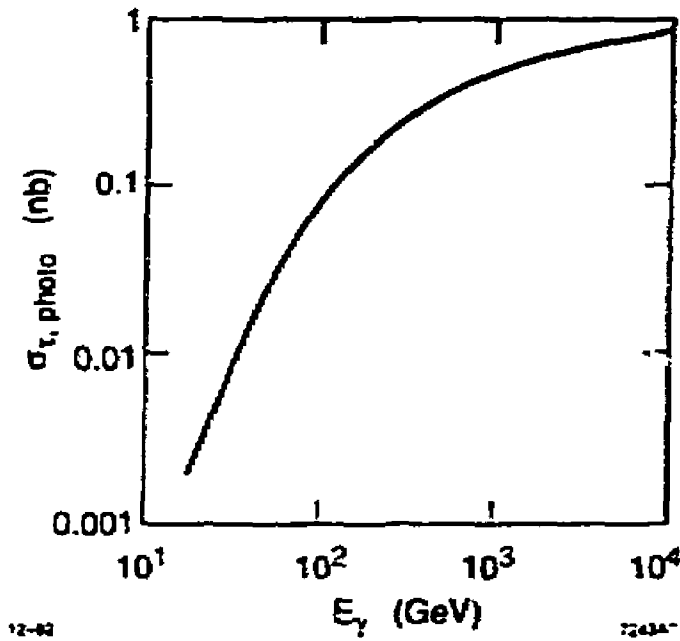


Figure 4

## D. Photoproduction of $\tau^2$ s

$\tau$  pairs can be produced by photoproduction Tsai (1979)

$$\gamma + N \rightarrow \tau^+ + \tau^- + N' \quad (48)$$

as shown in Fig. 3a and by electroproduction (virtual photoproduction)

$$e^- + N \rightarrow e^- + \tau^+ + \tau^- + N' \quad (49)$$

as shown in Fig. 3b. Here  $N$  is a target proton or nucleus and  $N'$  is the final hadronic state. The cross section,  $\sigma_{\tau, photo}$ , for a proton target is given in Fig. 4 as a function of energy.

As an example, suppose that at SLAC one photoproduces  $\tau$  pairs with a photon beam of maximum energy 40 GeV and intensity  $10^{12}$   $\gamma/s$ . Then in a 1 radiation length hydrogen target using an average cross section of  $3 \times 10^{-36}$   $\text{cm}^{-2}$ , the  $\tau$  pair production rate would be

$$\tau \text{ pairs}/s \sim 100 \quad (50)$$

Thus in a one month run of effective length  $10^6$  s one could produce  $10^8$   $\tau$  pairs.

There has been very little discussion of the physics that might be done with photoproduced  $\tau$  pairs. Tsai (1992) has suggested that a  $\nu_\tau$ ,  $\bar{\nu}_\tau$  beam could be made this way.

*It is useful to remember that in  $\tau$  pair photoproduction the basic process is*

$$\gamma + \gamma_{\text{virtual}} \rightarrow \tau^+ + \tau^- \quad (51)$$

in contrast to production by  $e^+e^-$  annihilation where the basic process is

$$\gamma_{\text{virtual}} \rightarrow \tau^+ + \tau^- \quad (52)$$

In the next section on the proposal for production of  $\tau$  pairs in heavy ion collisions the basic process is

$$\gamma_{\text{virtual}} + \gamma_{\text{virtual}} \rightarrow \tau^+ + \tau^- \quad (53)$$

Therefore some of the goals of heavy ion tau physics may be applicable to photoproduction  $\tau$  physics.

Returning to the first topic in this paper,  $\tau^+\tau^-$  atoms, consider

$$\gamma + N \rightarrow \tau^+\tau^- \text{ atom} + N' \quad (54)$$

Olsen (1986) has discussed the relativistic production of positronium

$$\gamma + N \rightarrow e^+e^- \text{ atom} + N' \quad (55)$$

He shows that at high energy there is the crude relationship

$$\sigma(\gamma + N \rightarrow \ell^+\ell^- \text{ atom} + N') \sim \alpha^3 \sigma(\gamma + N \rightarrow \ell^+ + \ell^- + N') \quad (56)$$

The  $\alpha^3$  comes from  $\alpha_0^{-3}$  (Eq. 3) involved in the phase space factor for the atom relative to the phase space factor for the unbound pair. Applying Eq. 56 to the unbound  $\tau$  pair cross section in Fig. 4 we see that the cross section for photoproduction of a  $\tau^+\tau^-$  atom is in the range of  $10^{-39}$  to  $10^{-41}$  cm<sup>2</sup>, much too small to use.

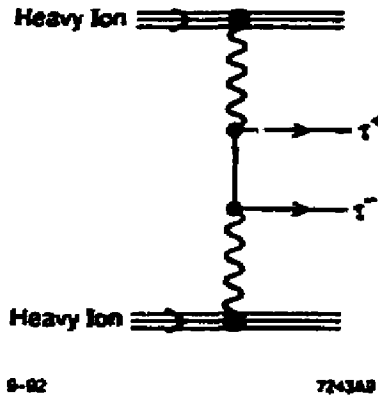


Figure 5

## E. $\tau$ Pair Production in Heavy Ion Collisions

There have been a number of papers on the production of  $\mu$  pairs and  $\tau$  pairs in relativistic collisions of heavy ions (Botzcher and Strayer 1990, del Aquila *et al.* 1991, Almeida *et al.* 1991, Amaglobeli *et al.* 1991). The overall process is

$$\text{ion} + \text{ion} \rightarrow \tau^+ + \tau^- + \text{ion} + \text{ion} \quad (57)$$

as shown in Fig. 5. And the basic process is given in Eq. 53.

At sufficiently high energies the cross section will be of the order of

$$\sigma_0(\text{coherent}) = \frac{\alpha^4 (\hbar c)^2 Z^4}{m_p^2 c^4} \quad (58)$$

The charge  $Ze$  at each ion- $\gamma$ -ion vertex entering the amplitude as  $Ze$ . At lower energies the momentum transfer to the ions becomes large and the process has an incoherent cross section of the order of

$$\sigma_0(\text{incoherent}) = \frac{\alpha^4 (\hbar c)^2 Z^2}{m_p^2 c^2} \quad (59)$$

Bottcher and Strayer (1990) have studied the production cross section when the ion is  $^{197}_{79}\text{Au}$ . First consider  $\text{Au} + \text{Au}$  at the LHC with 7.5 TeV per proton which is 3.0 TeV per nucleon. Extrapolating the Bottcher and Strayer calculation

$$\sigma(3.0 \text{ TeV/nucleon}) \approx 40\sigma(\text{coherent}) \approx 0.5 \text{ mb} \quad (60)$$

On the other hand, at a RHIC energy of 0.25 TeV per proton which is 0.1 TeV per nucleon, they obtain

$$\begin{aligned} \sigma(0.1 \text{ TeV/nucleon}) &\approx 0.2\sigma_0(\text{coherent}) \\ &\approx 2.8 \times 10^{-3} \text{ mb} \end{aligned} \quad (61)$$

This is still larger than

$$\sigma_0(\text{incoherent}) = 2.0 \times 10^{-5} \text{ mb} \quad (62)$$

hence there is still some coherence at 0.1 TeV/nucleon. As another example del Aguila *et al.* (1991), consider the  $^{20}_{8}\text{Ne}$  ion. For the LHC they find a cross section of 1 mb, similar to Eq. 60.

If we take the proposed LHC heavy ion luminosity as  $10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ , a 1 mb cross section for  $10^7 \text{ s/year}$  gives a yield of  $10^8$   $\tau$  pairs per year, comparable to a tau-charm factory. Can these pairs be used to do  $\tau$  physics? This has been partially discussed by del Aguila *et al.* (1991). They point out that most of the  $\tau$  pair events will be clean with the ions themselves proceeding along the beam pipe and no additional particles produced. But I think there is a problem in non- $\tau$  events contaminating the data sample, since the cross section for non- $\tau$  events is so much larger. It may be that the only clean samples are the old faithful

$$\tau^+ + \tau^- \rightarrow e^\pm + \mu^\mp + \text{missing energy} \quad (63)$$

events.



There have been two suggestions for the tau physics that might be done with  $\tau$  pairs produced in heavy ion collisions. The suggestion of del Aguila *et al.* (1991) is that one can measure the anomalous magnetic moment of the  $\tau$ .

$$\mu_{\tau}(\text{anom}) = a_{\tau} \frac{e\hbar}{2m_{\tau}c} \quad (64a)$$

$$a_{\tau} = \frac{\alpha}{2\pi} + \sum_{n \geq 1} c_n \alpha^n \quad (64b)$$

to about 1%. And one can also look for unconventional behavior of the  $\tau - \gamma - \tau$  vertex such as an electric dipole moment.

Amaglobeli *et al.* (1991) have suggested using high rate  $\tau$  production to look for the unconventional decay

$$\tau^{-} \rightarrow \mu^{-} + \mu^{+} + \mu^{-} \quad (65)$$

A  $\tau$  pair event with one such decay would stand out in the data sample. It would have 4 or 6 charged particles, with 3 of the particles being  $\mu$ 's whose invariant mass is the  $\tau$  mass.

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