Production of $(\tau^+\tau^-)$ at VEPP-4M and BEPCII

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Introduction

$(\tau^+\tau^-)$ is an electromagnetically bound state of τ^+ and τ^- similar to positronium (e^-e^+) and $(\mu^+\mu^-)$. It was theoretically predicted in 1975 (J.W. Moffat, *Phys. Rev. Lett.* **35**, 1605 (1975)) but never found experimentally. Our primary aim is to show the possibility of the production of $(\tau^+\tau^-)$ at VEPP-4M and BEPCII even in the present experimental conditions.

The energy levels are given as for hydrogen atom with a reduced mass $m_\tau/2$

$$E_n = -\frac{m_\tau \alpha^2}{4n^2} = -\frac{25}{n^2}\ KeV. \tag{1}$$

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Decay channels

There are two classes of decay channels. In the first class the τ^- or τ^+ decay through the weak interaction and the atomic state disappears. The decay width is

$$\Gamma((\tau^+\tau^-), \tau \ decay) = 2\Gamma_\tau = \frac{2}{\tau} = 4.53 \times 10^{-3} \ eV, \qquad (2)$$

where Γ_τ is the total decay width of tau lepton and τ is it's lifetime

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Electromagnetic decay

In the second class of decay channels the τ^- and τ^+ annihilate. The annihilation requires that the atomic wave function $\Psi(r)$ be unequal to 0 at r=0 *i.e.* $\Psi(0) \neq 0$. Here r is the distance between the τ^- and τ^+. Therefore in lowest order, annihilation occurs only in L=0 state, *i.e.* S state.

$$(\tau^+\tau^-) \to \gamma + \gamma + \gamma, \tag{3}$$

$$\Gamma((\tau^+\tau^-) \to 3\gamma) = \frac{2(\pi^2 - 9)\alpha^6 m_\tau}{9\pi n^3} = \frac{1.95 \times 10^{-5}}{n^3}\ eV. \tag{4}$$

$$(\tau^+\tau^-) \to e^- + e^+, \tag{5}$$

$$(\tau^+\tau^-) \to \mu^+ + \mu^-, \tag{6}$$

$$\Gamma((\tau^+\tau^-) \to e^- + e^+) = \frac{\alpha^5 m_\tau}{6n^3} = \frac{7.04 \times 10^{-3}}{n^3}\ eV. \tag{7}$$

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Hadron decay

Finally there is hadron channel

$$(\tau^+\tau^-) \to hadrons. \quad (8)$$

For $(\tau^+\tau^-)$ we can calculate the width of this channel using colliding beams e^-e^+ annihilation data at $E_{tot} \sim 2m_\tau$

$$\sigma(e^- + e^+ \to hadrons) \approx 2\sigma(e^- + e^+ \to \mu^+ + \mu^-). \quad (9)$$

Therefore

$$\Gamma((\tau^+\tau^-) \to hadrons) \approx 2\Gamma_{ee} = 1.41 \times 10^{-2} eV. \quad (10)$$

Neglecting $\Gamma((\tau^+\tau^-) \to 3\gamma)$ we get the total width

$$\Gamma_n \approx \Gamma((\tau^+\tau^-), \tau\ decay) + 4\Gamma_{ee} = \left(4.5 + \frac{28.1}{n^3}\right) \times 10^{-3} eV. \quad (11)$$

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Production cross section of $(\tau^+\tau^-)$

According to the Breit-Wigner equation

$$\sigma_n(e^- + e^+ \to (\tau^+\tau^-)) = \frac{3\pi}{4m_\tau^2}\frac{\Gamma_{een}\Gamma_n}{(E-2m_\tau)^2+\Gamma_n^2/4}. \qquad (12)$$

The peak cross section is

$$\sigma_n(e^- + e^+ \to (\tau^+\tau^-), peak) = \frac{3\pi}{m_\tau^2}\frac{\Gamma_{een}}{\Gamma_n}. \qquad (13)$$

Taking into account the radiative corrections we get

$$\sigma_r^{(n)} = \sigma_n \exp\left(-\frac{4\alpha}{\pi} ln\frac{m_\tau}{m_e} ln\frac{m_\tau}{\Gamma_1}\right). \qquad (14)$$

Radiative production of $(\tau^+\tau^-)$

If initial e^- or e^+ radiate a soft photon

$$\frac{\omega}{m_\tau} \ll 1. \qquad (15)$$

The criteria of perturbative theory application in this case are

$$\alpha ln\frac{m_\tau}{m_e} \ll 1, \qquad \frac{\alpha}{\pi} ln\frac{m_\tau}{m_e} ln\frac{m_\tau}{\omega_{min}} \ll 1. \qquad (16)$$

We can put ω_{min} equal to the decay width of 1^3S_1 state of $(\tau^+\tau^-)$. The cross section of radiative production of $(\tau^+\tau^-)$ is

$$\sigma_{rad}^{(n)} = \frac{\pi}{2n^3}\frac{\alpha^6}{m_\tau \omega_{min}}\left(2ln\frac{m_\tau}{m_e} - 1\right). \qquad (17)$$

As the electrons and positrons in accelerator beams have some energy spread so we should use an average value of cross section

$$< \sigma >= \int \sigma(E)\rho(E)dE. \qquad (18)$$

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Production of $(\tau^+\tau^-)$ at VEPP-4M

At VEPP-4M we have $\triangle E = 1.07\ MeV$.

$$< \sigma_r^{(n)} >= \sigma_r^{(n)} \frac{\pi}{2} \frac{\Gamma_n}{\triangle E}, \tag{19}$$

$$< \sigma_{rad}^{(n)} >= \sigma_{rad}^{(n)} \frac{\omega_{min}}{\triangle E} \left(ln \frac{\triangle E}{\omega_{min}} - 1 \right), \tag{20}$$

$$< \sigma >= \sum_n < \sigma^{(n)} >= \sum_n (< \sigma_r^{(n)} > + < \sigma_{rad}^{(n)} >) = 19.31 pb. \tag{21}$$

Having $L = 1.605\ pb^{-1}$ at $< E >= 1776.896\ MeV$

$$N_{(\tau\tau)} =< \sigma > L \simeq 31\ events. \tag{22}$$

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At $< E >= 1776.896\ MeV$ 6 $\tau\tau$ events were reported.

$$N_e = 2N_{\tau\tau}B_\tau \simeq 2\ events. \qquad (23)$$

Here $B_\tau = 0.1785$ is the branching ratio $\tau \to e\nu\overline{\nu}$.
1. Weak decay of the constituents of $(\tau^+\tau^-)$ similarly as $\tau^+\tau^-$.
2. Annihilation: $(\tau^+\tau^-) \to e^-e^+$, collinear & $E_{cm} \simeq 2m_\tau$.
These e^-e^+ are eliminated by the cut on the total energy measured at KEDR, which is required to be $E < 2200\ MeV$.

$$N_e^{(\tau\tau)} = \sum_n < \sigma^{(n)} > L\left(2B_\tau\frac{\Gamma_\tau}{\Gamma_n}\right) \simeq 1.3\ events. \qquad (24)$$

Observed number of $\tau^+\tau^-$ is 2 and $(\tau^+\tau^-)$ is 31; $\sigma_{\tau\tau}^{obs} \simeq 1.3\ pb$. Big error bars in the result of KEDR indicate that this reduction of cross section will have no significant effect on the determination of the mass of tau lepton. 31 $(\tau^+\tau^-)$ events detected by KEDR is a first experimental evidence of the existence of $(\tau^+\tau^-)$.

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Production of $(\tau^+\tau^-)$ at BEPCII

At BEPCII $\triangle E = 1.4\ MeV$ so the total cross section will be

$$< \sigma >= 14.97\ pb. \tag{25}$$

Number of $(\tau^+\tau^-)$ which will be produced at BEPCII having luminosity $L = 63\ pb^{-1}$ are

$$N =< \sigma > L = 943\ events. \tag{26}$$

The best way to observe $(\tau^+\tau^-)$ is through the detection of ee or $\mu\mu$ events at BESIII. For $(\tau^+\tau^-)$ there are two ways to decay into e^-e^+ pair as it was discussed in the previous section: Annihilation of $(\tau^+\tau^-)$ into e^-e^+ pair will give a clear signature of the existence of $(\tau^+\tau^-)$.

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The cross section $\sigma(e^-e^+ \to \tau^+\tau^-)$ just below τ pair threshold at 3.5538 GeV, with the account of all the radiative corrections is

$$\sigma(e^- + e^+ \to \tau^+ + \tau^-) = 110\ pb. \tag{27}$$

Branching ratio for $\tau \to e\nu\overline{\nu}$ is $B_\tau = 0.1785$ where as for $(\tau^+\tau^-) \to e^-e^+$ is $B_b = 0.22$, so we have

$$\sigma(e^-e^+ \to \tau^+\tau^- \to e^-e^+) = \sigma(e^-e^+ \to \tau^+\tau^-)B_\tau^2 = 3.5\ pb. \tag{28}$$

$$\sigma(e^-e^+ \to (\tau^+\tau^-) \to e^-e^+) = \sum_n < \sigma^{(n)} > \left[\left(B_\tau \frac{\Gamma_\tau}{\Gamma_n}\right)^2 + \frac{\Gamma_{een}}{\Gamma_n}\right] = 2.9\ pb. \tag{29}$$

Comparing "(28)" and "(29)" we see that free $\tau^+\tau^-$ pair contributes 55% and $(\tau^+\tau^-)$ contributes 45% to the ee events. Almost the same will be true for $\mu\mu$ events. Detection of extra ee and $\mu\mu$ events contributed by $(\tau^+\tau^-)$ will be a direct evidence for the existence of $(\tau^+\tau^-)$.

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Conclusion

It follows from our estimates for $(\tau^+\tau^-)$ decay rates and production cross section that $(\tau^+\tau^-)$ gives some contribution to the electron (positron) events detected in a recent experiment of KEDR collaboration at VEPP-4M. They have observed 2 electron (positron) events at $< E >= 1776.896 MeV$, we have shown that almost 1.3 of these events are a decay product of $(\tau^+\tau^-)$ atom which ultimately means that almost 31 $(\tau^+\tau^-)$ atoms were produced in this experiment. It is a first ever experimental evidence for the existence of $(\tau^+\tau^-)$. This result will be improved in a coming experiment at BEPCII. $(\tau^+\tau^-)$ decays will give 45% contribution to ee and $\mu\mu$ events at BEPCII. It would be possible to observe decay products of about 943 $(\tau^+\tau^-)$ atoms at BEPCII using BESIII.