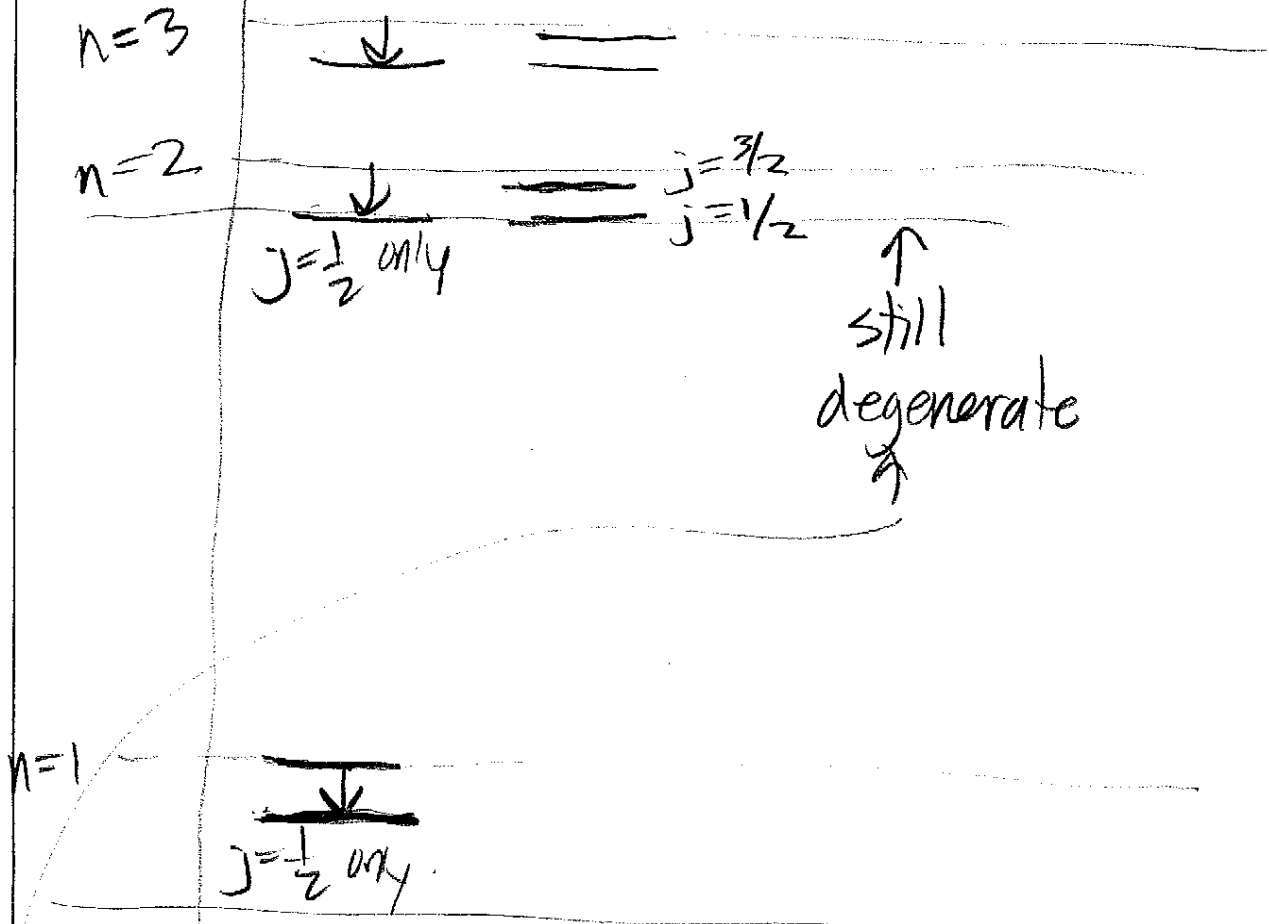


(proton spin neglectable)



l=0 l=1
s p

$$\Delta E = -\alpha^4 mc^2 \frac{1}{4n^4} \left(\frac{2n}{j + \frac{1}{2}} - \frac{3}{2} \right)$$

$$\frac{v}{c} = \alpha$$

QFT "Broken" by Higher order diagrams
"Lamb Shift" $\propto^5 mc^2 \left\{ k(l, j, l) \pm \frac{1}{\pi(j + \frac{1}{2})(l + \frac{1}{2})} \right\}$

Positronium → "Parentage" → → Combine spins
L + (combined spin)

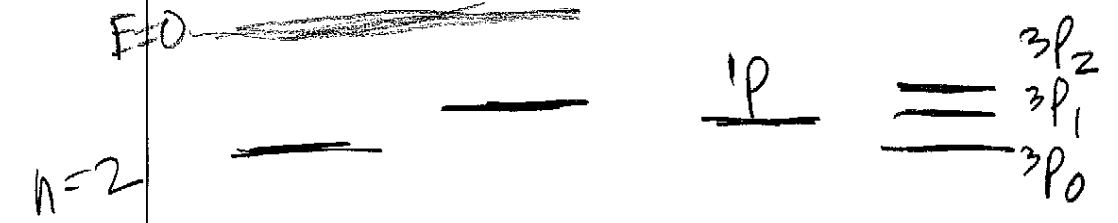


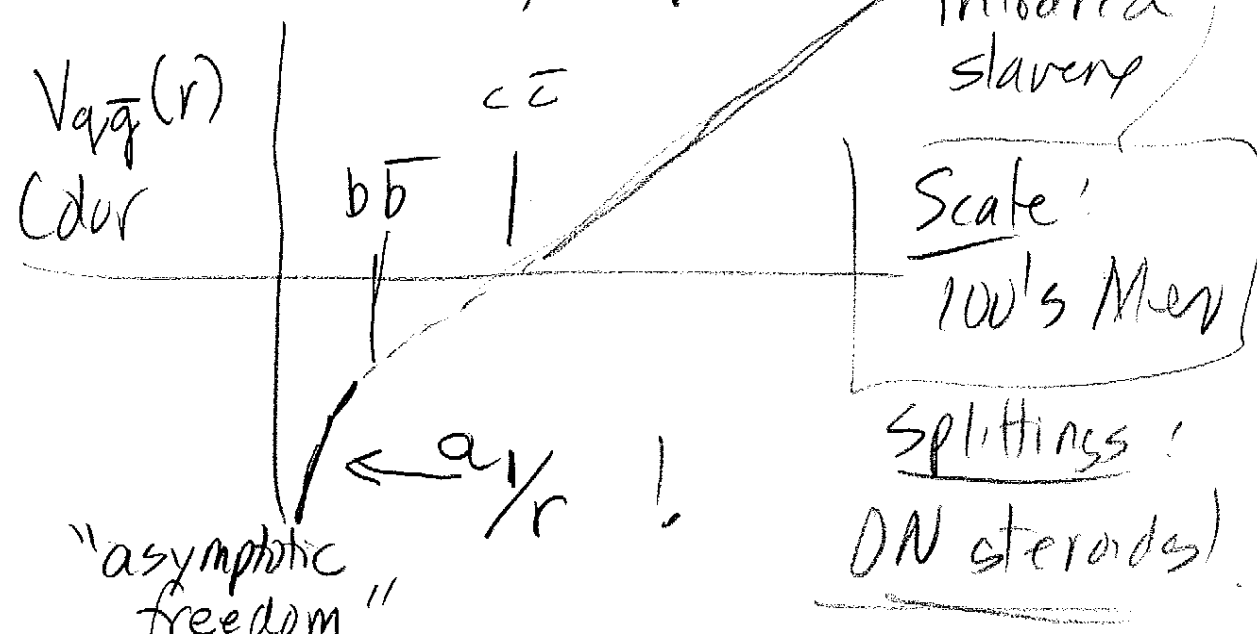
Fig 5.6

$1S_0$ $3S_1$ $1P_1$ $3P$

$(2S+1) \binom{2L+1}{S_{\text{fact}}}$

Why $c\bar{c}$ $b\bar{b}$

heavy quark



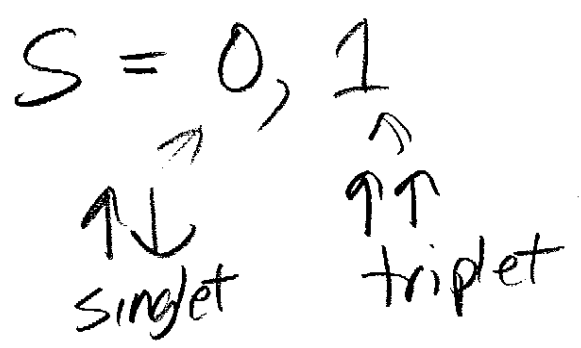
Positronium, Heavy Quark Mesons



$$\mu = \frac{m_e m_e}{m_e + m_e} = \frac{1}{2} m_e$$

① BE: $-\frac{1}{2} \frac{\alpha^2 \mu c^2}{n^2}$: $\frac{1}{2}$ hydrogen

② Spin: now + guy big deal



"S" states : L=0

$^1S, ^3S$ J=0, 1 = S

"P" states J=1 singlet

$^1P, ^3P$...
J=0, 1, 2

How do you make these things?

$(f\bar{f})$ bound states...

$$C : (-1)^{l+s} \quad \underline{\text{note, no } J!}$$

$l=0$: easiest to make

why?

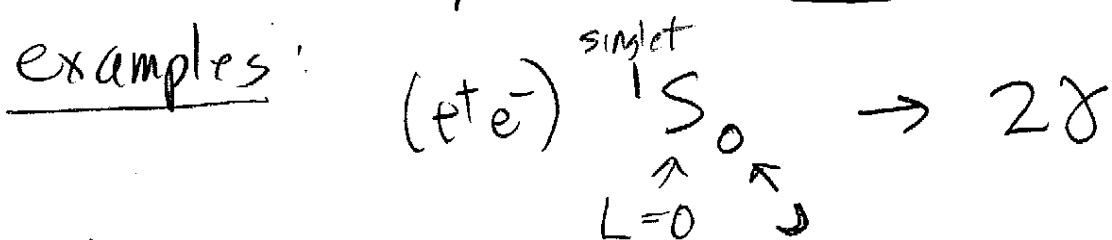
NON ZERO
WAVE FUNCTION
AT $\text{sep} = 0$

$$C = (-1)^s$$

"singlet": $S=0$ $C = (-1)^0 = 1$

Decays to : 2γ

examples:



"para-positronium", $\tau = 0.124 \text{ ns}$

used in PET

$e^+ \rightarrow$
 $e^- \leftarrow$

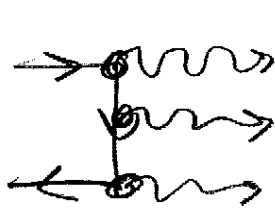
$\gamma \leftarrow$ $\gamma \rightarrow$ $E_\gamma = m_e c^2$

Also: $\pi^0, \pi, \pi', \pi_c(cc), \pi_b(bb)$.

"triplet": $S=1$ $C=(-)^1 = -1$
 $(L=0)$ Decays into: 3γ

$(e^+e^-) {}^3S_1 \rightarrow 3\gamma$

$\tau = 0.139 \mu s$



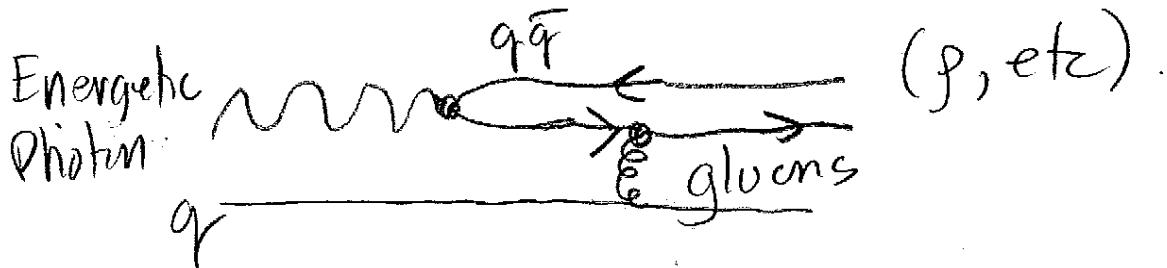
$\sum E_{\gamma i} = 2m_e c^2$

$q\bar{q}$: $\rho, \omega, \phi, \psi/\psi', \gamma$
 $\underbrace{\quad}_{u\bar{u}/d\bar{d}} \quad s\bar{s} \quad c\bar{c} \quad b\bar{b}$

CRUCIAL POINT

$(-1)^1 = -1$ means these states "mix" with photon.

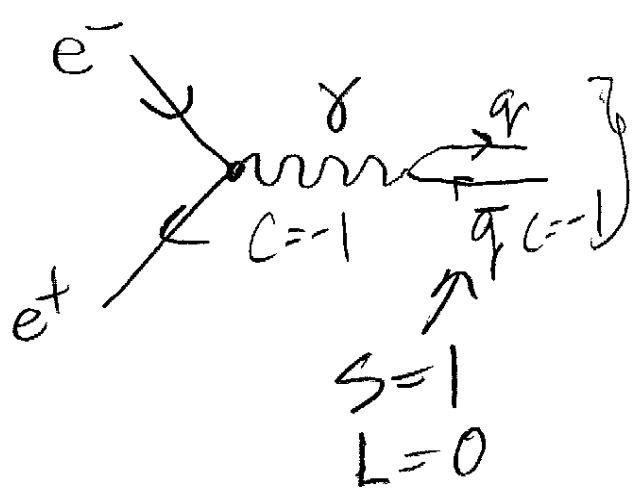
① Photon is also a hadron (!)



② "Resonances" in e^+e^- scattering.



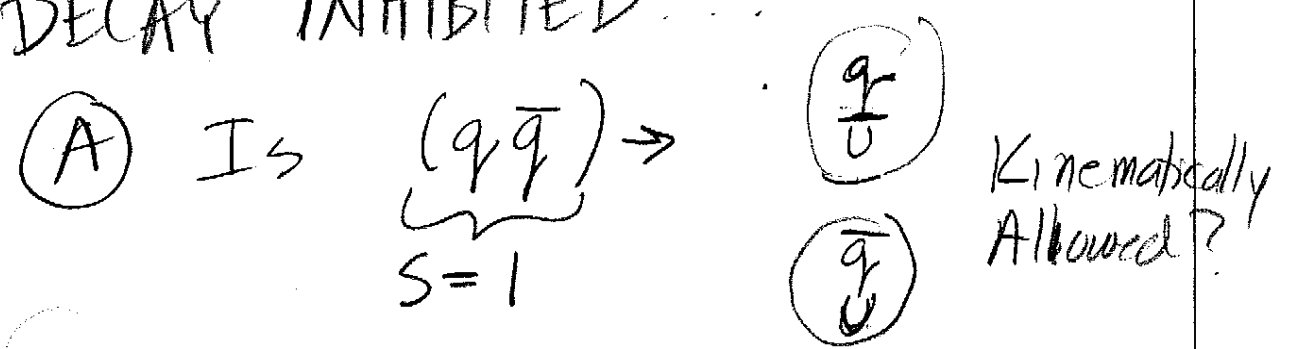
If $E_{e^+} + E_{e^-}$ just right ...



most famous J/ψ : $m_{J/\psi} c^2 = 3096.916 \text{ MeV}$

(figure)

- EASY TO MAKE.
- DECAY INHIBITED.



look

J/ψ : $m_{J/\psi} c^2 = 3096.916 \text{ MeV}$
 $\frac{c}{v} D^0, 2m_{D^0} c^2 = 3729.7 \text{ MeV}$

Interesting: look at other mesons. (Homework)