Physics 129: Particle Physics
Lecture 18: Quarkonium

Oct 27, 2020

- Suggested Reading:
  - Thomson 10.8
  - Griffiths 5.1-5.7
- Announcements:
  - Quiz 3 and Quiz 4 delayed one week: See updated bCourses schedule

Introduction

- We have seen that hadrons are built from constituents
  - SU(3): Patterns consistent with mesons as $q\overline{q}$ bound states and baryons as qqq bound states
  - Deep Inelastic Scattering (DIS): Proton composed of partons
    - Partons probed using leptons have spin-$\frac{1}{2}$ and charges consistent with the quarks
    - These charged partons carry about half the momentum of the proton
    - Postulate that the other half is carried by gluons that don't feel the EM or weak interaction
- DIS allowed us to measure the probability that a given parton carries a fraction x of the proton's momentum
  - This quantity is related to the wave function of partons within the proton
- Unfortunately, calculating the wave functions for hadrons not yet possible in QCD
  - α_S is large: perturbation theory doesn't work
  - Quarks are relativistic: need a complete QFT treatment
- There is hope using latttice QCD: an area of active research

Gaining physical intuition on how quarks are bound into hadrons?

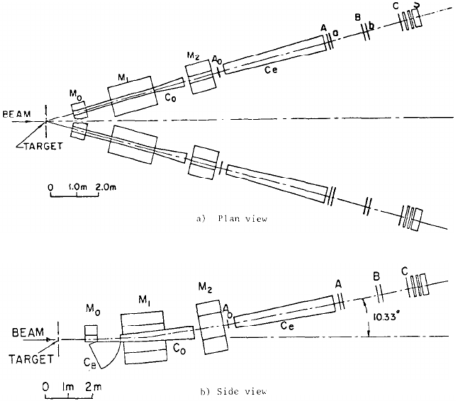
- Look at a system with heavier quarks
  - If quark heavy enough, it won't be very relativisic
- Rather than calculating potential from first principles (as we do using the Coulomb potential when we find the wave functions for Hydrogen), try to measure the form of the potential by looking at the bound state energies
  - This is how the hydrogen atom was first studied: measure the energy levels
- The best system for doing this: Quarkonium
  - Bound states of two heavy quarks (charm or bottom)
  - NB: No bound states of the top quark exist since the quark decays too rapidly to create a bound state
- Today's lecture:
  - Review the history of how the charmonium and bottomonium were discovered
  - Learn what these systems can tell us about the force that holds the quarks inside hadrons

Discovery of the J/ψ

- Nov 1974: mass=3.1 GeV resonance observed simultaneously in $p + Be \to e^+e^-X$ at BNL and e^+e^- annihilation at SLAC
  - BNL team named it the J
  - SLAC team names it the ψ

  Compromise: call it the J/ψ
- Incredible thing about the J/ψ: it's very narrow
  - Not consistent with expectations for a standard strong decay
    - Must be conserved quantum number that suppresses the decay
- It turns out that strong decays are possible, but there is a suppression factor in the matrix element
  - We'll see why in a few minutes

Discovery of the J/ψ in Hadron Collisions (I)



Fixed target experiment at BNL: proton collisions on Be target

- Study e^+e^- pairs produced in pBe collisions
  - Be to minimize multiple scattering
- Goal: Measure the leptonic widths of meson decays
  - Two arm spectrometer
  - cherenkov counters to separate electrons from hadrons
- Measure $M_{e^+e^-}$:

$$m^2_{e^+e^-} = m_1^2 + m_2^2 + 2\left[E_1E_2 - p_1p_2\cos(\theta_1+\theta_2)\right]$$

Discovery of the J/ψ in Hadron Collisions (II)

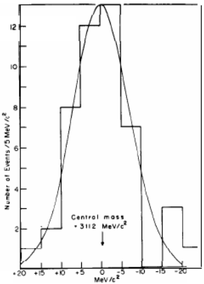


Fig. 12b. The measurement of the width of the J. The width is shown to be less than 5 MeV.

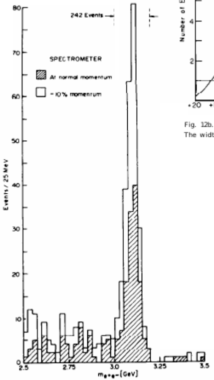
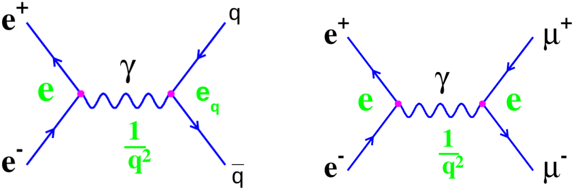


Fig. 12a Mass spectrum for events in the mass range $2.5 < m_{ee} < 3.5$ GeV/c. The shaded events correspond to those taken at the normal magnet setting, while the unshaded ones correspond to the spectrometer magnet setting at - 10% lower than normal value.

- Narrow peak in e^+e^- spectrum
- Width consistent with exp resolution (~ 20 MeV)
  - Real width $\Gamma_J << 20$ MeV
- Question:
  Why is the resonance so narrow?
- Low statistics available makes more insightful measurements impossible
  - Turn now to e^+e^- annihilation to continue the story

A different approach: $e^+e^- \rightarrow hadrons$

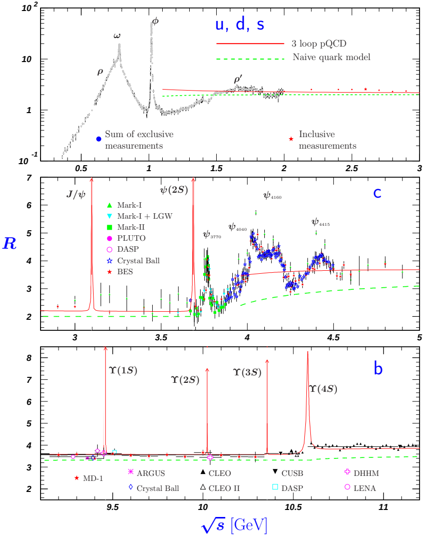


- Describe process $e^+e^- \rightarrow hadrons$ as $e^+e^- \rightarrow q\bar{q}$ where q and $\bar{q}$ turn into hadrons with probability=1
- Same Feynman diagram as $e^+e^- \rightarrow \mu^+\mu^-$ except for charge. To lowest order (no QCD corrections)

$$R = \frac{\sigma(e^+e^- \rightarrow hadrons)}{e^+e^- \rightarrow \mu^+\mu^-} = N_C \sum_q e_q^2$$

where N_C counts number of color degrees of freedom and sum is over all quark species kinematically allowed

$e^+e^- \to hadrons$: Measurement of R



$$R \equiv \frac{\sigma(e^+e^- \to hadrons)}{e^+e^- \to \mu^+\mu^-} = N_C \sum_q e_q^2$$

where N_C is number of colors

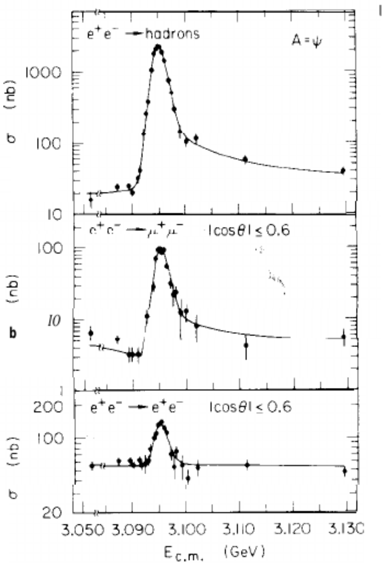
- Below $\sqrt{s} \sim 3.1$ GeV, $R = 2$

  Only u, d, s quark-antiquark pairs can be created

$$\sum_q e_q^2 = \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2 = \frac{6}{9} = \frac{2}{3} \Rightarrow N_c = 3$$

- Above 3.1 GeV, R increases by $3(\frac{2}{3})^2 = \frac{4}{3}$
  - Pass threshold for producing a new quark with $e_1 = \frac{2}{3}$: Charm
- Above 9.4 GeV, R increases by $3(\frac{-1}{3})^2 = \frac{1}{3}$
  - Pass threshold for producing a new quark with $e_1 = \frac{1}{3}$: Bottom

Discovery of the J/ψ in e^+e^- annihilation



- e^+e^- collisions at SPEAR collider at SLAC
- Huge counting rate in narrow range of E_{beam}
- Spread of beam energy comes from synchrotron radiation of the beams: $\sigma_{E_{beam}} = 0.56$ MeV
- Apparent width of peak $= 1.3$ MeV, consistent with E_{cm} resolution
- Produced in e^+e^- annihilation; resonance presumed to have same quantum numbers as the photon

$$J^{PC} = 1^{--}$$

Describing particle decays using QM wave functions: the Breit Wigner

- If particle decays, wf normalization changes with time

$$\int \psi^* \psi = 1 \Rightarrow \int \psi^2 \psi = e^{-t/\tau} = e^{-\Gamma t}$$

in rest frame of particle

- Can achieve this by replacing

$$\psi \propto e^{-imt} \Rightarrow \psi \propto e^{-imt} e^{-\Gamma t/2}$$

or equivalently

$$m \Rightarrow m - i\Gamma/2$$

- How does this affect the propagator in $e^+e- \rightarrow q\overline{q}$?

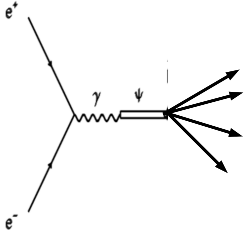
$$\frac{1}{q^2 - m^2} \Rightarrow \frac{1}{q^2 - m^2 + im\Gamma}$$

- That means

$$|\mathcal{M}|^2 \propto \left| \frac{1}{s - m^2 - im\Gamma} \right|^2 = \frac{1}{(s-m)^2 + m^2\Gamma^2}$$

- Tbis is called a Breit-Wigner (also know as a Lorenzian)

Determining the J/ψ Width: Breit-Wigner Decays



- Definition of a Breit-Wigner including spin factors and normalization:

$$\sigma(E) = \frac{4\pi}{k^2} \frac{2J+1}{(2s_1+1)(2s_2+1)} \frac{\Gamma^2/4}{(E-E_R)^2+\Gamma^2/4}$$

where

  - s_1 and s_2 are the spins of the initial particles
  - J is the spin of the resonance
  - k is the center-of-mass momentum for the collision
  - E_R is the mass of the resonance

- The Γ^2 in the numerator is really the product of the widths from the left and the right vertices
- For a state in turning into a state out

$$\sigma(E) = \frac{4\pi}{k^2} \times \frac{2J+1}{(2s_1+1)(2s_2+1)} \frac{\Gamma_{in}\Gamma_{out}/4}{(E-E_R)^2+\Gamma^2/4}$$

where $\Gamma = \sum_n \Gamma_i$ is a sum over all partial decay rates

- For the J/ψ we know $J = 1$, $s_1 = s_2 = \frac{1}{2}$
- Using these facts about Breit-Wigners, you will prove the next HW that:

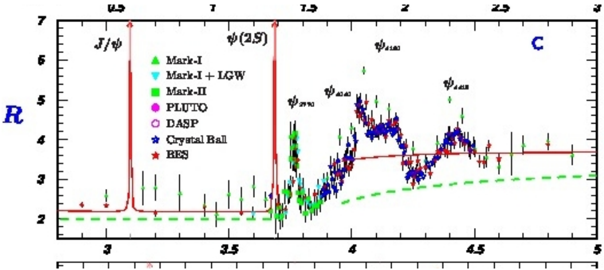
$$\Gamma = 0.068 \text{ Mev}$$

Interpreting the J/ψ as a $c\bar{c}$ bound state

- Before J/ψ discovery, theorists predicted existence of a 4^{th} quark: charm
  - We'll talk about why next week
- Natural interpretation of the J/ψ:
  - A $c\bar{c}$ bound state
  - Strong decays conserve quark flavor
    - We would normally expect it to decay into two mesons each with one charm quark
    - If the J/ψ mass is below threshold for producing a pair of charmed mesons, then that decay mode is closed
    - Thus, decays only occur though $c\bar{c}$ annihilation

Interpreting the J/ψ as a $c\bar{c}$ bound state

- Interpretation of J/ψ as $c\bar{c}$ bound state supported by behaviour of R
  - Two narrow states below charmed meson threshold
  - Wider states can decay to charmed particles
  - Jump in R above threshold indicates charge 2/3 quark



What Makes Charmonium Special?

- Charm quark mass ~ 1.5 GeV
- Charmonium bound state almost non-relativistic
  - $\beta \sim 0.4$
- Can treat using non-relativistic QM (with perturbative relativistic corrections)
- Our insight from postronium will help understand the system
- Note: When we get to the Υ (Bottomonium) even less relativistic

Review: Quantum Numbers

- J/ψ produced in e^+e^- from a virtual photon
  $J^{PC} = 1^{--}$ (odd parity and charge conjugation)
- Use same quantum number description as for positronium

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

  First combine spin of the q and $\overline{q}$, then combine with orbital angular momentum to get J
- We will see that

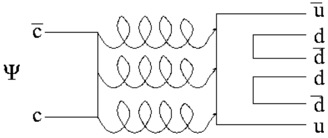
  $$J/\psi \equiv {}^3S_1$$

  Quark spin=1, orbital angular momentum=0, total J/ψ spin=1

How does the J/ψ Decay? (I)

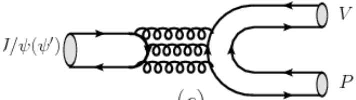
- Cannot decay to open charm: Mass too low
- Can only decay into odd number of gluons (Charge conjugation parity: the same reason $3S_1$ positronium must decay to 3 photons).
  - Single virtual gluon decay not possible since initial state colorless and gluons have color charge (single photon decay is possible)
  - Annihilation into 3-gluon state possible
  - Other possible decays: $2g + \gamma$ and annihilation through a virtual γ
    - You have already calculated leptonic decay rate through single photon for other mesons on your HW
  - Decays rates all depend on $|\psi(0)|^2$ so relative rates can be calculated (see next slide)
  - Need for 3 rather than 1 gluon plus the wf at origin factor explains "long" lifetime and narrow width

  Dominant decay: through annihilation to 3 gluons

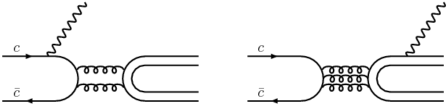


How does the J/ψ Decay? (II)

(a)



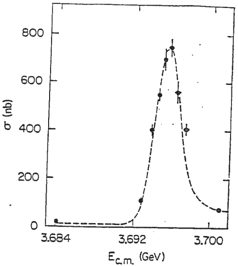
(c)



(a) (b)

***J/ψ*(1*S*) DECAY MODES**		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	*p* (MeV/*c*)
hadrons		(87.7 ± 0.5) %		–
virtual $\gamma \to$ hadrons		(13.50 ± 0.30) %		–
ggg		(64.1 ± 1.0) %		–
γgg		(8.8 ± 1.1) %		–
e^+e^-		(5.971 ± 0.032) %		1548
$e^+e^-\gamma$	[a]	$(8.8 \pm 1.4) \times 10^{-3}$		1548
$\mu^+\mu^-$		(5.961 ± 0.033) %		1545

Discovery of the J/ψ' in e^+e^- annihilation



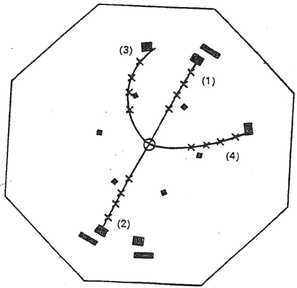


Figure 5.12 Example of the decay

- Another narrow resonance with same quantum numbers as photon
- Mass of $\psi' = 3686$ MeV
- The ψ' is also called the $\psi(2S)$
- Observed decays include:
  - To other $c\bar{c}$ states:
    - $\psi\pi\pi$ (50%)
    - $\chi_C + \gamma$ (24%)
      (More on the χ_c in a couple of slides)
  - Dileptons ($\sim 1\%$ per lepton species)
  - Additional hadronic decays make up the rest

Heavy Quark Bound States: Probing the QCD Potential

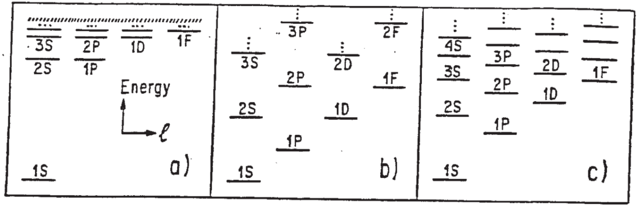


Fig. 3. Comparison of level structures in various potentials. a) Coulomb; b) harmonic oscillator; c) idealization of actual quarkonium case.

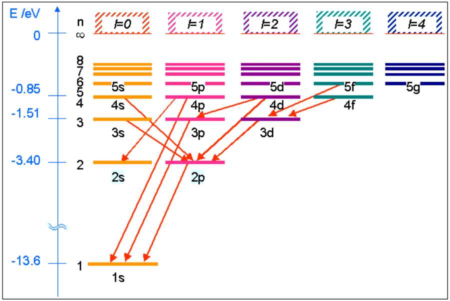
- Model effect of multiple gluon exchange with "effective potential" that describes the $q\bar{q}$ binding
- Long range potential is linear $V = kr$
- At very short distances, potential Coulomb-like
- One phenomenological model of $V(r)$:

$$V_{QCD} = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

  with $\alpha_s \sim 0.2$ at the J/ψ and $k \sim 1$ GeV/fm.

- Other choices possible since charmonium only probes limited range of r

Reminder: Spectroscopy in the hydrogen atom



- Spectrum of photons absorbed or emitted provides essential information on hydrogen wave function
- Transition rate dominated by dipole transitions
- Selection rules

$$\begin{aligned} \Delta\ell &= \pm 1 \\ \Delta m &= 0, \pm 1 \\ \ell = 0 \to \ell = 0 & \quad \text{not allowed} \end{aligned}$$

These rules result from $J^{PC} = 1^{--}$ for the photon

- Same rules hold for photon transitions in charmonium
- Other transitions (single or double pion emission) also possible, with own selection rules

Charmonium Spectroscopy

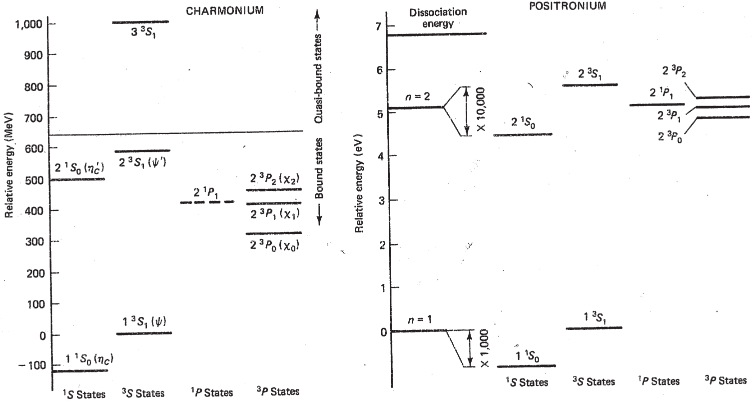
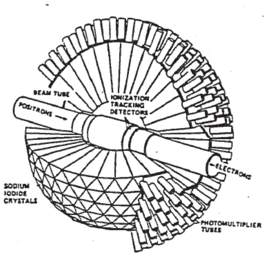
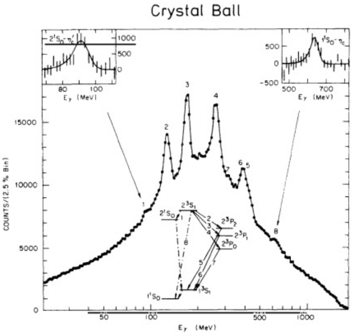


Figure 5.7 Spectrum of energy levels in positronium and charmonium. Note that the scale is greater by a factor of 100 million for charmonium. In positronium the various combinations of angular momentum cause only minuscule shifts in energy (shown by expanding the vertical scale), but in charmonium the shifts are much larger. All energies are given with reference to the 1^3S_1 state. At 6.8 electron volts positronium dissociates. At 633 MeV above the energy of the ψ charmonium becomes quasi-bound, because it can decay into D^0 and $\bar{D}^0$ mesons. (From "Quarkonium," by E. Bloom and G. Feldman.)

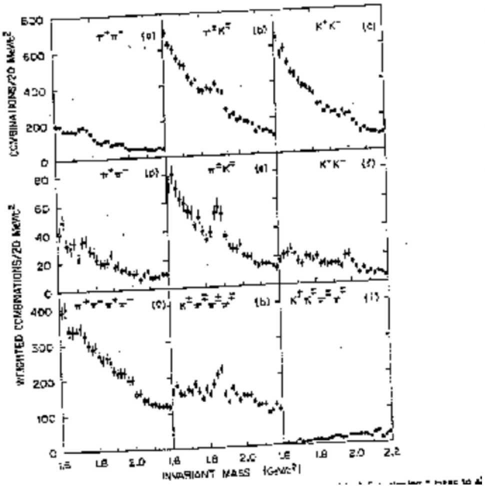
States Not Produced Directly in e^+e^-





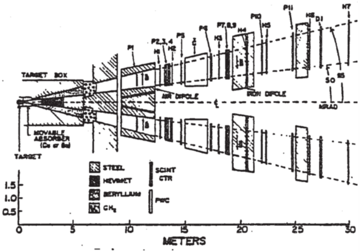
- Only states with $J^{PC} = 1^{--}$ can be produced directly in e^+e^- annihilation
- Can produce other states through radiative decays
- The "Crystal Ball" Detector
- NaI crystals with good EM energy resolution
- Studied photons producted when $\psi(2s)$ decays

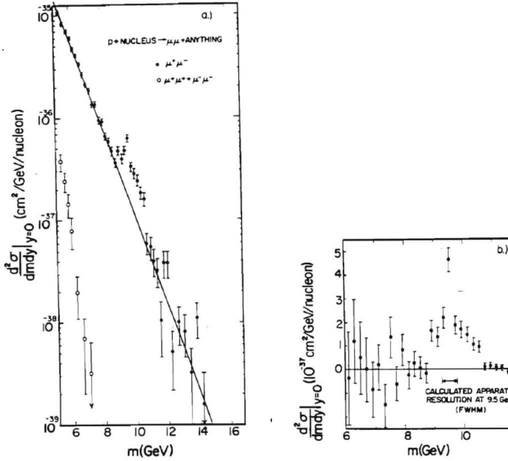
Open Charm



- $\psi(3s)$ can decay to charmed mesons
- Study charm meson decays by looking for peaks in invariant mass of π and K combinations
- Peaks in cases with one K
- Interpret as weak decay where $c \to s$

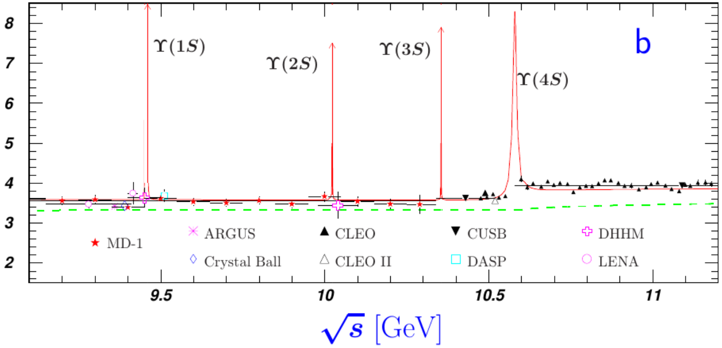
History Repeats Itself: The Υ





- First discovery in hadronic collisions at Fermilab
  - Dimuon spectrum in proton collisions from nuclear target
- Confirmation a few months later from e^+e^- at DESY
- Peak shown here in fact two states merged together (due to

e^+e- cross section in region of the Υ



- Three narrow states $\Upsilon(1s)$-$\Upsilon(3s)$ below $B\overline{B}$ threshold
- $\Upsilon(4s)$ decays to $B\overline{B}$
- Step in R above $\Upsilon(4s)$ consistent with charge $-1/3$ quark

Υ Spectroscopy

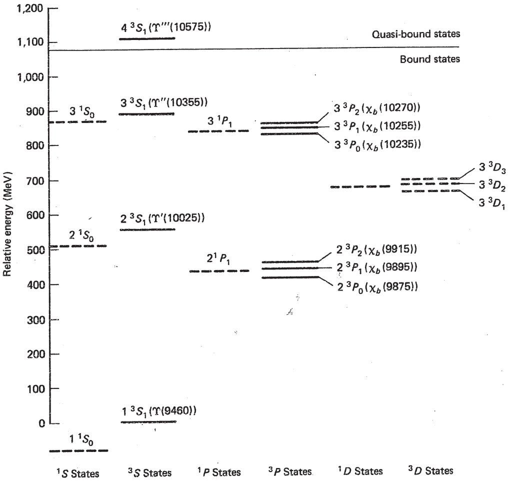


Figure 5.9 Bottomonium. Note that there are far more bound states than for charmonium—compare Fig. 5.7. (From "Quarkonium," by E. Bloom and G. Feldman. Copyright © May 1982 by Scientific American, Inc. All rights reserved.)

Charmonium: Current status

Term symbol $n^{2S+1}L_J$	$I^G(J^{PC})$	**Particle**	**mass (MeV/c^2) [1] (http://pdglive.lbl.gov /listing.brl?fsizein=1& group=MXXX025)**
1^1S_0	$0^+(0^{-+})$	$\eta_c(1S)$	$2\,980.3 \pm 1.2$
1^3S_1	$0^-(1^{--})$	$J/\psi(1S)$	$3\,096.916 \pm 0.011$
1^1P_1	$0^-(1^{+-})$	$h_c(1P)$	$3\,525.93 \pm 0.27$
1^3P_0	$0^+(0^{++})$	$\chi_{c0}(1P)$	$3\,414.75 \pm 0.31$
1^3P_1	$0^+(1^{++})$	$\chi_{c1}(1P)$	$3\,510.66 \pm 0.07$
1^3P_2	$0^+(2^{++})$	$\chi_{c2}(1P)$	$3\,556.20 \pm 0.09$
2^1S_0	$0^+(0^{-+})$	$\eta_c(2S)$, or η'_c	3637 ± 4
2^3S_1	$0^-(1^{--})$	$\psi(3686)$	$3\,686.09 \pm 0.04$
1^1D_2	$0^+(2^{-+})$	$\eta_{c2}(1D)^\dagger$	
1^3D_1	$0^-(1^{--})$	$\psi(3770)$	$3\,772.92 \pm 0.35$
1^3D_2	$0^-(2^{--})$	$\psi_2(1D)$	
1^3D_3	$0^-(3^{--})$	$\psi_3(1D)^\dagger$	
2^1P_1	$0^-(1^{+-})$	$h_c(2P)^\dagger$	
2^3P_0	$0^+(0^{++})$	$\chi_{c0}(2P)^\dagger$	
2^3P_1	$0^+(1^{++})$	$\chi_{c1}(2P)^\dagger$	
2^3P_2	$0^+(2^{++})$	$\chi_{c2}(2P)^\dagger$	
$?^??_?$	$1^{++}\dagger$	$X(3872)$	$3\,872.2 \pm 0.8$
$?^??_?$	$?^?(1^{--})$	$Y(4260)$	$4263\ ^{+8}_{-9}$

Notes:

* Needs confirmation.

† Predicted, but not yet identified.

Bottomonium: Current status

Term symbol $n^{2S+1}L_J$	$I^G(J^{PC})$	**Particle**	**mass (MeV/c^2)[2] (http://pdglive.lbl.gov /listing.brl?fsizein=1&exp=Y& group=MXXX030)**
1^1S_0	$0^+(0^{-+})$	$\eta_b(1S)$	9 390.9 ± 2.8
1^3S_1	$0^-(1^{--})$	$\Upsilon(1S)$	9 460.30 ± 0.26
1^1P_1	$0^-(1^{+-})$	$h_b(1P)$	
1^3P_0	$0^+(0^{++})$	$\chi_{b0}(1P)$	9 859.44 ± 0.52
1^3P_1	$0^+(1^{++})$	$\chi_{b1}(1P)$	9 892.76 ± 0.40
1^3P_2	$0^+(2^{++})$	$\chi_{b2}(1P)$	9 912.21 ± 0.40
2^1S_0	$0^+(0^{-+})$	$\eta_b(2S)$	
2^3S_1	$0^-(1^{--})$	$\Upsilon(2S)$	10 023.26 ± 0.31
1^1D_2	$0^+(2^{-+})$	$\eta_{b2}(1D)$	
1^3D_1	$0^-(1^{--})$	$\Upsilon(1\mathrm{D})$	
1^3D_2	$0^-(2^{--})$	$\Upsilon_2(1D)$	10 161.1 ± 1.7
1^3D_3	$0^-(3^{--})$	$\Upsilon_3(1D)$	
2^1P_1	$0^-(1^{+-})$	$h_b(2P)$	
2^3P_0	$0^+(0^{++})$	$\chi_{b0}(2P)$	10 232.5 ± 0.6
2^3P_1	$0^+(1^{++})$	$\chi_{b1}(2P)$	10 255.46 ± 0.55
2^3P_2	$0^+(2^{++})$	$\chi_{b2}(2P)$	10 268.65 ± 0.55
3^3S_1	$0^-(1^{--})$	$\Upsilon(3S)$	10 355.2 ± 0.5
3^3P_J	$0^+(J^{++})$	$\chi_b(3P)$	10 530 ± 5 (stat.) ± 9 (syst.)[4]
4^3S_1	$0^-(1^{--})$	$\Upsilon(4S)$ or $\Upsilon(10580)$	10 579.4 ± 1.2
5^3S_1	$0^-(1^{--})$	$\Upsilon(5S)$ or $\Upsilon(10860)$	10 865 ± 8
6^3S_1	$0^-(1^{--})$	$\Upsilon(11020)$	11 019 ± 8

Notes:

* Preliminary results. Confirmation needed.

Phenomenological fit to static QCD potential

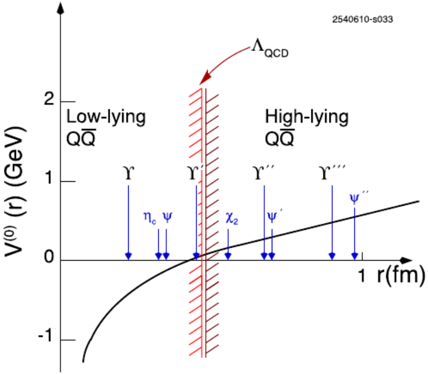


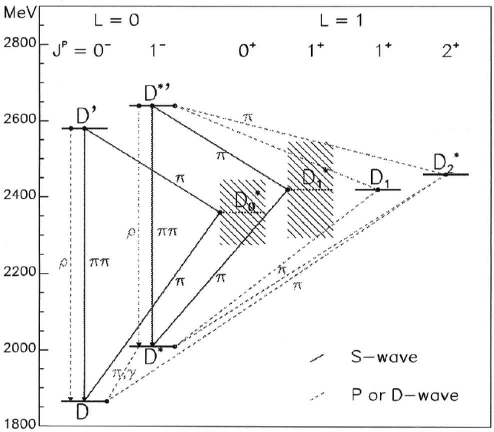
FIG. 33: Static $Q\overline{Q}$ potential as a function of quarkonium radius r

Important test system for lattice QCD calculations

More on Mesons With One Heavy Quark

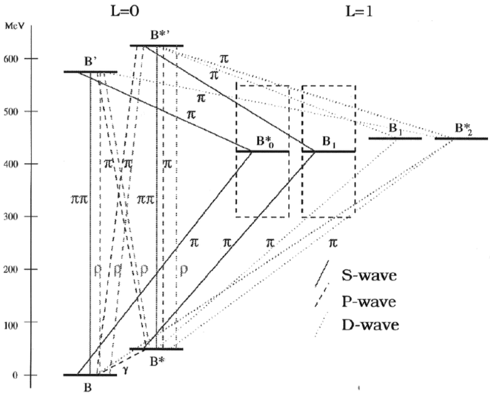
- The $\psi(3S)$ and $\Upsilon(4S)$ are above threshold for producing charm and bottom pairs respectively
  - Charmed mesons called D, D^*
  - Bottom mesons called B, B^*
  - Charm and bottom baryons also exist, although they are too heavy to be produced at the $\psi(3S)$ or $\Upsilon(4S)$; Same for D_s and B_s
    - These states have been studied at LEP and in hadron collisions
- In both cases, just above threshold, so no additional pions produced
- Sitting on these resonances allows for detailed studies of the properties of these mesons
- Quark model predicts what states we expect and estimates of their masses
- These particles decay weakly
  - We'll talk about the weak decays of the lowest lying states in a couple of weeks
  - Today, quickly review the spectroscopy and strong decays

Charmed Meson Spectrocopy



- D mesons: $c\overline{u}$, $c\overline{d}$ $\overline{c}u$, $\overline{c}d$; D_s mesons: $c\overline{s}$, $\overline{c}s$
- Like hydrogen atom, heavy fermion bound to light one
- But here light fermion relativistic
- Lowest mass state must decay weakly, others can decay strongly via π emission

Bottom Meson Spectrocopy



- B mesons: $b\overline{u}$, $b\overline{d}$ $\overline{b}u$, $\overline{b}d$; B_s mesons: $b\overline{s}$, $\overline{b}s$
- Similar pattern as for D mesons