Franck-Condon principle in excited Heavy Quarkonia

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Juan M. Torres-Rincon
in collaboration with Felipe J. Llanes-Estrada

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Dpto. Física Teórica I.
Universidad Complutense de Madrid. Spain

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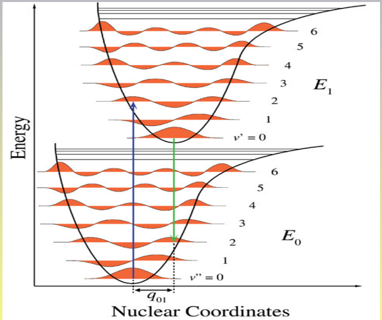
Outline

Franck-Condon Principle

During an electronic transition, the electron orbital relaxes to the ground state in a time too short for the nuclei to react. The nuclear positions and velocities change significantly during the transition, and the nuclear wavefunction remains the same after the transition.



Franck-Condon Principle

Key Points to remember:

- Mass-scale separation: $M_N \gg m_e$
- Position and Velocity of the slow subsystem unchanged
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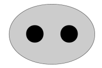
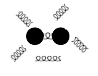
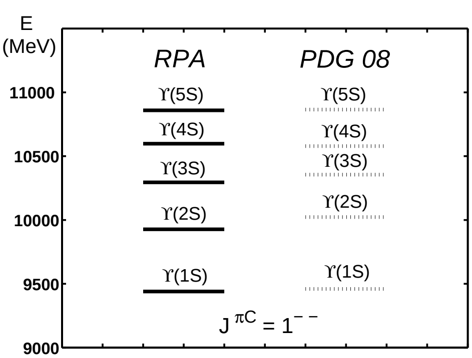
Molecule $\rightarrow$ bottomonium ($b\bar{b}$):



- Nuclei $\rightarrow$ b and $\bar{b}$ valence quarks
- Electronic cloud $\rightarrow$ light degrees of freedom

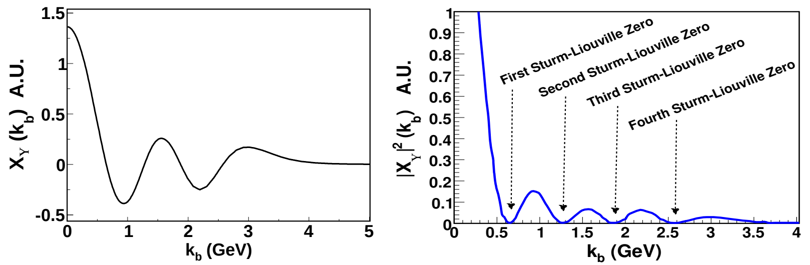


$\Upsilon(nS)$ Spectrum



Left panel: Theoretical many-body calculation. Right panel: Spectrum from the Particle Data Group

Wave function of $\Upsilon(5S)$

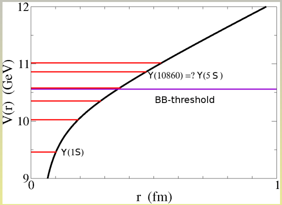


The squared wavefunction gives the probability of finding a b quark with momentum k_b. One clearly sees the four Sturm-Liouville zeros, characteristic from excited states.

Very low probability of finding a b quark inside the $\Upsilon(5S)$ with momentum near the Sturm-Liouville nodes.

Effective Theory

The ground state $\Upsilon(1S)$ is located well below the $B\overline{B}$ threshold.
It cannot feel the linear part of the static potential.
Non-relativistic system $\rightarrow$ follows pNRQCD counting rules



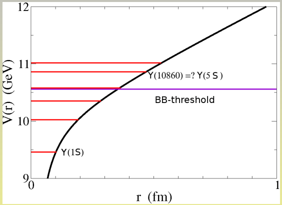
$$M \gg Mv \gg Mv^2 \gg \Lambda_{QCD} \quad (v \ll 1)$$

$$\alpha_s(Mv) \ll 1; \alpha_s(Mv^2) \ll 1$$

pNRQCD is a good EFT for the ground state.

Effective Theory

However the $\Upsilon(5S)$ is located above $B\overline{B}$ threshold. The system is no longer non-relativistic due to the large kinetic and potential energy. $Mv^2 \sim \Lambda_{QCD}$.



One can still use the hierarchy $M \gg \Lambda_{QCD}$ to understand the transition. This is the scale separation appearing for instance in HQET.

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$$M \gg \Lambda_{QCD}$$

Velocity Superselection Rule

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Adaptation for $\Upsilon(5S)$

Inside a region of $\sim \Lambda_{QCD}$ above the $B\overline{B}$ threshold, the velocity v_b of the b quark in the $\Upsilon(5S)$ is approximately equal to v_B, the velocity of the final B-meson.

The final B meson momentum k is related to the b quark momentum k_b as

$$k = k_b + \mathcal{O}(\Lambda_{QCD}) \to v = v_b + \mathcal{O}(\Lambda_{QCD}/M)$$

At lowest order the $\Upsilon(5S)$ squared wavefunction gives direct information of the k distribution, and therefore, of the decay rates.

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The final state (2-,3-body decays) should carry information about $|X^{\Upsilon}(q)|^2$

Belle Results for open-flavor decays of $\Upsilon(10680)$

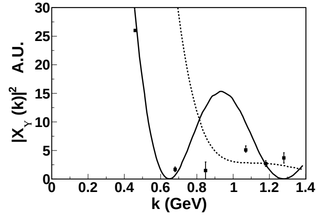
Decay channel fractions per bb-pair

- $BB : 5.5 \pm 1.4\%$ $B^*B : 13.7 \pm 2.4\%$ $B^*B^* : 37.5 \pm 5\%$
- $B_sB_s : 0.5 \pm 0.5\%$ $B_s^*B_s : 1.4 \pm 0.6\%$
  $B_s^*B_s^* : 17.6 \pm 0.8\% \sim 12 \times \Gamma[B_s^*B_s]$
- 3-,4- body 17.5%
  - $BB\pi : 0.0 \pm 1.5\%$
  - $B^*B\pi : 7.3 \pm 3.0\%$
  - $B^*B^*\pi : 1.0 \pm 1.8\%$
  - Residual: $9.2 \pm 3.9\%$
- Other: 8.9%

Note that from spin counting: $\Gamma[B_s^*B_s^*] = \frac{7}{4}\,\Gamma[B_s^*B_s]$
(From Belle Collaboration, 2010)

2- and 3-body decays

$$\Upsilon(5S) \to B\overline{B}$$

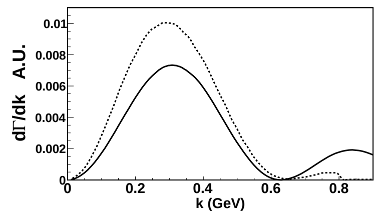


Solid line: Sq. Wavefunction; Dashed line: Effect of ${}^3P_0$ vertex and phase-space; Points: Experimental data from Belle Coll.

Large fraction of $B_s^* B_s^*$ decay understood

2- and 3-body decays

$$\Upsilon(5S) \to B\overline{B}\pi$$



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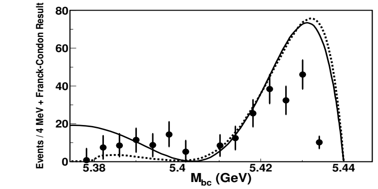
Comparison to experiment



Solid line: Sq. Wavefunction; Dashed line: Effect of $^3P_0$ vertex and phase-space; Points: Experimental data from Belle Coll.

$$M_{bc} = \sqrt{(M_\Upsilon/2)^2 - k^2}$$

The dip around $M_{bc} = 5.4$ GeV is caused by the first Sturm-Liouville zero of the $\Upsilon(5S)$ wave function.

Another example in charmonium

Is $\psi(4415) = \psi(4S)$?

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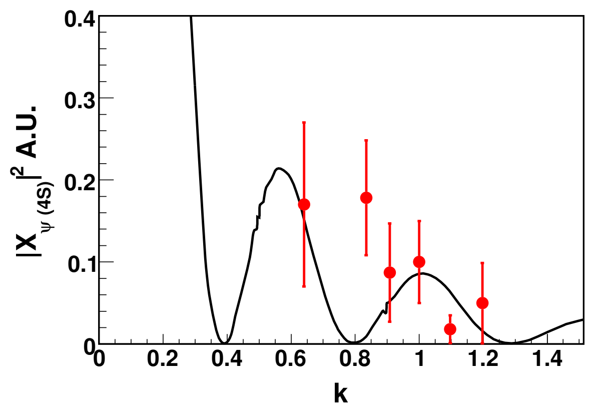

2-body decay experimental data from Belle and BaBar collaborations.

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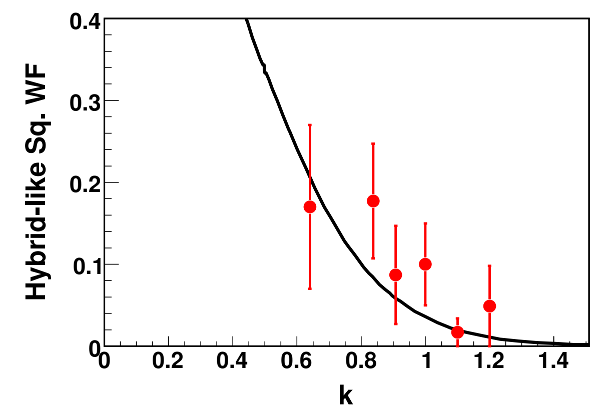

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Conclusions

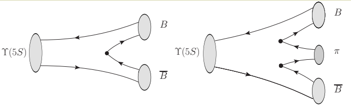
- We have applied the Franck-Condon principle to open-flavor decays of $\Upsilon(5S)$.
- The precise effective theory to describe the system is not well stablished. However, due to the mass-scale separation one can apply the superselection velocity rule.
- We obtain good results of 2-body and 3-body decay fractions working at LO.
- The Sturm-Liouville zeros distribution of the $\Upsilon(5S)$ is a key feature to understand the large decay fraction of $B_s^* B_s^*$ and the dip at $k = 600$ MeV in the 3-body decay.

Auxiliary slide: Decay Model

Masses and wave functions are obtained from a relativistic many-body calculation in the Coulomb-gauge Hamiltonian. We use BCS approximation for the ground state and RPA for the excitations.

$$H = \int dx \Psi^\dagger (-i\alpha\nabla + \beta m)\Psi - \frac{1}{2}\int dxdy\ \rho^a(x)V(|x-y|)\rho^a(y)$$

Meson wavefunction: $\mathcal{X}^{\Upsilon\ ab,\ \alpha}_{P,\ ij} = Y_{00}(\hat{\mathbf{q}}) \left(\frac{i\sigma^\alpha \sigma_2}{\sqrt{2}}\right)_{ij} X^{\Upsilon}_P(|\mathbf{q}|)\frac{\delta^{ab}}{\sqrt{3}}$



The $q\bar{q}$ creation vertex is given by the ${}^3P_0$ model.