Heavy Baryons: the Υ Rooftops

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STRONG INTERACTIONS BEYOND THE STANDARD MODEL

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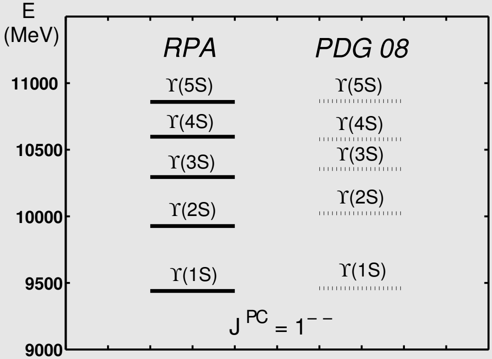
Introduction

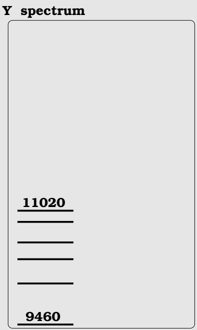
Bottomonium

Corner of QCD where we understand how the hadronic bound-states are composed of quarks.



Υ-spectrum

Pure Exotics



Observation: Resonances in $B_c\overline{B_c}$ should be (hidden) exotic.

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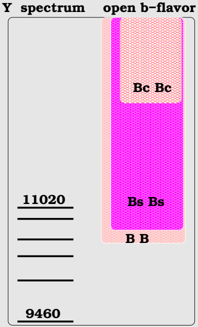

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- Direct test of weak vs strong pNRQCD regime (Coulombic interaction: very weak resonances, bound states)
- Roof of future B-factory's energy should reach B_c B_c threshold to be exhaustive (B, B_s, B_c).

Υ-spectrum

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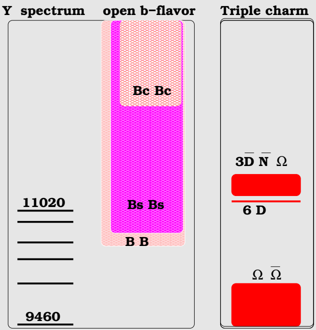

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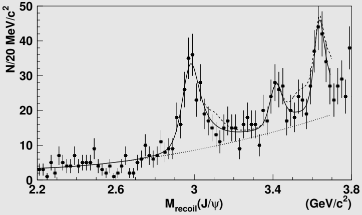
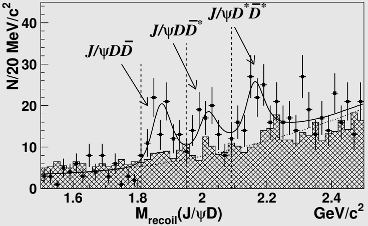
Triple Charm

Look for Ω_{ccc} in $e^+e^- \to \Omega_{ccc}\overline{p}\overline{DDD}$ by recoil method.

Double charmonium/charm production

Since 1987 (WA75 collaboration)





Using recoil method and missing mass.
Tagging D-mesons in final state.
Lots of experience.

BELLE collaboration hep-ex/0507019

Triple charm?

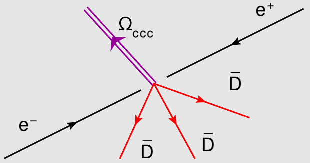
Thresholds

Closed charm: Triple c not reported ($3 \times M_{J/\psi} = 9300\ MeV$)
Open charm: Produce $ccc + \bar{c}\bar{c}\bar{c}$

- $DDD + \overline{DDD} \rightarrow \quad 6 \times 1867 = 11202$
- Triply charmed baryon $\Omega_{ccc} + \overline{DDD} + \overline{N}$

No measurement of triply charmed baryons yet: theory.

Recoil



Static potential in pNRQCD

Expansion in α, $1/m$

$$V^{(0)} = V^{(0)}_{LO} + V^{(0)}_{NLO} + V^{(0)}_{NNLO} \cdots$$

Leading Order (LO)

The leading order potential is just the colour Coulomb potential

$$V^{(0)}_{LO} = -\frac{4}{3}\frac{\alpha_s(r^{-2})}{r}$$

Static potential in pNRQCD

NLO and NNLO

$$V_{NLO}^{(0)} = V_{LO}^{(0)} \left(a_1 + 2\gamma_E \beta_0\right) \frac{\alpha_s\left(r^{-2}\right)}{4\pi}$$

$$V_{NNLO}^{(0)} = V_{LO}^{(0)} \left(\gamma_E(4a_1\beta_0 + 2\beta_1) + \left(\frac{\pi^2}{3} + 4\gamma_E^2\right)\beta_0^2 + a_2\right)\frac{\alpha_s^2(r^{-2})}{(4\pi)^2}$$

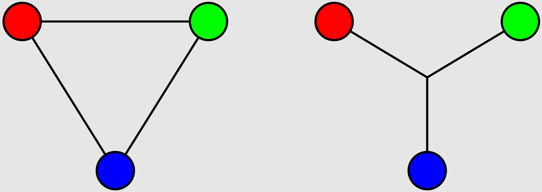
$V_{1/m}$ (convention dependent)

$$V_{m^{-1}} = \frac{-\alpha_s^2(\mu)}{m_r r^2} \times \left(\frac{7}{9}\right) - \frac{\alpha_s^3}{3\pi m_r r^2}\left\{-b_2 + \log(e^{2\gamma_E}\mu^2 r^2)\left(\frac{7\beta_0}{6} + \frac{68}{3}\right)\right\}$$

(A. Vairo 2001; N. Brambilla et al. 2000)

Ω_{ccc}: Potential in pNRQCD

Δ or Y-Shaped potential



Ω_{ccc}: Potential in pNRQCD

LO Potential: Δ-shaped

$$V_{LO}^{(0)} = \frac{-2\alpha_s}{3}\sum_{i=1}^{3}\frac{1}{|\mathbf{r}_i|} \qquad (\text{with } \mathbf{r}_1 = \mathbf{r}_2 - \mathbf{r}_3,\ \text{etc})$$

i.e. sum of two-body Coulomb interactions

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NLO Potential: Still Δ-shaped

$$V_{LO}^{(0)} + V_{NLO}^{(0)} = \frac{-2}{3} \sum_i \alpha_s(|\mathbf{r}_i|^{-2}) \frac{1}{|\mathbf{r}_i|} \left[1 + \frac{\alpha_s(|\mathbf{r}_i|^{-2})}{4\pi} (2\beta_0\gamma_E + a_1)\right]$$

Ω_{ccc}: Potential in pNRQCD

NNLO Potential: Δ-shaped Component

$$V^{(0)}_{NNLO-2} = \frac{-2}{3} \sum_i \frac{\alpha_s(\mathbf{r}_i^{-2})}{|\mathbf{r}_i|} \frac{\alpha_s(\mathbf{r}_i^{-2})^2}{(4\pi)^2} \times$$

$$\left(a_2 - 36\pi^2 + 3\pi^4 + \left(\frac{\pi^2}{3} + 4\gamma_E^2 \right) \beta_0^2 + \gamma_E (4a_1\beta_0 + 2\beta_1) \right)$$

Ω_{ccc}: Potential in pNRQCD

NNLO Potential: Δ-shaped Component

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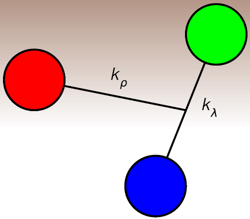
NNLO Potential: Finally a Y-shaped potential

$$V^{(0)}_{NNLO-3} = 2\left(V_{aux}(\mathbf{r}_2,\mathbf{r}_3) + V_{aux}(\mathbf{r}_1,-\mathbf{r}_3) + V_{aux}(-\mathbf{r}_2,-\mathbf{r}_1)\right)$$

$$V_{\rm aux}(\mathbf{r}_2,\mathbf{r}_3) = FT.\ \hat{V}_{\rm aux}(\mathbf{q}_2,\mathbf{q}_3) = \frac{(-i/2)(4\pi)^3\alpha_s^3}{8|\mathbf{q}_2|^2|\mathbf{q}_3|^2}\times$$

$$\left[\frac{|\mathbf{q}_2+\mathbf{q}_3|}{|\mathbf{q}_2||\mathbf{q}_3|} + \frac{\mathbf{q}_2\cdot\mathbf{q}_3 + |\mathbf{q}_2||\mathbf{q}_3|}{|\mathbf{q}_2||\mathbf{q}_3||\mathbf{q}_2+\mathbf{q}_3|} - \frac{1}{|\mathbf{q}_2|} - \frac{1}{|\mathbf{q}_3|}\right]$$

Variational



Jacobi coordinates

$$F(\mathbf{k}_\rho, \mathbf{k}_\lambda) = \psi\left(\frac{\mathbf{k}_\rho}{\alpha_\rho}\right)\psi\left(\frac{\mathbf{k}_\lambda}{\alpha_\lambda}\right)$$

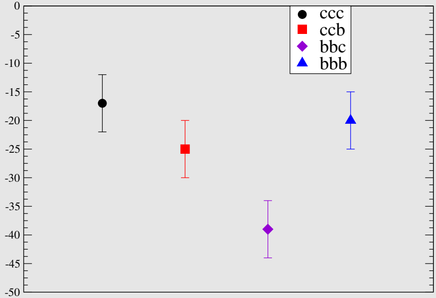
Minimize

$$\langle N|H|N\rangle(\alpha_\rho, \alpha_\lambda)$$

Parameters α_ρ, α_λ

Binding of three-body force

M_Υ - M_Δ

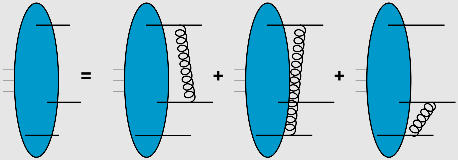


- Including three-body force → increased binding.
- Equal flavour objects more tightly bound than mixed flavour
- Little quark mass dependence.

Faddeev equations in QCD

Covariant Faddeev equations

- Good news for Faddeev Equations (three-body force neglected).
- Nucleon studies suggest quark-diquark picture reasonable.



Also apply to triply heavy quark systems.

H. Sanchis-Alepuz *et al*, Phys. Rev. D **84** (2011) 096003.
H. Sanchis-Alepuz *et al*, PoS QCD-TNT-II (2011) 041

Results for Ω_{ccc}

Predicted Masses

NNLO pNRQCD

- 4800(250) MeV

Covariant Faddeev equations

- 4400 MeV (Gluon model MRT)
- 4900 MeV (Gluon model AFW)

Parameter Fitting

In both approaches, observables from meson sector are fit.
(see papers for details)

Summary and Outlook

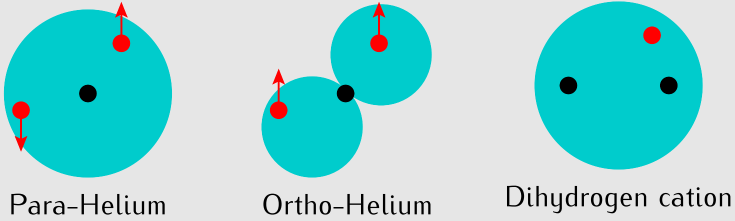
Summary

- pNRQCD static potential at NLO, NNLO. Fit experimental data.
- Covariant Faddeev equations in RL. Best fit to experiment.
- Constrain triply heavy baryon systems.
- Three-body force is small at NNLO
  - Good news for Faddeev equation.

Super-B should pay attention to triple charm

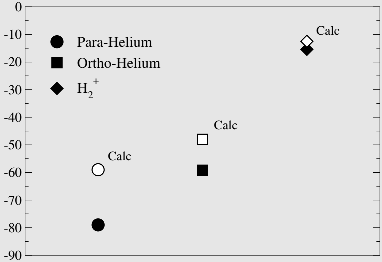
Error estimate: Variational Method

Compare to (simple) atomic/molecular systems



Error estimate: Variational Method

Binding energies



- Para-Helium:
  −79.0 eV (Calc. −59 eV)
- Ortho-Helium:
  −59.2 eV (Calc. −48 eV)
- H_2^+:
  −15.4 eV (Calc. −12.5 eV)

Binding energy underestimated by 25%.
For 3-body, sign known.