Short range interaction in $\pi J/\psi - D\bar{D}^*$ channel

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"New aspects of the Hadron and Astro/Nuclear Physics"

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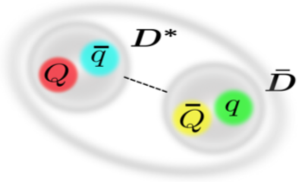
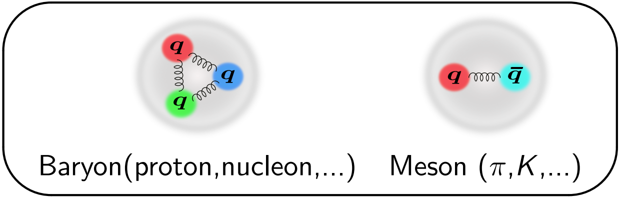
Outline

- Introduction
  - Exotic hadrons
  - $Z_c(3900)$
- Interaction model
  - Meson exchange model
  - Quark exchange model
- Summary



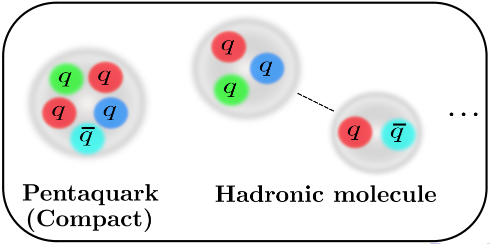
Exotic hadron

- Ordinary Hadrons: Baryon (qqq) and Meson ($q\bar{q}$)

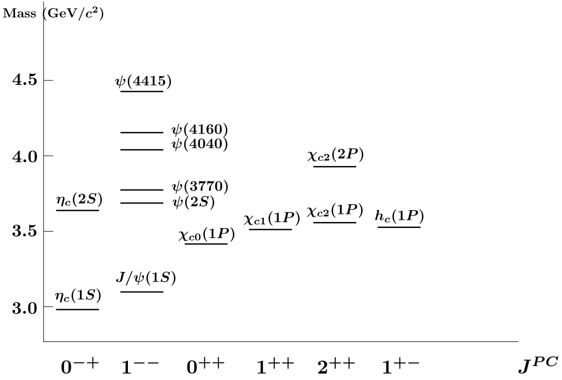


*q: "Constituent quark"

- Exotic Hadrons ($\neq qqq$, $q\bar{q}$): **Multiquark? Multihadron?**



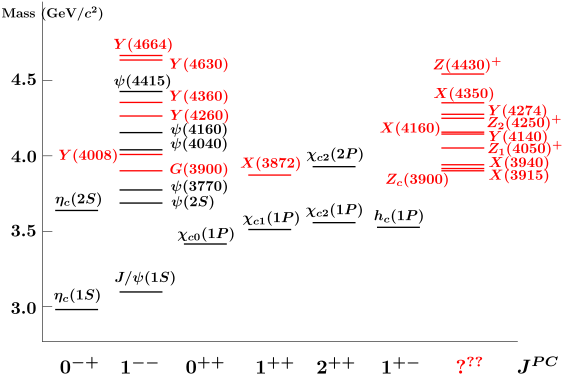
- e.g. $c\bar{c}$ mesons (Charmonium)



N. Brambilla,*et al.* Eur.Phys.J.C **71**(2011)1534, S. Godfrey and N. Isgur, PRD**32**(1985)189

Constituent quark picture and beyond

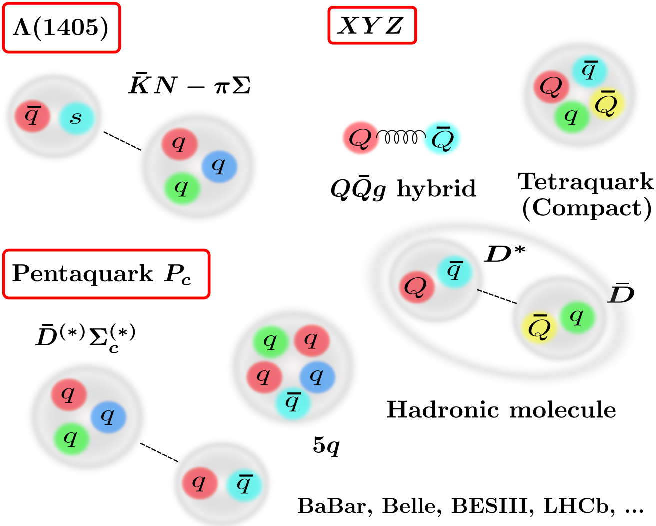
▷ e.g. $c\bar{c}$ mesons (Charmonium) and **Unexpected *X*, *Y*, *Z***



N. Brambilla, *et al.* Eur.Phys.J.C **71**(2011)1534, S. Godfrey and N. Isgur, PRD**32**(1985)189

- Exotics $\neq c\bar{c}$ have been observed in the Experiments (BaBar, Belle, BESIII, LHCb,...) $\Rightarrow$ **Q. Structure? Physics?**

Many exotic candidate!! Many models!!



BaBar, Belle, BESIII, LHCb, ...

T. Hyodo, D. Jido, PPNP**67**(2012)55, N. Brambilla *et al.*,Eur.Phys.J.C(2011)71,1534

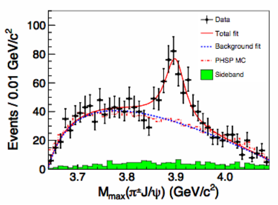
H.X.Chen, et al., Phys.Rept.**639**(2016)1,...

Charged Charmonium: $Z_c(3900)$

Introduction

- Charged Charmonium??
- $Y(4260) \to Z_c(3900)\pi \to J/\psi\pi\pi$

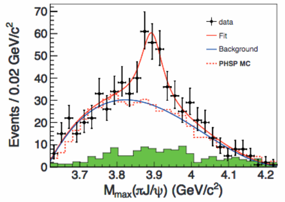
BESIII,PRL**110**(2013)252001



$M = 3899.0 \pm 3.6_{sta} \pm 4.9_{sys}$ MeV

$\Gamma = 46 \pm 10_{sta} \pm 20_{sys}$ MeV

Belle,PRL**110**(2013)252002



$M = 3894.5 \pm 6.6_{sta} \pm 4.5_{sys}$ MeV

$\Gamma = 63 \pm 24_{sta} \pm 26_{sys}$ MeV

CLEO-c,PLB**727**(2013)366(2013), DØ,PRD**98**(2018)052010

- Charged Charmonium??
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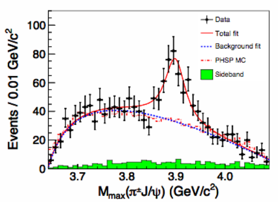

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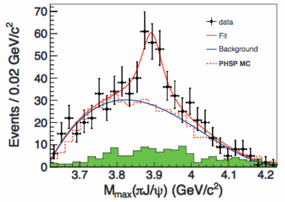

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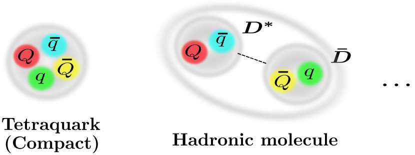
CLEO-c,PLB**727**(2013)366(2013), DØ,PRD**98**(2018)052010

▷ Ordinal Charmonium $c\bar{c}$: no electric charge.
$\Rightarrow Z_c^+(3900)$: **Genuine Exotic State!?** $c\bar{c}u\bar{d}$

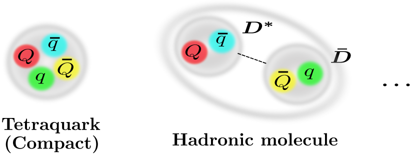
What is the structure of $Z_c(3900)$?



Multiquark states?

A. Hosaka *et al.* PTEP **2016** (2016) no.6, 062C01, D.-Y. Chen *et al.* PRD**88**(2013)036008,...

- Molecules? — $Z_c(3900)$ close to the $D\bar{D}^*$ threshold (~ 3875)



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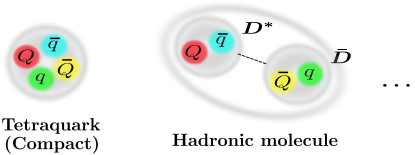
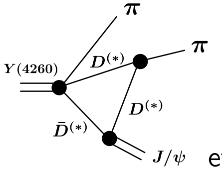
$\Rightarrow$ Exotic state may be **a loosely bound state (resonance)** of the meson-meson.
$\rightarrow$ Analogous to atomic nuclei (Deuteron: B ~2.2 MeV)



Multiquark states?



etc.

No bound state?

A. Hosaka *et al.* PTEP **2016** (2016) no.6, 062C01, D.-Y. Chen *et al.* PRD**88**(2013)036008,...

- Molecules? — $Z_c(3900)$ close to the $D\bar{D}^*$ threshold (~ 3875)

$\Rightarrow$ Exotic state may be **a loosely bound state (resonance)** of the meson-meson.

$\rightarrow$ Analogous to atomic nuclei (Deuteron: B ~2.2 MeV)

$\Leftrightarrow$ Kinematical effect? **No bound state explanation**

D.-Y. Chen,X.Liu,T.Matsuki,PRD**88**(2013)036008,J.He,D.-Y.Chen,EPJC**78**(2018)94,...

$Z_c(3900)$: Lattice QCD (Numerical Experiments)

Introduction

- Lattice QCD simulation by HALQCD at $m_\pi = 410 - 700$ MeV

$\Rightarrow$ Coupled-channel $\pi J/\psi - \rho\eta_c - D\bar{D}^*$

PRL 117, 242001 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

Fate of the Tetraquark Candidate $Z_c(3900)$ from Lattice QCD

Yoichi Ikeda,[1,2] Sinya Aoki,[3,4] Takumi Doi,[2] Shinya Gongyo,[3] Tetsuo Hatsuda,[2,5] Takashi Inoue,[6] Takumi Iritani,[7] Noriyoshi Ishii,[1] Keiko Murano,[1] and Kenji Sasaki[3,4]

(HAL QCD Collaboration)

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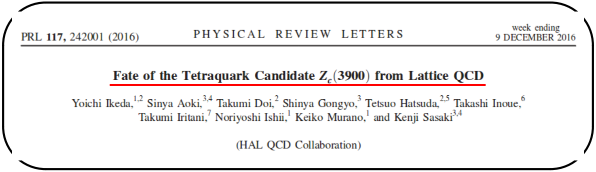
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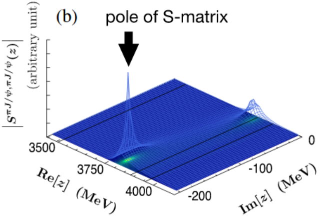

$\Rightarrow$ **Virtual state** is obtained.

- $Z_c(3900)$ is Threshold cusp

Ikeda, *et al.*,PRL**117**(2016)242001

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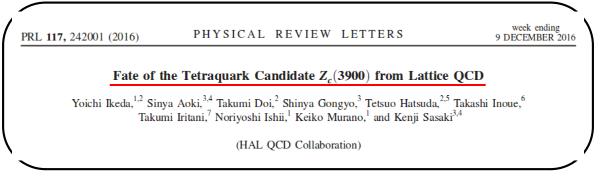
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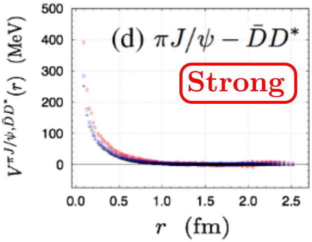


$\Rightarrow$ **Virtual state** is obtained.

- $Z_c(3900)$ is Threshold cusp induced by $\pi J/\psi - \bar{D}D^*$ **potential**

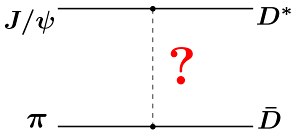
Charm flavor exchange?

Ikeda, *et al.*,PRL**117**(2016)242001

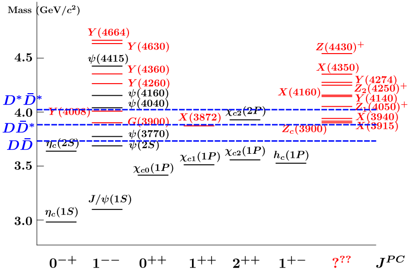
Exotic structure:
Bound state? Cusp?

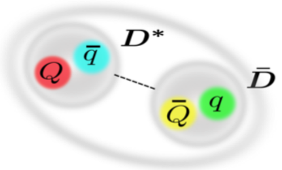
**Exotic structure:
Bound state? Cusp?**

⇔



- **Hadron-hadron interaction** is important to understand the nature of exotic states! not only Z_c but also others.





- **Long-range force:** one π exchange potential (OPEP)
  Lightest meson π, Importance in the nuclear force,
  Heavy Quark Spin Symmetry ($0^- - 1^-$ mixing)

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- **Short-range force:** Charm ($\boldsymbol{c}$) exchange

▷ How can we understand **strong $\pi J/\psi - D\bar{D}^*$ potential?**

Model of Hadron-hadron interaction

- **Long-range force:** one π exchange potential (OPEP)
  Lightest meson π, Importance in the nuclear force,
  Heavy Quark Spin Symmetry ($0^- - 1^-$ mixing)
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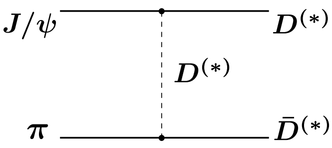
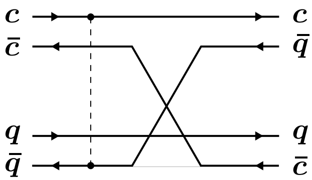
▷ How can we understand **strong $\pi J/\psi - D\bar{D}^*$ potential?**

(a) $D^{(*)}$ meson exchange?



→ next sec.

(b) Quark exchange?



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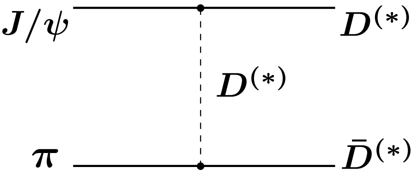
Comparison between **D exchange** and **Quark exchange**

Meson exchange model



- Coupled channel: $\pi J/\psi - D\bar{D}^* - D^*\bar{D}^*$

▷ $D^{(*)}\bar{D}^{(*)} - D^{(*)}\bar{D}^{(*)}$: π exchange

▷ $\pi J/\psi - D^{(*)}\bar{D}^{(*)}$: $D^{(*)}$ exchange

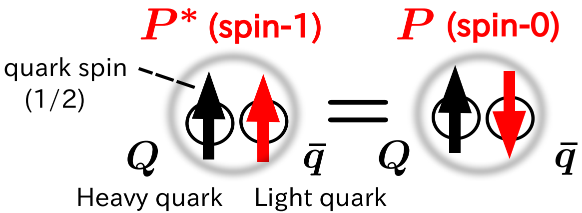
Yasuhiro Yamaguchi (RIKEN), Yukihiro Abe (RCNP, Osaka Univ.), Kenji Fukukawa (Suma Gakuen), Atsushi Hosaka (RCNP, Osaka Univ.), in preparation

Heavy Quark Spin Symmetry (HQS) N.Isgur,M.B.Wise,PLB**232**(1989)113

- **Suppression of Spin-spin force** in $m_Q \to \infty$.

  $\Rightarrow$ **Mass degeneracy** of hadrons with the different J

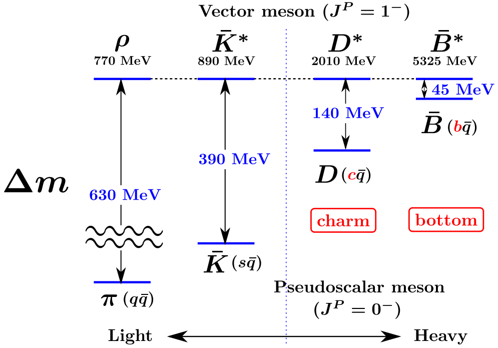
- e.g. $Q\bar{q}$ meson



$\Rightarrow$ Mass degeneracy of spin-0 and spin-1 states!

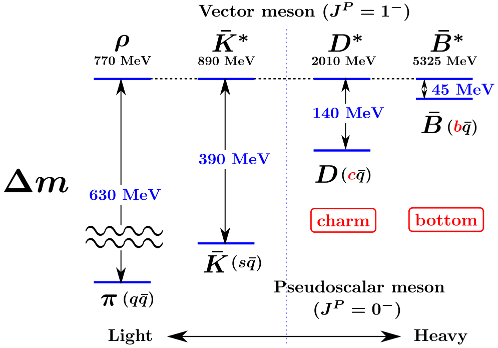
Mass degeneracy of heavy hadrons
Meson exchange model

- Mass difference between vector and pseudoscalar mesons. ($Q\bar{q}$, $q = u, d$)



▷ Δm decreases when the quark mass increases.

- Mass difference between vector and pseudoscalar mesons. $(Q\bar{q},\ q = u, d)$



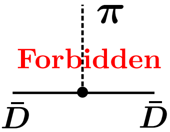
▷ Δm decreases when the quark mass increases.
$\Rightarrow$ **Degeneracy of Heavy hadrons!**

For $Z_c(3900)$, $D - D^*$ mixing $\Rightarrow D\bar{D}^* - D^*\bar{D}^*$ coupled-channel

Heavy hadron-π coupling
Meson exchange model

- Effective Lagrangians: Heavy hadron and π

R. Casalbuoni *et al.*, Phys.Rept.**281** (1997)145, T. M. Yan, *et al.*, PRD**46**(1992)1148



▷ Heavy meson: **($DD\pi$: Parity violation)**

Heavy hadron-π coupling
Meson exchange model

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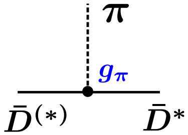


▷ Heavy meson: $\bar{D}^{(*)}\bar{D}^{(*)}\pi$ **($DD\pi$: Parity violation)**

$$\mathcal{L}_{\pi HH} = -\frac{g_\pi}{2f_\pi}\mathrm{Tr}\left[H\gamma_\mu\gamma_5\partial^\mu\hat{\pi}\bar{H}\right], \quad \mathbf{H} = \frac{1+\not{v}}{2}\left[\mathbf{D}^*_\mu\gamma^\mu - \mathbf{D}\gamma_5\right]$$

- One coupling const. $g_\pi = 0.59$ (from $D^* \to D\pi$ decay)

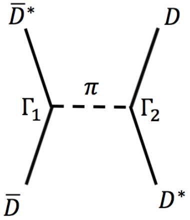
▷ Form factor (Hadron has **finite size**)

$$F(q^2) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - q^2}, \quad \Lambda_{\bar{D}} \sim 1130 \text{ MeV (by Quark model)}$$

One pion exchange potential in $D^{(*)}\bar{D}^{(*)}$

Meson exchange model

- One boson exchange potential (OBEP)



$D\bar{D}^*$ potential

$DD^*\pi$ vertex induces OPEP ($DD\pi$ vertex violates the parity conservation)

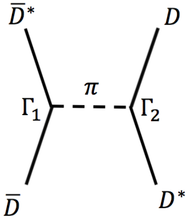
OPEP

$$V^{\pi} = -\frac{1}{2}\left(\frac{g_\pi}{f_\pi}\right)^2 \left[\vec{S}_1 \cdot \vec{S}_2 C(r) + S_{12}(\hat{r}) T(r)\right] \vec{\tau}_1 \cdot \vec{\tau}_2$$

Comments

- HQS induces **$D(0^-) - D^*(1^-)$ coupling** $\rightarrow$ OPEP works!

- One boson exchange potential (OBEP) **with Tensor force!**



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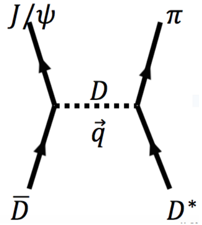
Comments

- HQS induces **$D(0^-) - D^*(1^-)$ coupling** $\to$ OPEP works!
- Tensor force $T(r) \Rightarrow$ **the driving force** in atomic nuclei
  $S_{12}(\hat{r}) = 3(\vec{S}_1 \cdot \hat{r})(\vec{S}_2 \cdot \hat{r}) - \vec{S}_1 \cdot \vec{S}_2 \to S$-$D$ mixing

- $D^{(*)}$ meson exchange potential in $\pi J/\psi - D^{(*)}\bar{D}^{(*)}$



$\pi J/\psi - D\bar{D}^*$ potential

D exchange

$$V^D = \frac{2}{3}\frac{g_\psi g_\pi}{f_\pi\sqrt{E_\pi}}\left[\vec{S}_1\cdot\vec{S}_2 C(r) + S_{12}(\hat{r})T(r)\right]$$

D^* exchange

$$V^{D^*} = \frac{2}{3}\frac{g_\psi g_\pi}{f_\pi\sqrt{E_\pi}}\left[2\vec{S}_1\cdot\vec{S}_2 C(r) - S_{12}(\hat{r})T(r)\right]$$

$g_\psi = 8.0$ (Assuming VMD), $\Lambda_\psi = 2.2$ GeV

A. Deandrea, G. Nardulli and A. D. Polosa, PRD**68**(2003)034002

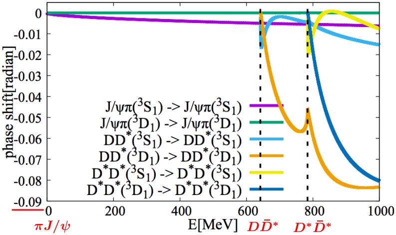
Comments

- Spin-spin ($\vec{S}_1\cdot\vec{S}_2$) and Tensor (S_{12}) terms
- Energy-dependence ($1/\sqrt{E_\pi}$)

Numerical results: Phase shift
Meson exchange model

- We found...

- We found... **No Bound state, No Resonance**
  Very Small phase shift $|\delta| < 0.09$ [rad]



- $D^{(*)}\bar{D}^{(*)}$ channel: **Small** contribution from OPEP

- $\pi J/\psi$ channel: $D^{(*)}$ exchange is **Negligible**

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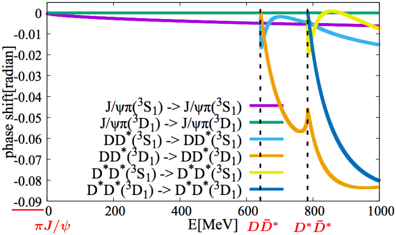


- $D^{(*)}\bar{D}^{(*)}$ channel: **Small** contribution from OPEP
  Why?: Isospin factor $\vec{\tau}_1 \cdot \vec{\tau}_2$, -3 $(I = 0)$, but Z_c:$+1$ $(I = 1)$
- $\pi J/\psi$ channel: $D^{(*)}$ exchange is **Negligible**
  Why?: Volume Integral $V_C^D(\vec{q}^{\,2} = 0) = 3.14$ GeV^{-2}
  $\leftrightarrow V_{NN}^{\sigma} \sim$ **3.00 $\times 10^2$ GeV^{-2}**

D meson exchange
Meson exchange model

- No resonance is found

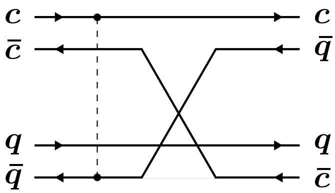
⇔ The strong $\pi J/\psi - D\bar{D}^*$ contribution is not explained.

- No resonance is found

$\Leftrightarrow$ The strong $\pi J/\psi - D\bar{D}^*$ contribution is not explained.

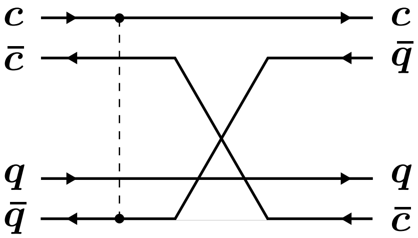
$\Downarrow$ Another Short range force

Quark exchange interaction!



$\rightarrow$next section

Quark exchange model]



Meson-meson scattering by the quark exchange

- Only $\pi J/\psi - D\bar{D}^*$ channel

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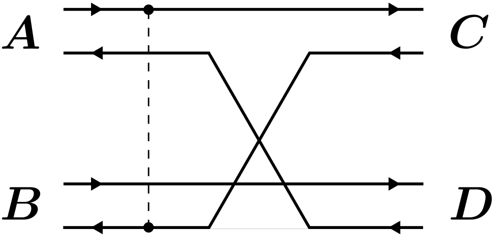
in preparation

- **Born-order quark-exchange diagram**

  T. Barnes and E. S. Swanson, PRD**46**(1992)131. Swanson, Ann. Phys. **220**(1992)73.

- $AB \to CD$ scattering $\quad \mathcal{M}_{fi} \propto \langle C, D|H_I|A, B\rangle$



- Ingredients: Meson Wavefunctions(A, B, C, D)
  Quark interaction (Quark Model)
- Born amplitude $\Rightarrow$ Meson-meson Potential can be obtained

- Quark Hamiltonian (One gluon exchange + Linear potentials)

Barnes and Swanson, PRD**46**(1992)131.; Swanson, Ann. Phys. **220**(1992)73.

$$H^q_{ij} = K_q + \left(-\frac{3}{4}br + \frac{\alpha_s}{r} - C\right)\vec{F}_i\cdot\vec{F}_j - \frac{8\pi\alpha_h}{3m_im_j}\left(\frac{\sigma^3}{\pi^{3/2}}e^{-\sigma^2 r_{ij}^2}\right)\vec{S}_i\cdot\vec{S}_j\vec{F}_i\cdot\vec{F}_j$$

▷ Parameters are fixed to reproduce the mass of mesons

Table: Quark Model Parameters from Ann.Phys.**220**(1992)73.

$m_q = 0.375$ GeV	$m_c = 1.9$ GeV
$\alpha_s = 0.857$	$\alpha_h = 0.840$
$b = 0.154$ GeV^{-2}	$C = -0.4358$ GeV
$\sigma = 0.70$ GeV	

- Single Gaussian Approximation **(Simple)**

$$\psi(r) = (4\pi\lambda)^{-3/4} \exp\left(-\frac{r^2}{8\lambda}\right)$$

- λ is determined to minimize $E(\lambda) = \langle\psi|H^q|\psi\rangle$

	$(m\,[\text{GeV}], \lambda\,[\text{GeV}^{-2}])$		$(m\,[\text{GeV}], \lambda\,[\text{GeV}^{-2}])$		$(m\,[\text{GeV}], \lambda\,[\text{GeV}^{-2}])$
π	$(0.258, 0.854)$	D	$(1.876, 0.965)$	η_c	$(2.826, 0.261)$
ρ	$(0.782, 2.549)$	D^*	$(2.016, 1.298)$	J/ψ	$(2.910, 0.290)$

▷ π wavefunc.$\Rightarrow$ Single Gaussian is not enough

Meson Wavefunction

Quark exchange interaction

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▷ **π wavefunc.** $\Rightarrow$ Single Gaussian is not enough

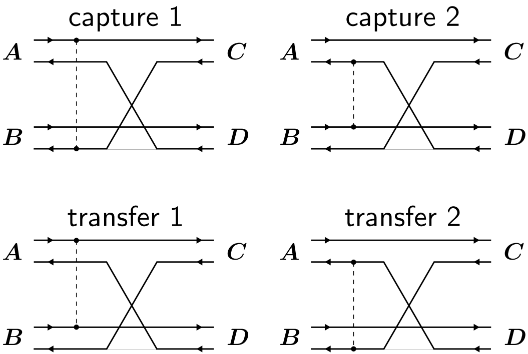
$\rightarrow$ We use $\boldsymbol{\lambda = 2.20}$ **GeV^{-2}** by T. Barnes and E. S. Swanson ($\pi\pi$ phase shift is reproduced)

Single Gaussian Wavefunc. is obtained $\rightarrow$ Amplitude

Scattering Amplitude

Quark exchange interaction

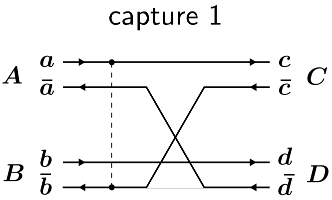
- Born quark exchange diagrams T. Barnes and E. S. Swanson, PRD**46**, 131 (1992).
  Quark interaction between Mesons ⇒ Four diagrams



- Scattering Amplitude $\mathcal{M}_{fi} \propto \langle C, D | H^q | A, B \rangle$

$$\mathcal{M}_{fi}^{tot} = \mathcal{M}_{fi}^{capture1} + \mathcal{M}_{fi}^{capture2} + \mathcal{M}_{fi}^{transfer1} + \mathcal{M}_{fi}^{transfer2}$$

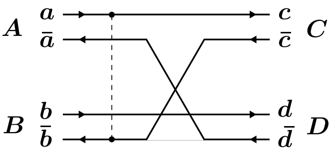
Scattering Amplitude
Quark exchange interaction



- Meson momenta: A, B, C, D
- Quark momenta: $a, \bar{a}, b, \bar{b}, c, \bar{c}, d, \bar{d}$
- Conservation: $A + B = C + D$, $\bar{a} = \bar{d}$, $b = d$

- Amplitude

$$\rightarrow \int\int d^3 a d^3 c \phi^*_C(2\vec{c} - \vec{C})\phi^*_D(2\vec{a} - 2\vec{A} - \vec{C}) V(\vec{a} - \vec{c})\phi_A(2\vec{a} - \vec{A})\phi_B(2\vec{a} - \vec{A} - 2\vec{C})$$



- Meson momenta: A, B, C, D
- Quark momenta: $a, \bar{a}, b, \bar{b}, c, \bar{c}, d, \bar{d}$
- Conservation: $A + B = C + D$, $\bar{a} = \bar{d},\ b = d$

- Amplitude

$$\to \int\int d^3a d^3c \phi_C^*(2\vec{c} - \vec{C})\phi_D^*(2\vec{a} - 2\vec{A} - \vec{C})V(\vec{a} - \vec{c})\phi_A(2\vec{a} - \vec{A})\phi_B(2\vec{a} - \vec{A} - 2\vec{C})$$

- Potentials (momentum space)

Coulomb: $V^{Coul}(q) = -\frac{\alpha_s}{2\pi^2}\frac{1}{\vec{q}^{\,2}}$, **Hyperfine:** $V^{Hyp}(q) = -\frac{8\pi\alpha_h}{3m_i m_j}e^{-\vec{q}^{\,2}/4\sigma^2}$

Linear (Regularized):

$$V^{Lin}(r) = br \times e^{-\varepsilon r} \to V^{Lin}(q) = b\left[\frac{-8\pi}{(\vec{q}^{\,2} + \varepsilon^2)^2} + \frac{32\pi\varepsilon^2}{(\vec{q}^{\,2} + \varepsilon^2)^3}\right]$$

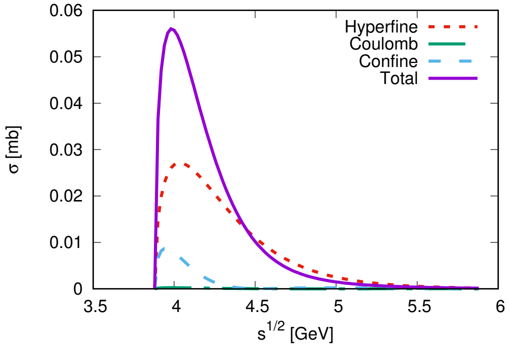
- $\pi J/\psi - D\bar{D}^*$: Amplitude

$\Rightarrow$ Cross section $\propto |(\text{Coulomb}) + (\text{Confine}) + (\text{Hyperfine})|^2$

Cross Section (Born term): $\pi J/\psi - D\bar{D}^*$
Numerical Result

- $\pi J/\psi - D\bar{D}^*$: Amplitude

$\Rightarrow$ Cross section $\propto |(\text{Coulomb}) + (\text{Confine}) + (\text{Hyperfine})|^2$



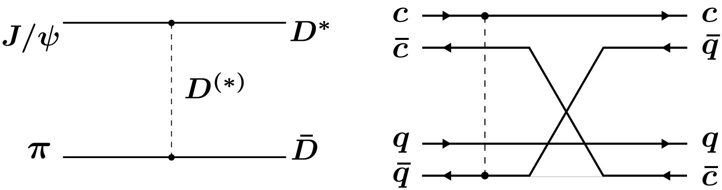
- Dominant role of the Hyperfine (Spin-spin) term

$\Leftrightarrow$ Minor role of the Coulomb term.

- Comparing results of Quark exchange and $D^{(*)}$ exchange

(a) $D^{(*)}$ meson exchange

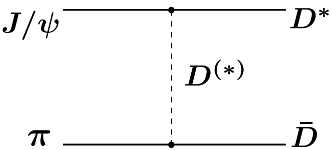
(b) Quark exchange



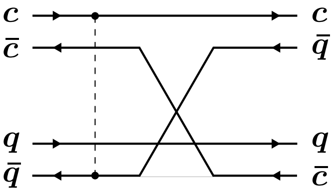
Cross Section: Quark exchange vs $D^{(*)}$ exchange

- Comparing results of Quark exchange and $D^{(*)}$ exchange

(a) $D^{(*)}$ meson exchange



(b) Quark exchange



$$\mathcal{L}_{\pi HH} = -\frac{g_\pi}{2f_\pi}\mathrm{Tr}\left[H\gamma_\mu\gamma_5\partial^\mu\hat{\pi}\bar{H}\right],\ \mathcal{L}_\psi = g_\psi \mathrm{Tr}\left[\mathcal{J}\bar{H}_2\overleftrightarrow{\partial}_\mu\gamma^\mu\bar{H}_1\right]$$

$$\Downarrow$$

D exchange $$V^D = \frac{2}{3}\frac{g_\psi g_\pi}{f_\pi\sqrt{E_\pi}}\left[\vec{S}_1\cdot\vec{S}_2 C(r) + S_{12}(\hat{r})T(r)\right]$$

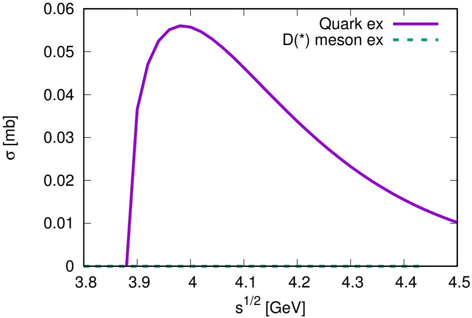
D^* exchange $$V^{D^*} = \frac{2}{3}\frac{g_\psi g_\pi}{f_\pi\sqrt{E_\pi}}\left[2\vec{S}_1\cdot\vec{S}_2 C(r) - S_{12}(\hat{r})T(r)\right]$$

$g_\pi = 0.59$ ($D^* \to D\pi$) $g_\psi = 8.0$ (Assuming VMD), $\Lambda_D = 1.1$ GeV, $\Lambda_\psi = 2.2$ GeV

Cross Section: Quark exchange vs $D^{(*)}$ exchange
Quark exchange interaction

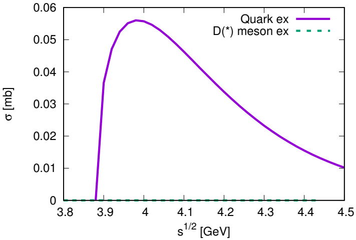
- Comparing results of Quark exchange and $D^{(*)}$ exchange

(i) Quark ex vs $D^{(*)}$ ex

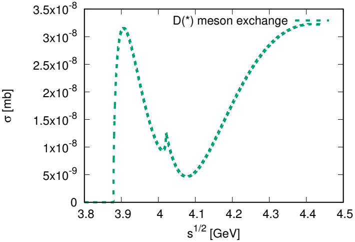


- Comparing results of Quark exchange and $D^{(*)}$ exchange

(i) Quark ex. vs $D^{(*)}$ ex.



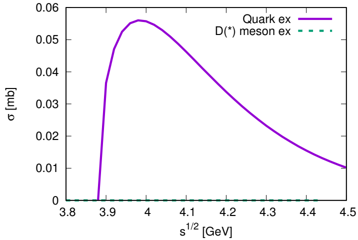
(ii) $D^{(*)}$ ex. (Zoom)



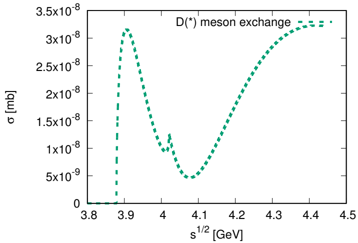
- $D^{(*)}$ exchange:

- Comparing results of Quark exchange and $D^{(*)}$ exchange

(i) Quark ex. vs $D^{(*)}$ ex.

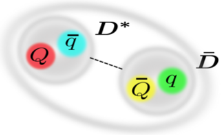


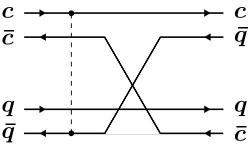
(ii) $D^{(*)}$ ex. (Zoom)



- $D^{(*)}$ exchange: $\boldsymbol{\sigma < 3.5 \times 10^{-8}}$ **mb**
- Large difference between Quark exchange and $D^{(*)}$ exchange

Summary

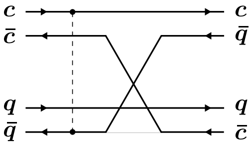




- Many exotic states near the threshold.
  $\rightarrow$ Understanding **the hadron-hadron interaction** is needed.
- Charged charmonium $Z_c(3900)$ has been discussed as the Hadronic molecules or the threshold cusp.
- OPEP contribution is not strong. $D^{(*)}$ meson exchange is **negligible**.
- Quark exchange interaction is introduced as Short range $\pi J/\psi - D^{(*)}\bar{D}^{(*)}$ potential.
  We find **Large difference** between results from Quark exchange and $D^{(*)}$ meson exchange.

Future Work

$\pi J/\psi - D^{(*)}\bar{D}^{(*)}$ potential



- Single Gaussian $\rightarrow$ Multi-Gaussian (Especially π)
- Beyond Born-order $\rightarrow$ $T = V + VGT$

  $\Rightarrow$ To compare the Exp. and Lattice result
- Introducing $\rho\eta_c$, $\psi'\pi$,...
- Bottom Sector: $Z_b(10610)$ and $Z_b(10650)$ $\Rightarrow$ $\pi\Upsilon - B\bar{B}^*$

Thank you for your kind attention.