X(3872) electromagnetic decay in a coupled-channel model

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Motivation

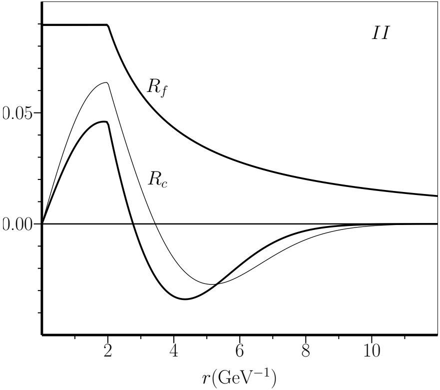
- The $X(3872)$ was discovered in 2003 by Belle, and later confirmed by CDF and D0 experiments
- $M_X = 3871.69 \pm 0.17\,\text{MeV}$ (PDG)
- $\Gamma < 1.2\,\text{MeV}$
- State does not fit into "quenched" quark models
- Quantum numbers 1^{++} or 2^{-+}
  - 1^{++} is experimentally favored and will be assumed here

Motivation

- Hadronic decays of $X(3872)$ include $\rho^0 J/\psi$, $\omega J/\psi$ and $DD\pi$ (mainly through a DD^* channel)
  - $\rho^0 J/\psi$ and $\omega J/\psi$ decays are OZI forbidden and $\rho^0 J/\psi$ also violates isospin conservation: Both channels are highly suppressed
  - Mass is below or on top of DD^* threshold ($E_{D^0 D^{0*}} = 3871.84$ MeV and $E_{D^\pm D^{\mp *}} = 3879.90$ MeV)
  - Can be described as a $c\bar{c}$ and DD^* bound state in an unitarized meson model
  - Decay achieved mainly by $D^* \to D\pi$ meson

Motivation

- Configuration space calculation with $c\bar{c}$ and $D^0 D^{0*}$ components predicts a state that is approximately 10% $c\bar{c}$ [1]



[1] S. Coito, G. Rupp, E. Beveren, Eur.Phys.J. C73 (2013) 2351

Motivation

- Decays electromagnetically into $J/\psi\gamma$ and $\psi(2S)\gamma$
- Experimental Results

Collaboration	$\mathcal{R}_{\psi\gamma}$
Belle [2]	< 2.1
BaBar [3]	3.4 ± 1.4
LHCb[4]	$2.46 \pm 0.64 \pm 0.29$

with

$$\mathcal{R}_{\psi\gamma} = \frac{\Gamma(X(3872) \to \psi'\gamma)}{\Gamma(X(3872) \to J/\psi\gamma)}$$

[2] Bhardwaj, V. and others, Phys.Rev.Lett. 107 (2011), pp. 091803
[3] B. Aubert et al., Phys.Rev.Lett. 102 (2009), pp. 132001
[4] R. Aaij et al., arXiv:1404.0275

Method

- Obtain wave-functions of J/ψ, $\psi(2S)$ and $X(3782)$
  - Consider all $c\bar{c}$ components
  - Consider DD (for vectors), DD^* and D^*D^* channels
- Calculate electromagnetic transition matrix elements and decay widths

Model

- Unitarized Meson model: $|\psi\rangle = \sum_c |\psi^c_{q\bar{q}}\rangle + \sum_j |\psi^j_{MM}\rangle$
- Confining potential : Harmonic oscillator with universal (i. e. mass independent) frequency

$$V_{Q\bar{Q}}(r) = \frac{1}{2}\mu_c \omega^2 r^2$$

- String breaking through a delta-shell potential

$$V_{cj} = \frac{\lambda g_{cj}}{2\mu_c}\delta(r-a)$$

- Parameters
  - $m_c = 1.562\,\mathrm{GeV}$
  - $\omega = 0.190\,\mathrm{GeV}$
  - a, λ_X and λ_ψ are fixed from the particle masses
  - g_{cj} are $^3P_0$ coupling coefficients

Model

- Schrödinger equation:

$$\begin{bmatrix} \hat{h}^c_{q\bar{q}} & V_{cj} \\ V^\dagger_{jc} & \hat{h}^j_{MM} \end{bmatrix} \begin{bmatrix} u_c \\ v_j \end{bmatrix} = E \begin{bmatrix} u_c \\ v_j \end{bmatrix}$$

with

$$\hat{h}^c_{q\bar{q}} = m^c_q + m^c_{\bar{q}} + \frac{\hbar^2}{2\mu_c}\left(-\frac{d^2}{dr^2} + \frac{l_c(l_c+1)}{r^2}\right) + \frac{1}{2}\mu_c \omega^2 r^2$$

$$\hat{h}^j_{MM} = M^j_1 + M^j_2 + \frac{\hbar^2}{2\mu_j}\left(-\frac{d^2}{dr^2} + \frac{L_j(L_j+1)}{r^2}\right)$$

$$V_{cj} = \frac{\lambda g_{cj}}{2\mu_c}\delta(r-a)$$

Solve Model

- Solutions given by

$$u_c(r) = \begin{cases} a_c M(-\nu_c, l_c + \frac{3}{2}, \mu_c \omega r^2) e^{-\frac{1}{2}\mu_c \omega r^2} r^{1+l_c} & , r < a \\ b_c U(-\nu_c, l_c + \frac{3}{2}, \mu_c \omega r^2) e^{-\frac{1}{2}\mu_c \omega r^2} r^{1+l_c} & , r > a \end{cases}$$

$$v_j(r) = \begin{cases} A_j i_{L_j}(q_j r)\, r & , r < a \\ B_j k_{L_j}(q_j r)\, r & , r > a \end{cases}$$

with $\nu_c = \frac{E - 2m_c}{\hbar\omega} - \frac{l_c}{2} - \frac{3}{4}$ and $E = M_1^j + M_2^j - \frac{\hbar^2}{2\mu_j} q_j^2$

Solve Model

- Continuity of wave-function:

$$a_c M_c = b_c U_c \qquad \text{and} \qquad A_j i_j = B_j k_j$$

- Derivative:

$$\begin{aligned} b_c U_c' - a_c M_c' &= \lambda \frac{e^{\frac{1}{2}\mu_c \omega a^2} a^{-l-2}}{2\mu_c \omega} \sum_j g_{cj} A_j i_j \\ B_j k_j' - A_j i_j' &= \lambda \sum_c \frac{g_{cj} \mu_j e^{-\frac{1}{2}\mu_c \omega a^2} a^{1+l}}{q_j \mu_c a^2} M_c a_c \end{aligned}$$

Solve Model

- Eliminating A_j, B_j and b_c, one obtains ($\alpha_c = a_c M_c$)

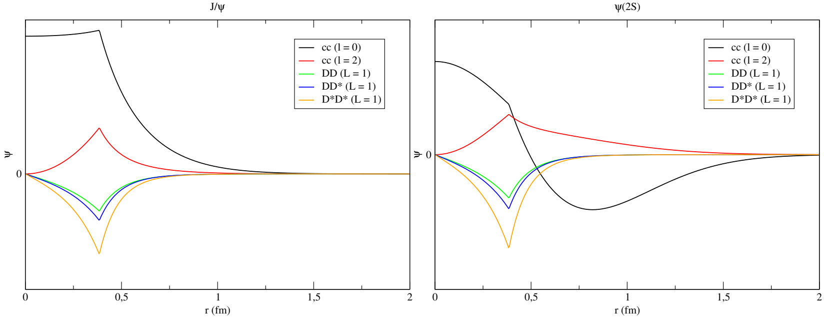
$$\left(\frac{U_c'}{U_c} - \frac{M_c'}{M_c}\right)\alpha_c = \lambda^2 \sum_j \frac{\mu_j g_{cj}}{2\mu_c \omega q_j a^3}\left(\frac{k_j'}{k_j} - \frac{i_j'}{i_j}\right)^{-1} \sum_d \frac{e^{\frac{1}{2}(\mu_c-\mu_d)\omega a^2} g_{dj}}{\mu_d}\,\alpha_d$$

$$D_c \alpha_c = \lambda^2 G_{cd} \alpha_d$$

- Generalized eigenvalue problem for fixed E (and unknown λ)
- Transcendental equation for fixed λ (and unknown E)

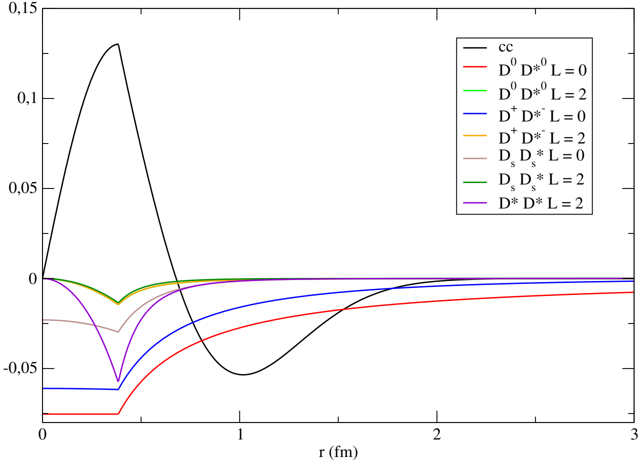
Wave-functions

- Used the masses of J/ψ and $\psi(2S)$ to set the string breaking distance to $a = 1.95\,GeV^{-1}$
- Wave-function components of J/ψ and $\psi(2S)$



Wave-functions

- Wave-function components of the $X(3872)$



Wave-functions

- Radii of $X(3872)$ components:

	$\sqrt{\langle r^2 \rangle}$(fm)
$c\bar{c}$	1.0
$D^0 D^{0*}$	8.1
$D^{\pm} D^{\mp *}$	1.3
Total	6.5

Results

- State composition:

	$c\bar{c}$	DD	$D_0 D_0^*$	$D_\pm D_\mp^*$	$D^* D^*$
J/ψ	84%	2.5%	3.6%		10%
$\psi(2S)$	95%	1.5%	1.3%		2.6%
$X(3872)$	29%	-	63%	7%	1%

Electromagnetic Decay

- Decay width given by Fermi Golden Rule

$$\Gamma_{i \to f} = \frac{2\pi}{\hbar} |\langle \Psi_f | \hat{H}_{int} | \Psi_i \rangle| \rho_f$$

- Density of states: $\rho_f = \frac{1}{2\pi\hbar c}$
- Initial State: $|\Psi_i\rangle = |\psi_{nJM}\rangle \otimes |0\rangle$
- Final State: $|\Psi_f\rangle = |\psi_{n'J'M'}\rangle \otimes |\gamma_{\lambda klm}\rangle$

Electromagnetic decay[5]

- $\langle \Psi_f | \hat{H}_{int} | \Psi_i \rangle = \sum_{cc'} \langle \psi^c_{q\bar{q}} | \hat{h}^{cc'}_{int} | \psi^{c'}_{q\bar{q}} \rangle + \sum_{jj'} \langle \psi^j_{MM} | \hat{h}^{jj'}_{int} | \psi^{j'}_{MM} \rangle$
- Consider only transitions of the type

$$(Q\bar{Q})^* \to Q\bar{Q} + \gamma$$

and

$$(M_1 M_2)^* \to M_1 M_2 + \gamma$$

while neglecting

$$M_1^* M_2^* \to M_1 M_2 + \gamma$$

[5]Based on Verschuren, A.G.M. and Dullemond, C. and van Beveren, Eef, Phys.Rev. D44 (1991), 2803-2817.

Electromagnetic decay

- Hamiltonian has the form

$$\hat{H} = \hat{H}_{q\bar{q}-MM} + \hat{H}_{em} + \hat{H}_{int}$$

- Free electromagnetic Hamiltonian: $\hat{H}_{em} = \int d^3\mathbf{x}\,\frac{\mathbf{E}^2+\mathbf{B}^2}{8\pi}$
- Interaction Hamiltonian elements:

$$\hat{h}_{int} = \sum_i \frac{iQ_i}{m_i c}\,\mathbf{A}(\mathbf{x}_i)\cdot\nabla_i - \mu_i\mathbf{S}_i\cdot\mathbf{B}(\mathbf{x}_i) + \frac{Q_i^2}{2m_i c^2}\mathbf{A}(\mathbf{x}_i)^2$$

using radiation Gauge

$$\nabla.\mathbf{A} = 0 \qquad \text{and} \qquad A^0 = 0$$

Electromagnetic decay

- Vector potential is expanded as

$$\mathbf{A}(\mathbf{r},t) = \sqrt{4\pi}\hbar c \sum_{\lambda lm} \int \frac{dk}{2\pi} \frac{1}{\sqrt{2\omega_k}} \left[\mathbf{f}^{(\lambda)}_{klm}(\mathbf{r}) e^{-i\omega_k t} a_{\lambda lm}(k) + h.\,c.\right]$$

with

$$[a_{\lambda lm}(k), a^\dagger_{\lambda' l' m'}(k')] = 2\pi\delta(k'-k)\delta_{\lambda'\lambda}\delta_{l'l}\delta_{m'm}$$

- $\mathbf{f}^{(e)}_{klm}(\mathbf{r})$ and $\mathbf{f}^{(m)}_{klm}(\mathbf{r})$ have opposite parities

$$\mathbf{f}^{(e)}_{klm}(-\mathbf{r}) = (-1)^{1+l}\mathbf{f}^{(e)}_{klm}(\mathbf{r}) \qquad \mathbf{f}^{(m)}_{klm}(-\mathbf{r}) = (-1)^{l}\mathbf{f}^{(m)}_{klm}(-\mathbf{r})$$

Decay Channels

- For the decay of a 1^{++} state into a 1^{--} state, two electromagnetic channels are possible
  - Electric dipole radiation $l = 1$
  - Magnetic quadrupole radiation $l = 2$

Results

- Computed decay widths in keV (preliminary results):

	Complete	$Q\bar{Q}$	Mesons	Quenched
$\Gamma_e(X \to J/\psi\gamma)$	28.8	16.2	1.82	0.47
$\Gamma_m(X \to J\psi\gamma)$	0.52	0.39	0.01	0.14
$\Gamma_e(X \to \psi'\gamma)$	31.9	30.8	0.01	158
$\Gamma_m(X \to \psi'\gamma)$	0.08	0.08	0.00	0.26

- $\mathcal{R}_{\psi\gamma} = 1.10$

Discussion/Conclusion

- $c\bar{c}$ component of $X(3872)$ becomes more important (30%) as more channels are included
- The presence of meson-meson components changes considerably the electromagnetic decay widths
- Predictions consistent with Belle but not totally agreeing with BaBar and LHCb, though greatly improved as compared to quenched HO calculation