Production of the spin-2 partner of $X(3872)$ in e^+e^- collisions

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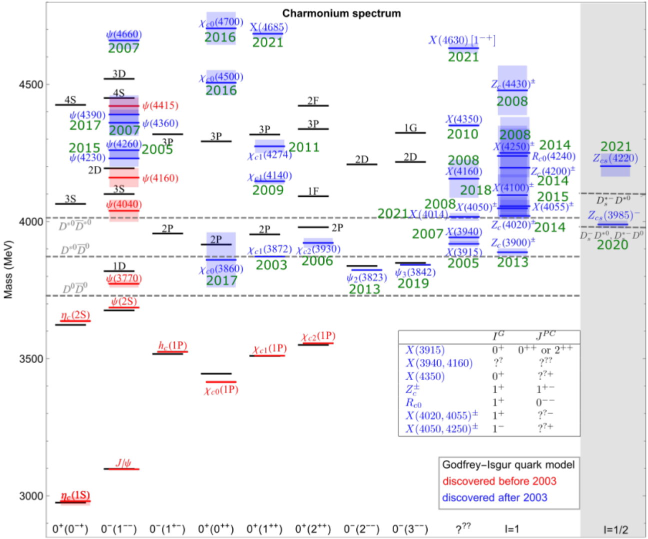
PPS, Jorgivan. M. Dias, F.-K. Guo, Phys.Lett.B 843(2023)137987

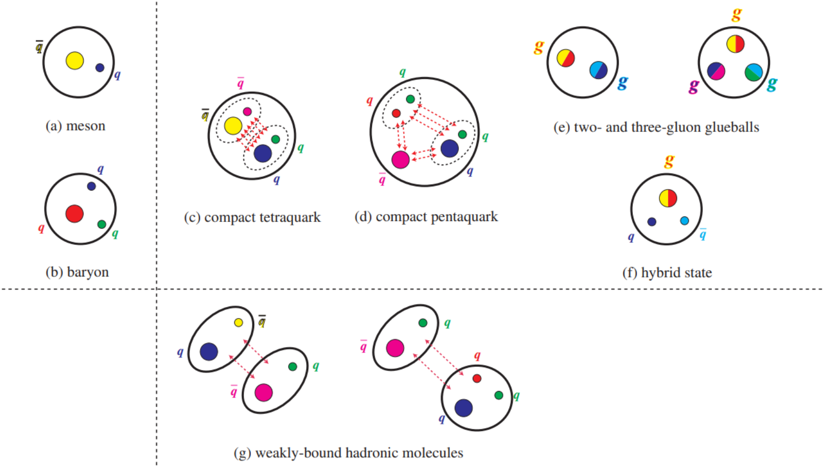
PPS, Vadim. Baru, Feng.-Kun. Guo, Christoph. Hanhart, Alexey. Nefediev, arXiv:2312.05389

Exotic states in the hidden-charm sector



	I^G	J^{PC}
$X(3915)$	0^+	0^{++} or 2^{++}
$X(3940, 4160)$	$?^?$	$?^{??}$
$X(4350)$	0^+	$?^{?+}$
$Z_c^\pm$	1^+	1^{+-}
R_{c0}	1^+	0^{--}
$X(4020, 4055)^\pm$	1^+	$?^{?-}$
$X(4050, 4250)^\pm$	1^-	$?^{?+}$

Categorization of hadrons



H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, Rep. Prog. Phys. 86(2023)026201

Predictions of molecules in the hidden-charm sector

- in the hidden-charm sector, six S-wave isoscalar molecules are predicted in terms of HQSS

J^{PC}	$H\bar{H}$	$^{2S+1}L_J$	V_C	E ($\Lambda = 0.5$ GeV)	E ($\Lambda = 1$ GeV)	Exp [7]
0^{++}	$D\bar{D}$	$^1S_0$	C_{0a}	3706 ± 10	3712^{+13}_{-17}	–
1^{++}	$D^*\bar{D}$	$^3S_1$	$C_{0a} + C_{0b}$	Input	Input	3872
1^{+-}	$D^*\bar{D}$	$^3S_1$	$C_{0a} - C_{0b}$	3814 ± 17	3819^{+24}_{-27}	–
0^{++}	$D^*\bar{D}^*$	$^1S_0$	$C_{0a} - 2C_{0b}$	Input	Input	3917
1^{+-}	$D^*\bar{D}^*$	$^3S_1$	$C_{0a} - C_{0b}$	3953 ± 17	3956^{+25}_{-28}	3942
2^{++}	$D^*\bar{D}^*$	$^5S_2$	$C_{0a} + C_{0b}$	4012 ± 3	4012^{+4}_{-9}	–

$C_{0a} = -3.53(-1.06)$ fm^2 and $C_{0b} = 1.59(0.27)$ fm^2 for $\Lambda = 0.5(1.0)$ GeV

J. Nieves, *et al.*, Phys.Rev.D 86(2012)056004

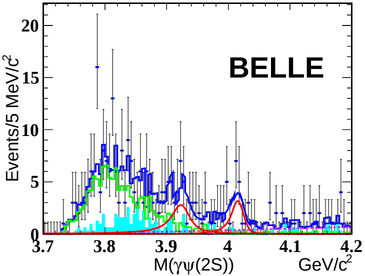
- at LO, $D^*\bar{D}$ (1^{++}) and $D^*\bar{D}^*$ (2^{++}) have same interaction
- the search for the spin-2 partner of $X(3872)$, denoted as X_2, can provide valuable insights into understanding the nature of $X(3872)$

Experimental signal for spin-2 partner of $X(3872)$

In the process $\gamma\gamma \to \psi(2S)\gamma$, two structures are reported by Belle

X.-L. Wang, *et al.* [Belle], Phys. Rev. D 105(2022)112011

- first structure $M_1 = 3922.4 \pm 6.5 \pm 2.0$ MeV, $\Gamma_1 = 2 \pm 17 \pm 4$ MeV which is consistent with $X(3915)$ or $\chi_{c2}(3930)$
- second structure
  - $M_2 = 4014.3 \pm 4.0 \pm 1.5$ MeV
  - $\Gamma = 4 \pm 11 \pm 6$ MeV
  - global significance 2.8σ
  - $\Gamma_{\gamma\gamma}\text{Br}[R_2 \to \psi(2S)\gamma]$:
    0^{++}: $6.2 \pm 2.2 \pm 0.8$ eV ;
    2^{++}: $1.2 \pm 0.4 \pm 0.2$ eV



Properties of the second structure

- the second structure is the perfect candidate of 2^{++} $D^*\bar{D}^*$ molecule
  - production in the $\gamma\gamma$ process: the quantum number can be 0^{++} or 2^{++}
  - $D^*\bar{D}^*$ threshold: this structure is close to $D^*\bar{D}^*$ threshold
  - OBE: more strong coupling for 2^{++} molecule than 0^{++} molecule

    R. Molina, E. Oset, Phys.Rev.D 80(2009)114013
  - mass: its mass is identical to the prediction of the HQSS;
    at heavy quark limit, the same potentials for the scattering of $D\bar{D}^*$ (1^{++}) and $D^*\bar{D}^*(2^{++})$ are consistent with the mass split
    $M_{X_2} - M_{X(3872)} \sim M_{D^*} - M_D \sim 140$ MeV

    J. Nieves, *et al.*, Phys.Rev.D 86(2012)056004
  - decay width: based on the HQSS, $X_2 \to D\bar{D},\ D\bar{D}^*\ \left(\mathcal{O}(1\text{ MeV})\right)$,
    $X_2 \to D\bar{D}^*\gamma\ \left(\mathcal{O}(1\text{ keV})\right)$

    M. Albaladejo, *et al.*, Eur.Phys.J.C 75(2015)547
- beside, this state is explored as a 0^{++} $D^*\bar{D}^*$ molecule

  M.-Y. Duan, *et al.*, Eur.Phys.J.C 82(2022)968; Z.-L. Yue, *et al.*, Phys.Rev.D 106(2022)054008

Lagrangian

- interacrion between ψ and charmed mesons

$$\mathcal{L}_\psi = g_2\psi_\mu\left(\bar{D}^{*\dagger\nu}\overleftrightarrow{\partial}_\nu D^{*\dagger\mu} + \bar{D}^{*\dagger\mu}\overleftrightarrow{\partial}_\nu D^{*\dagger\nu} - \bar{D}^{*\dagger\nu}\overleftrightarrow{\partial}^\mu D^{*\dagger}{}_\nu\right) - g_2\psi_\mu\bar{D}^\dagger\overleftrightarrow{\partial}^\mu D^\dagger$$
$$- ig_2\epsilon^{\mu\nu\alpha\beta}\psi_\mu v_\alpha\left(\bar{D}^{*\dagger}{}_\nu\overleftrightarrow{\partial}_\beta D^\dagger - \bar{D}^\dagger\overleftrightarrow{\partial}_\beta D^{*\dagger}{}_\nu\right) + \text{h.c.}$$

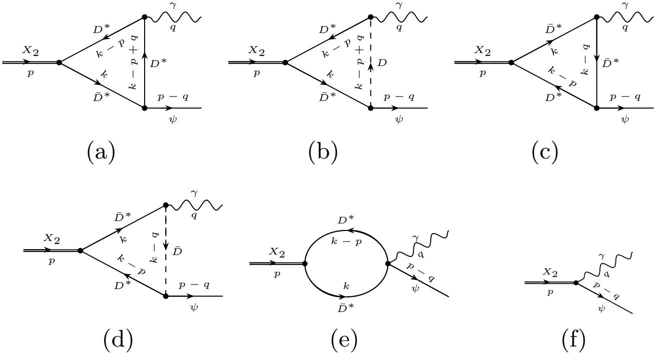
- magnetic interaction J. Hu and T. Mehen, Phys. Rev. D 73(2006)054003

$$\mathcal{L}_m = -ieF^{\mu\nu}\left(D^{*\dagger}_\mu D^*_\nu - D^{*\dagger}_\nu D^*_\mu\right)\left(\frac{Q\beta'}{2} - \frac{Q'}{2m_c}\right) + e\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}v_\alpha\left(D^\dagger D^*_\beta + D^{*\dagger}_\beta D\right)$$
$$+ ieF^{\mu\nu}\left(\bar{D}^{*\dagger}_\mu\bar{D}^*_\nu - \bar{D}^{*\dagger}_\nu\bar{D}^*_\mu\right)\left(\frac{Q\beta'}{2} - \frac{Q'}{2m_c}\right) + e\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}v_\alpha\left(\bar{D}^\dagger\bar{D}^*_\beta + \bar{D}^{*\dagger}_\beta\bar{D}\right)$$

- electric interaction

$$\mathcal{L}_e = -\frac{1}{2}D^{*\dagger}_{\mu\nu}D^{*\mu\nu} + m^2_{D^*}D^{*\dagger}_\mu D^{*\mu}$$
$$+ ie\text{Q}_{D^*}A_\mu\left(D^{*\dagger}_\nu\overleftrightarrow{\partial^\mu}D^{*\nu} + \partial_\nu D^{*\dagger\mu}D^{*\nu} - D^{*\dagger\nu}\partial_\nu D^{*\mu}\right)$$
$$- e^2\text{Q}^2_{D^*}\left(A_\mu A^\mu D^{*\dagger}_\nu D^{*\nu} - A_\mu A_\nu D^{*\dagger\nu}D^{*\mu}\right),$$

Radiative decay process $X_2 \to \gamma\psi$



$$iM = ie\,\chi_{\rm nr}\, g_2\, \epsilon^{*\mu\nu}(X_2)\epsilon^{\beta}(\gamma)\epsilon^{\sigma}(\psi)\sqrt{m_{X_2} m_{\psi}}\int \frac{d^4k}{(2\pi)^4} S^{\rho}_{\nu}(k) S^{\alpha}_{\mu}(k-p)$$

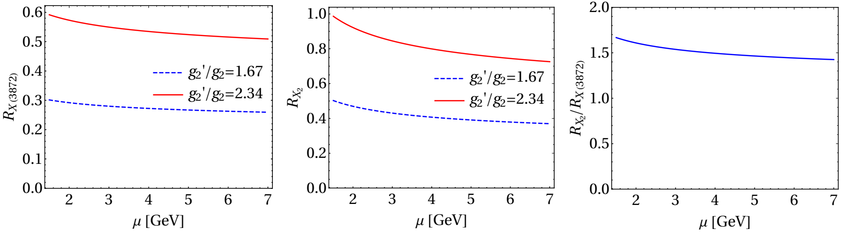
$$\left(J^{(a)m,e}_{\alpha\rho\beta\sigma}(k) + J^{(b)m}_{\alpha\rho\beta\sigma}(k) + J^{(c)m,e}_{\alpha\rho\beta\sigma}(k) + J^{(d)m}_{\alpha\rho\beta\sigma}(k) + J^{(e)e}_{\alpha\rho\beta\sigma}(k)\right).$$

PPS, J. M. Dias, F.-K. Guo, Phys.Lett.B 843(2023)137987

Ratio of partial widths between $\Gamma[X_2 \to \psi(2S)\gamma]$ and $\Gamma[X_2 \to J/\psi\gamma]$

- we use dimensional regularisation scheme with $\overline{\text{MS}}$ subtraction scheme
- $g_2'(g_2)$ is the coupling constant for the interaction between $\psi(2S)$ (J/ψ) and charmed mesons
  - VMD $g_2'/g_2 = 1.67$ Y.-B. Dong, *et al.*, J.Phys.G 38(2011)015001
  - taking the upper limit for the ratio of $X(3872)$ reported by BESIII as input $(R_{X(3872)} \simeq 0.59)$, $g_2'/g_2 = 2.34$

    BESIII, Phys.Rev.Lett. 124(2020)242001, F.-K. Guo, *et al.*, Phys.Lett.B 742(2015)394



Radiative decay for X_2 and $\chi_{c2}(2P)$

- ratio for the radiative decay of $\chi_{c2}(2P)$

	$\Gamma_{J/\psi}$ [keV]	$\Gamma_{\psi(2S)}$ [keV]	$R_{2^3P_2}$
Ref. [1]	53	207	3.9
Ref. [2]	81	304	3.8

[1] T. Barnes, *et al.*, Phys.Rev.D 69(2004)054008

[2] T. Barnes, *et al.*, Phys.Rev.D 72(2005)054026

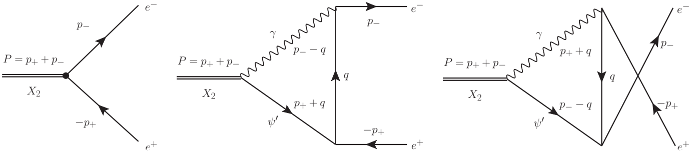
- $R_{X_2} < 1$ (molecular picture) , while $R_{\chi_{c2}} > 1$ ($2P$ charmonium)
- given $X(3872)$ is dominated by the hadronic molecular component, as its partner, the measurement of R_{X_2} can help us distinguish two kinds of pictures
- based on the signal yield of X_2 (19 ± 7) in the in $\psi(2S)\gamma$ invariant mass distribution, we predict at least 35 events can be produced in $J/\psi\gamma$ invariant mass distribution

X.-L. Wang, *et al.* [Belle], Phys. Rev. D 105(2022)112011

Process for $X_2 \to e^+e^-$

The same amplitudes for $X_2 \to e^+e^-$ and $e^+e^- \to X_2$ due to time reversal and P-parity (the principle of detailed balance)

- decay process $X_2 \to \psi/V\gamma \to e^+e^-$
  with $\psi = J/\psi,\ \psi(2S)$ and $V = \rho,\ \omega$
- based on the significantly small contribution for the process $X(3872) \to e^+e^-$ A. Denig, *et al.*, Phys.Lett.B 736(2014)221
  - $\Gamma[X(3872) \to V\gamma \to e^+e^-] \sim 10^{-7}$ eV
  - $\Gamma[X(3872) \to \psi\gamma \to e^+e^-] \sim 10^{-3} - 10^{-2}$ eV
- as the spin-2 partner of $X(3872)$, we consider the process $X_2 \to \psi\gamma \to e^+e^-$ with $\psi = J/\psi,\ \psi(2S)$



Parameters

- interaction between X_2 and $\psi\gamma$ is

$$\mathcal{L}_{X_2\psi\gamma} = g_{X_2\psi\gamma} X_2^{\rho\sigma} F_{\sigma\beta} \psi_\rho^\beta,$$

  where the coupling is extracted from the partial width $X_2 \to \psi\gamma$
- estimation of the partial width for $X_2 \to \psi\gamma$
  - $\Gamma_{X_2}^{\gamma\gamma} \mathrm{Br}(X_2 \to \psi(2S)\gamma) = (1.2 \pm 0.4 \pm 0.2)$ eV
    X.-L. Wang, *et al.* [Belle], Phys. Rev. D 105(2022)112011
  - $\Gamma_{X_2}^{\gamma\gamma} = 0.1$ keV to estimate the branch ratio for $X_2 \to \psi(2S)\gamma$
    V. Baru, C. Hanhart, A. V. Nefediev, JHEP 06(2017)010
  - $\Gamma[X_2 \to \psi(2S)\gamma]/\Gamma[X_2 \to J/\psi\gamma] \sim 1$
    PPS, J. M. Dias, F.-K, Guo, Phys.Lett.B 843(2023)137987
- VMD model is utilized to estimate the vertex $\psi \to \gamma^* \to e^+e^-$

$$\mathcal{L}_{\psi\gamma} = -\frac{e}{2}\frac{f_\psi Q_c}{M_\psi} F^{\mu\nu}\psi_{\mu\nu}$$

Decay width

- branch ratio for $X_2 \to e^+e^-$ as the function of the energy scale μ

PPS, V. Baru, F.-K. Guo, C. Hanhart, A. Nefediev, arXiv:2312.05389

μ [GeV]	2.0	4.0	6.0
$\mathrm{Br}_{\mathrm{loop}}[X_2 \to e^+e^-] \times 10^9$	2	7	11

- branch ratios for X_2 and $\chi_{c2}(2P)$: $\Gamma^{\gamma\gamma}_{\chi_{c2}(3930)} = 1.0$ keV (quark model) and $\Gamma^{ee}_{\chi_{c2}(1P)} \sim \Gamma^{ee}_{\chi_{c2}(2P)} = 0.07$ eV (NRQCD)

C. M. A., R. Dhir, (2023), arXiv:2311.05274; N. Kivel and M. Vanderhaeghen, JHEP 02(2016)032; E. J. Eichten, C. Quigg, Phys.Rev.D 52(1995)1726

Channel	$J/\psi\gamma$	$\psi(2S)\gamma$	$\gamma\gamma$	e^+e^-
$(D^*\bar{D}^*)_{J=2}$	10^{-2}	10^{-2}	$10^{-4}/10^{-5}$	10^{-9}
$\chi_{c2}(2P)$	10^{-3}	10^{-3}	10^{-4}	10^{-9}

- because of large uncertainty of X_2 width ($\Gamma_{X_2} = 4 \pm 11 \pm 6$ MeV), we consider different values of Γ_{X_2}:
  - $\Gamma[X_2 \to e^+e^-] \sim \mathcal{O}(10^{-2})$ eV for $\Gamma_{X_2} \sim 10$ MeV
  - $\Gamma[X_2 \to e^+e^-] \sim \mathcal{O}(10^{-3})$ eV for $\Gamma_{X_2} \sim 1$ MeV

Directly production of X_2

- based on the principle of detailed balance, the cross section for the directly production of X_2 is

PPS, *et al.*, Phys.Rev.D 105(2022)034024

$$\sigma_C \simeq \frac{20\pi\Gamma^{ee}_{X_2}}{\Gamma_{X_2} M^2_{X_2}} = \frac{20\pi}{M^2_{X_2}}\text{Br}[X_2 \to e^+e^-] \simeq 7 \text{ pb},$$

- search for X_2 in the $\psi\gamma$ invariant mass distribution

$$\text{Br}[\psi(2S) \to \pi^+\pi^- J/\psi] \simeq (34.68 \pm 0.30)\%,$$
$$\text{Br}[J/\psi \to \ell^+\ell^-] \simeq (11.93 \pm 0.07)\% \quad (\ell = e,\ \mu),$$

Search for X_2 in the e^+e^- collisions

Search for X_2 in BESIII and STCF:

- BESIII: During the period from 2011 to 2014, BESIII accumulated an integrated luminosity of around 53 pb^{-1} at the centre-of-mass energy $\sqrt{s} = 4090$ MeV and we expect that $\mathcal{O}(10^2)$ events can be produced
- STCF: considering the integrated luminosity of a year is 1 ab^{-1}, at $\sqrt{s} \simeq 4014$ MeV, the number of events constructed in $\psi\gamma$ final state can be
  - $\mathcal{O}(10^2)$ for $\chi_{c2}(2P)$
  - $\mathcal{O}(10^3)$ for X_2 as a molecule

The STCF is expected to search for X_2 in the $\psi(2S)\gamma$ and $J/\psi\gamma$ invariant mass distribution

1. Introduction
2. Radiative decay of X_2
3. Production of X_2 in e^+e^- collisions
4. Summary

Summary

- $X_2 \to \psi\gamma$: considering the structure observed by Belle as a S-wave $D^*\bar{D}^*$ molecule with $I(J^{PC}) = 0(2^{++})$, we estimate the ratio $R_{X_2} < 1$, which is significantly different with that of $\chi_{c2}(2P)$;
- production of X_2 in e^+e^- collision (principle of detailed balance):
  - the partial width for $X_2 \to e^+e^-$ is at $\mathcal{O}(10^{-3}) - \mathcal{O}(10^{-2})$ eV level in terms of the value of Γ_{X_2}
  - STCF can be used to search for X_2 in the $\psi\gamma$ invariant mass distribution

Thank you for your attention!

Backup

The independent and gauge invariant structure coupled with the tensor polarization is

$$\begin{aligned}
\mathcal{S}^{(1)}_{\rho\sigma} &= g_{\rho\sigma}(\partial_\alpha F_{\mu\nu})(\partial^\alpha \psi^{\mu\nu}),\\
\mathcal{S}^{(2)}_{\rho\sigma} &= (\partial_\rho F_{\mu\nu})(\partial_\sigma \psi^{\mu\nu}) + (\partial_\sigma F_{\mu\nu})(\partial_\rho \psi^{\mu\nu}) - \frac{1}{2} g_{\rho\sigma}(\partial_\alpha F_{\mu\nu})(\partial^\alpha \psi^{\mu\nu}),\\
\mathcal{S}^{(3)}_{\rho\sigma} &= (\partial_\rho \partial_\sigma F_{\mu\nu})\psi^{\mu\nu} + F_{\mu\nu}(\partial_\rho \partial_\sigma \psi^{\mu\nu}),\\
\mathcal{S}^{(4)}_{\rho\sigma} &= F_{\rho\beta}\psi^\beta_\sigma + F_{\sigma\beta}\psi^\beta_\rho - \frac{1}{2} g_{\rho\sigma} F_{\mu\nu}\psi^{\mu\nu},
\end{aligned}$$

with $\psi^{\mu\nu} \equiv \partial^\mu \psi^\nu - \partial^\nu \psi^\mu$. Since $\mathcal{S}^{(1)}_{\rho\sigma}$, $\mathcal{S}^{(2)}_{\rho\sigma}$ and $\mathcal{S}^{(3)}_{\rho\sigma}$ are suppressed by the third power of momentum at heavy quark limit, and the the last term of $\mathcal{S}^{(4)}_{\rho\sigma}$ vanishes due to the traceless tensor polarization. Then the Lagrangian is

$$\mathcal{L}_{X_2\psi\gamma} = g_{X_2\psi\gamma} X_2^{\rho\sigma} F_{\sigma\beta}\psi^\beta_\rho.$$