From Hadronic Atoms to Hadronic Molecules

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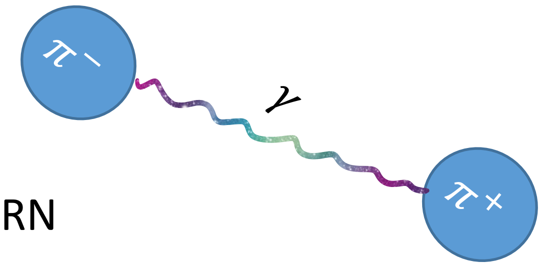
Based on:

Z.-H. Zhang, FKG, $D^{\pm}D^{*\mp}$ *hadronic atom as a key to revealing the X(3872) mystery*, Phys. Rev. Lett. 127, 012002 (2021) [arXiv:2012.08281]

P.-P. Shi, Z.-H. Zhang, FKG, $D^{+}D^{-}$ *hadronic atom and its production in* pp *and* $p\bar{p}$ *collisions*, Phys. Rev. D 105, 034024 (2022) [arXiv:2111.13496]

Hadronic atoms

- Composite systems of hadrons with opposite electric charges, bound by the Coulomb force, corrections due to strong interaction



- Examples:
  - ✓ Pionium: $[\pi^+\pi^-]$; $\pi^\pm K^\mp$ atoms
  - ✓ Pionic/kaonic hydrogen: $[p\pi^-/K^-]$
  - ✓ Pionic/kaonic deuterium: $[d\pi^-/K^-]$

  - DIRAC @CERN
  - Pionic Hydrogen Col. @PSI
  - DEAR, SIDDHARTA(-2), ADMEUS @LNF-INFN

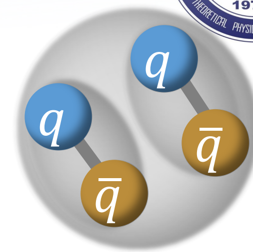
- Some properties:
  - ✓ Bohr radius: $r_B = \frac{1}{\alpha\mu}$, binding energy: $\frac{\alpha^2\mu}{2n^2}$
  - ✓ Probing the longest distance strong interaction, measuring the scattering lengths
  - ✓ Mass shift due to strong interaction: Deser-Goldberger-Baumann-Thirring (DGBT) formula: $\Delta E_{\rm str} \propto |\psi(0)|^2 a$
  - ✓ Decays due to strong interaction, e.g., $[\pi^+\pi^-] \to \pi^0\pi^0 \;\; \Rightarrow \;\; (a_0 - a_2)_{\pi\pi}$

$$|a_0^0 - a_0^2| = 0.2533^{+0.0080+0.0078}_{-0.0078-0.0073}$$

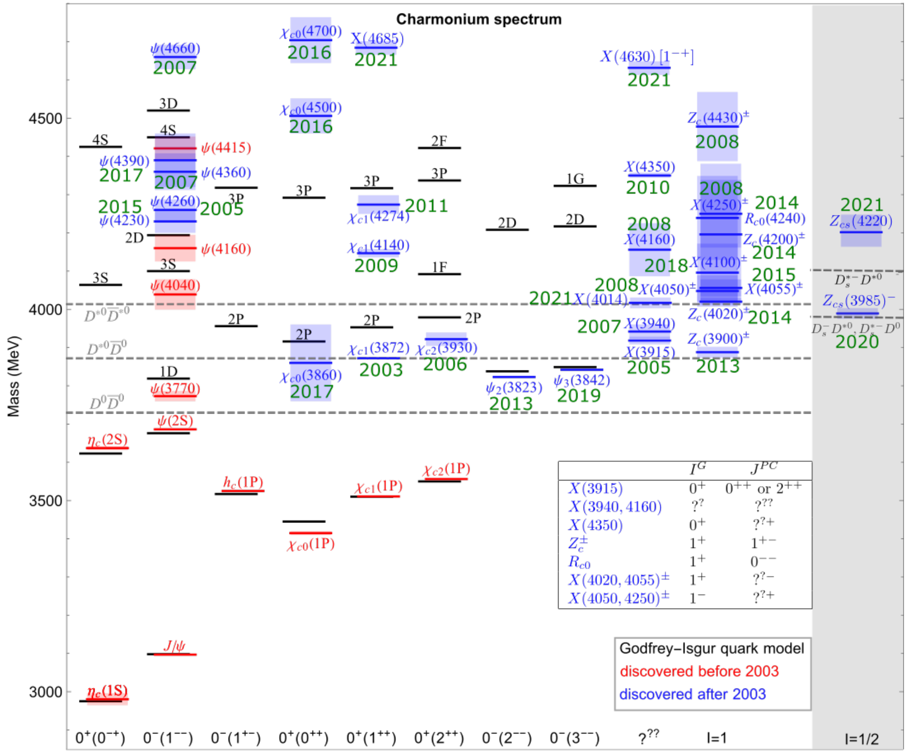
B.Adeva et al. [DIRAC], PLB704(2011)24

Review: J. Gasser, V. E., Lyubovitskij, A. Rusetsky, Hadronic atoms in QCD+QED, Phys. Rept. 456 (2008) 167

Hadronic molecules



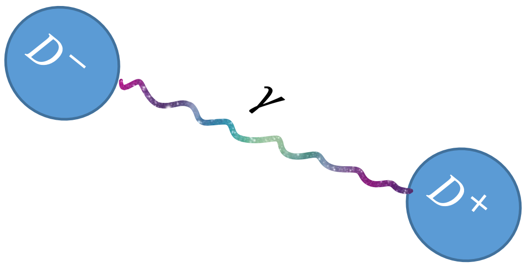
- Composite systems of hadrons, analogues of light nuclei
  - Extended object, $\sqrt{2\mu\delta} \ll \Lambda_{\text{had}} \sim 1\ \text{GeV}$
- Bound by strong force, e.g., the exchange of pions, light vector mesons, …
- Many resonances are good candidates of hadronic molecules

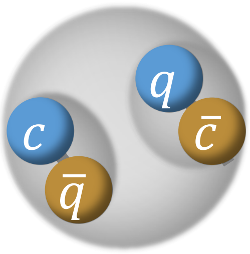


- $f_0(980), a_0(980)$
- $\Lambda(1405)$
- $D^*_{s0}(2317), D_{s1}(2460)$
- $X(3872), Y(4260)$, …
- $P_c(4312,4440,4457)$
- $P_{cs}(4338)$
- T_{cc}
- …

Review: FKG, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, Hadronic molecules, RMP 90 (2018) 015004

From hadronic atoms to hadronic molecules





- Bound by Coulomb force
- Probes the long-distance part of the strong force (scattering length)
- Effects of strong interaction
  - Energy shift
  - Decay width, into neutral channel

- Bound by Strong force
- Universal properties of loosely bound states determined by the scattering length
  - Long-distance wave function
  - Effective coupling

$X(3872)$ aka $\chi_{c1}(3872)$

- Discovered in $B^\pm \to K^\pm J/\psi\pi^+\pi^-$ Belle, PRL91(2003) 262001
- $J^{PC} = 1^{++}$ LHCb, PRL110(2013) 222001 couple to $D^0\bar{D}^{*0} + c.c.$ in S-wave
- Mass: extremely close to the $D^0\bar{D}^{*0}$ threshold, binding energy $\delta \equiv M_{D^0} + M_{D^{*0}} - M_X$

  $\delta = 0.01 \pm 0.14$ MeV LHCb, PRD102(2020)092005; $\delta = 0.12 \pm 0.13$ MeV LHCb, JHEP08(2020)123

  Inclusive b-hadron decays $B^+ \to K^+X(3872)$

- BW width: < 1.2 MeV Belle, PRD84(2011)052004

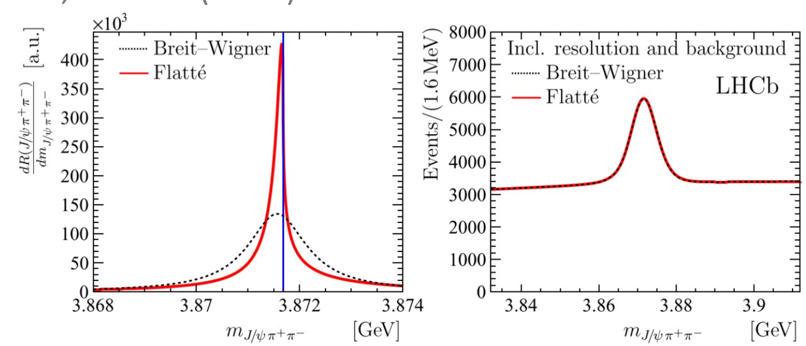
  1.39 ± 0.26 MeV LHCb, PRD102(2020)092005; 0.96 ± 0.28 MeV LHCb, JHEP08(2020)123

  from BW fits;

  width from the Flatté analysis is much smaller: LHCb, PRD102(2020)092005

Mode (MeV)	Mean (MeV)	FWHM (MeV)
$3871.69^{+0.00+0.05}_{-0.04-0.13}$	$3871.66^{+0.07+0.11}_{-0.06-0.13}$	$0.22^{+0.06+0.25}_{-0.08-0.17}$

BW not suitable for near-threshold structures



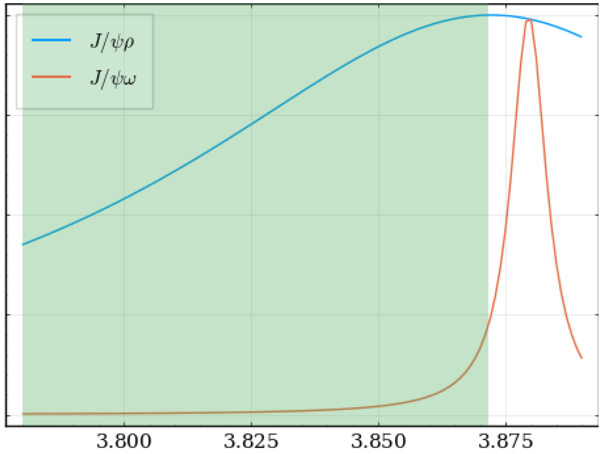
- Strong coupling to $D^0\bar{D}^{*0} + c.c.$: $\mathcal{B} > 30\%$ Belle, PRD81(2010)031103

$X(3872)$ aka $\chi_{c1}(3872)$

- Huge isospin breaking

PDG2020, average of BESIII, 122(2019)232002 and BaBar, PRD82(2010)011101

$$\frac{\mathcal{B}(X\to\omega J/\psi)}{\mathcal{B}(X\to\rho J/\psi)} = 1.1 \pm 0.4$$, largely from phase space difference



$$\frac{g_{X\rho J/\psi}}{g_{X\omega J/\psi}} = 0.29 \pm 0.04$$ LHCb, arXiv:2204.12597

- Radiative decays

$$\frac{\mathcal{B}(X\to\gamma\psi')}{\mathcal{B}(X\to\gamma J/\psi)} = 3.4 \pm 1.4$$ BaBar, PRL102(2009)132001

$= 2.46 \pm 0.70$ LHCb, NPB886(2014)665

< 2.1 @90% C.L. Belle, PRL107(2011)091803

< 0.59 @90% C.L. BESIII, PRL124(2020)242001

- Productions: found in $B \to KX, B \to K\pi X, e^+e^- \to \gamma X, pp/p\bar{p}$ inclusive, PbPb, $\gamma^*\gamma$

Models and crucial quantities

- $D\bar{D}^*$ hadronic molecule, predicted by N.A.Törnqvist ZPC61(1993)525
- Diquark-antidiquark tetraquark L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer, PRD71(2005)014028
- Mixture of $D\bar{D}^*$ hadronic molecule with $c\bar{c}$ Yu.S. Kalashnikova, PRD72(2005)034010; C. Meng, H. Han, K.-T. Chao, PRD96(2017)074014 ; … E. Eichten et al., PRD17(1978)3090, PRD21(1980)203

Important quantities in determining the $D\bar{D}^*$ component (compositeness $\tilde{X} \equiv 1 - Z$) inside $X(3872)$:

- width of long-distance processes: $X \to D^0\bar{D}^0\pi^0, D\bar{D}\gamma$ => coupling constant to $D\bar{D}^*$
- Line shape
- binding energy
- $D\bar{D}^*$ scattering length (from lattice)

$$g_{\rm NR}^2 = \tilde{X}\frac{2\pi}{\mu^2}\sqrt{2\mu\delta}\left[1 + \mathcal{O}\left(\sqrt{2\mu\delta}/\beta\right)\right] \qquad a_0 = \frac{-2\tilde{X}}{(1-\tilde{X})\sqrt{2\mu\delta}}$$

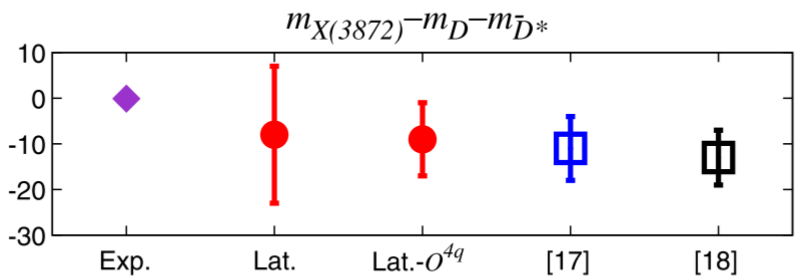
S. Weinberg, PR137(1965)B672;
FKG, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, RMP90(2018)015004

Lattice results

Evidence found below $D\bar{D}^*$ threshold

- Isospin symmetric calculation
- Both $\bar{c}c$ and $D\bar{D}^*$ operators are needed

S. Prelovsek, L. Leskovec, PRL111(2013)192001;
M. Padmanath, C. Lang, S. Prelovsek, PRD92(2015)034501



[18] S.H. Lee et al. [Fermilab&MILC], arXiv:1411.1389

ERE parameters from S. Prelovsek, L. Leskovec (2013) w/ a small lattice volume: $L = 1.98$ fm

$$a_{D\bar{D}^*} = (-1.7 \pm 0.4)\ \text{fm}, \qquad r_{D\bar{D}^*} = (0.5 \pm 0.1)\ \text{fm}$$

lead to an estimate of the compositeness $\tilde{X} \gtrsim 0.7$

- ✓ Early phenomenological studies: $0.6 \sim 0.7$ — Kalashnikova, Nefediev, PRD80(2009)074004
  $0.56 \sim 0.72$ — C.Meng,H.Han,K.-T.Chao, PRD96(2017)074014
- ✓ Recent determinations from the LHCb measured line shape:
  $\tilde{X} \gtrsim 0.9$, — V. Baru et al., PLB833(2022)137290
  $\tilde{X} \in [0.86, 0.95]$ — A. Esposito et al., PRD105(2022) L031503

Debates

Debates regarding processes involving short-distance physics, e.g., what can be concluded from productions at hadron colliders

Factorization into short-distance and long-distance parts E. Braaten, M. Kusunoki, PRD72(2005)014012

- Long-distance: computable in NREFT
- Short-distance: could correspond to physics due to the $c\bar{c}$ component

  the more extended, the more difficult to be produced, $\sigma \propto \delta^{1/2}$ (universality)
  Often assumed that tetraquark is much more compact than molecule;
  the $X(3872)$ is extended by observation: $D^0\bar{D}^{*0}$ component

X atoms

Z.-H. Zhang, FKG, PRL127(2021)012002

- $X(3872)$: strong coupling to $D^0\bar{D}^{*0}$

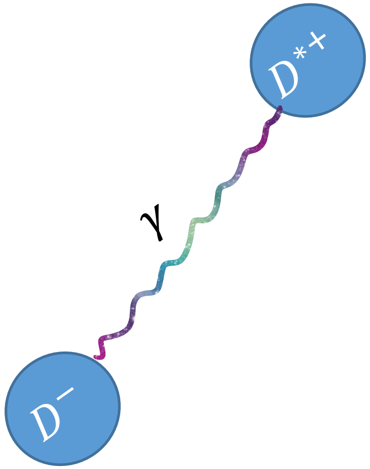
  Unavoidably extended, large radius, $r_X \simeq \frac{1}{\sqrt{2\mu_0\delta}} \gtrsim 10$ fm

- The same order as the Bohr radius of Coulomb bound state of $D^\pm D^{*\mp}$: hadronic atoms $r_B = \frac{1}{\alpha\mu_c} = 27.86$ fm

  $\mu_0 = \frac{m_{D^0}m_{D^{*0}}}{\Sigma_0}$ $\mu_c = \frac{m_D m_{D^*}}{\Sigma_c}$ thresholds: $\Sigma_{0,c}$

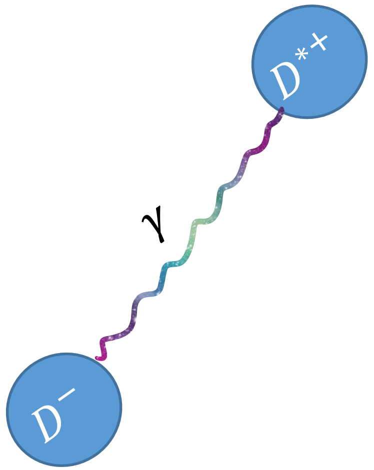
- Coulomb binding energies: $E_n = \frac{\alpha^2\mu_c}{2n^2} = \frac{25.81\ \text{keV}}{n^2}$

- X atoms: The $D^\pm D^{*\mp}$ atoms with $C = +$



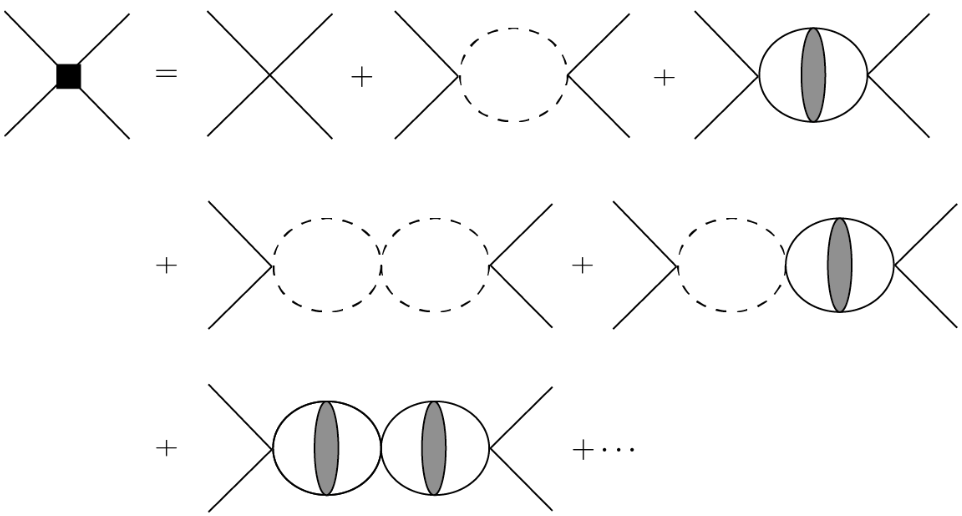
X atoms

- Scale separation: $r_B \Lambda_{QCD} \gg 1$, strong interaction provides corrections to QED of hadronic atoms:
  - Correction to the binding energy: $\Delta E_n = O(\alpha^3)$
  - Decay modes: $D^0 \bar{D}^{*0}, D^0 \bar{D}^0 \pi^0, J/\psi \pi\pi, \ldots$
- For X atoms, strong interaction by itself is nonperturbative due to the existence of $X(3872)$



X atoms: formalism

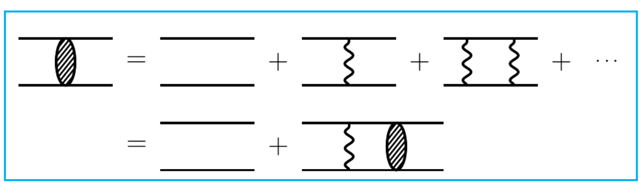
- Nonrelativistic effective field theory (NREFT) for coupled channels:
  - 1^{++} $D^0\bar{D}^{*0}$
  - 1^{++} $D^{\pm}D^{*\mp}$; the $D^{\pm}D^{*\mp}$ Green function contains both Coulomb bound states and continuum



- Parameter-free predictions
  - Ground state X atom binding energy and decay width (due to decays of $D^{*\mp}$ & to $D^0\bar{D}^{*0}$)

$$\mathrm{Re}\, E_{A1} = E_1 - \frac{\alpha^3\mu_c^2}{\sqrt{2\mu_c\Delta}} \simeq 22.92\ \mathrm{keV}$$

$$M_{A1} = (3879.89 \pm 0.07)\ \mathrm{MeV}$$



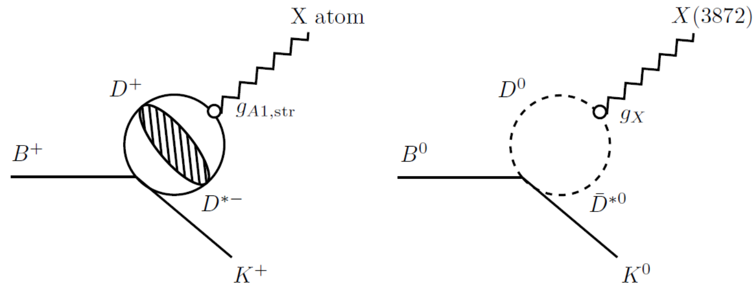
$$\Gamma_c + 2\,\mathrm{Im}\, E_{A1} = \Gamma_c + \frac{2\alpha^3\mu_c^2}{\sqrt{2\mu_c\Delta}} = (89.2 \pm 1.8)\ \mathrm{keV}$$

Γ_c = (83.4 ± 1.8) keV

X atoms: production

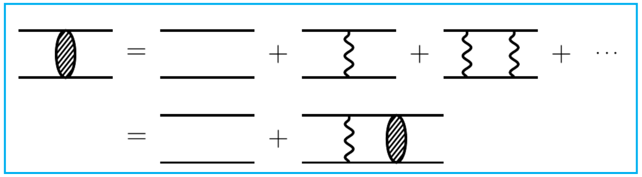
- Productions of the $X(3872)$ and the X atom
- Scale separation: factorization

Braaten, Kusunoki, PRD72(2005)014012



$$\mathcal{A}_{B^+\to AK^+} = \mathcal{A}^{\mathrm{s.d.}}_{B^+\to(DD^*)_+K^+} g_{A1,\mathrm{str}}$$
$$\mathcal{A}_{B^0\to XK^0} = \mathcal{A}^{\mathrm{s.d.}}_{B^0\to(DD^*)^0_+K^0} g_X\,,$$

Calculable in NREFT



$\mathcal{A}^{\mathrm{s.d.}} = \mathcal{A}^{\Lambda}_{\mathrm{s.d.}}\frac{\mu\Lambda}{\pi^2}$, with $\mathcal{A}^{\Lambda}_{\mathrm{s.d.}} \propto \Lambda^{-1}$; the leading UV divergences are the same

- Isospin symmetry: the short-distance parts are the same, productions of the X(3872) and the X atom are related

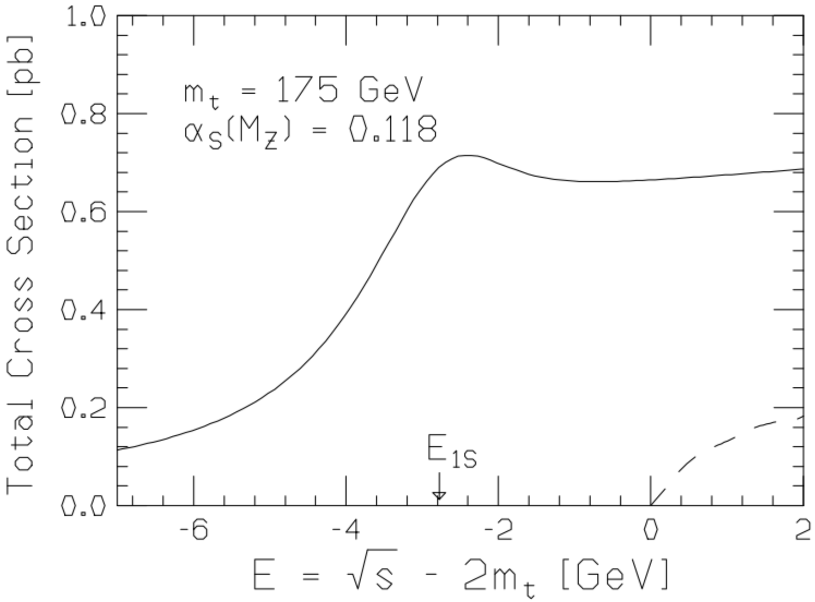
$$R_\Gamma \equiv \frac{\Gamma_{B^+\to AK^+}}{\Gamma_{B^0\to XK^0}} = \frac{|g_{A1,\mathrm{str}}|^2}{|g_X|^2} \qquad R_\sigma \equiv \frac{d\sigma_{pp\to A+y}}{d\sigma_{pp\to X+y}} = \frac{|g_{A1,\mathrm{str}}|^2}{|g_X|^2}$$

- Production rate for the X atom: $R_\Gamma \simeq R_\sigma \gtrsim 1\times10^{-3}$
- Null signal leads to a lower bound on the $X(3872)$ binding energy

$$\delta \simeq \frac{0.25\ \mathrm{eV}}{R_\Gamma^2} \simeq \frac{0.25\ \mathrm{eV}}{R_\sigma^2}$$

X atoms: line shape

- Since the width is larger than the binding energy of the ground state, the line shape will have collective behavior of the whole series of Coulomb bound states, similar to the toponia



Y. Sumino, *Adv.Ser.Direct.High Energy Phys.* 19 (2005) 135

- Possible enhancement due to triangle singularities to be explored: $D^*\bar{D}^* \to A\pi/A\gamma$

Dionium: D^+D^- atom

P.-P. Shi, Z.-H. Zhang, FKG, PRD 105 (2022) 034024

- D^+D^- atom: named as dionium

  - Ground state Coulomb binding energy: $E_1 = \frac{\alpha^2\mu_c}{2} \simeq 24.9\ \text{keV}$
  - Strong interaction induced energy shift and $\Gamma([D^+D^-] \to D^0\bar{D}^0)$ depend on $D\bar{D}$ scattering lengths

$$\Delta E_1^{\text{str}} - i\frac{\Gamma_1}{2} = \frac{\alpha^3\mu_c^3}{\pi}\,\frac{w_+(1-R) - i\,\frac{\mu_0}{2\pi}\sqrt{2\mu_0\Delta R}}{w_+^2(1-R)^2 + \left(\frac{\mu_0}{2\pi}\right)^2 2\mu_0\Delta R^2}$$

$w_\pm$ and R are functions of the scattering lengths a_0, a_1

  - With lattice QCD input for $D\bar{D}$ bound state with $\delta = 4.0^{+5.0}_{-3.7}$ MeV,

S. Prelovsek et al., JHEP 06 (2021) 035

$$\text{Re}E_A = E_1 - \Delta E_1^{\text{str}} \simeq 22.9^{+0.3}_{-0.4}\ \text{keV},$$
$$\Gamma_1 \simeq 1.8^{+1.4}_{-0.6}\ \text{keV},$$

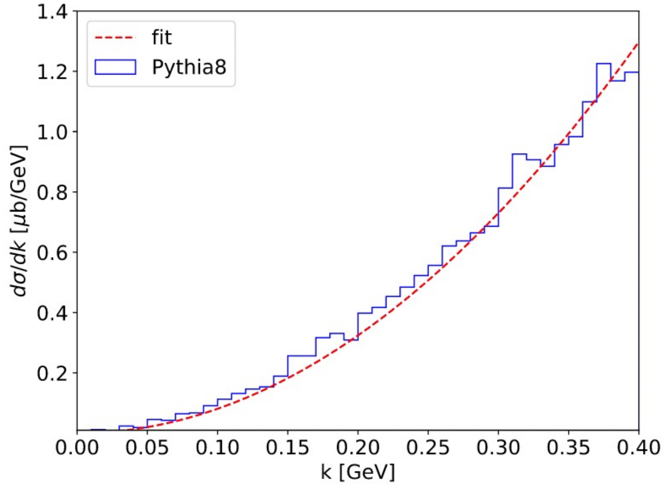
pushed up due to the $D\bar{D}$ hadronic molecule;

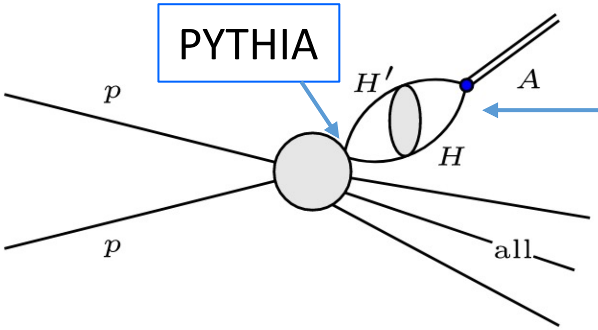
much more stable than the X atom

Production of dionium

P.-P. Shi, Z.-H. Zhang, FKG, PRD 105 (2022) 034024

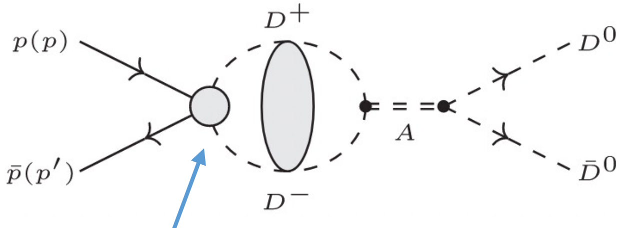
- Inclusive production in pp collisions





Λ (GeV)	0.5	1.0
$\sigma(pp \to A_{D^+D^-}$ +all) (pb)	1^{+7}_{-1}	49^{+76}_{-33}

- Exclusive production in $p\bar{p}$ collisions



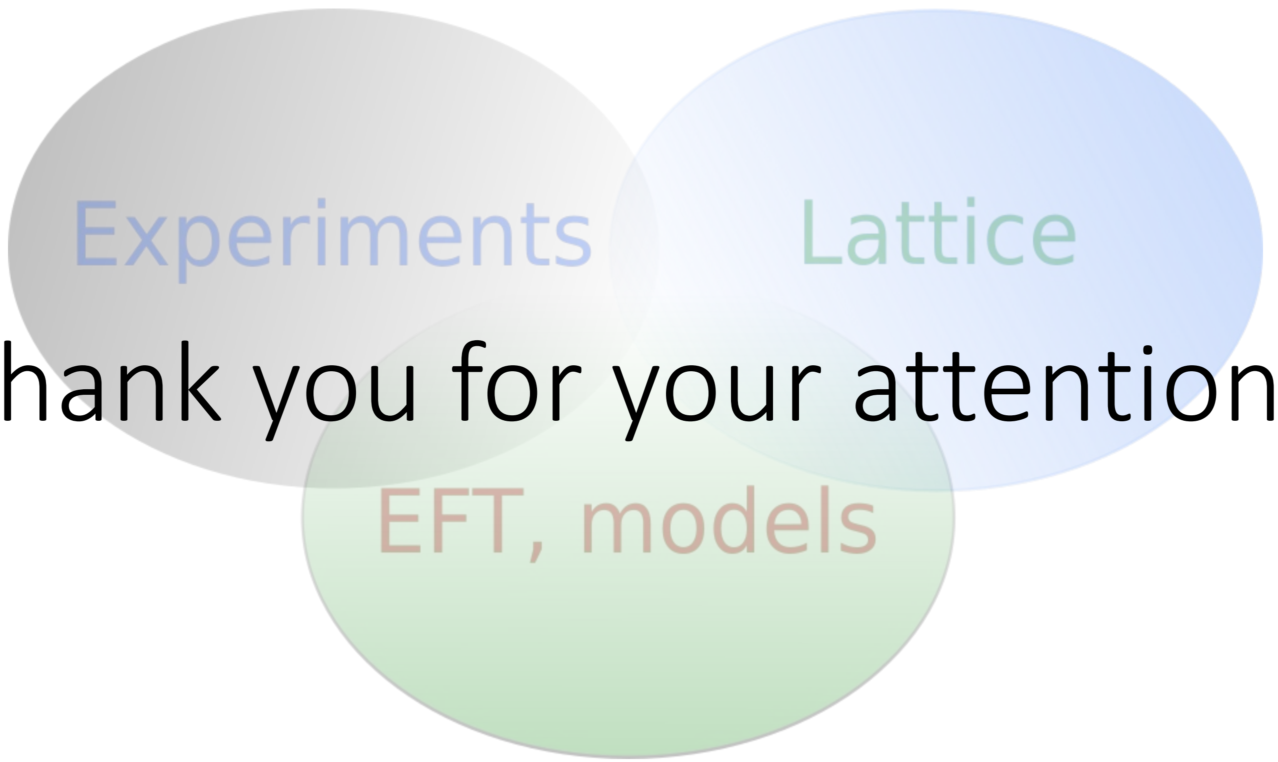
Σ_c-exchange

Λ (GeV)	0.5	1.0
$\sigma(p\bar{p} \to A_{D^+D^-} \to D^0\bar{D}^0)$ (μb)	$0.002^{+0.013}_{-0.002}$	$0.1^{+0.2}_{-0.1}$

Consider an integrated luminosity of 2 fb^{-1} at PANDA, PANDA, EPJA 55(2019)42
$(0.04 \sim 2)\times 10^8$ events ⇒ $\mathcal{O}(10^3 \sim 10^5)$ events with $D^0/\bar{D}^0$ reconstructed from $K^\mp\pi^\pm$

Conclusion

- Hadronic atoms can be used measure low-energy strong interaction observables
- Connection to hadronic molecules can be made through NREFT, parameter-free predictions
  - Productions
  - Long-distance properties
- Hidden-charm hadronic atoms may be searched for at PANDA

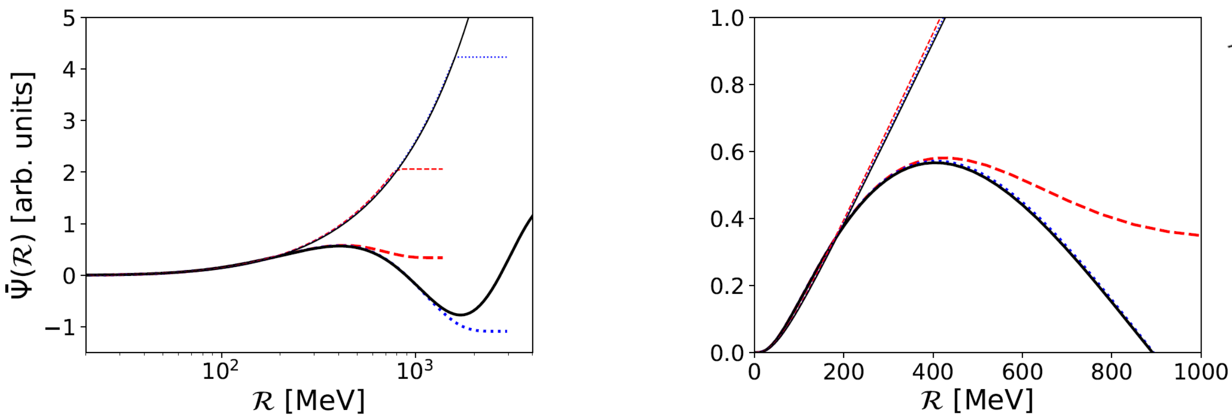


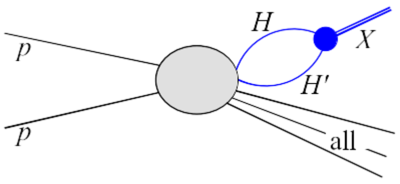
Thank you for your attention!

Production estimates

- Order-of-magnitude estimates of cross sections at hadron colliders in the molecular picture M. Albaladejo, FKG, C. Hanhart, U.-G. Meißner, J. Nieves, A. Nogga, Z. Yang, CPC41(2017)121001

  - The deuteron as an example





  - $\mathcal{R}$ must be much larger, $\mathcal{R} \sim 300$ MeV see also: Artoisenet, Braaten, PRD81(2010)114018

$\sigma(pp/\bar{p} \to X)$ [nb]	Exp.	Λ=0.1 GeV	Λ=0.5 GeV	Λ=1.0 GeV
CDF [IJMPA20(2005)3765]	37-115	0.07 (0.05)	7 (5)	29 (20)
CMS [JHEP1304(2013)154]	13-39	0.12 (0.04)	13 (4)	55 (15)

here $\Lambda \simeq 2\sqrt{2/\pi}\mathcal{R} \simeq 1.6\mathcal{R}$

X atoms: formalism

- Around the threshold, LO in NREFT: constant contact terms for strong interaction

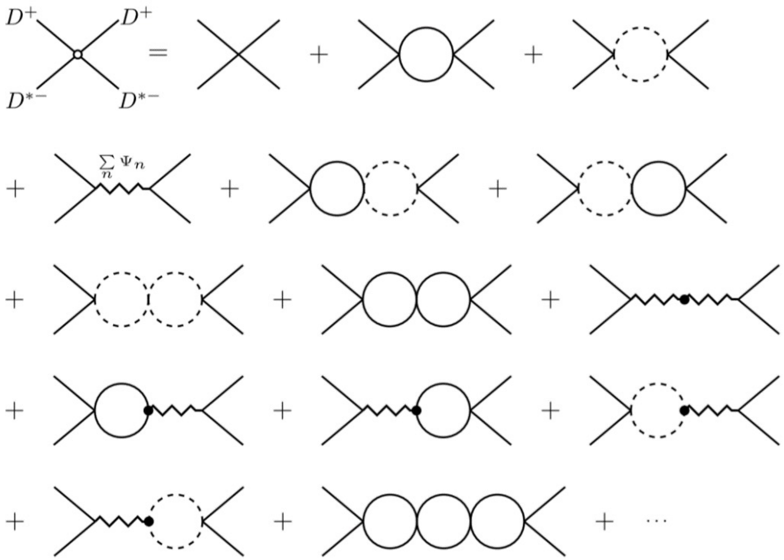
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_{\phi=D^{\pm},D^0,\bar{D}^0} \phi^\dagger \left(iD_t - m_\phi + \frac{\nabla^2}{2m_\phi}\right)\phi$$
$$+ \sum_{\phi=D^{*\pm},D^{*0},\bar{D}^{*0}} \phi^\dagger \left(iD_t - m_\phi + i\frac{\Gamma_\phi}{2} + \frac{\nabla^2}{2m_\phi}\right)\phi$$
$$- \frac{C_0}{2}(D^+D^{*-} - D^-D^{*+})^\dagger(D^+D^{*-} - D^-D^{*+})$$
$$- \frac{C_0}{2}\left[(D^+D^{*-} - D^-D^{*+})^\dagger(D^0\bar{D}^{*0} - \bar{D}^0D^{*0}) + \mathrm{h.c.}\right]$$
$$- \frac{C_0}{2}(D^0\bar{D}^{*0} - \bar{D}^0D^{*0})^\dagger(D^0\bar{D}^{*0} - \bar{D}^0D^{*0}) + \cdots,$$

- Approximation: Isospin-1 strong interaction neglected
  - No isovector state was found
  - Isospin breaking in the couplings is small: Hanhart et al., PRD85(2012)011501

$$\frac{g_{X\rho}}{g_{X\omega}} = 0.26^{+0.08}_{-0.05}$$

X atoms: formalism

- The T-matrix for positive C parity channels: $T(E) = V[1 - G(E)V]^{-1}$

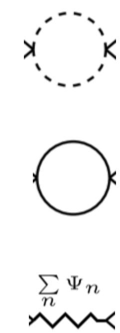


$$V = C_0 \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}, \quad G(E) = \begin{pmatrix} J_0(E) & 0 \\ 0 & J_c(E) + J_{|\Psi\rangle}(E) \end{pmatrix}$$

$$J_0(E) = \frac{\mu_0}{2\pi}\left(-\frac{2\Lambda}{\pi} + \sqrt{-2\mu_0(E + \Delta + i\Gamma_0/2)}\right),$$

$$J_c(E) = \frac{\mu_c}{2\pi}\left(-\frac{2\Lambda}{\pi} + \sqrt{-2\mu_c(E + i\Gamma_c/2)}\right),$$

$$J_{|\Psi\rangle}(E) = \sum_{n=1}^{\infty} \frac{\alpha^3\mu_c^3}{\pi n^3} \frac{1}{E + E_n + i\Gamma_c/2},$$



$$\Delta = \Sigma_c - \Sigma_0$$

- The T-matrix has infinity of poles: $X(3872)$, hadronic atoms

$$T(E) = \frac{1}{C_0^{-1} - \left[J_0(E) + J_c(E) + J_{|\Psi\rangle}(E)\right]} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Renormalization: $C_{0R}^{-1} = C_0^{-1} + \Lambda(\mu_0 + \mu_c)/\pi^2$

X atoms: formalism

- $X(3872)$ gives the renormalization condition: pole at $E = -\Delta - \delta - i\dfrac{\Gamma_0}{2}$

$$C_{0R}^{-1} = \frac{\mu_0}{2\pi}\sqrt{2\mu_0\delta} + \frac{\mu_c}{2\pi}\sqrt{2\mu_c\left(\Delta + \delta - i\frac{\delta\Gamma}{2}\right)} - \sum_{n=1}^{\infty}\frac{\alpha^3\mu_c^3}{\pi n^3}\frac{1}{\Delta + \delta - E_n - i\delta\Gamma/2}$$
$$= \frac{\mu_c}{2\pi}\sqrt{2\mu_c\Delta}\left[1 + \mathcal{O}\left(\frac{\delta}{\Delta}, \frac{\delta\Gamma}{\Delta}, \frac{\alpha^3\mu_c^{3/2}}{\Delta^{3/2}}\right)\right]$$

- S-wave hadronic atom poles: $E = -E_{An} - i\dfrac{\Gamma_c}{2}$

$$0 = C_{0R}^{-1} + i\frac{\mu_0}{2\pi}\sqrt{2\mu_0\left(\Delta - E_{An} - i\frac{\delta\Gamma}{2}\right)} - \frac{\mu_c}{2\pi}\sqrt{2\mu_c E_{An}} - \sum_{n=1}^{\infty}\frac{\alpha^3\mu_c^3}{\pi n^3}\frac{1}{-E_{An} + E_n}$$

- Ground state X atom binding energy and decay width (due to decays of D^{*-} & to $D^0\bar{D}^{*0}$)

$$\mathrm{Re}\,E_{A1} = E_1 - \frac{\alpha^3\mu_c^2}{\sqrt{2\mu_c\Delta}} \simeq 22.92\ \mathrm{keV}$$

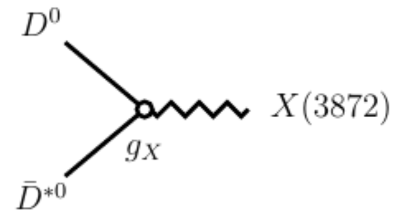
$M_{A1} = (3879.89 \pm 0.07)$ MeV

$$\Gamma_c + 2\,\mathrm{Im}\,E_{A1} = \Gamma_c + \frac{2\alpha^3\mu_c^2}{\sqrt{2\mu_c\Delta}} = (89.2 \pm 1.8)\ \mathrm{keV}$$

where $\Gamma_c = (83.4 \pm 1.8)$ keV

X atoms: formalism

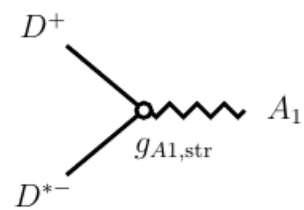
- Effective coupling for $D^0\bar{D}^{*0} \to X(3872)$



$$g_X^2 = \lim_{E\to -\Delta-\delta-i\frac{\Gamma_0}{2}} \left(E+\Delta+\delta+i\frac{\Gamma_0}{2}\right) T_{11}(E) = \frac{2\pi}{\mu_0^2}\sqrt{2\mu_0\delta}\left[1+\mathcal{O}\left(\frac{\delta^{1/2}}{\Delta^{1/2}}\right)\right]^{-1}$$

reproducing the famous relation

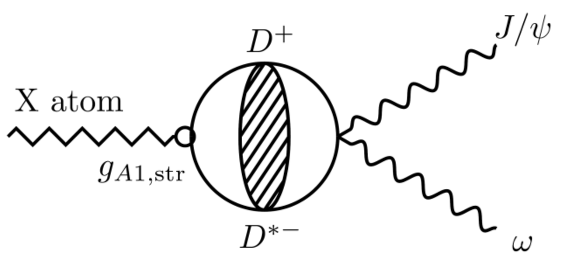
- Effective coupling for $D^+D^{*-} \to A_1$



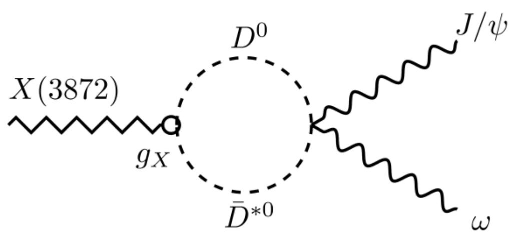
$$g_{A1,\mathrm{str}}^2 = \lim_{E\to -E_{A1}-i\frac{\Gamma_c}{2}} \left(E+E_{A1}+i\frac{\Gamma_c}{2}\right) T_{22}(E) = -i\frac{\pi\alpha^3}{\Delta}\left[1+\mathcal{O}\left(\frac{\alpha^2\mu_c}{\Delta}\right)\right]^{-1}$$

X atoms: decay

- Decay modes:
  - through decays of $D^{*\pm} \to D^{\pm}\gamma, D\pi$ $\Gamma_c = (83.4 \pm 1.8)$ keV
  - $A_1 \to D^0 \bar{D}^{*0} + c.c.$ $\Gamma_s = \frac{2\alpha^3\mu_c^2}{\sqrt{2\mu_c\Delta}} = 5.8$ keV
  - $A_1 \to J/\psi\pi\pi, J/\psi\pi\pi\pi$ highly suppressed in comparison with those of X



$$\mathcal{A}_{[A\to J/\psi\omega]} = g_{A1,\mathrm{str}} \mathcal{A}^{\mathrm{s.d.}}_{[(DD^*)_+ \to J/\psi\omega]}$$



$$\mathcal{A}_{[X(3872)\to J/\psi\omega]} = g_X \mathcal{A}^{\mathrm{s.d.}}_{[(DD^*)^0_+ \to J/\psi\omega]}$$

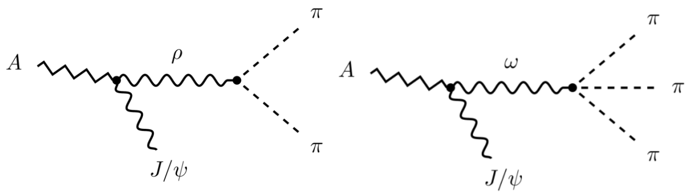
$$\frac{\Gamma_{[A\to J/\psi\pi^+\pi^-\pi^0]}}{\Gamma_{[X(3872)\to J/\psi\pi^+\pi^-\pi^0]}} = \frac{|g_{A1,\mathrm{str}}|^2}{|g_X|^2} \frac{\Phi_{[A\to J/\psi\pi^+\pi^-\pi^0]}}{\Phi_{[X(3872)\to J/\psi\pi^+\pi^-\pi^0]}} \gtrsim 3.76 \times 10^{-3}$$

Z.-H. Zhang, FKG, Hanhart, Rusetsky, in preparation

- Total decay width: $\Gamma_{A1,\mathrm{tot}} \approx \Gamma_c + \Gamma_s = (89.2 \pm 1.8)$ keV

X atoms: decay

- Decay modes:
  - $A_1 \to J/\psi\pi\pi, J/\psi\pi\pi\pi$



X atom: maximally mixed isovector and isoscalar

$$|D^+D^{*-}\rangle = \frac{1}{\sqrt{2}}(|I=1\rangle + |I=0\rangle)$$

	X atom	X(3872)
Couplings (input)	$R_A = \frac{g_{[A\to J/\psi\rho]}}{g_{[A\to J/\psi\omega]}} = 1$	$R_X = \frac{g_{[X(3872)\to J/\psi\rho]}}{g_{[X(3872)\to J/\psi\omega]}} = 0.26$
Branching fractions	$\frac{\mathrm{Br}_{[A\to J/\psi\pi\pi]}}{\mathrm{Br}_{[A\to J/\psi\pi^+\pi^0\pi^-]}} = 3.34$	$\frac{\mathrm{Br}_{[X(3872)\to J/\psi\pi\pi]}}{\mathrm{Br}_{[X(3872)\to J/\psi\pi^+\pi^0\pi^-]}} = 0.91$ (Exp.: 1.1 ± 0.4)

$$\frac{\mathrm{Br}_{[A\to J/\psi\pi\pi]}}{\mathrm{Br}_{[A\to J/\psi\pi^+\pi^0\pi^-]}} \simeq 3.65 \frac{\mathrm{Br}_{[X(3872)\to J/\psi\pi\pi]}}{\mathrm{Br}_{[X(3872)\to J/\psi\pi^+\pi^0\pi^-]}}$$