Production of hadronic molecules in high energy collisions

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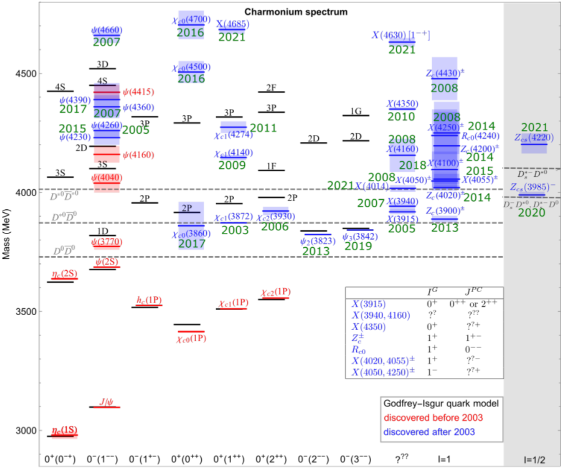
PPS, Zhen-Hua Zhang, Feng-Kun Guo, Zhi Yang, Phys. Rev. D 105(2022) 034024

PPS, Feng-Kun Guo, Zhi Yang, hep-ph/2208.02639

outline

1. **Introduction**
2. **The production of the dionium in pp and $p\bar{p}$ collisions**
3. **Semi-inclusive electroproduction of hidden-charm and double-charm hadronic molecules**
4. **Summary**

- Since $X(3872)$ is observed at Belle, many hadrons are reported in high-energy experiments.

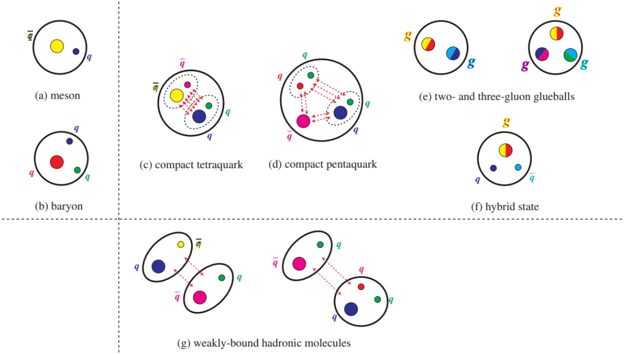


Categorization of hadrons

- The debates about the nature of exotics still exist

Ordinary hadrons

Exotic hadrons



H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, hep-ph/2204.02646

The inclusive cross section for $X(3872)$ at experiments

- The cross section for $X(3872)$ at $p\bar{p}$ collisions

$$\sigma[p\bar{p} \to X(3872) + \text{all}] \cdot \text{Br}[X(3872)] = 3.1 \pm 0.7 \text{ nb}$$

where $\text{Br}[X(3872)] = \text{Br}[X(3872) \to J/\psi\pi^+\pi^-]$.

CDF, Int.J.Mod.Phys.A20(2005)3765

- The cross section for inclusively production of $X(3872)$ at LHCb

$$\sigma[pp \to X(3872) + \text{all}] \cdot \text{Br}[X(3872)] = 5.4 \pm 1.3 \pm 0.8 \text{ nb}$$

LHCb, EPJC72(2012)1972

- The cross section for $X(3872)$ at CMS

$$\sigma[pp \to X(3872) + \text{all}] \cdot \text{Br}[X(3972)] = 1.06 \pm 0.11 \pm 0.15 \text{ nb}$$

CMS, JHEP04(2013)154

- The prompt production of $X(3872)$ VS $\psi(2S)$

LHCb, PRL126(2021)092001

Debates about the inclusive production of $X(3872)$

- The upper limit of the cross section for the production of $X(3872)$ ($D^0\bar{D}^{*0}$ with relative momentum [0,35] MeV) ~ 0.085 nb $< 3.1 \pm 0.7$ nb (CDF measurement)

  C. Bignamini, B. Grinstein, F. Piccinini, A.D Polosa, C. Sabelli, PRL103(2009)162001

- Since the rescattering of charmed-mesons is taken into account, the upper limit of the cross section for producing $X(3872)$ is compatible with the CDF measurement.

  P. Artoisenet, E. Braaten, PRD81(2010)114018

- The upper limit of the relative momentum of hadron pair is too small to estimate that of cross section for producing $X(3872)$; the production cross section are compatible with the Tevatron measurement.

  M. Albaladejo, F.-K. Guo, C. Hanhart, U.-G. Meißner, J. Nieves, A. Nogga, and Z. Yang, CPC41(2017)121001

Production mechanism of molecules

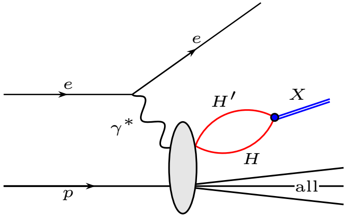
- The amplitude for the production of molecules is factorized into the short-distance part and long-distance part

  E. Braaten, M. Kusunoki, PRD72(2005)014012

- Semi-inclusive electroproduction of the HH' hadronic molecule X

  Z.Yang, F.-K.Guo, CPC45(2021)123101

  - short distance : Monte Carlo event generator, e.g., Pythia
  - long distance : the final state interaction



$$\propto \sigma[HH'] \times |G_{\mathrm{NR}}|^2 \times |T_X|^2$$

Inclusive production of hadronic molecules

- Charm-strange hadronic molecules: $D_{s0}^*(2317)$, $D_{s1}(2460)$, $D_{sJ}(2860)$, and $D_{s2}(2910)$ at LHC $0.01 \sim 1\ \mu$b

  F.-K. Guo, U.-G. Meißner, W. Wang, Z. Yang, JHEP 05(2014)138

- Hidden-charm/bottom molecules at Tevatron and LHC: $X(3872)$ (its cross section is compatible with CDF and CMS measurements); X_{c2} $\mathcal{O}(10 \sim 10^3$ nb); X_b, and X_{b2} $\mathcal{O}(0.1 \sim 10$ nb)

  F.-K. Guo, U.-G. Meißner, W. Wang, Z. Yang, EPJC 74(2014)3063

- Charged charmonium-like and bottomonium-like states: $Z_c(3900), Z_c(4020), Z_b(10610), Z_b(10650)$ at Tevatron and LHC $\mathcal{O}(0.01 \sim 100$ nb)

  F.-K. Guo, U.-G. Meißner, W. Wang, Commun. Theor. Phys. 61(2014)354

- P_c states: $\mathcal{O}(0.1 \sim 10$ nb)

  P. Ling, X.-H. Dai, M.-L. Du, Q. Wang, EPJC81(2021)819

- Lepto-production of hidden-charm exotics: tetraquark $\mathcal{O}(10^2 \sim 10^3$ pb); the P_c states: $\mathcal{O}(0.1 \sim 100$ pb)

  Z. Yang, F.-K. Guo, CPC45(2021)123101

The dionium

- Dionium $A_{D^+D^-}$: the ground $|D^+D^- >$ hadronic atom with $C=+$; coulomb binding energy: $-E_0 = -\alpha^2\mu_c/2 = -24.9$ keV; Bohr radius: $r_e = 1/\alpha\mu_c = 28.91$ fm;
- Considering the $D^0\bar{D}^0 - D^+D^-$ coupling-channel system, the T is

$$\mathbf{T}_s = \frac{1}{\det}(E)\begin{pmatrix} \frac{1}{2C^R_{0a}} + \frac{1}{2C^R_{1a}} - J_c(E) & \frac{1}{2C^R_{1a}} - \frac{1}{2C^R_{0a}} \\ \frac{1}{2C^R_{1a}} - \frac{1}{2C^R_{0a}} & \frac{1}{2C^R_{0a}} + \frac{1}{2C^R_{1a}} - J_0(E) \end{pmatrix},$$

where $J_0(E)$ and $J_c(E)$ are finite part of the Green's function for the neutual and charged charmed-meson pairs, $\det(E) =$
$\left[\frac{1}{2C^R_{0a}} + \frac{1}{2C^R_{1a}} - J_0(E)\right]\left[\frac{1}{2C^R_{0a}} + \frac{1}{2C^R_{1a}} - J_c(E)\right] - \left[\frac{1}{2C^R_{1a}} - \frac{1}{2C^R_{0a}}\right]^2.$

- Low-energy constants: $C^R_{0a} \gg C^R_{1a}$, we set C^R_{1a} as high order contribution; C^R_{0a} is solved from $\det(E_B) = 0$ with $E_B = 4.0^{+5.0}_{-3.7}$ MeV for the $D^0\bar{D}^0$ bound state in LQCD calculation

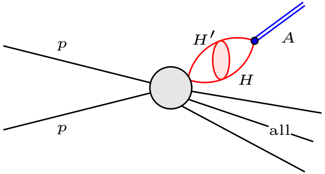
S. Prelovsk, S. Collins, D. Mohler, M. Padmanath, S. Piemonte, JHEP 06(2021)035

- Binding energy: $E_A = 22.9^{+0.3}_{-0.4}$ keV; decay width of $A_{D^+D^-} \to D^0\bar{D}^0$: $\Gamma_0 = 1.8^{+1.4}_{-0.6}$ keV.
- Effective couplings of D^+D^- to dionium ($g_{\rm str}$) and the $D^0\bar{D}^0$ bound state to its constituents can be extracted from the residues of $\mathbf{T}_s$

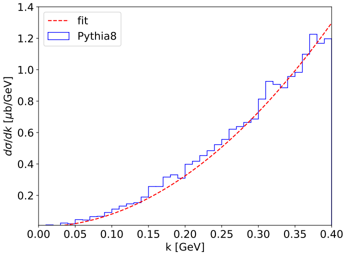
$$g^2_{\rm str} = \lim_{E\to -E_A}(E+E_A)\mathbf{T}_{s22}(E) \simeq \left[3.2^{+2.1}_{-2.8} - \left(3.5^{+4.0}_{-1.5}\right) i\right] \times 10^{-8}\ \mathrm{MeV}^{-1}$$

$$g^2_0 = \lim_{E\to -E_B}(E+E_B)\mathbf{T}_{s11}(E) \simeq \left(3.9^{+1.4}_{-2.5}\right) \times 10^{-4}\ \mathrm{MeV}^{-1},$$

The production of dionium in pp collisions



$$\propto \sigma[HH'] \times |G_{\rm NR}|^2 \times |T_X|^2$$



- The cross section for the inclusive production of the dionium is $1^{+7}_{-1}(49^{+76}_{-33})$ pb with cutoff $\Lambda = 0.5(1.0)$ GeV at CMS (c.m collision energy is 7 TeV)
- The cross section for the inclusive production of the dionium is $\mathcal{O}(0.1$ nb$)$ at LHCb, which is estimated with

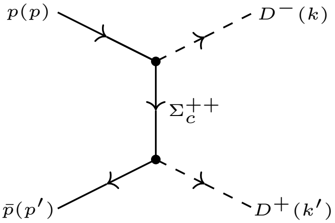
$$\left(\frac{\sigma_{A_{D^+D^-}}}{\sigma_{X(3872)}}\right)_{\rm CMS} \sim \left(\frac{\sigma_{A_{D^+D^-}}}{\sigma_{X(3872)}}\right)_{\rm LHCb}.$$

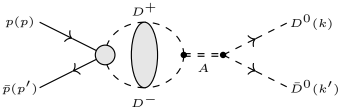
CMS, JHEP04(2013)154; LHCb, EPJC72(2012)1972

The production of dionium in $p\bar{p}$ collisions

- The cross section for $p\bar{p} \to A_{D^+D^-} \to D^0\bar{D}^0$ is calculated with the flavor SU(4) model (the Σ_C^{*++} is largely suppressed)

  J. Haidenbauer, F. Krein, U.-G. Meißner, L. Tolos, EPJA47(2011)18; R. Shyam, H. Lenske, PRD93(2016)034016; Y.-B. Dong, A. Faessler, T. Gutsche, V.E. Lyubovitskij, PRD90(2014)094001



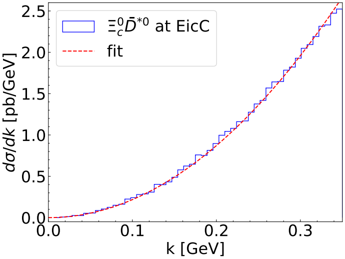


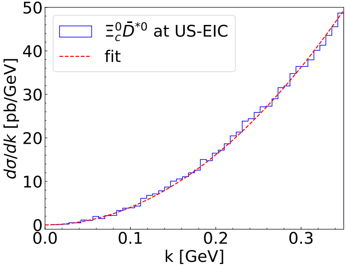
- The cross section of the production of dionium is $0.002^{+0.013}_{-0.002}$ $(0.1^{+0.2}_{-0.1})$ μb at $\sqrt{s} = 3739.3$ MeV.
- Since the integrated luminosity of PANDA is 2 fb^{-1} in five months and Br$[D^0 \to K^-\pi^+] \simeq 4\%$, there will be $\mathcal{O}(10^3 \sim 10^5)$ events.

Cross sections estimate at EicC and EIC

- the differential cross section for the production of the hadron pairs at EicC and EIC

	EicC	US-EIC	JLab
e [GeV]	3.5	18	24
p [GeV]	20	275	0
Luminosity [$cm^{-2}s^{-1}$]	2×10^{33}	10^{34}	10^{36}
Integrated Luminosity [fb^{-1}]	60	300	3×10^{4}





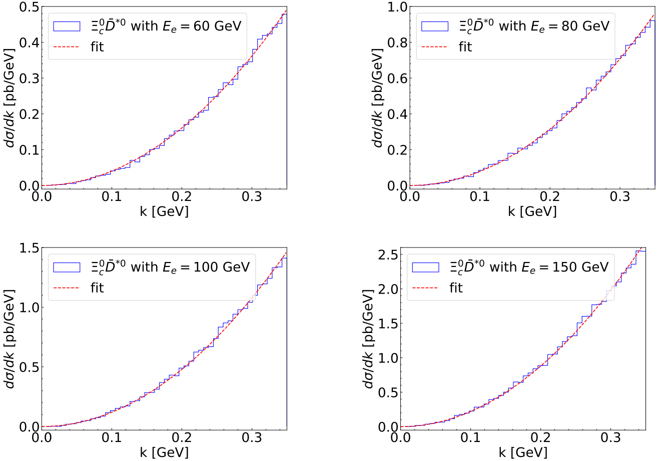
	Constituents	$IJ^{P(C)}$	EicC [pb]	US-EIC [pb]
T_{cc}^+	DD^*	01^+	0.3×10^{-3} (1.2×10^{-3})	$0.1(0.5)$
T_{cc}^*	D^*D^*	01^+	0.2×10^{-3} (1.0×10^{-3})	0.1 (0.4)
P_{cs}	$\Xi_c\bar{D}$	$0\frac{1}{2}^-$	0.1 (1.6)	1.8 (30)
P_{cs}	$\Xi_c\bar{D}^*$	$0\frac{1}{2}^-$	0.1 (0.5)	1.3 (8.8)
P_{cs}	$\Xi_c\bar{D}^*$	$0\frac{3}{2}^-$	0.1 (0.9)	2.6 (18)
	$\Lambda_c\bar{\Lambda}_c$	00^{-+}	0.3 (3.0)	9.6 (110)
	$\Sigma_c\bar{\Sigma}_c$	00^{-+}	0.7×10^{-3} (5.2×10^{-3})	0.04 (0.29)
	$\Sigma_c\bar{\Sigma}_c$	10^{-+}	0.7×10^{-3} (5.3×10^{-3})	0.04 (0.29)
	$\Xi_c\bar{\Xi}_c$	00^{-+}	1.4×10^{-3} (1.1×10^{-2})	$0.1(0.5)$
	$\Xi_c\bar{\Xi}_c$	10^{-+}	0.1×10^{-3} (1.7×10^{-3})	3.9×10^{-3} (7.1×10^{-2})
	$\Lambda_c\bar{\Sigma}_c$	10^-	0.01 (0.12)	0.5 (5.5)
	$\Lambda_c\bar{\Xi}_c$	$\frac{1}{2}0^-$	0.01 (0.14)	0.2 (5.3)
	$\Xi_c\bar{\Sigma}_c$	$\frac{1}{2}0^-$	0.8×10^{-3} (7.3×10^{-3})	0.04 (0.36)

M.-L. Du *et al*, PRD105(2022)014024; X.-K. Dong *et al*, Progr.Phys. 41(2021)65-93

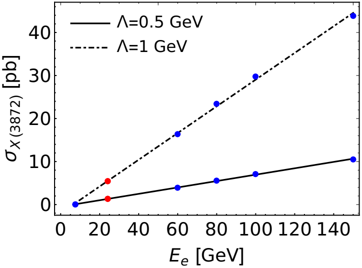
- At EicC, the T_{cc}^+ events $(18\sim72)$ are significantly smaller than that of Ξ_{cc} (4×10^5) EicC white paper, nucl-ex/2102.09222
- The same order-of-magnitude cross sections for the P_{cs} states and the $\Lambda_c\bar{\Lambda}_c$ molecule

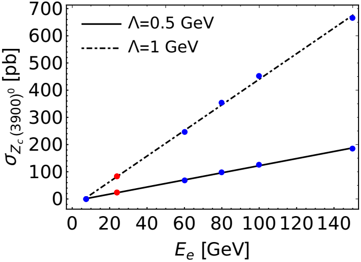
Cross sections estimate at CEBAF

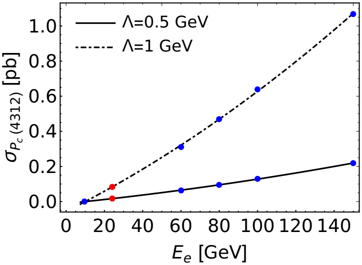
- the differential cross sections of hadron pairs (c.m. collision energy 6.7 GeV)

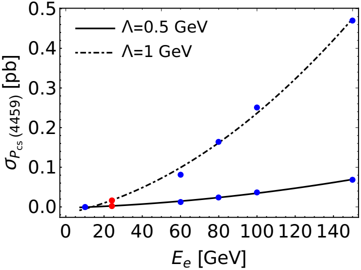


- Extrapolate the cross sections to 24 GeV









	Constituents	$IJ^{P(C)}$	E_B [MeV]	σ_X [pb]
$X(3872)$	$D\bar{D}^*$	01^{++}	4.15	1.3 (5.5)
$Z_c(3900)^0$	$D\bar{D}^*$	11^{+-}	-12.57	22.9 (82.4)
$Z_c(3900)^+$	$D^{*+}\bar{D}^0$	11^{+}	-13.30	16.2 (59.2)
$P_c(4312)$	$\Sigma_c\bar{D}$	$\frac{1}{2}\frac{1}{2}^-$	6.68	0.02 (0.08)
$P_c(4440)^+$	$\Sigma_c\bar{D}^*$	$\frac{1}{2}\frac{3}{2}^-$	21.06	0.01 (0.06)
$P_c(4457)^+$	$\Sigma_c\bar{D}^*$	$\frac{1}{2}\frac{1}{2}^-$	3.06	3.4×10^{-3} (16.4×10^{-3})
$P_c(4380)^+$	$\Sigma_c^*\bar{D}$	$\frac{1}{2}\frac{3}{2}^-$	7.18	0.03 (0.15)
$P_{cs}(4459)$	$\Xi_c\bar{D}^*$	$0\frac{3}{2}^-$	18.83	4.9×10^{-3} (33.2×10^{-3})
$P_{cs}(4459)$	$\Xi_c\bar{D}^*$	$0\frac{1}{2}^-$	18.83	2.4×10^{-3} (16.6×10^{-3})

- Although the cross sections for hidden-charm molecules at JLab are smaller than that at EicC (about two orders of magnitude), the large luminosity (3×10^4 fb^{-1}) provides opportunities to observe hidden-charm molecules.
- Taking branching ratios Br$(X(3872)\to J/\psi\pi\pi)=3.8\pm1.2\%$ and Br$(J/\psi\to l^+l^-)=12\%$, the reconstructed event numbers will be about $9\times10^4\sim3.8\times10^5$ with the detection efficiency is 50%.

Summary

- Production mechanism: we employ a Monte Carlo event generator Pythia to produce the hadron pairs and then bind them together to form molecules through the final state interaction;
- The dionium: Based on $D^0\bar{D}^0 - D^+D^-$ coupled-channel system, we predict the dionium with $M = 3739.3 \pm 0.1$ MeV and $\Gamma = 1.8^{+1.4}_{-0.6}$ keV. The cross section for the production of the dionium at CMS and LHCb are $\mathcal{O}(10$ pb$)$ and $\mathcal{O}(0.1$ nb$)$, respectively. We estimate that about $\mathcal{O}(10^3 \sim 10^5)$ events can be collected at PANDA .
- EicC and EIC : we proposed a number of P_{cs} states and $\Lambda_c\bar{\Lambda}_c$ molecules with $J^{PC} = 0^{-+}$ are produced at EicC and EIC; the T_{cc} states and other hidden-charm baryon-antibaryon molecules can be searched at EIC; JLab: because of the high luminosity, we can search the hidden-charm exotics at the proposed JLab.

Thanks for your attention!

- The amplitude for the production of molecules is

  P. Artoisenet, E. Braaten, PRD83(2011)014019; F.-K.Guo, U.-G Meißner, W.Wang, Z.Yang, EPJC74(2014)3063

$$\mathcal{M}[X+\text{all}] = \mathcal{M}[HH'+\text{all}] \times G_{\text{NR}} \times T_X,$$

  where $G_{\text{NR}}(E,\Lambda) = -\frac{\mu}{\pi^2}\left\{\sqrt{2\pi}\frac{\Lambda}{4} + \frac{k\pi}{2}e^{-2k^2/\Lambda^2}\left[i - \text{erfi}\left(\frac{\sqrt{2}k}{\Lambda}\right)\right]\right\}$ and T_X is the T-matrix for $HH' \to X$. For the shallow molecules, the T_X is estimated as an effective coupling g_{eff} and extracted from the $HH' \to HH'$ scattering matrix.

- The differential cross section for $ep \to HH' + \text{all}$

$$d\sigma[HH'(k)]_{\text{MC}} = K_{HH'}\frac{1}{\text{flux}}\sum_{\text{all}}\int d\phi_{HH'+\text{all}}\left|\mathcal{M}[HH'(k)+\text{all}]\right|^2 \frac{d^3k}{(2\pi)^3 2\mu}$$

- The cross section for the production of the molecules

$$\sigma[X+\text{all}] \simeq \frac{1}{4m_H m_{H'}}\left|G_{\text{NR}}g_{\text{eff}}\right|^2 \left(\frac{d\sigma[HH'(k)+\text{all}]}{dk}\right)_{\text{MC}}\frac{4\pi^2\mu}{k^2}$$