



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

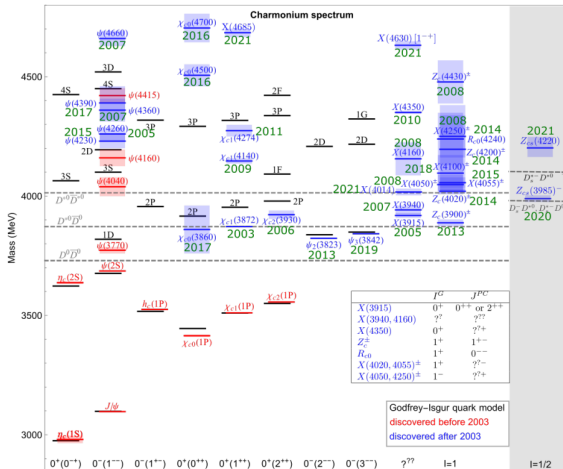
PPS, Feng-Kun Guo, Zhi Yang, hep-ph/2208.02639

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

Exotic states

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

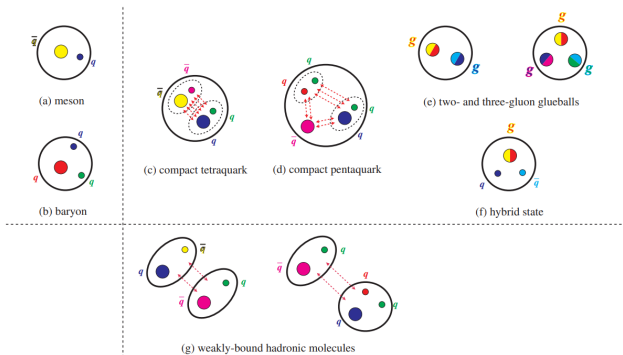


Categorization of hadrons

- 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

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

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

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

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

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

LHCb, EPJC72(2012)1972

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

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

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)
 $0.085 \text{ nb} < 3.1 \text{ } 0.7 \text{ nb}$ (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

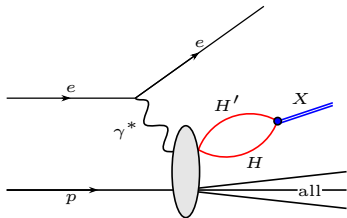
- The amplitude for the production of molecules is factorized into the short-distance part and long-distance part

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

- Semi-inclusive electroproduction of the HH^0 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



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

Inclusive production of hadronic molecules

- Charm-strange hadronic molecules: $D_{s0}(2317)$, $D_{s1}(2460)$, $D_{sJ}(2860)$, and $D_{s2}(2910)$ at LHC $0.01 \sim 1 \mu\text{b}$
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} $O(10 \sim 10^3 \text{ nb})$; X_b , and X_{b2} $O(0.1 \sim 10 \text{ nb})$
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 $O(0.01 \sim 100 \text{ nb})$
F.-K. Guo, U.-G. Meißner, W. Wang, Commun. Theor. Phys. 61(2014)354
- P_c states: $O(0.1 \sim 10 \text{ nb})$
P. Ling, X.-H. Dai, M.-L. Du, Q. Wang, EPJC81(2021)819
- Lepto-production of hidden-charm exotics: tetraquark $O(10^2 \sim 10^3 \text{ pb})$; the P_c states: $O(0.1 \sim 100 \text{ pb})$
Z. Yang, F.-K. Guo, CPC45(2021)123101

The dionium

- **Dionium** A_{D^+D} : the ground $j_{D^+D} >$ 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 $D^0 \bar{D}^0 \quad D^+ D^-$ coupling-channel system, the T is

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

where $J_0(E)$ and $J_c(E)$ are finite part of the Green's function for the neutral and charged charmed-meson pairs, $\det(E) =$

$$\left[\frac{1}{2C_{0a}^R} + \frac{1}{2C_{1a}^R} \quad J_0(E) \right] \left[\frac{1}{2C_{0a}^R} + \frac{1}{2C_{1a}^R} \quad J_c(E) \right] \left[\frac{1}{2C_{1a}^R} \quad \frac{1}{2C_{0a}^R} \right]^2.$$

- Low-energy constants: C_{0a}^R , C_{1a}^R , we set C_{1a}^R as high order contribution; C_{0a}^R 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

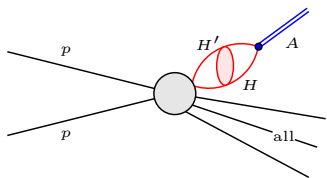
S. Prelovsk, S. Collins, D. Mohler, M. Padmanath, S. Piemonte, JHEP 06(2021)035

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

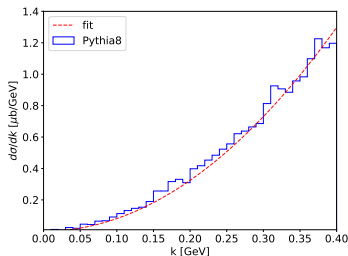
$$g_{\text{str}}^2 = \lim_{E \rightarrow E_A} (E + E_A) \mathbf{T}_{S22}(E) \cdot [3.2^{+2.1}_{-2.8} \quad (3.5^{+4.0}_{-1.5}) i] \cdot 10^{-8} \text{ MeV}^{-1}$$

$$g_0^2 = \lim_{E \rightarrow E_B} (E + E_B) \mathbf{T}_{S11}(E) \cdot (3.9^{+1.4}_{-2.5}) \cdot 10^{-4} \text{ MeV}^{-1},$$

The production of dionium in pp collisions



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



- 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 $O(0.1 \text{ nb})$ at LHCb, which is estimated with

$$\left(\frac{\sigma_{A_{D+D}}}{\sigma_{X(3872)}} \right)_{\text{CMS}} \quad \left(\frac{\sigma_{A_{D+D}}}{\sigma_{X(3872)}} \right)_{\text{LHCb}}$$

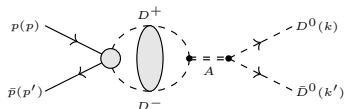
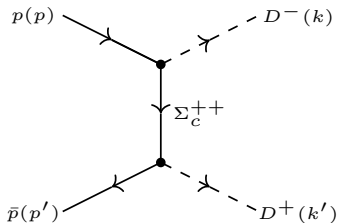
CMS, JHEP04(2013)154; LHCb, EPJC72(2012)1972

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

- The cross section for $p\bar{p} \rightarrow A_{D^+D^-} \rightarrow D^0\bar{D}^0$ 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

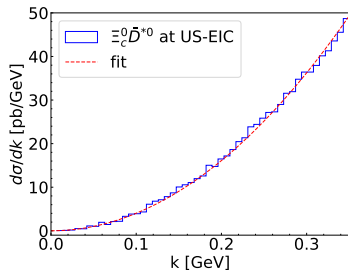
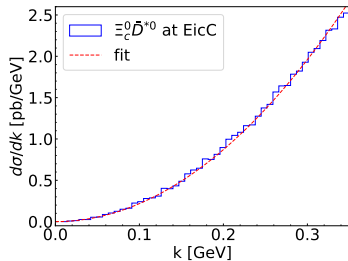


- The cross section of the production of dionium is $0.002^{+0.013}_{-0.002}$ ($0.1^{+0.2}_{-0.1}$) μb at $\sqrt{s} = 3739.3$ MeV.
- Since the integrated luminosity of PANDA is 2 fb^{-1} in five months and $\text{Br}[D^0 \rightarrow K^+ \pi^-] \approx 4\%$, there will be $O(10^3 - 10^5)$ events.

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 [$\text{cm}^{-2}\text{s}^{-1}$]	$2 \cdot 10^{33}$	10^{34}	10^{36}
Integrated Luminosity [fb^{-1}]	60	300	$3 \cdot 10^4$



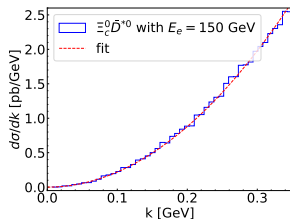
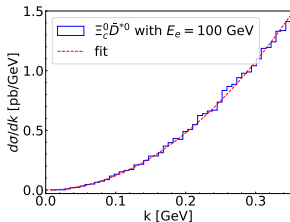
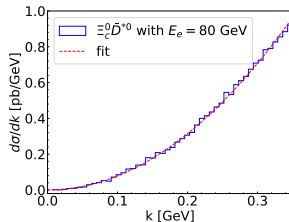
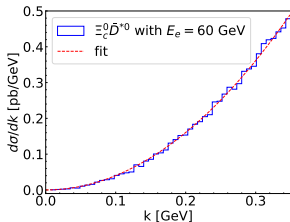
Constituents		$IJ^{P(C)}$	EicC [pb]			US-EIC [pb]
T_{cc}^+	DD	01^+	0.3	10^{-3}	(1.2 10^{-3})	0.1(0.5)
T_{cc}	$D D$	01^+	0.2	10^{-3}	(1.0 10^{-3})	0.1 (0.4)
P_{cs}	cD	$0\frac{1}{2}$			0.1 (1.6)	1.8 (30)
P_{cs}	cD	$0\frac{1}{2}$			0.1 (0.5)	1.3 (8.8)
P_{cs}	cD	$0\frac{3}{2}$			0.1 (0.9)	2.6 (18)
	$c c$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

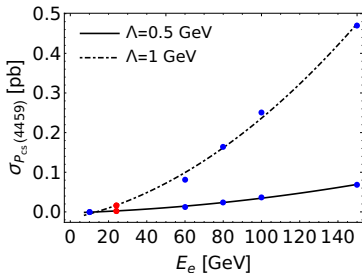
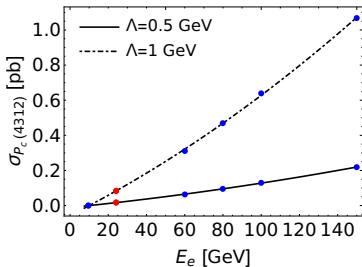
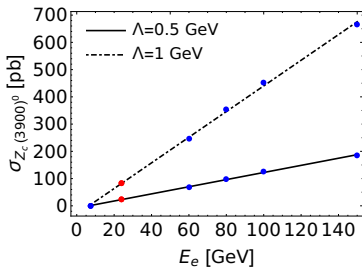
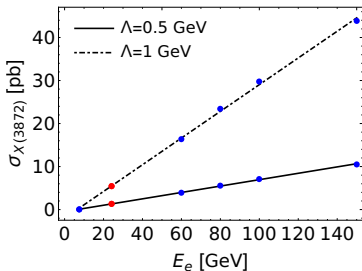
- At EicC, the T_{cc}^+ events (18 - 72) are significantly smaller than that of Ξ_{cc} ($4 - 10^5$) [EicC white paper, nucl-ex/2102.09222](#)
- The same order-of-magnitude cross sections for the P_{cs} states and the $\Lambda_c \bar{\Lambda}_c$ molecule

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]
$X(3872)$	DD	01^{++}	4.15	1.3 (5.5)
$Z_c(3900)^0$	DD	11^+	12.57	22.9 (82.4)
$Z_c(3900)^+$	$D + D^0$	11^+	13.30	16.2 (59.2)
$P_c(4312)$	$_cD$	$\frac{1}{2}\frac{1}{2}$	6.68	0.02 (0.08)
$P_c(4440)^+$	$_cD$	$\frac{1}{2}\frac{3}{2}$	21.06	0.01 (0.06)
$P_c(4457)^+$	$_cD$	$\frac{1}{2}\frac{1}{2}$	3.06	3.4 10^{-3} (16.4 10^{-3})
$P_c(4380)^+$	$_cD$	$\frac{1}{2}\frac{3}{2}$	7.18	0.03 (0.15)
$P_{cs}(4459)$	$_cD$	$0\frac{3}{2}$	18.83	4.9 10^{-3} (33.2 10^{-3})
$P_{cs}(4459)$	$_cD$	$0\frac{1}{2}$	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 ($3 \times 10^4 \text{ fb}^{-1}$) provides opportunities to observe hidden-charm molecules.
- Taking branching ratios $\text{Br}(X(3872) \rightarrow J/\psi\pi\pi) = 3.8 \sim 1.2\%$ and $\text{Br}(J/\psi \rightarrow l^+l^-) = 12\%$, the reconstructed event numbers will be about $9 \times 10^4 \sim 3.8 \times 10^5$ 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 $O(10$ pb) and $O(0.1$ nb), respectively. We estimate that about $O(10^3 - 10^5)$ events can be collected at PANDA .
- **EicC and EIC** : we proposed a number of P_{cc} 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

$$M[X + \text{all}] = M[HH^0 + \text{all}] G_{\text{NR}} T_X,$$

where $G_{\text{NR}}(E, \Lambda) = \frac{\mu}{\pi^2} \left\{ \frac{\rho}{2\pi} + \frac{k\pi}{2} e^{-2k^2/\Lambda^2} \left[i + \text{erfi} \left(\frac{\rho}{2k} \right) \right] \right\}$

and T_X is the T -matrix for $HH^0 \rightarrow X$. For the shallow molecules, the T_X is estimated as an effective coupling g_{eff} and extracted from the $HH^0 \rightarrow HH^0$ scattering matrix.

- The differential cross section for $ep \rightarrow HH^0 + \text{all}$

$$d\sigma[HH^0(k)]_{\text{MC}} = K_{HH^0} \frac{1}{\text{flux}} \sum_{\text{all}} \int d\phi_{HH^0+\text{all}} |M[HH^0(k) + \text{all}]|^2 \frac{d^3k}{(2\pi)^3 2\mu}$$

- The cross section for the production of the molecules

$$\sigma[X + \text{all}] = \frac{1}{4m_H m_{H^0}} j G_{\text{NR}} g_{\text{eff}}^2 \left(\frac{d\sigma[HH^0(k) + \text{all}]}{dk} \right)_{\text{MC}} \frac{4\pi^2 \mu}{k^2}$$