Hydrogenlike molecules composed of D_1D_1, $D_1D_2^*$ and $D_2^*D_2^*$

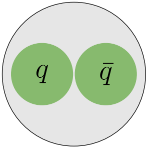
Cheng-Rong Deng,
Collaborators: Hu-Hua He, Mao-Jun Yan, and Chun-Sheng An

School of Physical Science and Technology
Southwest University, Chongqing, China

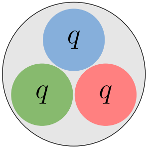
The 8^{th} Symposium on hadron spectra and structure, Guilin, July 11-15, 2025

Outline

- Conventional hadrons

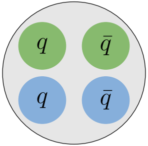


Meson

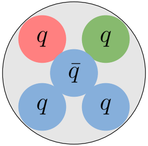


Baryon

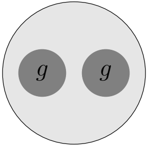
- Exotic hadrons



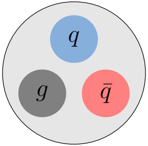
Four-quark



Five-quark



Glueball



Hybrid

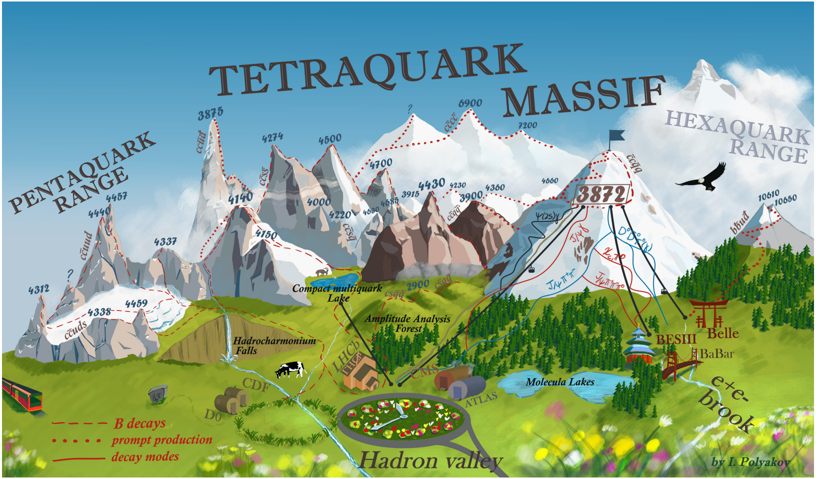


Figure 1: Illustration of new hadrons. Taken from Mod.Phys.Lett.A 40, 2530002 (2025).

Category			States/Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I=0$	$\chi-$like: $\underline{\chi_{c1}(3872)}$, $\chi_{c0}(3860)$, $\underline{\chi_{c0}(3915)}$, $\underline{\chi_{c2}(3930)}$, $X(3940)$
			$\psi-$like: $\underline{\psi(4230)}$, $\underline{\psi(4360)}$, $\psi(4660)$
			with $s\bar{s}$: $\underline{\chi_{c1}(4140)}$, $\underline{\chi_{c1}(4274)}$, $\chi_{c1}(4685)$, $\underline{\chi_{c1}(4500)}$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I=1$	seen in e^+e^-: $\underline{T_{c\bar{c}1}(3900)^{+/0}}$, $\underline{T_{c\bar{c}}(4020)^{+/0}}$, $T_{c\bar{c}}(4055)^+$
			seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $\underline{T_{c\bar{c}1}(4430)^+}$
		$I=\frac{1}{2}$	$T_{c\bar{c}s}(3985)^-$, $T_{c\bar{c}s1}(4000)^{-/0}$, $T_{c\bar{c}s1}(4220)^-$
	Hidden Bottom	$I=0$	$\underline{\Upsilon(10753)}$, $\underline{\Upsilon(10860)}$, $\underline{\Upsilon(11020)}$
		$I=1$	$\underline{T_{b\bar{b}1}(10610)^+}$, $\underline{T_{b\bar{b}1}(10650)^+}$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $\underline{T_{c\bar{c}c\bar{c}}(6900)}$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $\underline{D_{s0}^*(2317)^+}$, $\underline{D_{s1}(2460)^+}$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I=\frac{1}{2}(\frac{3}{2})$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I=0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$

1.4 Exotic hadron structure

- Exotic natures
  - valence quark number > 3
  - Mass/width and/or production and/or decay properties inconsistent with predictions for conventional states
- Study of exotic hadrons can
  - provide new insights into internal structure
  - broaden our understanding of non-perturbative behaviour of QCD
- Theoretical descriptions
  - Excited charmonium
  - Compact multiquark states
  - $c\bar{c}$-gluon hybrid
  - Hadron molecular states
  - Threshold effect
  - ......
  - Still far away from a unified picture
    The most popular one is hadron molecular states,
    such as $X(3872)(D\bar{D}^*)$, $T_{cc}(3875)$ (DD^*) and P_c $(\Sigma\bar{D}^{(*)})$,......

1.5 Open double charm family

- The only member: $T_{cc}^{+}(3875)$, observed by LHCb in 2021.
  - Its binding energy and decay width are

$$E_b = -361 \pm 40 \text{ keV}, \;\; \Gamma = 47.8 \pm 1.9 \text{ keV}.$$

  May be a deuteronlike structure DD^* with 01^+.
  - Where are its family members?

- Theoretical explorations
  - In the early 1980s, the states $QQ\bar{q}\bar{q}$ were pioneered.
  - The existing studies.
    - Mainly focus on di-mesons composed of two ground state mesons.
    - Di-mesons composed of excited state mesons are extremely scarce.

- We want to do
  - Searching for possible di-mesons D_1D_1, $D_1D_2^*$ and $D_2^*D_2^*$
  - Discussing their forming mechanisms.

2.1 Model Hamiltonian

- Model Hamiltonian

$$H_n = \sum_{i=1}^{n}\left(m_i + \frac{\mathbf{p}_i^2}{2m_i}\right) - T_c + \sum_{i>j}^{n}\left(V_{ij}^{oge} + V_{ij}^{con} + V_{ij}^{obe} + V_{ij}^{\sigma}\right)$$

- One-gluon-exchange and quark confinement

$$V_{ij}^{oge} = \frac{\alpha_s}{4}\boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c\left(\frac{1}{r_{ij}} - \frac{2\pi\delta(\mathbf{r}_{ij})\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j}{3m_i m_j}\right), \quad V_{ij}^{con} = -a_c\boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c r_{ij}^2$$

- One Goldstone boson exchange

$$V_{ij}^{obe} = V_{ij}^{\pi}\sum_{k=1}^{3}\mathbf{F}_i^k\mathbf{F}_j^k + V_{ij}^{K}\sum_{k=4}^{7}\mathbf{F}_i^k\mathbf{F}_j^k + V_{ij}^{\eta}(\mathbf{F}_i^8\mathbf{F}_j^8\cos\theta_P - \sin\theta_P)$$

$$V_{ij}^{\chi} = \frac{g_{ch}^2}{4\pi}\frac{m_\chi^3}{12m_i m_j}\frac{\Lambda_\chi^2}{\Lambda_\chi^2 - m_\chi^2}\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j\left(Y(m_\chi r_{ij}) - \frac{\Lambda_\chi^3}{m_\chi^3}Y(\Lambda_\chi r_{ij})\right), \quad \chi = \pi,\ K,\ \eta$$

- σ-meson exchange

$$V_{ij}^{\sigma} = -\frac{g_{ch}^2}{4\pi}\frac{\Lambda_\sigma^2 m_\sigma}{\Lambda_\sigma^2 - m_\sigma^2}\left(Y(m_\sigma r_{ij}) - \frac{\Lambda_\sigma}{m_\sigma}Y(\Lambda_\sigma r_{ij})\right)$$

2.2 Model parameters

- Solving Schrodinger equation and fitting spectrum with Minuit program

Table 1: Adjustable model parameters.

Parameters	Values	Parameters	Values	Parameters	Values
m_s	511.78±0.228	α_0	4.554±0.018	K	40.78±0.043
m_c	1601.7±0.441	Λ_0	9.173±0.175	r_0	35.06±0.156
m_b	4936.2±0.451	μ_0	0.0004±0.540		

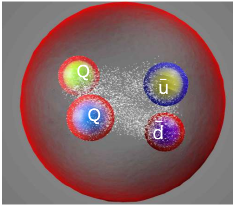
Table 2: Heavy-light meson spectra, mass unit in MeV and $\langle r^2\rangle^{\frac{1}{2}}$ unit in fm.

State	IJ^P	Theory	PDG	$\langle \mathbf{r}^2\rangle^{\frac{1}{2}}$	State	IJ^P	Theory	PDG	$\langle \mathbf{r}^2\rangle^{\frac{1}{2}}$
D^+	$\frac{1}{2}0^-$	1867±8	1869.66 ± 0.05	0.68	D_1	$\frac{1}{2}1^+$	2361±4	2422.1 ± 0.6	1.16
D^*	$\frac{1}{2}1^-$	2002±4	2006.85 ± 0.05	0.82	D_2^*	$\frac{1}{2}2^+$	2368±4	2461.1 ± 0.8	1.17
D_3^*	$\frac{1}{2}3^-$	2677±4	2763.1 ± 3.2	1.45					

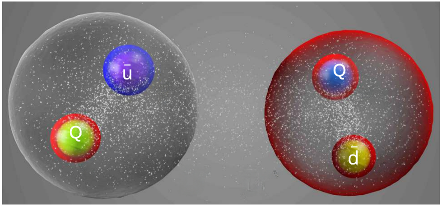
- Uncertainty of energy

$$\delta H = \sum_{i=1}^{8} \frac{\partial H(x_1, \ldots, x_8)}{\partial x_i}\delta x_i, \quad \delta E = \langle \Phi_{IJ}^{D} \left|\delta H\right| \Phi_{IJ}^{D}\rangle$$

3.1 Two configurations of T_{cc}



Diquark configuration



Meson-meson configuration

Figure 2: Two configurations

- Diquark configuration: compact, color force.
- Meson-meson configuration: relative loose, residual interactions.

- WF of charmed meson

$$\Phi_{IJ}^{D^{(*)}} = \chi_c \otimes \eta_i \otimes \psi_s \otimes \phi_{l_r m_r}(\mathbf{r})$$

  - Color part

$$\chi_c = \frac{1}{\sqrt{3}}(r\bar{r} + g\bar{g} + b\bar{b})$$

  - Isospin part

$$\eta_i = c\bar{u}, \quad c\bar{d}$$

  - Spin part

$$S=0: \quad \psi_s = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow); \quad S=1: \quad \psi_s = \downarrow\downarrow, \quad \frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow), \quad \uparrow\uparrow$$

  - Orbit part, Gaussian expansion method

$$\phi_{l_r m_r}(\mathbf{r}) = \sum_{n_r=1}^{n_{rmax}} c_{n_r} N_{n_r l_r} r^{l_r} e^{-\nu_{n_r} r^2} Y_{l_r m_r}(\hat{\mathbf{r}}), \quad \mathbf{r} = \mathbf{r}_c - \mathbf{r}_{\bar{q}}$$

- WF of di-meson state T_{cc} $(D_1 D_2)$

$$\Psi^{T_{cc}}_{IJ} = \sum_{\xi} c_\xi \mathcal{A}_{12} \left\{ \left[\Phi^{D_1}_{I_1 J_1} \Phi^{D_2}_{I_2 J_2} \right]_{IJ} \phi_{l_\rho m_\rho}(\boldsymbol{\rho}) \right\}.$$

  - $\xi = \{I_1, I_2, J_1, J_2, ...\}$ and c_ξ can be determined by the model dynamics.
  - $\mathcal{A}_{12}$ serves as an antisymmetrization operator

$$\mathcal{A}_{12} = P_{c_1 c_2} P_{\bar{q}_1 \bar{q}_2}, \qquad P_{c_1 c_2} = 1 - P_{c_1 c_2},\ P_{\bar{q}_1 \bar{q}_2} = 1 - P_{\bar{q}_1 \bar{q}_2}.$$

  - $\phi_{l_\rho m_\rho}(\boldsymbol{\rho})$ represents the relative motion WF between two mesons

$$\boldsymbol{\rho} = \frac{m_c \mathbf{r}_{c_1} + m_q \mathbf{r}_{\bar{q}_1}}{m_c + m_{\bar{q}}} - \frac{m_c \mathbf{r}_{c_2} + m_q \mathbf{r}_{\bar{q}_2}}{m_c + m_{\bar{q}}}.$$

Also, $\phi_{l_\rho m_\rho}(\boldsymbol{\rho})$ is expressed by Gaussian expansion method.

- Solving the four-body Schrödinger equation

$$(H_4 - E_4)\Psi_{IJ}^{T_{cc}} = 0$$

- Binding energy

$$\Delta E_4 = E_4 - E_{D_1} - E_{D_2}$$

- Contribution from each interaction V^χ and kinetic energy

$$\Delta\langle V^\chi\rangle = \langle\Psi_{IJ}^{T_{cc}}|V^\chi|\Psi_{IJ}^{T_{cc}}\rangle - \langle\Phi_{I_1J_1}^{D_1}|V^\chi|\Phi_{I_1J_1}^{D_1}\rangle - \langle\Phi_{I_2J_2}^{D_2}|V^\chi|\Phi_{I_2J_2}^{D_2}\rangle$$
$$\Delta\langle T\rangle = \langle\Psi_{IJ}^{T_{cc}}|T|\Psi_{IJ}^{T_{cc}}\rangle - \langle\Phi_{I_1J_1}^{D_1}|T|\Phi_{I_1J_1}^{D_1}\rangle - \langle\Phi_{I_2J_2}^{D_2}|T|\Phi_{I_2J_2}^{D_2}\rangle$$

- Average distance between D_1 and D_2

$$\langle\boldsymbol{\rho}^2\rangle^{\frac{1}{2}} = \langle\Psi_{IJ}^{T_{cc}}|\boldsymbol{\rho}^2|\Psi_{IJ}^{T_{cc}}\rangle^{\frac{1}{2}}$$

4.2 $T_{cc}(3875)$ in the model

Table 3: Binding energy of S-wave $D^{(*)}D^{(*)}$, the contribution from various interactions and kinetic energy, unit in MeV. $\langle \mathbf{r}^2\rangle^{\frac{1}{2}}$ is the size of mesons and $\langle \boldsymbol{\rho}^2\rangle^{\frac{1}{2}}$ is the distance between two mesons, unit in fm.

Constituent	IJ^P	ΔE_4	$\langle \mathbf{r}^2\rangle^{\frac{1}{2}}$	$\langle \boldsymbol{\rho}^2\rangle^{\frac{1}{2}}$	$\Delta\langle V^\sigma\rangle$	$\Delta\langle V^\pi\rangle$	$\Delta\langle V^\eta\rangle$	$\Delta\langle V^{\mathrm{conf}}\rangle$	$\Delta\langle V^{\mathrm{cm}}\rangle$	$\Delta\langle V^{\mathrm{coul}}\rangle$	$\Delta\langle T\rangle$
DD^*	01^+	Unbound									
D^*D^*	01^+	Unbound									
Coupling	01^+	0.34 ± 0.08	0.75	4.32	-2.68	-2.19	0.17	-1.00	-3.16	-1.13	9.65

- Matching the experimental data well. Phys.Rev.D 105, 054015 (2022); Sci.Bull. 67, 1522 (2022)
  - Binding energy: 0.34 ± 0.08 MeV.
  - Deuteronlike state: $\langle \boldsymbol{\rho}^2\rangle^{\frac{1}{2}} \simeq 4.32$ fm.
  - Vital coupled channel effect: $DD^*(99.6\%) + D^*D^*(0.4\%)$.
  - Binding mechanisms: $V^{\mathrm{cm}} > V^\sigma > V^\pi > V^{\mathrm{coul}} > V^{\mathrm{conf}}$
- Other states are unstable.

4.2 S-wave $D_1 D_1$

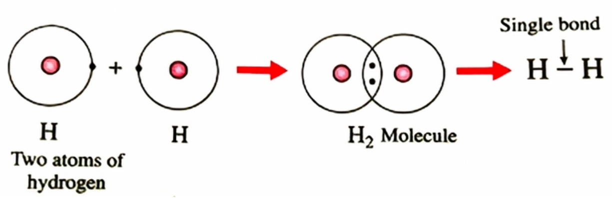
Table 4: Binding energy of the S-wave $D_1 D_1$, the contribution from various interactions and kinetic energy, unit in MeV. I, S and L represent total isospin, spin, orbital angular momentum, respectively.

Constituent	$I, S \oplus L$	ΔE_4	$\langle \mathbf{r}^2 \rangle^{\frac{1}{2}}$	$\langle \boldsymbol{\rho}^2 \rangle^{\frac{1}{2}}$	$\Delta\langle V^\sigma \rangle$	$\Delta\langle V^\pi \rangle$	$\Delta\langle V^\eta \rangle$	$\Delta\langle V^{\rm conf} \rangle$	$\Delta\langle V^{\rm cm} \rangle$	$\Delta\langle V^{\rm coul} \rangle$	$\Delta\langle T \rangle$
	$0, 0 \oplus 1$	Unbound									
$D_1 D_1$	$1, 0 \oplus 0$	-5.6 ± 0.1	1.15	1.89	-2.8	-0.3	-0.1	-2.8	-2.0	3.3	-0.9
	$1, 0 \oplus 2$	Unbound									

- Bound state: $D_1 D_1$ with $ISL = 100$.
  - Binding energy: -5.6 ± 0.1 MeV.
  - Partly overlapped: $2\langle \mathbf{r}^2 \rangle^{\frac{1}{2}} > \langle \boldsymbol{\rho}^2 \rangle^{\frac{1}{2}}$, hydrogenlike molecular state.
  - Binding mechanisms: $V^\sigma = V^{\rm conf} > V^{\rm cm} > T > V^\pi > V^\eta$.
- Unbound states: $D_1 D_1$ with $ISL = 001$ and 102.

4.3 QCD valence bond

- QED valence bonds.



  - Partly overlapped, shared electron

- QCD valence bonds.
  - Partly overlapped, light quark delocalization
  - Uncertainty principle, reduce kinetic energy

4.4 S-wave $D_1 D_2^*$

Table 5: Binding energy of the S-wave $D_1 D_2^*$, see the caption for Table 4.

Constituent	$I, S \oplus L$	ΔE_4	$\langle \mathbf{r}^2 \rangle^{\frac{1}{2}}$	$\langle \boldsymbol{\rho}^2 \rangle^{\frac{1}{2}}$	$\Delta\langle V^{\sigma} \rangle$	$\Delta\langle V^{\pi} \rangle$	$\Delta\langle V^{\eta} \rangle$	$\Delta\langle V^{\mathrm{con}} \rangle$	$\Delta\langle V^{\mathrm{cm}} \rangle$	$\Delta\langle V^{\mathrm{coul}} \rangle$	$\Delta\langle T \rangle$
	$0, 1 \oplus 0$	Unbound									
	$0, 1 \oplus 1$	Unbound									
	$0, 1 \oplus 2$	Unbound									
$D_1 D_2^*$	$1, 1 \oplus 0$	-19.4 ± 0.2	1.13	1.39	-3.8	-1.3	-0.3	-8.7	-1.7	8.2	-11.8
	$1, 1 \oplus 1$	Unbound									
	$1, 1 \oplus 2$	-3.6 ± 0.1	1.15	1.99	-3.0	-1.0	-0.2	-1.1	-1.4	9.3	-6.3

- Note that we just consider spin-spin and orbit-orbit coupling.
- Bound states: $D_1 D_2^*$ with $ISL = 110$ and 112.
  - Binding energy: -19.4 ± 0.2 MeV and -3.6 ± 0.1 MeV.
  - Partly overlapped: $2\langle \mathbf{r}^2 \rangle^{\frac{1}{2}} > \langle \boldsymbol{\rho}^2 \rangle^{\frac{1}{2}}$, hydrogenlike molecular state.
  - Mainly Binding mechanisms: QCD valence bonds.
- Unbound states: $D_1 D_2^*$ with $ISL = 010$, 011, 012 and 111.

Table 6: Binding energy of the S-wave $D_2^* D_2^*$, see the caption for Table 4

Constituent	$I, S \oplus L$	ΔE_4	$\langle \mathbf{r}^2 \rangle^{\frac{1}{2}}$	$\langle \boldsymbol{\rho}^2 \rangle^{\frac{1}{2}}$	$\Delta\langle V^{\sigma} \rangle$	$\Delta\langle V^{\pi} \rangle$	$\Delta\langle V^{\eta} \rangle$	$\Delta\langle V^{\text{con}} \rangle$	$\Delta\langle V^{\text{cm}} \rangle$	$\Delta\langle V^{\text{coul}} \rangle$	$\Delta\langle T \rangle$
$D_2^* D_2^*$	$0, 0 \oplus 1$	-1.1 ± 0.1	1.17	2.78	-1.8	-1.8	-0.0	-1.5	-2.1	0.3	5.8
	$0, 1 \oplus 0$	Unbound									
	$0, 1 \oplus 2$	Unbound									
	$0, 2 \oplus 1$	Unbound									

- Bound state: $D_2^* D_2^*$ with $ISL = 001$.
  - Binding energy: -1.1 ± 0.1 MeV.
  - Non-overlapped: $2\langle \mathbf{r}^2 \rangle^{\frac{1}{2}} > \langle \boldsymbol{\rho}^2 \rangle^{\frac{1}{2}}$, deuteronlike molecular state.
  - Binding mechanisms: $V^{\text{cm}} > V^{\sigma} = V^{\pi} > V^{\text{conf}}$.
- Unbound states: $D_2^* D_2^*$ with $ISL = 010$, 012 and 021.

4.5 S-wave $D_2^* D_2^*$

Table 7: Binding energy of the S-wave $D_2^* D_2^*$, see the caption for Table 4

Constituent	$I, S \oplus L$	ΔE_4	$\langle \mathbf{r}^2 \rangle^{\frac{1}{2}}$	$\langle \boldsymbol{\rho}^2 \rangle^{\frac{1}{2}}$	$\Delta\langle V^\sigma \rangle$	$\Delta\langle V^\pi \rangle$	$\Delta\langle V^\eta \rangle$	$\Delta\langle V^{\mathrm{con}} \rangle$	$\Delta\langle V^{\mathrm{cm}} \rangle$	$\Delta\langle V^{\mathrm{coul}} \rangle$	$\Delta\langle T \rangle$
	$1, 0 \oplus 0$	Unbound									
	$1, 0 \oplus 2$	Unbound									
$D_2^* D_2^*$	$1, 2 \oplus 0$	-19.6 ± 0.2	1.14	1.40	-3.8	-1.3	-0.3	-8.9	-1.9	8.2	-11.7
	$1, 1 \oplus 1$	Unbound									
	$1, 2 \oplus 2$	-3.7 ± 0.1	1.16	1.96	-3.0	-1.0	-0.2	-1.2	-1.5	9.4	-6.3

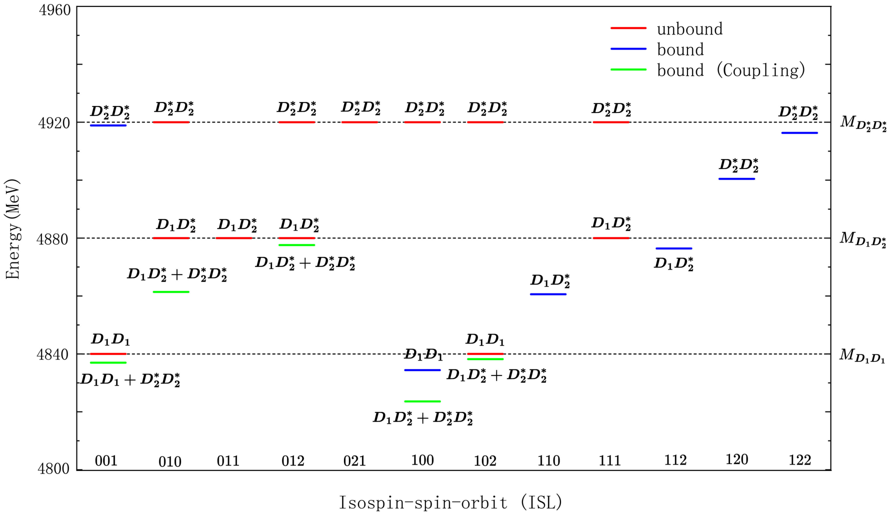
- Bound states: $D_2^* D_2^*$ with $ISL = 120$ and 122.
  - Binding energy: -19.6 ± 0.2 MeV and -3.7 ± 0.1 MeV.
  - Partly overlapped: $2\langle \mathbf{r}^2 \rangle^{\frac{1}{2}} > \langle \boldsymbol{\rho}^2 \rangle^{\frac{1}{2}}$, hydrogenlike molecular state.
  - Mainly Binding mechanisms: QCD valence bonds.
- Unbound states: $D_1 D_1$ with $ISL = 100$, 102 and 111.

Table 8: Channel coupled effects for the bound states.

Constituent	$I, S \oplus L$	Ratio	ΔE_4	$\langle \mathbf{r}^2 \rangle^{\frac{1}{2}}$	$\langle \boldsymbol{\rho}^2 \rangle^{\frac{1}{2}}$	$\Delta\langle V^\sigma \rangle$	$\Delta\langle V^\pi \rangle$	$\Delta\langle V^\eta \rangle$	$\Delta\langle V^{\rm con} \rangle$	$\Delta\langle V^{\rm cm} \rangle$	$\Delta\langle V^{\rm coul} \rangle$	$\Delta\langle T \rangle$
D_1D_1 $D_2^*D_2^*$	$0, 0 \oplus 1$	55% 45%	-3.0 ± 0.1	1.15	1.73	-2.7	-5.2	0.1	0.1	2.8	5.7	-3.8
$D_1D_2^*$ $D_2^*D_2^*$	$0, 1 \oplus 0$	56% 44%	-18.6 ± 0.3	1.13	1.34	-4.1	-12.5	0.9	-8.5	8.7	9.6	-12.7
$D_1D_2^*$ $D_2^*D_2^*$	$0, 1 \oplus 2$	71% 29%	-2.4 ± 0.2	1.15	2.02	-3.0	-8.8	0.6	-0.8	6.3	10.0	-6.7
D_1D_1 $D_2^*D_2^*$	$1, 0 \oplus 0$	85% 15%	-16.4 ± 0.2	1.13	1.41	-3.8	-1.3	-0.3	-6.2	0.8	9.2	-14.9
D_1D_1 $D_2^*D_2^*$	$1, 0 \oplus 2$	95% 5%	-1.8 ± 0.1	1.15	2.25	-2.5	-0.7	-0.2	-0.0	-0.3	7.6	-5.7
$D_1D_2^*$	$1, 1 \oplus 0$	100%	-19.4 ± 0.2	1.13	1.39	-3.8	-1.3	-0.3	-8.7	-1.7	8.2	-11.8
$D_1D_2^*$	$1, 1 \oplus 2$	100%	-3.6 ± 0.1	1.15	1.99	-3.0	-1.0	-0.2	-1.1	-1.4	9.3	-6.3
$D_2^*D_2^*$	$1, 2 \oplus 0$	100%	-19.6 ± 0.2	1.14	1.40	-3.8	-1.3	-0.3	-8.9	-1.9	8.2	-11.7
$D_2^*D_2^*$	$1, 2 \oplus 2$	100%	-3.7 ± 0.1	1.16	1.96	-3.0	-1.0	-0.2	-1.2	-1.5	9.4	-6.3

- Those bound states are hydrogenlike molecular states.
- In the states with $I = 0$, the meson exchanges are vital.
- In the states with $I = 1$, QCD valence bonds are paramount.

4.7 Energy Spectrum



- Summary
    - QCD valence bonds, orbit partly overlapped, light quark delocalization.
    - Nine stable hydrogenlike molecules composed of D_1D_1, $D_1D_2^*$ and $D_2^*D_2^*$.
    - In the states with $I = 0$, the meson exchanges are vital.
    - In the states with $I = 1$, QCD valence bonds are paramount.

Thank you for your attention!