



北京航空航天大学



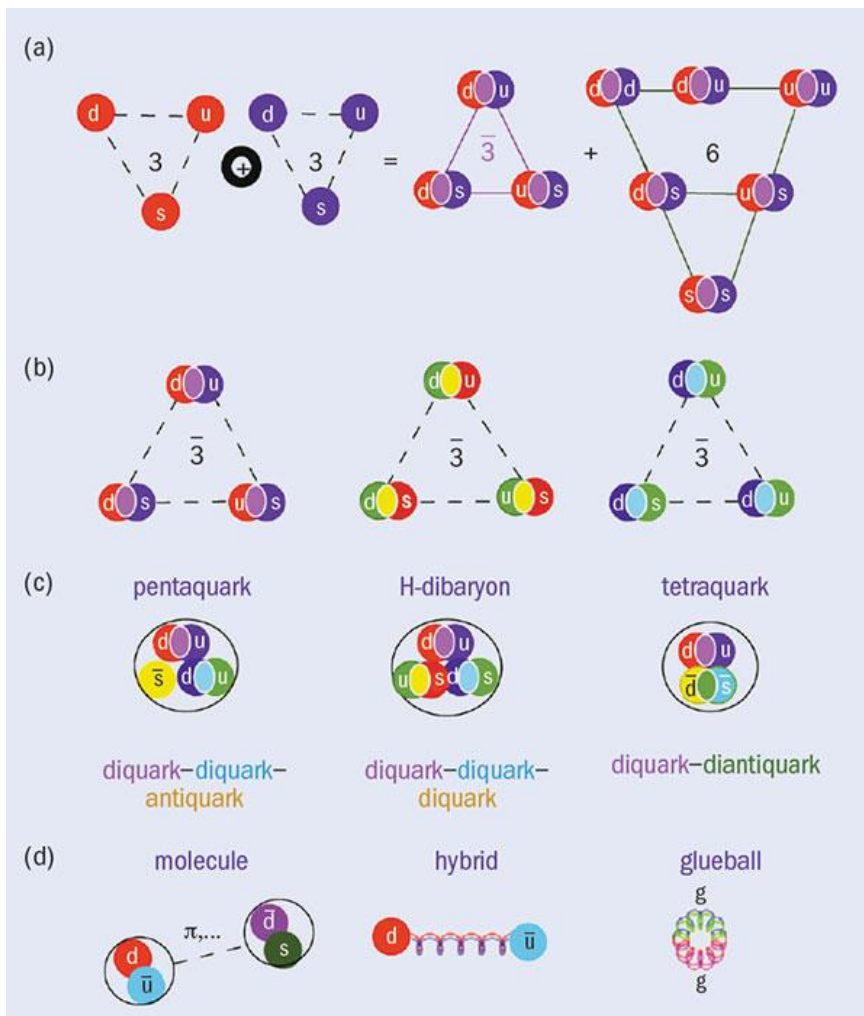
北航物理学院
SCHOOL OF PHYSICS, BUAA

Study on multi-hadron molecular states

Presenter: Tian-Wei Wu (吴天伟)

Collaborators: M.Z. Liu, E. Hiyama, L.S. Geng and M.P. Valderrama

XYZ粒子会议@青岛0518



一般强子:

介子: 由正反夸克对组成

重子: 由三个夸克组成

奇特强子态:

1. 胶球(glueball)

由胶子构成

2. 混杂态(hybrid)

由胶子和夸克构成

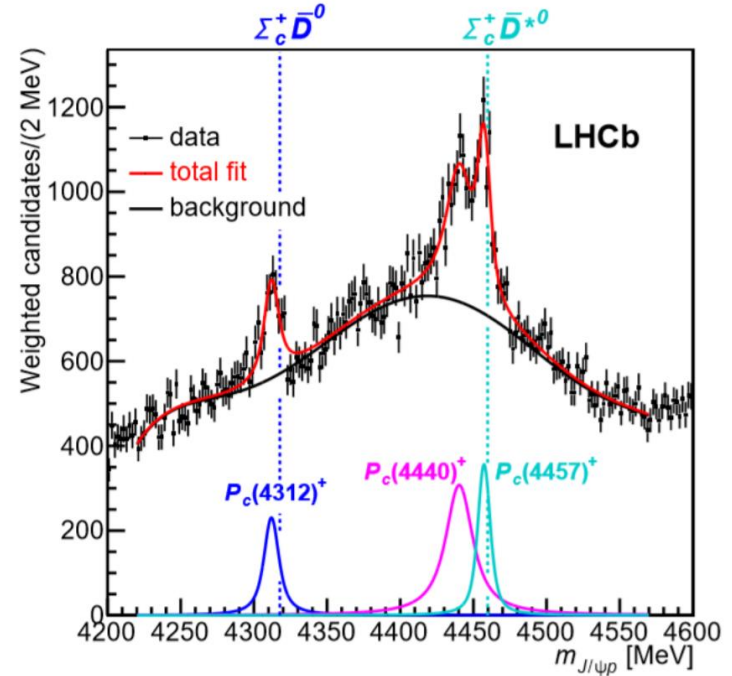
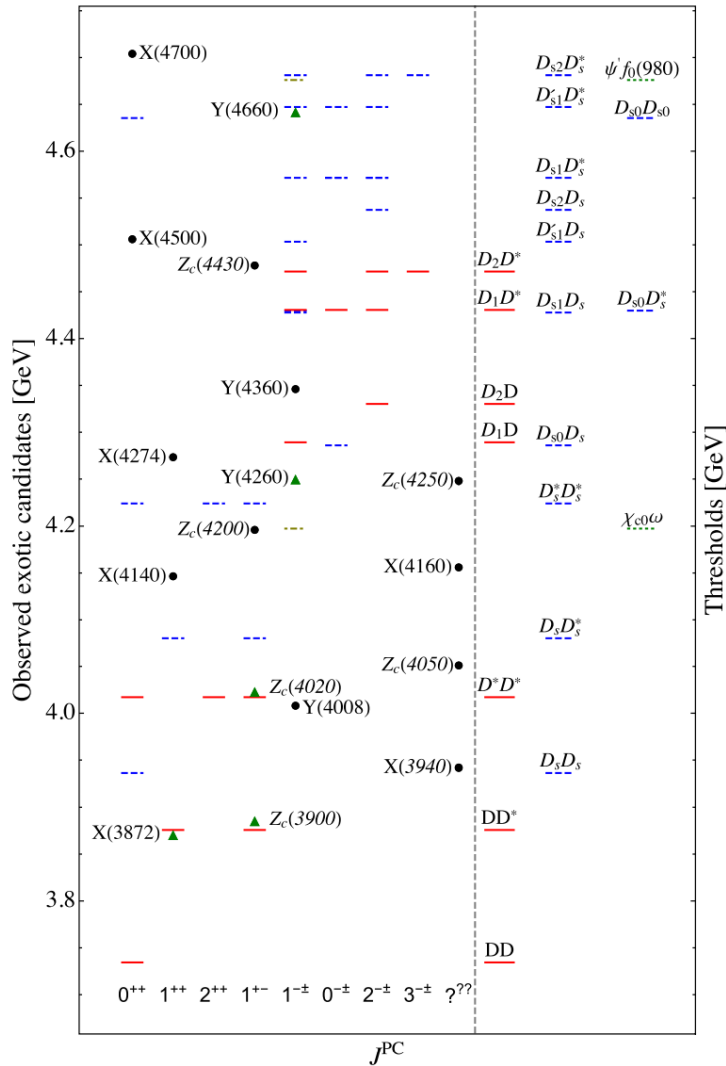
3. 多夸克态(multiquark state)

由超过三个夸克组成

4. 强子分子态(hadronic molecule)

由两个或多个强子组成的强子态

强子分子态



X(3872), P_c states, $D_{s0}^*(2317)$ 等许多近阈粒子被认为是强子分子态的有力候选者。

A. Martines, etc. Few-Body Syst (2020) 61:35

Components	States generated	Method used	References
$\bar{K} NN$	\bar{K} bound states	F V FCA	[76–88]
$2PN$	$1/2^+ \Sigma, \Lambda$ excited $1/2^+ N^*$ states ($N^*(1920)$)	χ^F χ^F	[53,55]
$\pi\pi N$	$N^*(1710)$	χ^F	[54]
$K \bar{K} N$	$N^*(1920)$	V, FCA	[56,70,89]
$KK \bar{K}$	$K(1460)$	χ^F CS F	[90–92]
$\pi K \bar{K}, \pi\pi\eta$	$\pi(1300), f_0(1790)$	χ^F	[93]
$\phi K \bar{K}, \phi\pi\pi$	$\phi(2170)$	χ^F	[50]
$\pi\rho\Delta$	$\Delta_{5/2^+}(2000)$	FCA	[94]
$\pi \bar{K} K^*$	$\pi_1(1600)$	FCA	[95]
$\eta \bar{K} K^*$	$0(1^-)$ state around 1700 MeV	FCA	[96]
$\rho K \bar{K}$	$\rho(1700)$	FCA	[97]
Multi- ρ	$f_2(1270), \rho_3(1690), f_4(2050),$ $\rho_5(2350), f_6(2510)$	FCA	[65]
K^* multi- ρ	$K_2^*(1430), K_3^*(1780)$ $K_4^*(2045), K_5^*(2380), K_6^*$	FCA	[74]
PVV	$\pi_2(1670), \eta_2(1645), K_2^*(1770)$	FC	[75]
K multi- ρ	several K^* states	FCA	[98]
DNN	D bound state	FCA V	[99,100]
$NDK, ND\bar{K},$ $ND\bar{D}$	bound states of 3050, 3150, 4400 MeV	FC	[100]
$DDK, DD_s\eta,$ $DD_s\pi$	$I = 1/2$ state around 4140 MeV	χ^F	[101,102]
DDK	Bound state, $B \simeq 70$ MeV	GE	[103]
$DDDK$	Bound state, $B \simeq 90 - 110$ MeV	GE	[103]
$J/\psi K \bar{K}$	$Y(4260)$	χ^F	[104]
$K D \bar{D}^*$	K^* Bound states	FCA	[105]
$DK \bar{K}$	D -like state at 2900 MeV	QSR, χ^F FC	[71,72]
$\rho D \bar{D}$	$I = 0, 1$ states 4200–4300 MeV	FCA	[106]
$\rho B^* \bar{B}^*$	$J = 3$ state at 10950 MeV	FCA	[107]
$D^{(*)} B^{(*)} \bar{B}^{(*)}$	Several bound states	FCA	[108]
$BD \bar{D}, BDD$	$BD \bar{D}$ bound state ~ 8950 MeV	FCA	[109]
$BB^* B^*,$ $B^* B^* B^*$	Bound $C = 3$ meson	F	[110]
$DD^* K, BB^* \bar{K}$	Bound states 4318 MeV, 11014 MeV	BO	[111]
$\bar{K}^* B \bar{B}, \bar{K}^* B^* \bar{B}^*$	Several bound states	FCA	[112]
BBB^*	Probable bound state	BO	[113]
D multi- ρ	Seven D^* states	FCA	[114]

P Pseudoscalar, F Faddeev, FCA Fixed center approximation, χ^F Chiral Faddeev, V Variational, GE Gaussian expansion, QSR QCD sum rules, BO Born–Oppenheimer, CS Complex scaling

Methods:

Faddeev equation

Fixed Center Approximation

χ Faddeev

Variational method

Gaussian Expansion Method

QCD Sum Rules

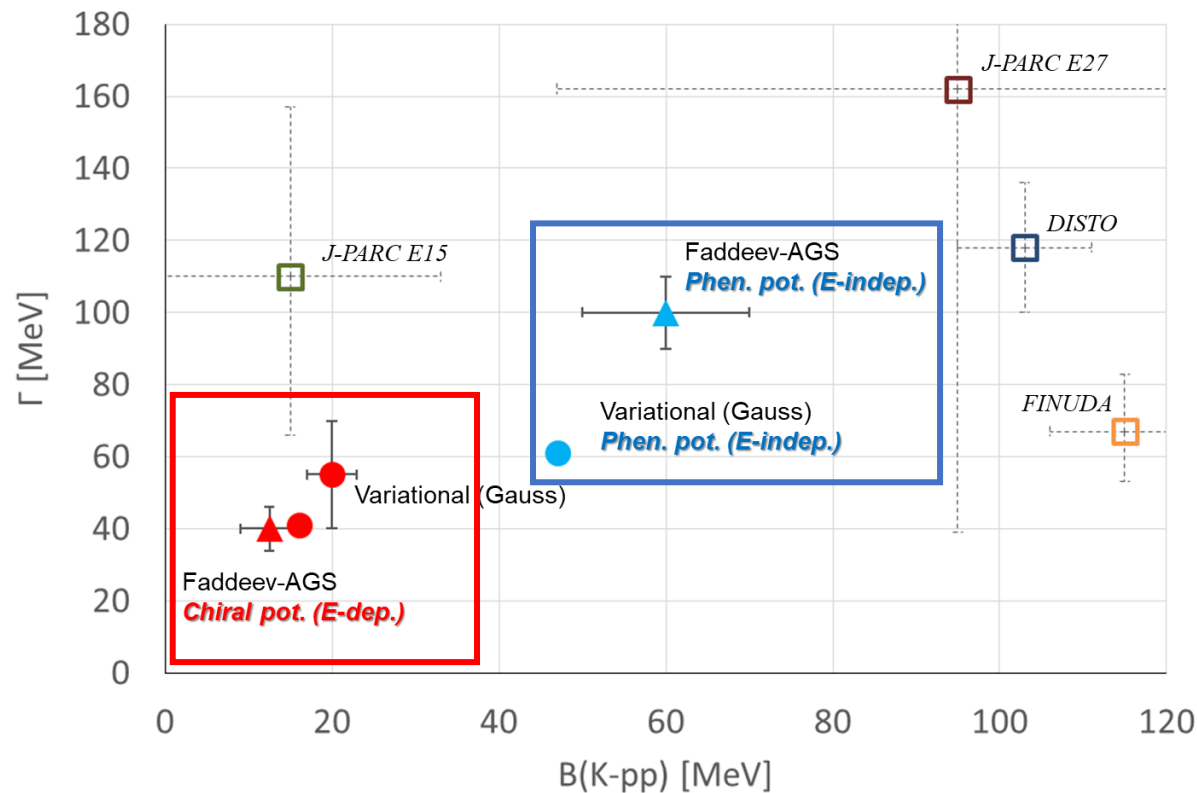
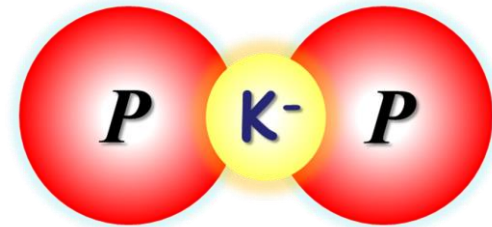
Born–Oppenheimer Approximation

Complex Scaling

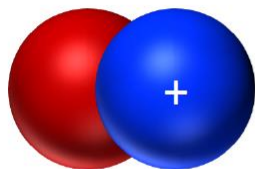
三体强子分子态?



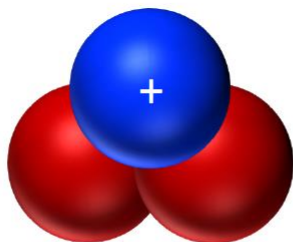
NN \bar{K} 的理论 and 实验研究



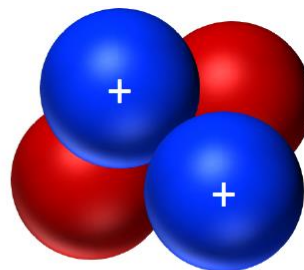
从核子到强子



deuteron



triton



alpha

元素和核素是有限的

np, nnp, nnpp...

NK, NNK, NNNK...

IUPAC Periodic Table of the Elements

1 H Hydrogen 1.008	2 He Helium 4.003											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948																		
3 Li Lithium 6.941	4 Be Beryllium 9.012	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	11 Na Sodium 22.990	12 Mg Magnesium 24.305	19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798								
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.906	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.36	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29	55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222
87 Fr Francium 223	88 Ra Radium 226	89-103 Actinoids	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 264	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Ds Darmstadtium 267	111 Rg Roentgenium 268	112 Cn Copernicium 269	113 Nh Nihonium 270	114 Fl Flerovium 271	115 Mc Moscovium 272	116 Lv Livermorium 273	117 Ts Tennessine 274	118 Og Oganesson 276																		



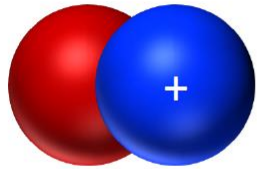
89 La Lanthanum 138.905	90 Ce Cerium 140.12	91 Pr Praseodymium 140.908	92 Nd Neodymium 144.24	93 Pm Promethium 144.913	94 Sm Samarium 150.36	95 Eu Europium 151.964	96 Gd Gadolinium 157.25	97 Tb Terbium 158.925	98 Dy Dysprosium 162.50	99 Ho Holmium 164.930	100 Er Erbium 167.259	101 Tm Thulium 168.934	102 Yb Ytterbium 173.054	103 Lu Lutetium 174.967
94 Ac Actinium 227	95 Th Thorium 232.038	96 Pa Protactinium 231.036	97 U Uranium 238.029	98 Np Neptunium 237.048	99 Pu Plutonium 244.064	100 Am Americium 243.061	101 Cm Curium 247.070	102 Bk Berkelium 247.070	103 Cf Californium 251.083	104 Es Einsteinium 252.083	105 Fm Fermium 257.103	106 Md Mendelevium 258.103	107 No Nobelium 259.103	108 Lr Lawrencium 260.103

For notes and updates to this table, see www.iupac.org. This version is dated 1 December 2018. Copyright © 2018 IUPAC, the International Union of Pure and Applied Chemistry.

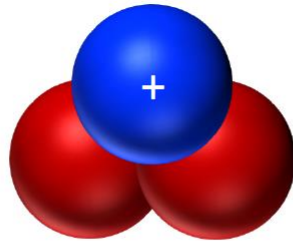
是否存在类核的多强子分子态?



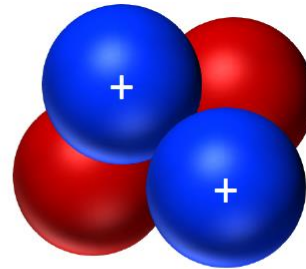
类核的多强子分子态?



deuteron



triton



alpha

np, nnp, nnpp...

NK, NNK, NNNK...

DK, DDK, DDDK? ...

...

特点:

由两种粒子构成;

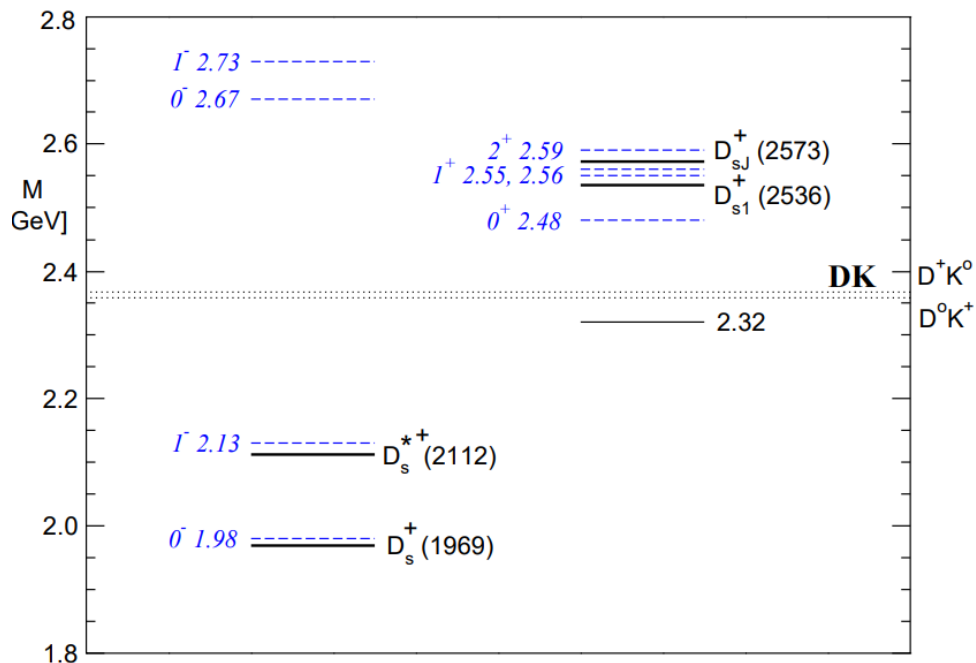
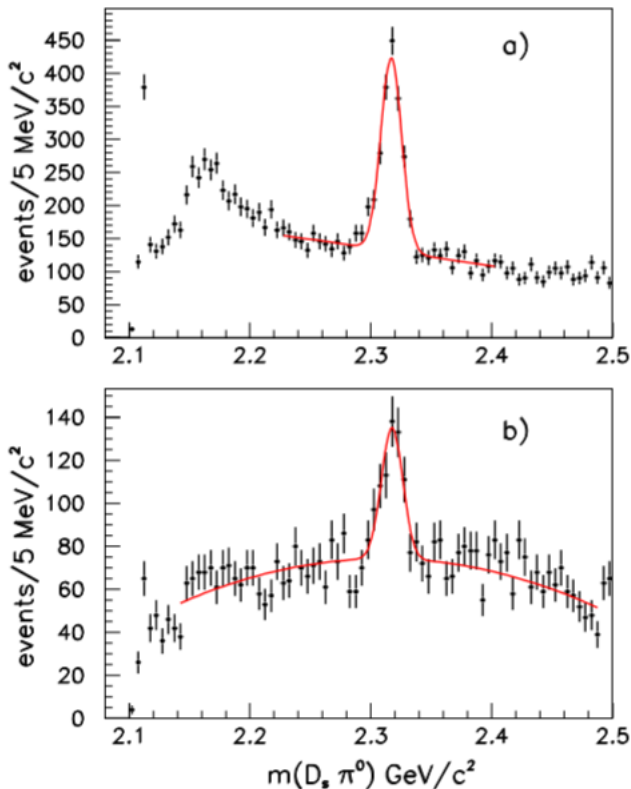
系统对称性高;

系统内相互作用单一;

理论上较易向多体发展;

介子系统没有泡利原理的限制。

Ds0 (2317)



PHYSICAL REVIEW D 68, 054006 (2003)

@PDG

质量: 2317.7 MeV
 总宽度: < 3.8 MeV
 伙伴态 Ds1: 2460 MeV
 M(Ds1)-M(Ds0)=140 MeV

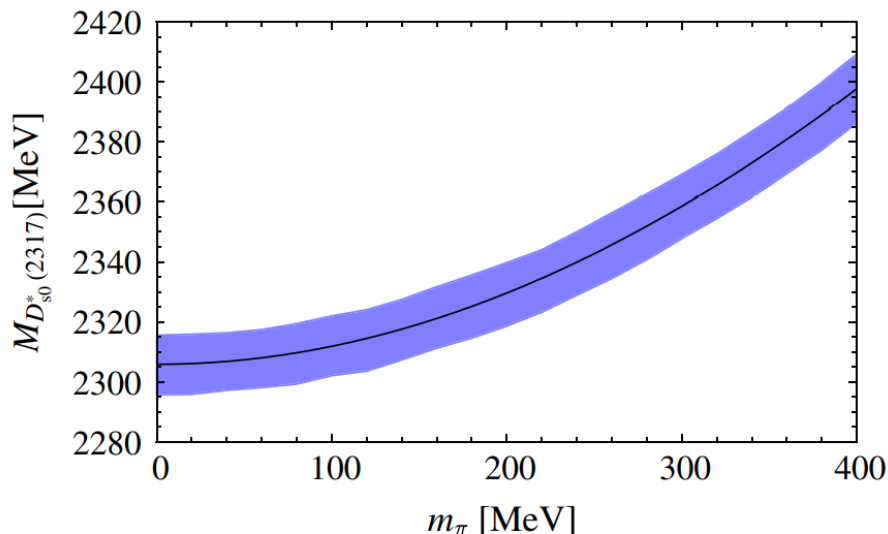
@Quark model

质量: 约2480 MeV
 总宽度: 270-990 MeV
 伙伴态 Ds1: 2560 MeV
 M(Ds1)-M(Ds0)=80 MeV

Ds0(2317) 的分子态解释



Phys. Rev. D 89, 014026

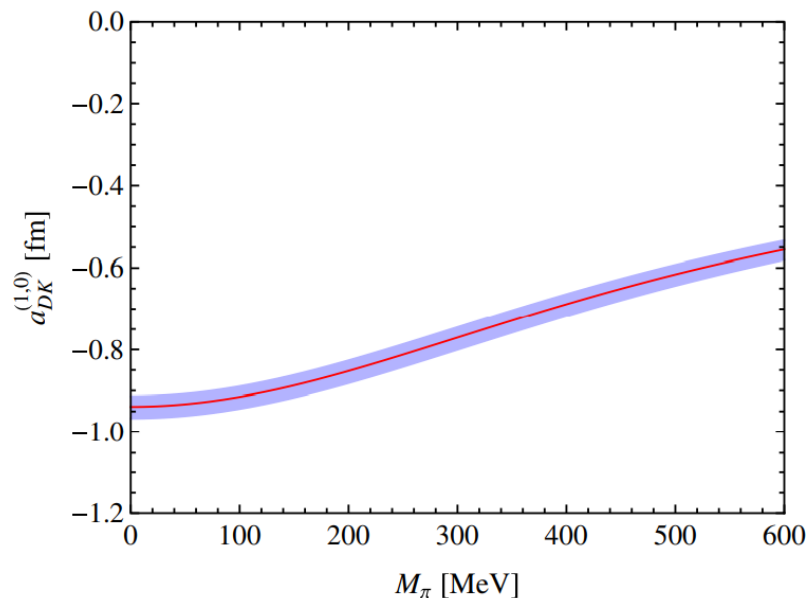


DK pole position@ChPT

TABLE V. Pole positions $\sqrt{s} = M - i\frac{\Gamma}{2}$ (in units of MeV) of charm mesons dynamically generated in the HQS UChPT.

(S, I)	$J^P = 0^+$	$J^P = 1^+$
(1, 0)	2317 ± 10	2457 ± 17
(0, 1/2)	$(2105 \pm 4) - i(103 \pm 7)$	$(2248 \pm 6) - i(106 \pm 13)$

Phys. Rev. D 87, 014508

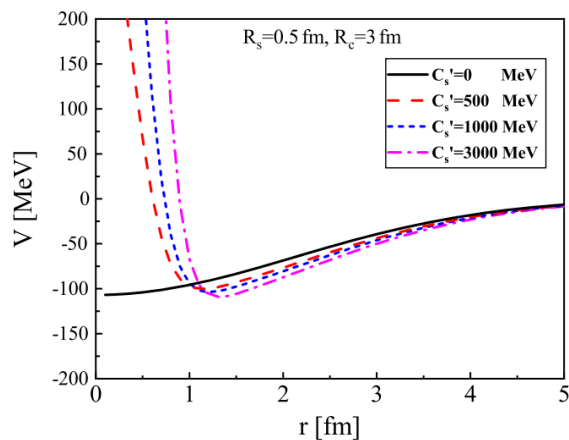
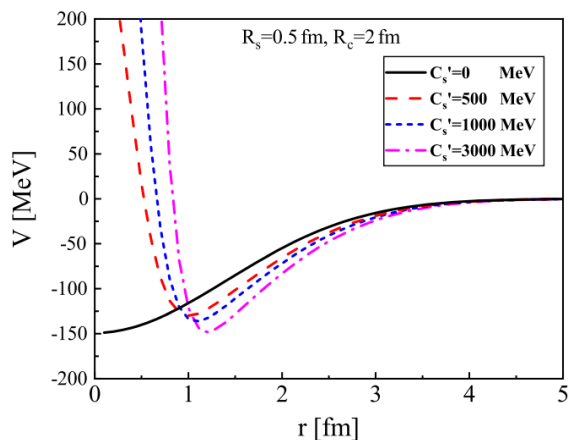
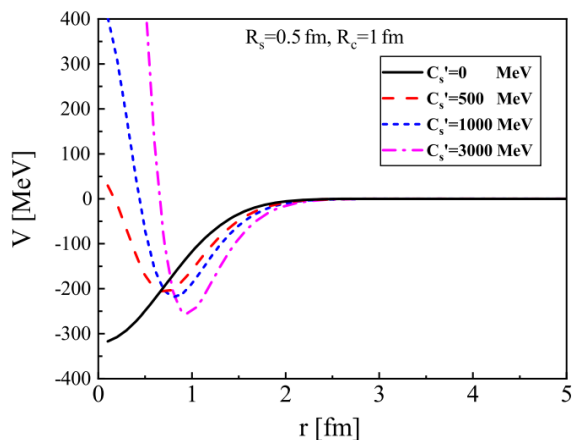


DK 散射长度@LQCD

Pole position: 2315_{-28}^{+18} MeV

$\Gamma(D_{s0}^*(2317) \rightarrow D_s \pi) = (133 \pm 22)$ keV.

手征、格点、实验均支持Ds0(2317)是DK分子态或至少含有很大的DK分子态成分。



LO Weinberg-Tomozawa (WT) DK interaction

LO attractive main part+NLO repulsive core

$$V_{DK}(\vec{q}) = -\frac{C_W(I)}{2f_\pi^2},$$

$$C_W(0) = 2 \quad \text{and} \quad C_W(1) = 0,$$

$$V_{DK}(\vec{r}) = -\frac{C_W(I)}{2f_\pi^2} \delta^{(3)}(\vec{r}),$$

$$V_{DK}(r; R_c) = -\frac{C_W(I)}{2f_\pi^2} \frac{e^{-(r/R_c)^2}}{\pi^{3/2} R_c^3},$$

$$\begin{aligned} V_{DK}(\vec{r}; R_c) &= C_S \frac{e^{-(r/R_S)^2}}{\pi^{3/2} R_S^3} + C(R_C) \frac{e^{-(r/R_c)^2}}{\pi^{3/2} R_c^3} \\ &= C'_S e^{-(r/R_S)^2} + C'_L e^{-(r/R_c)^2}, \end{aligned}$$

► 拟合Ds0的束缚能45MeV:

取固定短程排斥芯, $R_s(0.5 \text{ fm})$, $C_s'(0-3000 \text{ MeV})$;

取不同的cutoff $R_c(1-3\text{fm})$, R_c 表征有效力程。

DD单玻色子交换相互作用

$$V_{DD}(r; \Lambda) = V_\rho(r; \Lambda) + V_\omega(r; \Lambda) + V_\sigma(r; \Lambda)$$

各个交换势具体形式

$$V_\sigma(r; \Lambda) = -g_\sigma^2 m_\sigma W_C(m_\sigma r, \frac{\Lambda}{m_\sigma}),$$

$$V_\rho(r; \Lambda) = +\vec{\tau}_1 \cdot \vec{\tau}_2 g_\rho^2 m_\rho W_C(m_\rho r, \frac{\Lambda}{m_\rho}),$$

$$V_\omega(r; \Lambda) = +g_\omega^2 m_\omega W_C(m_\omega r, \frac{\Lambda}{m_\omega}),$$

其中

$$W_C(x, \lambda) = \frac{e^{-x}}{4\pi x} - \lambda \frac{e^{-\lambda x}}{4\pi \lambda x} - \frac{(\lambda^2 - 1) e^{-\lambda x}}{2\lambda} \frac{1}{4\pi}.$$

高斯展开法是一种通过变分原理求解少体系统薛定谔方程的基展开方法。

▶ 薛定谔方程和基展开

$$(H - E)\Psi_{JM} = 0$$
$$\Psi_{JM} = \sum_{n=1}^{n_{max}} C_n^{(J)} \Phi_{JM,n}.$$

▶ 转化为本征值问题求解

$$\sum_{n'=1}^{n_{max}} (H_{nn'}^{(J)} - EN_{nn'}^{(J)}) C_{n'}^{(J)} = 0,$$
$$H_{nn'}^{(J)} = \langle \Phi_{JM,n} | H | \Phi_{JM,n'} \rangle,$$
$$N_{nn'}^{(J)} = \langle \Phi_{JM,n} | 1 | \Phi_{JM,n'} \rangle.$$

▶ 高斯基

$$\phi_{nlm}^G(r) = \phi_{nl}^G(r) Y_{lm}(\hat{r}),$$

$$\phi_{nl}^G(r) = N_{nl} r^l e^{-\nu_n r^2},$$

$$N_{nl} = \sqrt{\frac{2^{l+2} (2\nu_n)^{l+\frac{3}{2}}}{\sqrt{\pi} (2l+1)!!}} \quad (n = 1 - n_{max}).$$

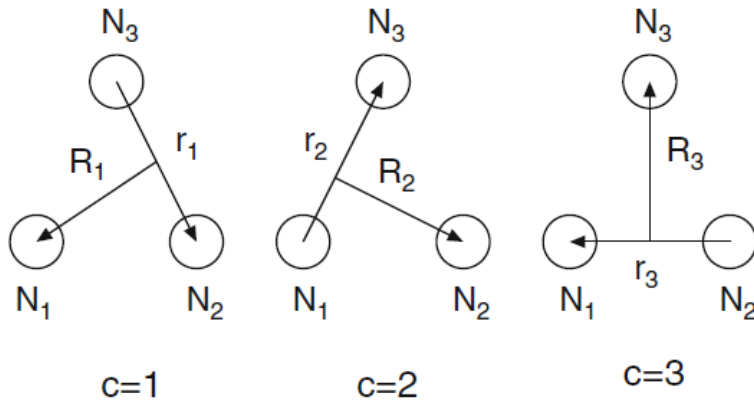
▶ 高斯基参数(变分参数)

$$\nu_n = \frac{1}{r_n^2},$$

$$r_n = r_1 a^{n-1} \quad (n = 1 - n_{max}).$$

变分和基展开使得高斯展开法同时具有精度高和收敛快的特点。

▶ 三体雅可比坐标系



▶ 总波函数

$$\Psi_{JM} = \Phi_{JM}^{(c=1)}(r_1, \mathbf{R}_1) + \Phi_{JM}^{(c=2)}(r_2, \mathbf{R}_2) + \Phi_{JM}^{(c=3)}(r_3, \mathbf{R}_3)$$

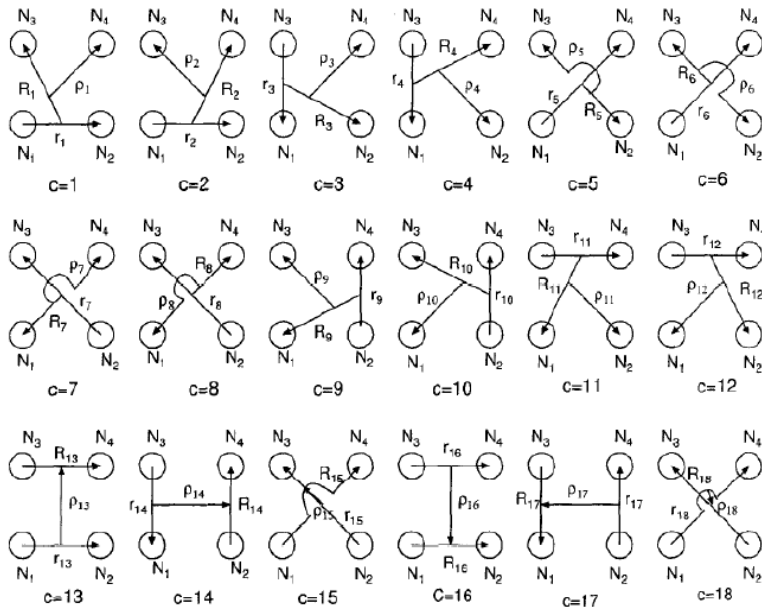
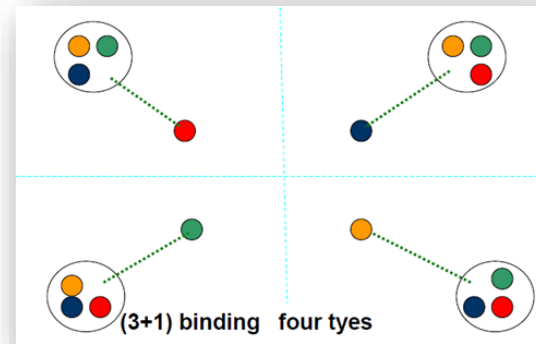
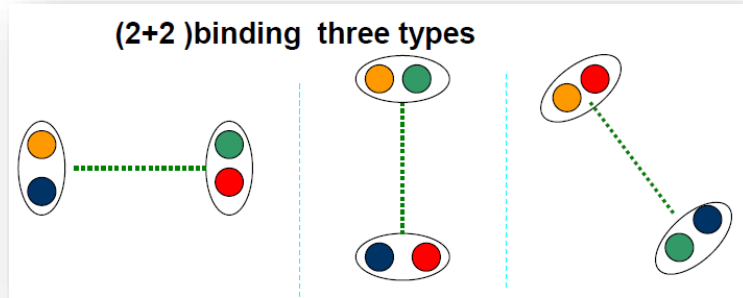
▶ 每个雅可比道的波函数

$$\Phi_{JM}^{(c)}(r_c, \mathbf{R}_c) = \sum_{n_c l_c, N_c L_c} A_{n_c l_c, N_c L_c}^{(c)} [\phi_{n_c l_c}^G(r_c) \psi_{N_c L_c}^G(\mathbf{R}_c)]_{JM}$$

$$\phi_{nlm}^G(\mathbf{r}) = \phi_{nl}^G(r) Y_{lm}(\hat{r}), \phi_{nl}^G(r) = N_{nl} r^l e^{-\nu_n r^2}$$

$$\psi_{NLM}^G(\mathbf{R}) = \psi_{NL}^G(R) Y_{LM}(\hat{R}), \phi_{NL}^G(R) = N_{NL} R^L e^{-\lambda_N R^2}$$

两个两体波函数耦合成三体波函数。



K型耦合 12个
H型耦合 6个

2-body: 1 Jacobian channel
3-body: 3 Jacobian channels
4-body: 18 Jacobian channels
5-body: 100+ Jacobian channels

Straightly but not easy!

Figure 1: Jacobian coordinates for the 18 rearrangement channels of four-body system

T. W. Wu, M. Z. Liu, L. S. Geng, E. Hiyama and M. P. Valderrama, Phys. Rev. D 100 (2019) 034029

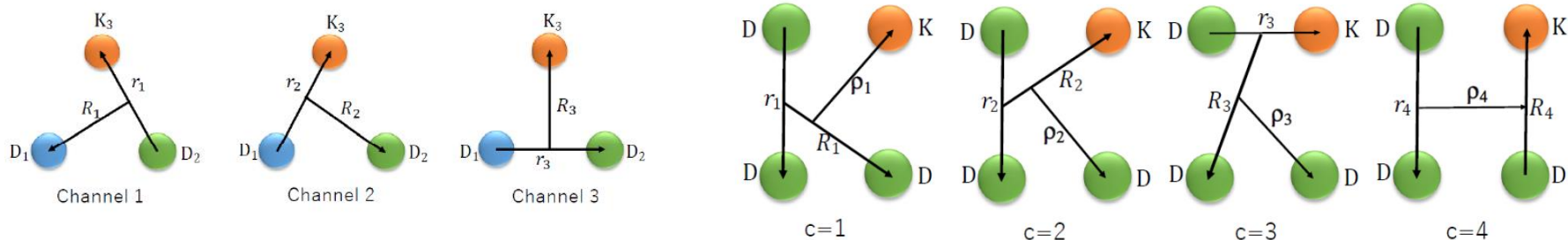
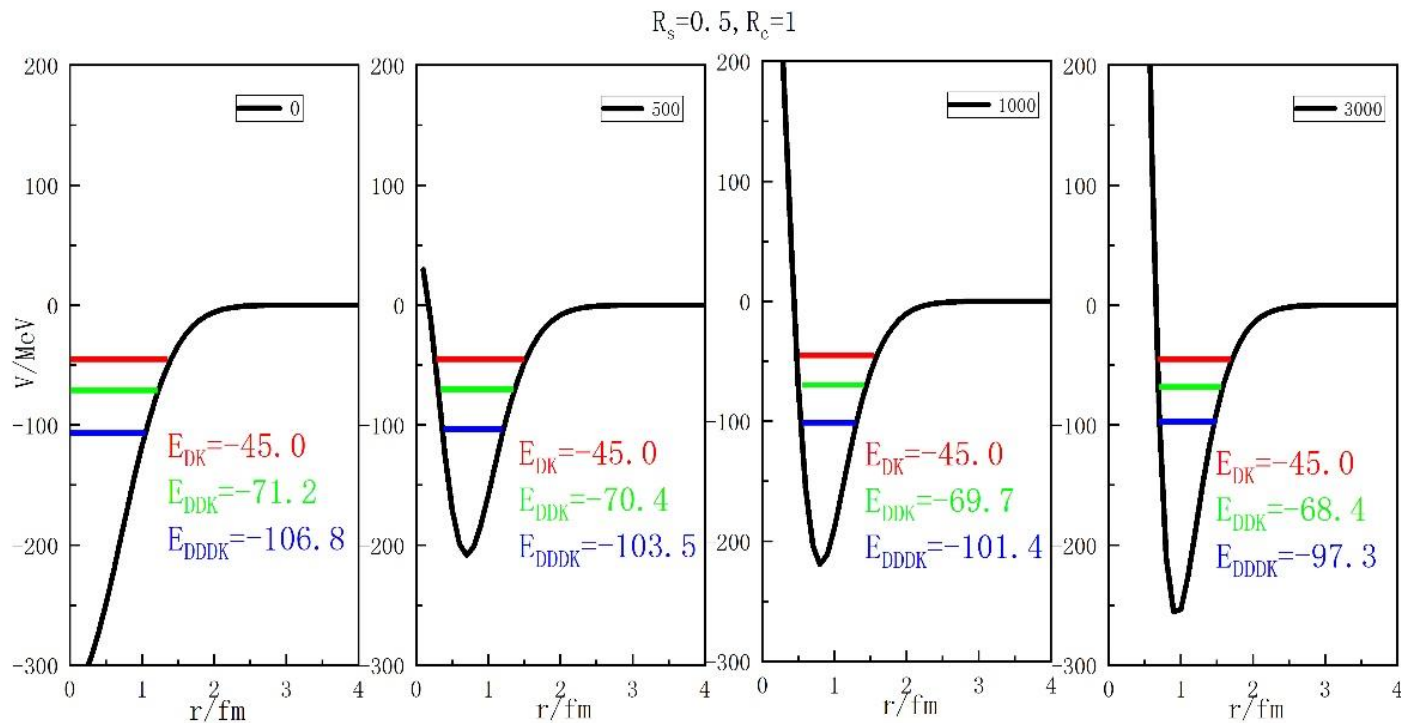


FIG. 2. Three Jacobian coordinates for DDK system



我们的研究表明，DK可以形成类核的多强子分子态集团。

DDK分子态的均方根半径与形状

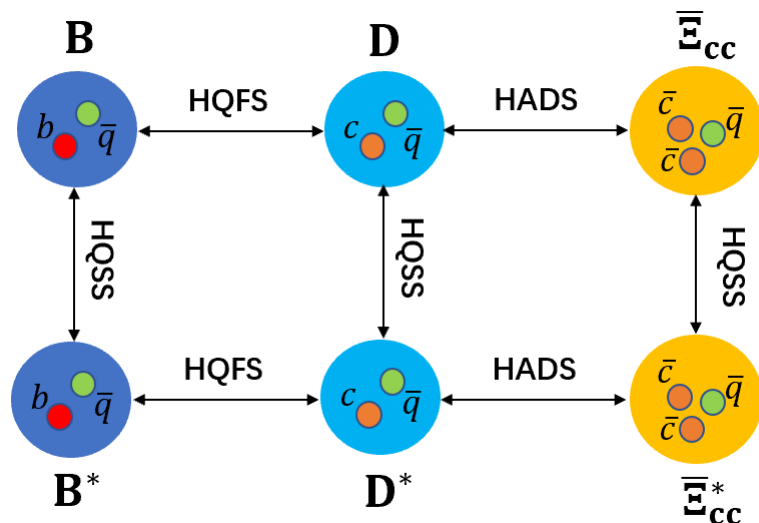


C'_S	C'_L	$r_2(DK)$	$r_3(DK)$	$r_3(DD)$	$\langle T \rangle$	$\langle V_{DK} \rangle$	$\langle V_{DD} \rangle$
		$R_S = 0.5 \text{ fm}$		$R_c = 1 \text{ fm}$			
0	-320.1	1.28	1.32	1.36	124.37	-189.61	-5.98
500	-455.4	1.39	1.44	1.47	99.51	-164.83	-5.03
1000	-562.6	1.46	1.53	1.54	91.43	-156.67	-4.51
3000	-838.7	1.61	1.69	1.68	93.24	-157.80	-3.82
		$R_S = 0.5 \text{ fm}$		$R_c = 2 \text{ fm}$			
0	-149.1	1.74	1.80	1.80	60.20	-125.74	-3.23
500	-178.4	1.91	1.98	1.96	51.00	-116.59	-2.64
1000	-195.0	1.99	2.07	2.04	50.63	-116.12	-2.43
3000	-225.9	2.13	2.22	2.15	53.61	-118.59	-2.24
		$R_S = 0.5 \text{ fm}$		$R_c = 3 \text{ fm}$			
0	-107.0	2.13	2.19	2.17	39.49	-105.35	-2.13
500	-119.4	2.31	2.38	2.34	34.80	-100.73	-1.77
1000	-125.6	2.37	2.47	2.42	34.90	-100.77	-1.65
3000	-136.2	2.53	2.61	2.53	36.66	-102.24	-1.54

$$r_3(DK) \approx r_3(DD)$$

DK均方根半径依赖于有效力程 R_c 的取值。DD的均方根半径也依赖于DK的力程。

Heavy quark symmetry partners of D meson



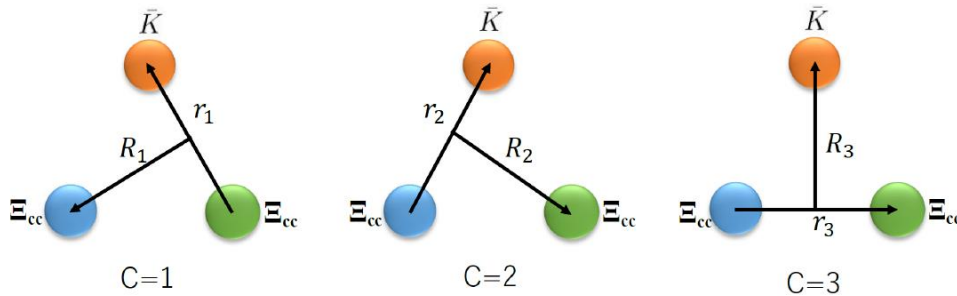
重夸克自旋对称性
(Heavy quark spin symmetry, HQSS)

重夸克味道对称性
(Heavy quark flavor symmetry, HQFS)

重反夸克-双夸克对称性
(Heavy antiquark-diquark symmetry, HADS)

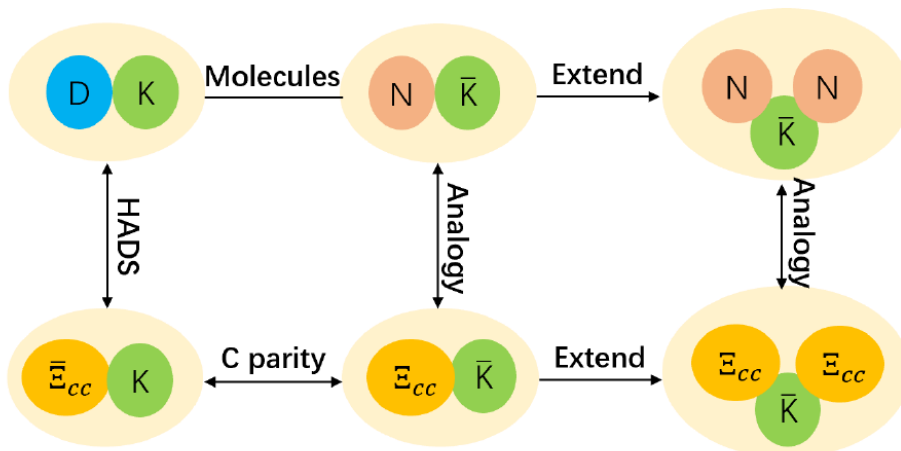
原则上只要DDK存在，其重夸克对称性伙伴态也存在。

Jacobian 坐标系



与DDK和NNK的关系

FIG. 2. $\Xi_{cc}\Xi_{cc}\bar{K}$ system reviewed from two kinds of logic.



T.W. WU, etc. Eur.Phys.J. C80 (2020) 901

$C(R_c)$	R_c	$B_2(\Xi_{cc}K)$	$B_3(\Xi_{cc}\Xi_{cc}K)$
$C_S = 0$		$R_s = 0.1$	
-862.4	0.5	63.6^{+72}_{-51}	118.4^{+109}_{-78}
-320.1	1.0	53.7^{+37}_{-31}	92.8^{+55}_{-47}
-198.7	1.5	50.6^{+27}_{-24}	$84.1^{+41}_{-36}, 54.2^{+31}_{-26}$
-149.1	2.0	49.1^{+23}_{-21}	$79.6^{+34}_{-31}, 55.5^{+28}_{-24}$
$C_S = 1000$		$R_s = 0.1$	
-884.7	0.5	63.2^{+70}_{-50}	117.5^{+106}_{-77}
-324.0	1.0	53.6^{+37}_{-31}	92.5^{+55}_{-41}
-200.2	1.5	50.6^{+27}_{-24}	$83.9^{+41}_{-36}, 54.2^{+31}_{-25}$
-149.9	2.0	49.1^{+23}_{-21}	$79.6^{+34}_{-31}, 55.5^{+28}_{-24}$

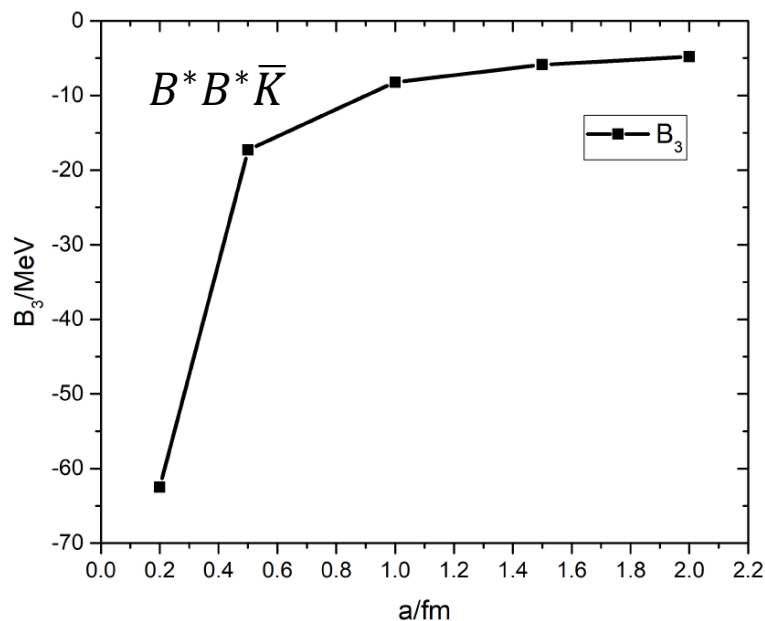
双重子+介子

$C(R_c)$	R_c	$B_2(NK)$	$B_3(NNK)$
$C_S = 0$		$R_s = 0.1$	
-925.9	0.5	29.4	35.2
-316.4	1.0	29.4	39.3
-132.6	2.0	29.4	41.8
-89.2	3.0	29.4	42.5
$C_S = 1000$		$R_s = 0.1$	
-946.6	0.5	29.4	35.4
-319.8	1.0	29.4	39.4
-133.2	2.0	29.4	41.8
-89.4	3.0	29.4	42.5

L. Thomas, Phys. Rev. **47**, 903 (1935)

系统AAB, 当 $\text{Mass}(A) \gg \text{Mass}(B)$ 时, 若 $V_{\{AB\}}$ 使得AB有固定的束缚能 B_2 , 那么三体束缚能 B_3 随着 $V_{\{AB\}}$ 的有效作用范围 a 趋于0而发散。

$B^* \bar{K}$ 束缚能1MeV时, $B^* B^* \bar{K}$ 束缚能随 a 的变化

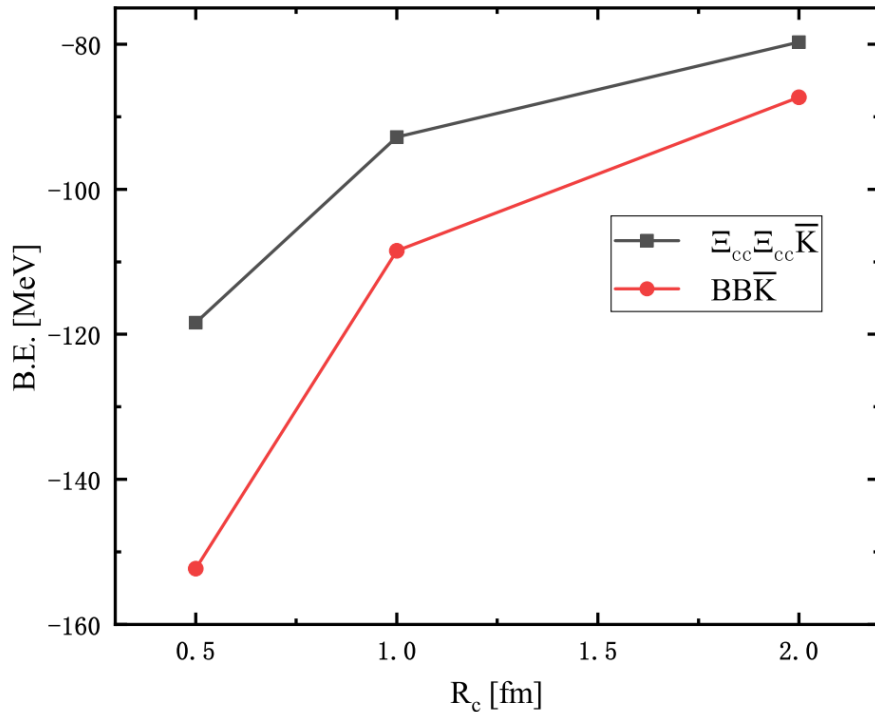


$$V_{B^* \bar{K}}(r) = C_G e^{-r^2/a^2}$$

C_G [MeV]	a [fm]	B_2	B_3
-45.0	2.0	-1	-4.79
-74.5	1.5	-1	-5.86
-155.7	1	-1	-8.22
-577.3	0.5	-1	-17.3
-3443	0.2	-1	-62.5

a 减小 B_3 增大

不考虑自旋同位旋时 $B^* B^* \bar{K}$ 的Thomas Collapse。



产生条件:

$$\lambda_\alpha = \frac{\sin 2\alpha}{2\alpha} \leq \lambda,$$

α 与质量比值相关:

$$\alpha = \arcsin \left(\frac{1}{1 + \frac{m_B}{m_A}} \right).$$

λ 与系统量子数相关:

$$\lambda = \left\langle H_{\frac{1}{2},0}^{c=1} \middle| H_{\frac{1}{2},0}^{c=2} \right\rangle = \frac{1}{2}.$$

$$\lambda_\alpha(\Xi_{cc}\Xi_{cc}\bar{K}) = 0.389$$

$$\lambda_\alpha(BB\bar{K}) = 0.321$$



$$\lambda_\alpha(DDK) = 0.531$$

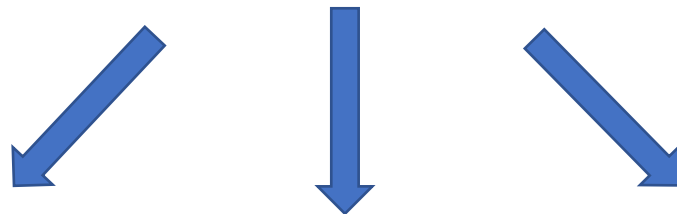
$$\lambda_\alpha(NN\bar{K}) = 0.693$$



- DDK: 双粲系统, 实验上较难观测到。

$B(R^{++} \rightarrow D + D_s^{*+})$, Phys.Rev. D102 (2020) no.11, 112001, @Belle

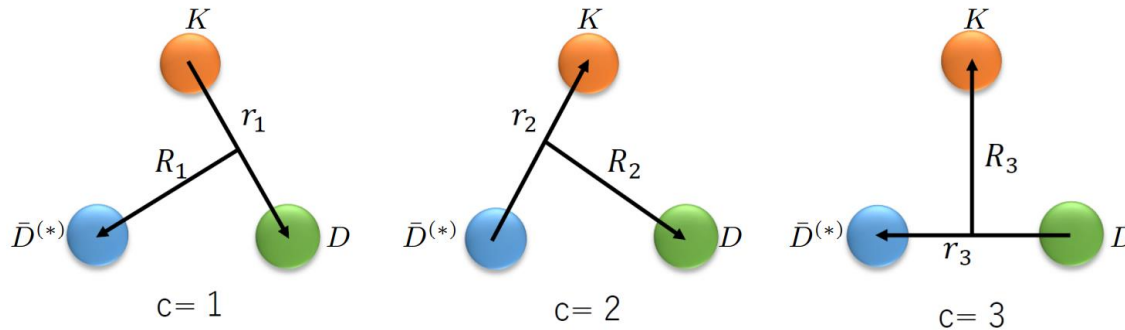
- 隐粲系统: XYZ, Zcs, Pcs, 实验容易观测到。



$\bar{D}_s^{(*)} D^{(*)} K$ $D\bar{D}K$ $\Sigma_c \bar{D}\bar{K}$

非类核多强子系统

T.W. Wu, M.Z. Liu and L.S. Geng, Phys.Rev. D103 (2021) L031501

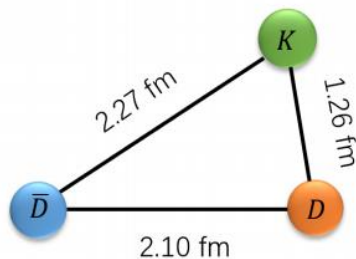


$D\bar{D}K$ 和 DD^*K 可以形成三体束缚态

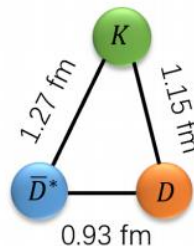
$$B_3(D\bar{D}K) \simeq 48.9_{-2.4}^{+1.4} \text{ MeV.}$$

$$B_3(DD^*K) \simeq 77.3_{-6.6}^{+3.1} \text{ MeV.}$$

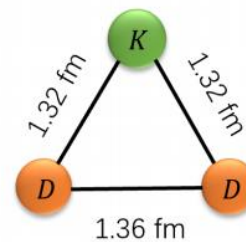
$D\bar{D}K$ 、 DD^*K 和 DDK 束缚态的均方根半径



约49MeV

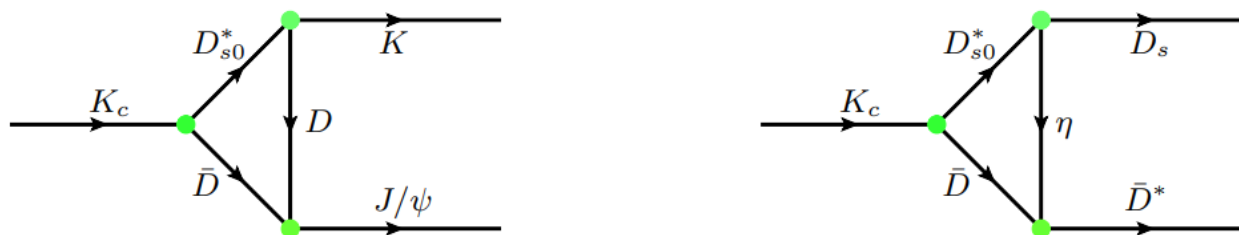


约77MeV



约70MeV

K_c 的衰变三角图



各个顶点的拉式量

$$\mathcal{L}_{K_c(x)} = g_{K_c D_{s0} \bar{D}} K_c^T(x) \int dy \Phi_{K_c}(y^2) D_{s0}(x + \omega_{\bar{D}} y) \bar{D}(x - \omega_{D_{s0}} y) + H.c.,$$

$$\mathcal{L}_{D_{s0} DK} = g_{D_{s0} DK} D_{s0} DK,$$

$$\mathcal{L}_{D_{s0} D_s \eta} = g_{D_{s0} D_s \eta} D_{s0} D_s \eta,$$

$$\mathcal{L}_{\psi \bar{D} D} = -ig_{\psi \bar{D} D} \psi_\mu (\partial^\mu D D^\dagger - D \partial^\mu D^\dagger),$$

$$\mathcal{L}_{\bar{D} \bar{D}^* \eta} = -ig_{\bar{D} \bar{D}^* \eta} (\bar{D}^\dagger \partial^\mu \eta \bar{D}^* - \bar{D} \partial_\mu \eta \bar{D}^{*\dagger}),$$

$$\Gamma[K_c \rightarrow] = \frac{1}{2J+1} \frac{1}{32\pi^2} \frac{|\vec{p}_1|}{m_{K_c}^2} |\mathcal{M}|^2 d\Omega,$$

分宽带0.5MeV

分宽带0.2MeV

- 我们预言存在**DK, DDK 和 DDDK**的强子分子态，并指出有可能存在类核的多强子分子态集团。
- 我们研究了 **$E_{cc}E_{cc}\bar{K}$** 和 **$BB\bar{K}$** 系统，并讨论了它们可以产生Thomas collapse现象。
- 我们预言了 **$D\bar{D}K$** 分子态的存在，并计算了它的衰变道和宽度，希望给实验的寻找提供方向。
- 如果这些新的奇特强子态被发现，将可以对强子分子态图像作非平庸检验。

- **如何找：产生过程、反应截面等**
期待实验和理论上的进一步研究。

