Study on Zcs and excited B_s^0 states in the chiral quark model

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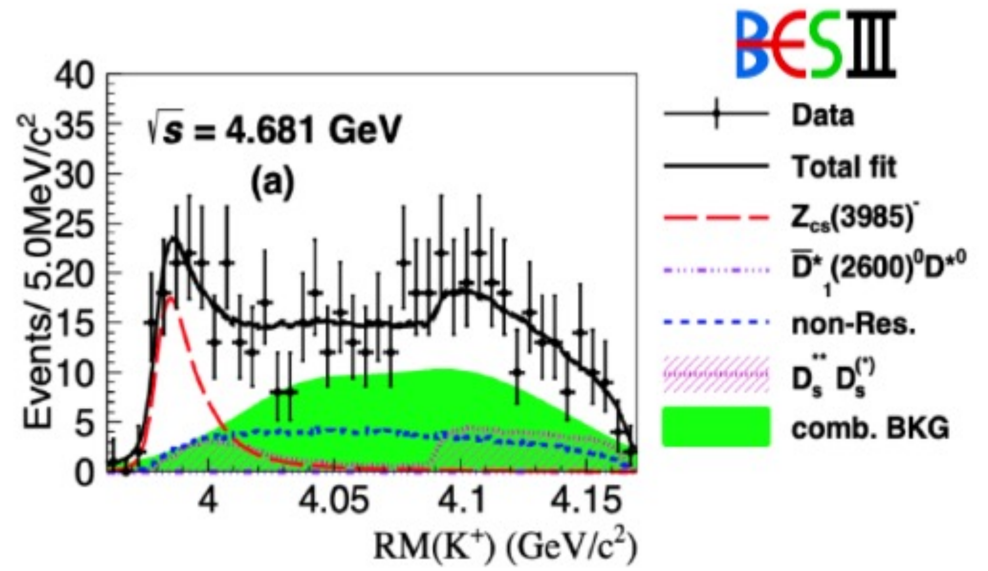
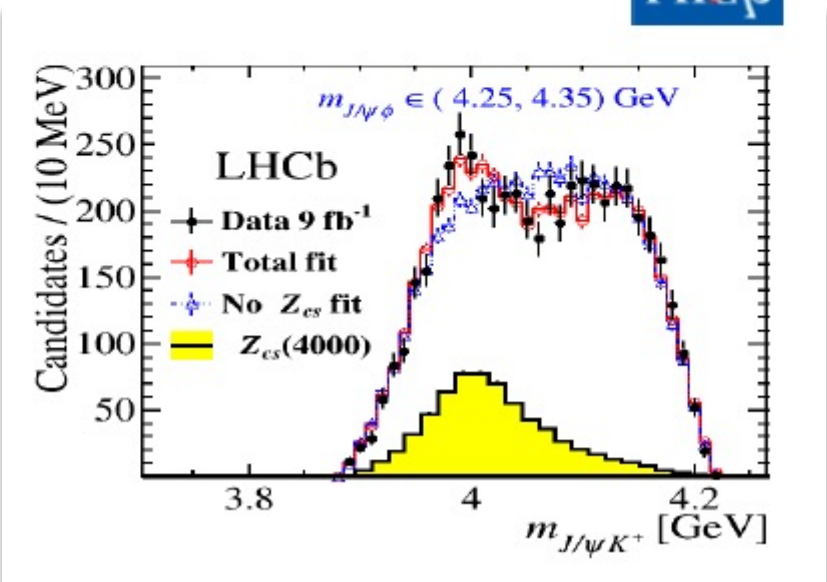
Outline

- Motivations
- Chiral quark model (ChQM) and wave functions of four-quark system
- Results of Zcs and excited Bs^0 states
- Summary

Motivations

- BESIII experiment recently reported 5.3σ observation of a very narrow Zcs(3985) in $D_s^- D^* + D D_s^{*-}$ mass distributions .
- LHCb experiment later reported wider Zcs(4000) as well as Zcs(4220).





Phys. Rev. Lett. 126 (2021) 102001

$$m(Z_{cs}(3985) = (3982.5^{+1.8}_{-2.6} \pm 2.1)\text{MeV}$$
$$\Gamma\,(Z_{cs}(3985) = \left(12.8^{+5.3}_{-4.4} \pm 3.0\right)\text{MeV}$$

arXiv:2103.01803

$$m(Z_{cs}(4000) = (4003 \pm 6^{+4}_{-14})\text{MeV}$$
$$\Gamma\,(Z_{cs}(4000) = (131 \pm 15 \pm 26)\text{MeV}$$

Motivations

Observation of new excited B_s^0 states

arXiv:2010.15931

LHCb collaboration†

Abstract

A structure is observed in the B^+K^- mass spectrum in a sample of proton–proton collisions at centre-of-mass energies of 7, 8, and 13 TeV, collected with the LHCb detector and corresponding to a total integrated luminosity of $9\,\text{fb}^{-1}$. The structure is interpreted as the result of overlapping excited B_s^0 states. With high significance, a two-peak hypothesis provides a better description of the data than a single resonance. Under this hypothesis the masses and widths of the two states, assuming they decay directly to B^+K^-, are determined to be

$$m_1 = 6063.5 \pm 1.2\ (\text{stat}) \pm 0.8\ (\text{syst})\,\text{MeV},$$
$$\Gamma_1 = 26 \pm 4\ (\text{stat}) \pm 4\ (\text{syst})\,\text{MeV},$$
$$m_2 = 6114 \pm 3\ (\text{stat}) \pm 5\ (\text{syst})\,\text{MeV},$$
$$\Gamma_2 = 66 \pm 18\ (\text{stat}) \pm 21\ (\text{syst})\,\text{MeV}.$$

Alternative values assuming a decay through $B^{*+}K^-$, with a missing photon from the $B^{*+} \to B^+\gamma$ decay, are also determined. The ratio of the total production cross-section times branching fraction of the new states relative to the previously observed B_{s2}^{*0} state is determined to be $0.87 \pm 0.15\ (\text{stat}) \pm 0.19\ (\text{syst})$.

Theoretical studies

- *molecular resonance is suggested*
- L. Meng, B. Wang and S. L. Zhu, Phys. Rev. D **102**,
- B.Wang, L. Meng and S. L. Zhu, Phys. Rev. D **103**, no.2, L021501 (2021).
- arXiv:2011.13013.
- arXiv:2011.09156.
- *Bound states*
- J. Ferretti and E. Santopinto, JHEP **04**, 119 (2020).
- *Other explanations*
- J. Z. Wang, Q. S. Zhou, X. Liu and T. Matsuki, Eur. Phys. J. C **81**, no.1, 51 (2021)(a reflection structure).
- Pablo G. Ortega et al. e-Print: 2103.07871(virtual state).
- Zhi Yang et al. Phys.Rev.D 103 (2021) 7, 074029(virtual state).

Chiral quark model（ChQM）

- **In ChQM: General form of Hamiltonian:**

J Vijande, F Fern´andez and A Valcarce, J. Phys. G 31 (2005) 481–506

$$H = \sum_{i=1}^{n}\left(m_i + \frac{p_i^2}{2m_i}\right) - T_{cm} + \sum_{i=1<j}^{n}\left(V_{ij}^{CON} + V_{ij}^{OGE} + \sum_{\chi=\pi,K,\eta,\sigma} V_{ij}^{\chi}\right)$$

The central part of potential:

$$V_{ij}^{CON} = (-a_c r_{ij}^2 - \Delta)\boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c$$

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

$$V_{ij}^{\pi} = \frac{g_{ch}^2}{4\pi}\frac{m_\pi^2}{12 m_i m_j}\frac{\Lambda_\pi^2\, m_\pi}{\Lambda_\pi^2 - m_\pi^2}\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \left[Y(m_\pi r_{ij}) - \frac{\Lambda_\pi^3}{m_\pi^3}Y(\Lambda_\pi r_{ij})\right]\sum_{a=1}^{3}\lambda_i^a \cdot \lambda_j^a,$$

$$V_{ij}^{K} = \frac{g_{ch}^2}{4\pi}\frac{m_K^2}{12 m_i m_j}\frac{\Lambda_K^2\, m_K}{\Lambda_K^2 - m_K^2}\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \left[Y(m_K r_{ij}) - \frac{\Lambda_K^3}{m_K^3}Y(\Lambda_K r_{ij})\right]\sum_{a=4}^{7}\lambda_i^a \cdot \lambda_j^a$$

$$V_{ij}^{\eta} = \frac{g_{ch}^2}{4\pi}\frac{m_\eta^2}{12 m_i m_j}\frac{\Lambda_\eta^2}{\Lambda_\eta^2 - m_\eta^2}m_\eta \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \left[Y(m_\eta r_{ij}) - \frac{\Lambda_\eta^3}{m_\eta^3}Y(\Lambda_\eta r_{ij})\right] \times \left[cos\theta_P(\lambda_i^8 \cdot \lambda_j^8) - sin\theta_P(\lambda_i^0 \cdot \lambda_j^0)\right],$$

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

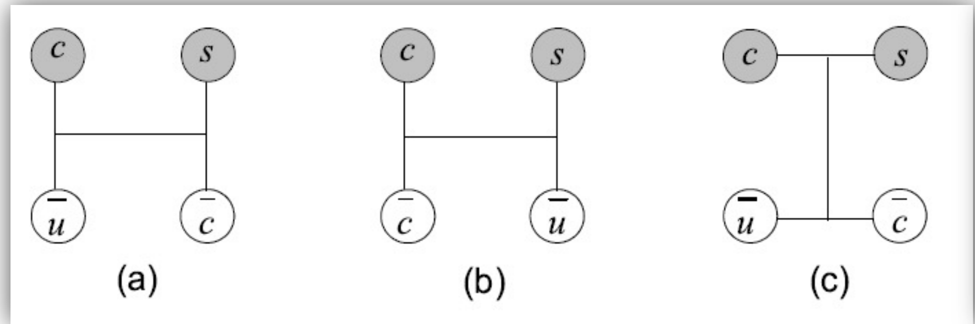
TABLE V. The mass spectra of some relevant mesons in present work in the chiral quark model, compared with the experimental data [39] (unit: MeV). q represents the u or d quark.

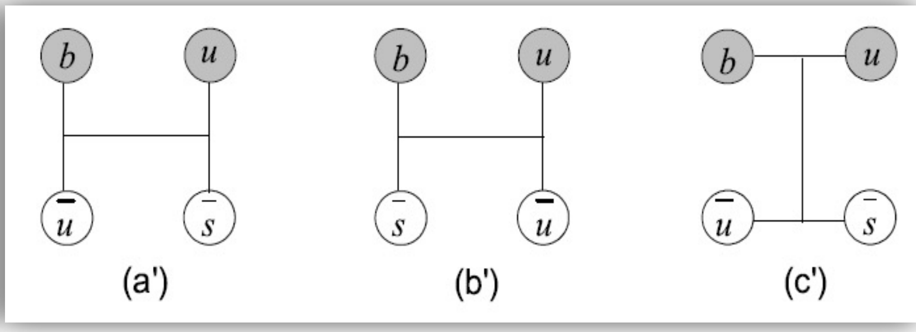
$n^{2S+1}L_J$	$E(D^{(*)})$	Expt	$E(D_s^{(*)})$	Expt	$E(B^{(*)})$	Expt	$E(K^{(*)})$	Expt	$E(c\bar{c})$	Expt	$E(q\bar{q})$	Expt
1^1S_0	1862.5	$D(1869)$	1952.5	$D_s^{\pm}(1968)$	5280.8	$B(5279)$	493.9	$K(493)$	3097.3	$\eta_c(1S)(2983)$	669.2	$\eta(547)$
2^1S_0	2721.2		2665.3		6090.2		1573.8		3592.1	$\eta_c(2S)(3639)$	1762.2	
1^3S_1	1980.5	$D^*(2006)$	2079.9	$D_s^*(2112)$	5319.5	$B^*(5325)$	913.5	$K^*(892)$	3161.2	$J/\psi(3096)$	701.6	$\omega(782)$
2^3S_1	2829.6		2777.4	$D_{s1}^*(2700)$	6127.7		1887.7		3650.4	$\psi(2S)(3686)$	1799.2	
1^3D_1	3017.6		2872.7		6358.1		1984.9		3706.9	$\psi(3770)$	1954.2	
2^3D_1	3823.5		3523.1		7122.4		2917.3		4156.6		2998.3	
1^3P_0	2351.5	$D_0^*(2400)$	2380.0	$D_{s0}^*(2317)$	5749.7		1149.0	$K_0^*(1430)$	3420.4	$\chi_{c0}(1P)(3414)$		
2^3P_0	3162.3		3028.2		6515.0		2109.6		3869.7	$\chi_{c0}(2P)(3915)$		
1^1P_1	2447.9		2478.1	$D_{s1}(2460)$	5783.4	$B_1(5721)$	1400.0	$K_1(1400)$	3455.1	$h_c(1P)(3525)$		
2^1P_1	3258.1		3134.9		6554.6		2327.4		3910.7			
1^3P_1	2417.9	$D_1(2420)$	2440.9		5777.1		1315.6	$K_1(1270)$	3439.7	$\chi_{c1}(1P)(3510)$		
2^3P_1	3228.4		3094.9		6545.3		2258.8		3892.9	$\chi_{c1}(2P)(3872)$		
1^3P_2	2474.8	$D_2^*(2460)$	2511.7	$D_{s2}^*(2573)$	5782.9	$B_2^*(5747)$	1499.5	$K_2^*(1430)$	3469.6	$\chi_{c2}(1P)(3556)$		
2^3P_2	3294.4		3175.9		6559.9		2447.4		3928.0	$\chi_{c2}(2P)(3927)$		

The chiral quark model is very successful in describing the meson spectra.

Wave functions of four-quark system

$c\bar{c}s\bar{u}$ system ***$b\bar{s}q\bar{q}$ system***





The wave function of the four-quark system

- For meson-meson structure

$$\Psi^{M_I M_J}_{IJ,i,j,k} = \mathcal{A}_2 [\Psi^{M_L}_L \chi^{\sigma i}_{SM_S}]^{M_J}_J \chi^{fj}_{m0} \chi^{ck}_m, \qquad \mathcal{A}_2 = \frac{1}{2}(1 - P_{13} - P_{24} + P_{13}P_{24}).$$

- for diquark-antidiquark structure:

$$\Psi^{M_I M_J}_{IJ,i,j,k} = \mathcal{A}_1 [\Psi^{M_L}_L \chi^{\sigma i}_{SM_S}]^{M_J}_J \chi^{fj}_{d0} \chi^{ck}_d, \qquad \mathcal{A}_1 = \frac{1}{2}(1 - P_{12} - P_{34} + P_{12}P_{34}).$$

Orbital wave functions:

$$\Psi_L^{M_L} = [[\Psi_{l_1}(\mathbf{r}_{12})\Psi_{l_2}(\mathbf{r}_{34})]_{l_{12}}\Psi_{L_r}(\mathbf{r}_{1234})]_L^{M_L} ,$$

$$\Psi_l^m(\mathbf{r}) = \sum_{n=1}^{n_{\max}} c_n \psi_{nlm}^G(\mathbf{r}),$$

$$\psi_{nlm}^G(\mathbf{r}) = N_{nl} r^l e^{-\nu_n r^2} Y_{lm}(\hat{\mathbf{r}}), \quad N_{nl} = \left[\frac{2^{l+2}(2\nu_n)^{l+\frac{3}{2}}}{\sqrt{\pi}(2l+1)}\right]^{\frac{1}{2}} .$$

$$\nu_n = \frac{1}{r_n^2}, \quad r_n = r_1 a^{n-1}, \quad a = \left(\frac{r_{n_{\max}}}{r_1}\right)^{\frac{1}{n_{\max}-1}} .$$

$(l_1 = l_2 = L_r = 0)$

E. Hiyama, Y. Kino, M. Kamimura, Prog. Part. Nucl. Phys. 51, 223 (2003)

Spin, flavor, color wave functions:

TABLE II. The wave functions of spin, flavor, color part for Z_{cs} and $b\bar{s}q\bar{q}$ system by considering all kinds of quark structures.

Spin	Flavor	Color
$\chi^{\sigma 1}_{00} = \chi_{00}\chi_{00}$	$\chi^{f1} = c\bar{u}s\bar{c}$	$\chi^{c1} = \frac{1}{3}(\bar{r}r + \bar{g}g + \bar{b}b)(\bar{r}r + \bar{g}g + \bar{b}b)$ $\chi^{c2} = \frac{\sqrt{2}}{12}(3\bar{b}r\bar{r}b + 3\bar{g}r\bar{r}g + 3\bar{b}g\bar{g}b + 3\bar{g}b\bar{b}g + 3\bar{r}g\bar{g}r + 3\bar{r}b\bar{b}r + 2\bar{r}r\bar{r}r + 2\bar{g}g\bar{g}g + 2\bar{b}b\bar{b}b - \bar{r}r\bar{g}g - \bar{g}g\bar{r}r - \bar{b}b\bar{g}g - \bar{b}b\bar{r}r - \bar{g}g\bar{b}b - \bar{r}r\bar{b}b)$
$\chi^{\sigma 2}_{00} = \sqrt{\frac{1}{3}}(\chi_{11}\chi_{1-1} - \chi_{10}\chi_{10} + \chi_{1-1}\chi_{11})$	$\chi^{f2} = c\bar{c}s\bar{u}$	
$\chi^{\sigma 3}_{11} = \chi_{00}\chi_{11}$	$\chi^{f3} = cs\bar{u}\bar{c}$	$\chi^{c3} = \frac{\sqrt{3}}{6}(rg\bar{r}\bar{g} - rg\bar{g}\bar{r} + gr\bar{g}\bar{r} - gr\bar{r}\bar{g} + rb\bar{r}\bar{b} - rb\bar{b}\bar{r} + br\bar{b}\bar{r} - br\bar{r}\bar{b} + gb\bar{g}\bar{b} - gb\bar{b}\bar{g} + bg\bar{b}\bar{g} - bg\bar{g}\bar{b})$
$\chi^{\sigma 4}_{11} = \chi_{11}\chi_{00}$	$\chi^{f4} = \frac{1}{2}(b\bar{d}d\bar{s} + b\bar{u}u\bar{s})$	$\chi^{c4} = \frac{\sqrt{6}}{12}(2rr\bar{r}\bar{r} + 2gg\bar{g}\bar{g} + 2bb\bar{b}\bar{b} + rg\bar{r}\bar{g} + rg\bar{g}\bar{r} + gr\bar{g}\bar{r} + gr\bar{r}\bar{g} + rb\bar{r}\bar{b} + rb\bar{b}\bar{r} + br\bar{b}\bar{r} + br\bar{r}\bar{b} + gb\bar{g}\bar{b} + gb\bar{b}\bar{g} + bg\bar{b}\bar{g} + bg\bar{g}\bar{b})$
$\chi^{\sigma 5}_{11} = \frac{1}{\sqrt{2}}(\chi_{11}\chi_{10} - \chi_{10}\chi_{11})$	$\chi^{f5} = -\frac{1}{2}(b\bar{s}u\bar{u} + b\bar{s}d\bar{d})$	
$\chi^{\sigma 6}_{22} = \chi_{11}\chi_{11}$	$\chi^{f6} = -\frac{1}{2}(bu\bar{u}\bar{s} + bd\bar{d}\bar{s})$	

All possible channels for $c\bar{c}s\bar{u}$ and $b\bar{s}q\bar{q}$ system

TABLE III. Allowed channels for Z_{cs} and $b\bar{s}q\bar{q}$ system, for saving context space, we give abbreviations for channels, *e.g.*, for meson-meson structure (picture (a)) of Z_{cs}, $'311'$ and $'312'$ represents $\chi_{11}^{\sigma 3}\chi^{f1}\chi^{c1}$ and $\chi_{11}^{\sigma 3}\chi^{f1}\chi^{c2}$, severally. And $'411'$ and $'412'$ represents $\chi_{11}^{\sigma 4}\chi^{f1}\chi^{c1}$ and $\chi_{11}^{\sigma 4}\chi^{f1}\chi^{c2}$, respectively. The rest channels can be read in the same manner. The last row gives the total numbers of channels by considering meson-meson structures, diquark-antidiquark structure, along with all kinds of color spin configurations for Z_{cs} and $b\bar{s}q\bar{q}$ system with quantum numbers $0(0^+)$, $0(1^+)$, $0(2^+)$.

system		Z_{cs}					$b\bar{s}q\bar{q}$					
$I(J^P)$		$\frac{1}{2}(1^+)$			$0(0^+)$			$0(1^+)$			$0(2^+)$	
Structure	(a)	(b)	(c)	(a')	(b')	(c')	(a')	(b')	(c')	(a')	(b')	(c')
	3 1 1	3 2 1	3 3 3				3 4 1	3 5 1	3 6 3			
	3 1 2	3 2 2	3 3 4	1 4 1	1 5 1	1 6 3	3 4 2	3 5 2	3 6 4			
channel	4 1 1	4 2 1	4 3 3	1 4 2	1 5 2	1 6 4	4 4 1	4 5 1	4 6 3	6 4 1	6 5 1	6 6 3
(spin · flavor · color)	4 1 2	4 2 2	4 3 4	2 4 1	2 5 1	2 6 3	4 4 2	4 5 2	4 6 4	6 4 2	6 5 2	6 6 4
	5 1 1	5 2 1	5 3 3	2 4 2	2 5 2	2 6 4	5 4 1	5 5 1	5 6 3			
	5 1 2	5 2 2	5 3 4				5 4 2	5 5 2	5 6 4			
number of channels	6	6	6	4	4	4	6	6	6	2	2	2
		total 18			total 12			total 18			total 6	

- Finally, the eigenvalues and eigenvectors of four-quark system are obtained by solving the Schrödinger equation:

$$H\,\Psi_{IJ}^{M_I M_J} = E^{IJ}\Psi_{IJ}^{M_I M_J}.$$

Results

Bound state calculation

		$E(a)$	$E(b)$	$E(c)$	$E(a)\otimes E(c)$	$E(b)\otimes E(c)$	$E(a)\otimes E(b)$	E_{cc}	the lowest thresholds
Z_{cs}	$\frac{1}{2}(1^+)$	3934.5	3656.3	4247.1	3934.5	3655.4	3934.5	3656.2	$3655.1(J/\psi K^-)$
		$E(a')$	$E(b')$	$E(c')$	$E(a')\otimes E(c')$	$E(b')\otimes E(c')$	$E(a')\otimes E(b')$	E_{cc}	the lowest thresholds
$b\bar{s}q\bar{q}$	$0(0^+)$	5776.6	6040.2	6283.2	5776.5	6040.2	5776.6	5775.3	$5774.8(B^-K^+)$
	$0(1^+)$	5815.4	6072.6	6316.9	5815.3	6072.6	5815.4	5814.1	$5813.5(B^{*-}K^+)$
	$0(2^+)$	6234.8	6114.9	6483.7	6234.7	6114.9	6234.8	6114.3	$6111.7(\bar{B}_s{}^*\omega)$

- the low-lying energies in diquark-antidiquark are all much larger than those in meson-meson structures.
- All of them are higher than the lowest theoretical thresholds.
- the effects of the structures mixing seem to be tiny for the *ground state energy*.
- The coupling energies *Ecc* are a little higher than the relevant thresholds.

we **cannot** find the bound states of $c\bar{c}s\bar{u}$ and $b\bar{s}q\bar{q}$.

Results

Resonance state calculation

- A stabilization method (real scaling method) is applied.

Resonance state lifetimes from stabilization graphs

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The stabilization method (SM) pioneered by Taylor and co-workers[1] has proven to be a valuable tool for estimating the energies of long-lived metastable states of electron–atom, electron–molecule, and atom–diatom complexes. In implementing the SM one searches for eigenvalues arising from a matrix representation of the relevant Hamiltonian H which are "stable" as the basis set used to construct H is varied.

To obtain lifetimes of metastable states, one can choose from among a variety of techniques[2–7] (e.g., phase shift analysis, Feshbach projection "golden rule" formulas, Siegert methods, and complex coordinate scaling methods), many of which use the stabilized *eigenvector* as starting information. Here we demonstrate that one can obtain an *estimate* of the desired lifetime directly from the stabilization graph in a manner which makes a close connection with the complex coordinate rotation method (CRM) for which a satisfactory mathematical basis exists.

The starting point of our development is the observation that both the stable eigenvalue (E_r) and the eigenvalue(s) (E_c) which come from above and cross E_r (see Fig. 1 and Refs. 9–11 and 13) vary in a nearly linear manner (with α) near their avoided crossing points. This observation leads us to propose that the two eigenvalues arising in each such avoided crossing can be thought of as arising from two "uncoupled" states having energies $\epsilon_r(\alpha)=\epsilon+S_r(\alpha-\alpha_c)$ and $\epsilon_c(\alpha)=\epsilon+S_c(\alpha-\alpha_c)$, where S_r and S_c are the *slopes* of the linear parts of the stable and "continuum" eigenvalues, respectively. α_c is the value of α at which these two straight lines would intersect, and ϵ is their common value at $\alpha=\alpha_c$. This modeling of ϵ_r and ϵ_c is simply based upon the *observa-*

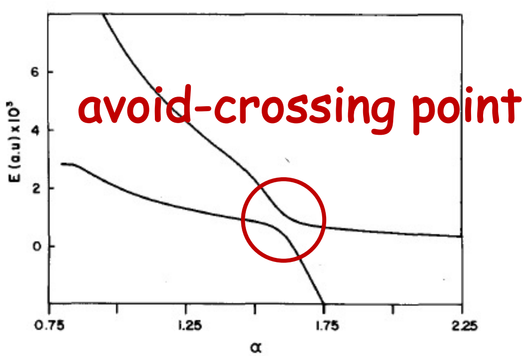


FIG. 1. Stabilization graph for the $^2\pi$ shape resonance state of LiH⁻ (Ref. 9).

J. Chem. Phys. 75(5), 1 Sept. 1981 0021-9606/81/172465-03$01.00

we multiply the Gaussian size parameters r_n by a factor α, only for the meson-meson structure with color singlet-singlet configuration.

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

$$\nu_n = \frac{1}{r_n^2}, \quad r_n = r_1 a^{n-1}$$

$r_n \to \alpha r_n$ ($\alpha = 1.0$~3.0)

J.Simon, J. Chem. Phys. 75, 2465 (1981)

$look\ for\ resonance\ for\ c\bar{c}s\bar{u}\ system$

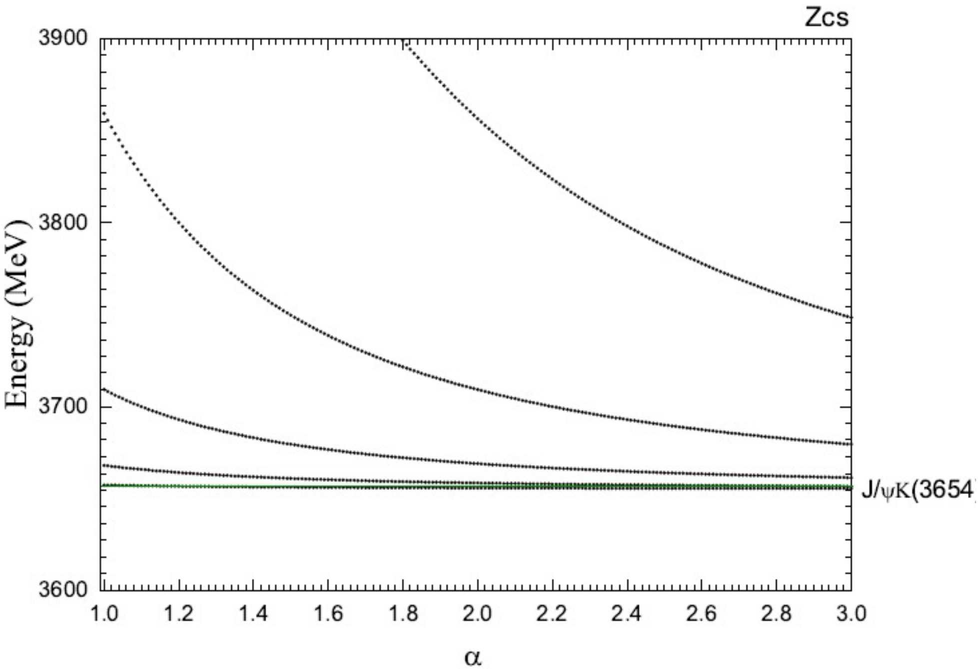


FIG. 3. The stabilization plots of the energies (3600 MeV ∼ 3900 MeV) of $c\bar{c}s\bar{u}$ states for $I(J^P) = \frac{1}{2}(1^+)$ with respect to the scaling factor α.

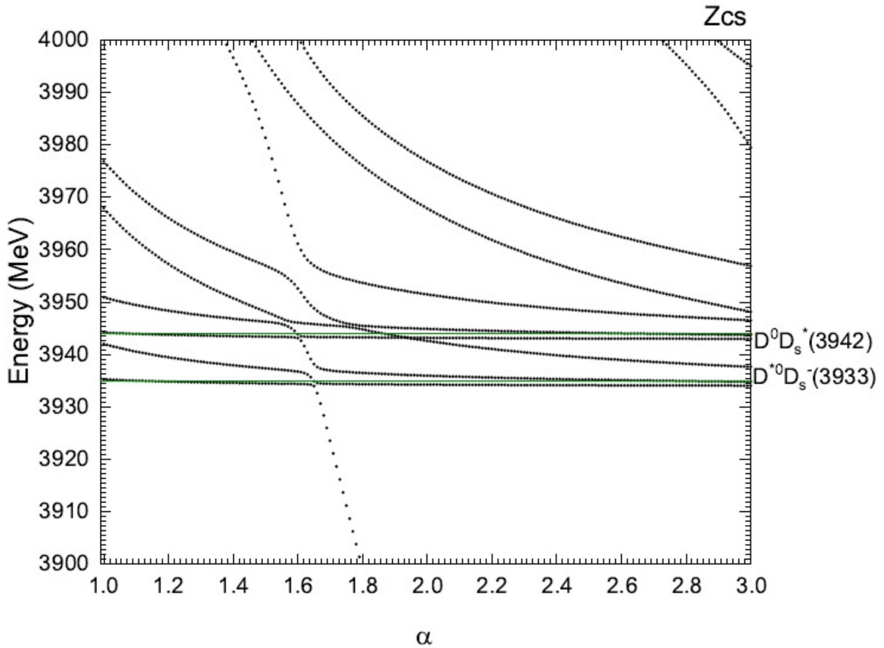


FIG. 4. The stabilization plots of the energies (3900 MeV ∼ 4000 MeV) of $c\bar{c}s\bar{u}$ states for $I(J^P) = \frac{1}{2}(1^+)$ with respect to the scaling factor α.

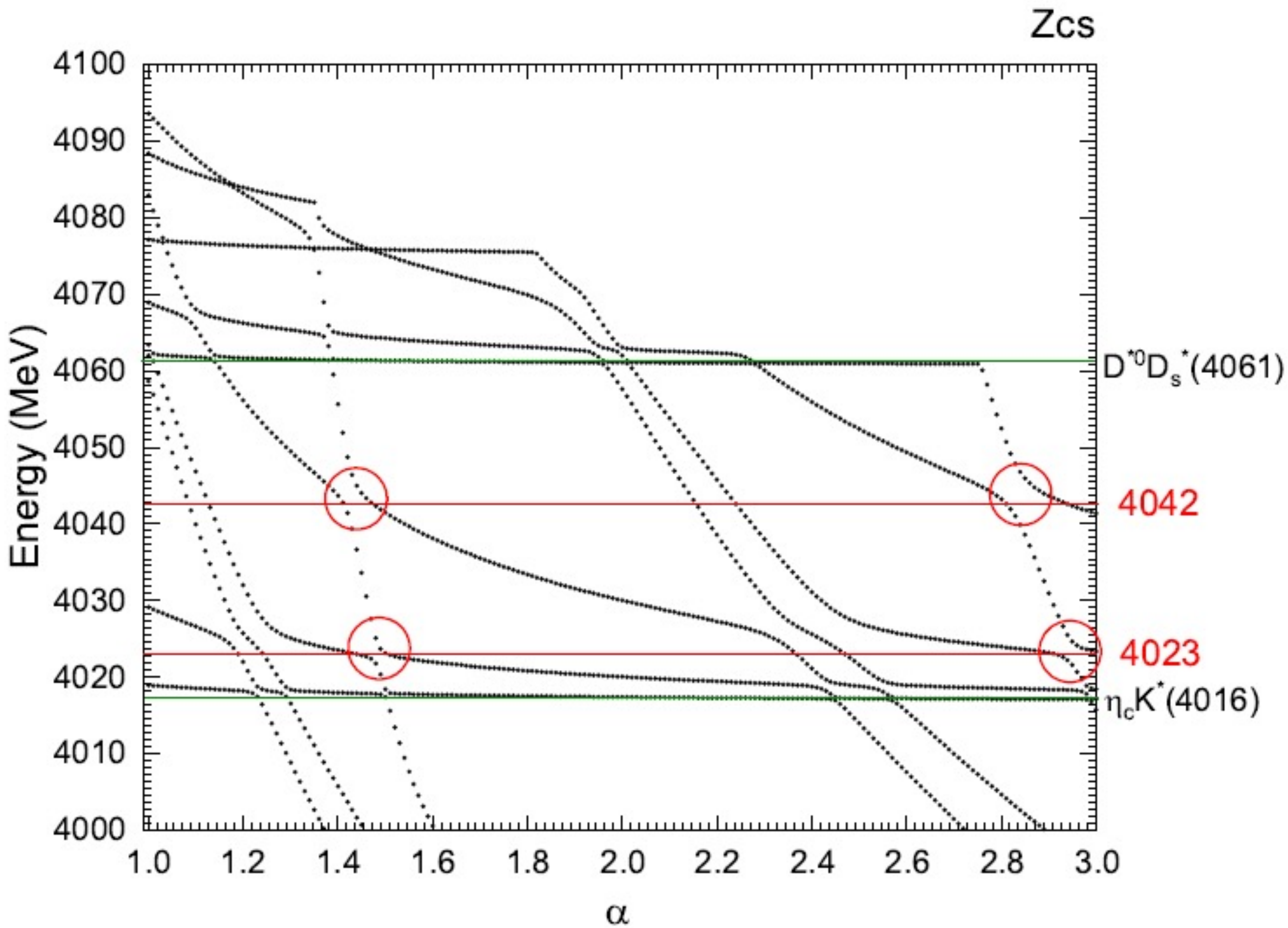


FIG. 5. The stabilization plots of the energies (4000 MeV ∼ 4100 MeV) of $c\bar{c}s\bar{u}$ states for $I(J^P) = \frac{1}{2}(1^+)$ with respect to the scaling factor α.

Two resonance states at 4023 MeV and 4042 MeV

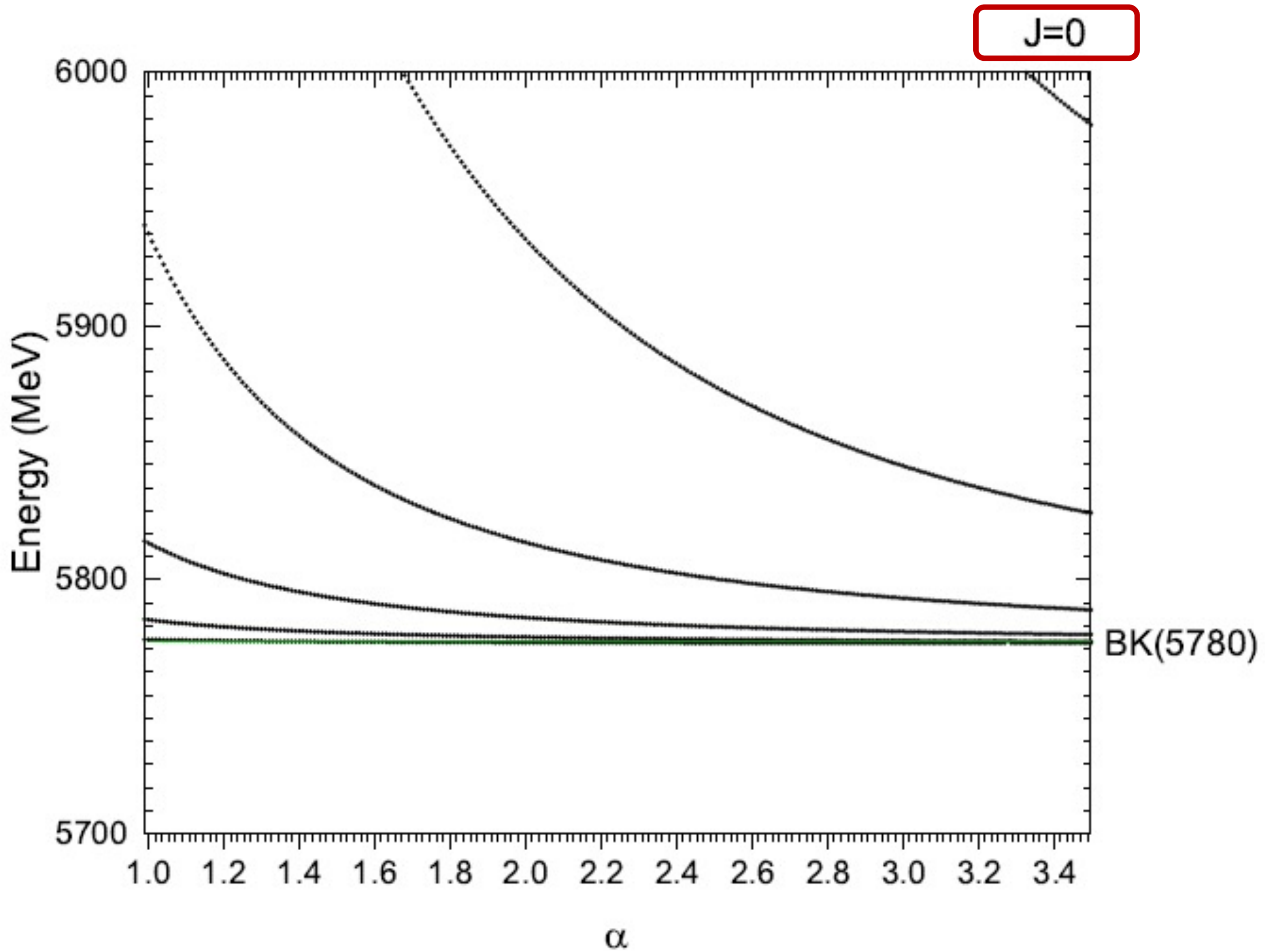
TABLE IV. The mass spectra of $b\bar{s}$ meson families in the chiral quark model in comparison with reference [20] and experimental data [39] (unit: MeV).

$n^{2S+1}L_J$	This work	Ref. [20]	Expt [39]
1^1S_0	5367.4	5390	5366.84±0.15
1^3S_1	5410.2	5447	5415.8±1.5
2^1S_0	6017.3	5985	
2^3S_1	6057.2	6013	
1^3P_0	5749.2	5830	
1^3P_1	5779.3	5859	5828.65±0.24
1^3P_2	5812.0	5875	5839.92±0.14
1^1P_1	5797.6	5858	
2^3P_0	6345.9	6279	
2^3P_1	6381.9	6291	
2^3P_2	6422.9	6295	
2^1P_1	6403.9	6284	
1^3D_1	6179.3	6181	
1^3D_2	6145.3	6185	
1^3D_3	6094.2	6178	
1^1D_2	6128.2	6180	
2^3D_1	6778.1	6542	
2^3D_2	6743.9	6542	
2^3D_3	6692.9	6534	
2^1D_2	6726.8	6536	

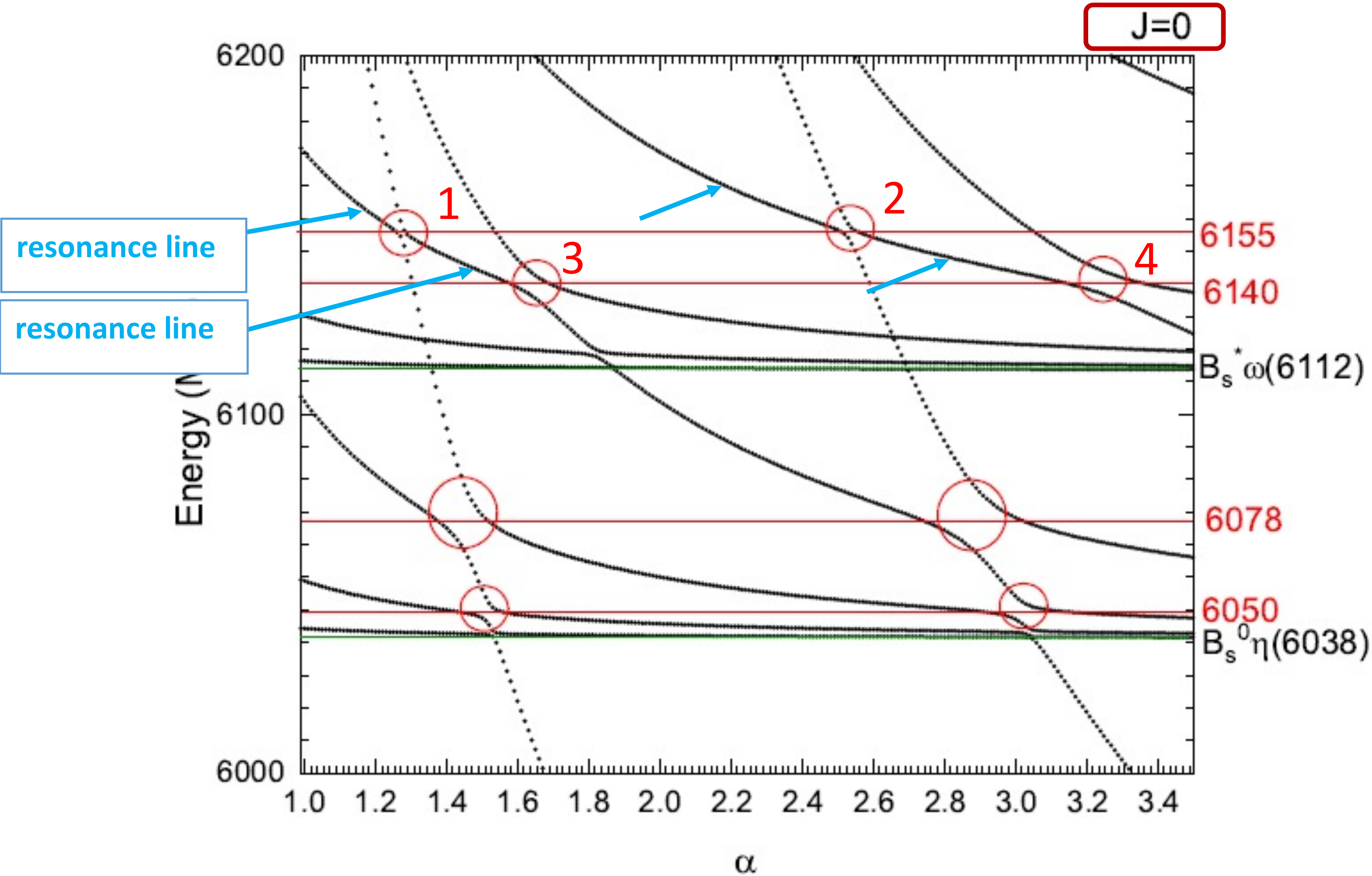
- For quark-antidiquark 2-body system, the *2S* and *1D* states have masses close to the newly observed B_s^0.

Ref.[20]:Phys. Rev. D 89, no.5, 054026 (2014)
Ref.[39]: P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 083C01 (2020).

$look\ for\ resonance\ for\ b\bar{s}q\bar{q}\ system$

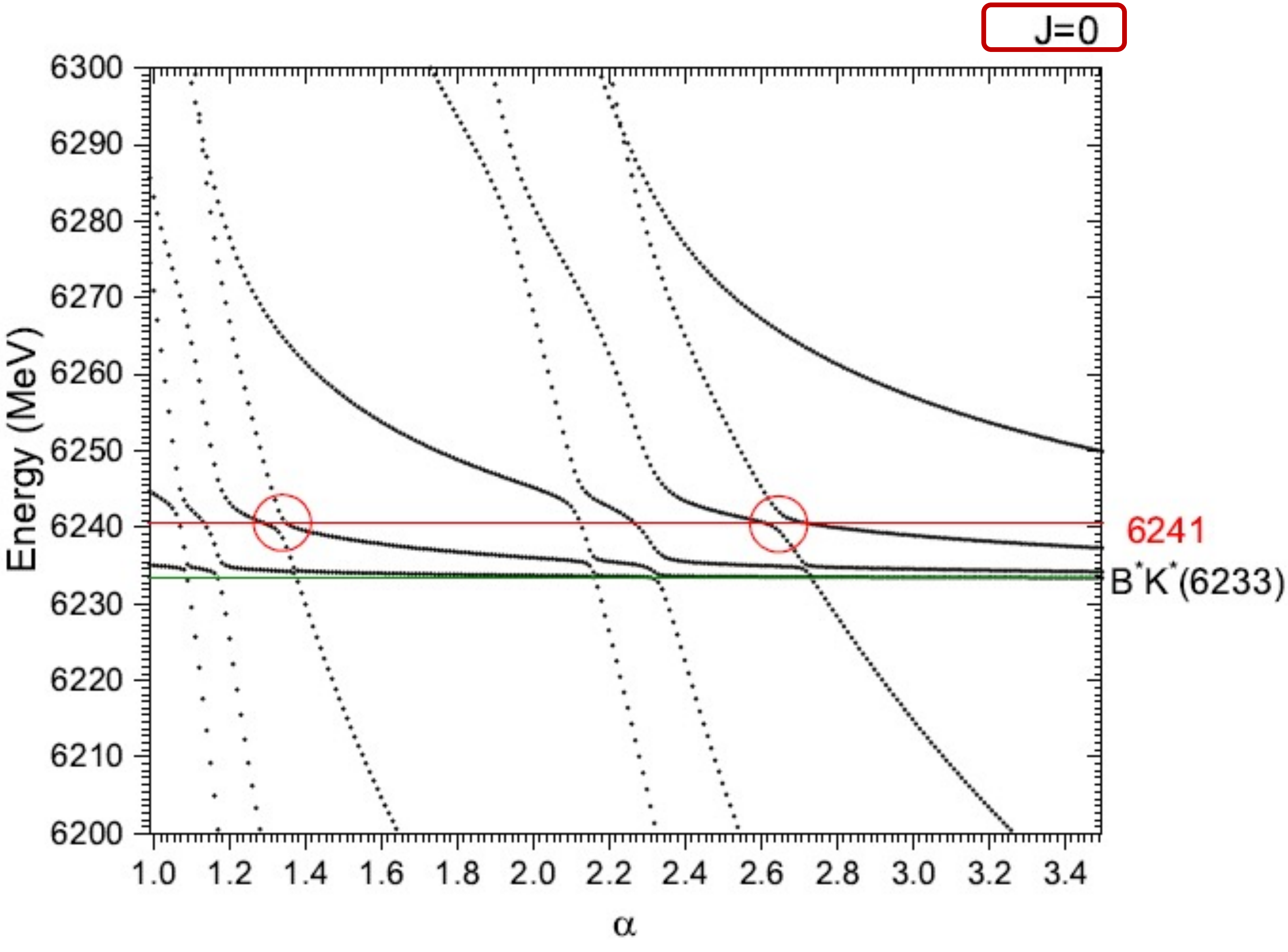


look for resonance for $b\bar{s}q\bar{q}$ system



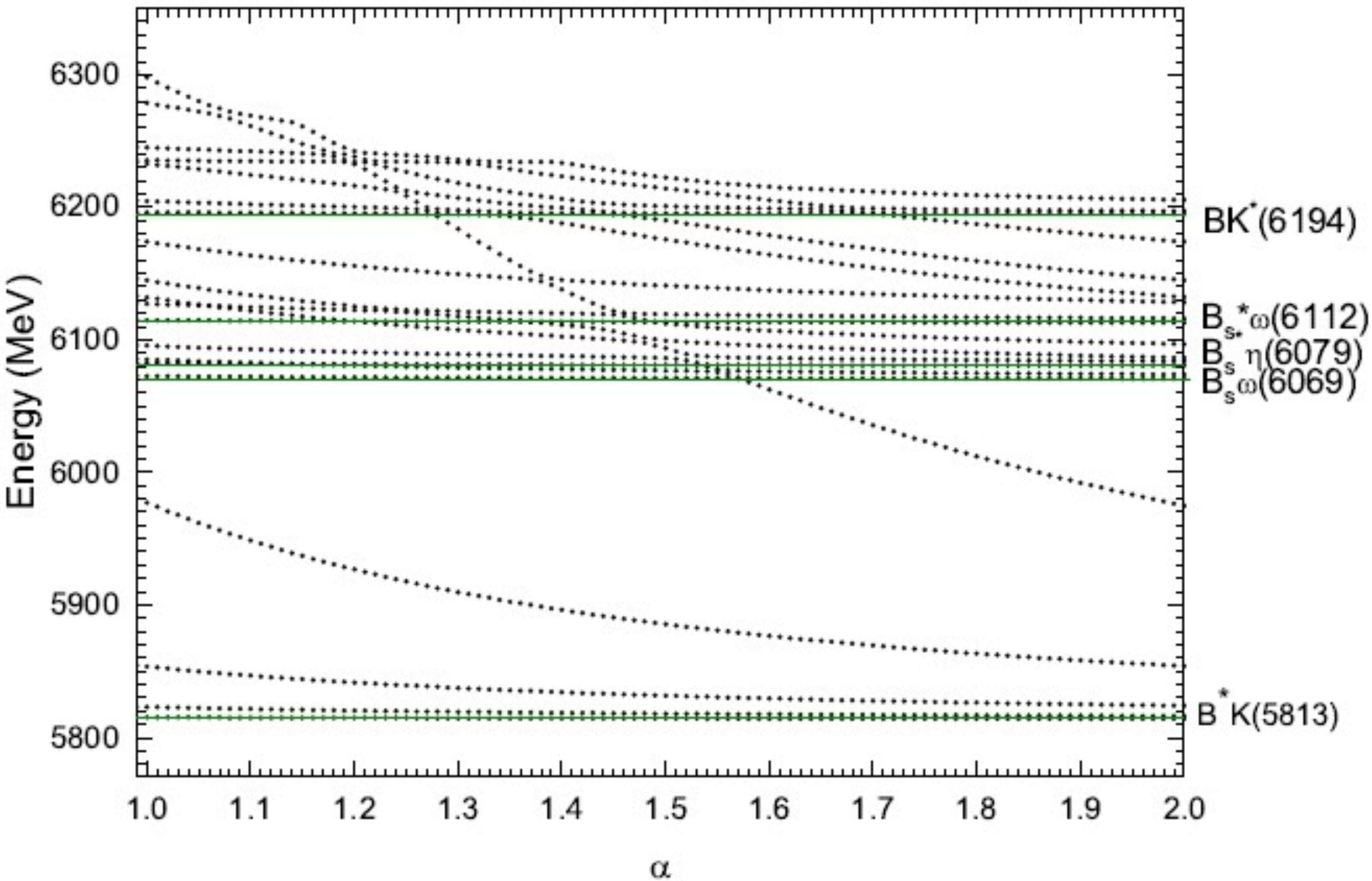
- Two resonances at 6050 MeV and 6078 MeV.
- Only one resonance exists at 6140MeV~6155 MeV.

look for resonance for $b\bar{s}q\bar{q}$ system

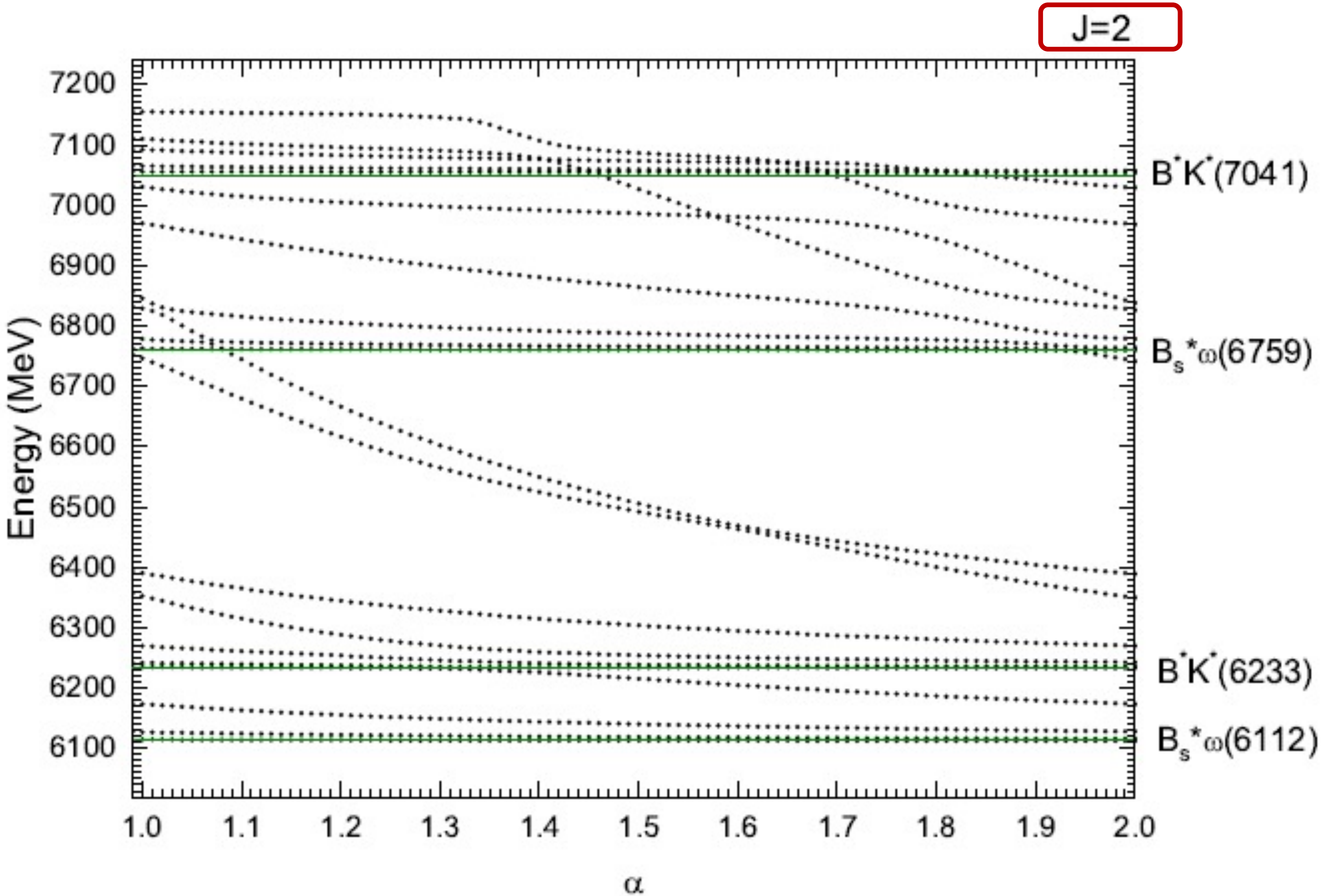


One resonance state at 6241 MeV

J=1



No resonances exist for 1^+



No resonances exist for 2^+

decay width of resonances

$$\Gamma = 4|V(\alpha)|\frac{\sqrt{|S_r||S_c|}}{|S_c - S_r|},$$

J.Simon, J. Chem. Phys. 75, 2465 (1981)

TABLE VII. The decay widths of resonances of $c\bar{c}s\bar{u}$ and $b\bar{s}q\bar{q}$ system. (unit: MeV).

Resonance State	Γ	Resonance State	Γ
$c\bar{c}s\bar{u}(4023)$	3.1	$c\bar{c}s\bar{u}(4042)$	13.7
$b\bar{s}q\bar{q}(6050)$	7.8	$b\bar{s}q\bar{q}(6078)$	44.1
$b\bar{s}q\bar{q}(6155)$	8.7	$b\bar{s}q\bar{q}(6241)$	4.1

➡ $\Gamma\ (Z_{cs}(3985)) = 12.8$ MeV

➡ $\Gamma(B_s(6063)) = 26$MeV

System	Resonances	$R_{c\bar{u}}$	$R_{s\bar{c}}$	R_{cs}	$R_{\bar{c}\bar{u}}$	$R_{c\bar{c}}$	$R_{s\bar{u}}$
$c\bar{c}s\bar{u}$	4023	0.7	0.6	5.3	5.3	5.2	5.3
	4042	0.8	0.7	4.1	4.2	4.1	4.2
	Resonances	$R_{b\bar{u}}$	$R_{u\bar{s}}$	R_{bu}	$R_{\bar{u}\bar{s}}$	$R_{b\bar{s}}$	$R_{u\bar{u}}$
$b\bar{s}q\bar{q}$	6050	4.2	4.3	4.2	4.3	0.5	0.7
	6078	2.6	2.7	2.6	2.7	0.5	0.8
	6155	2.7	2.8	2.7	2.8	0.6	0.8
	6241	0.9	1.0	2.3	2.3	2.1	2.2

molecular resonance is suggest in our work!

Summary

- For $c\bar{c}u\bar{s}$ and $b\bar{s}q\bar{q}$ system, no bound states are found in the chiral quark model.
- For $c\bar{c}u\bar{s}$, there are two resonance states at 4023 MeV and 4042 MeV. The state with 4042 MeV has a consistent decay width with the experimental data by BESIII, which is a molecular resonance.
- For B_s, in 2-body system, the 2S and 1D states have masses close to the newly observed B_s^0. For 4-body system, several resonances are emerged. The mass and decay width $b\bar{s}q\bar{q}$ (6078) state are relatively close to the experimental values M = 6063 MeV and Γ = 26 MeV by LHCb.
- The better way to investigate the highly excited B_s states is to invoke the unquenched quark model (X. Chen, J. Ping, C. D. Roberts and J. Segovia, Phys. Rev. D 97, no.9, 094016 (2018)).

Thank you !