## **Charmed baryons and their interactions**

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Workshop Heavy flavor and CP violation at Lanzhou, July 22-25, 2015

With Noumi, Shirotori, Kim, Sadato, Yoshida, Oka, Hiyama, Nagahiro, Yasui



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1. Introduction

2. Structure: How  $\rho\lambda$  modes appear in the spectrum

3. Productions

## 1. Introduction Particle data book (PDG)

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- Most baryons are light flavored qqq, mesons as qq
- Can we see more heavy baryons, exotics?
- How multiquarks of new exotics behave?

## J-PARC 50 GeV proton -> 30 GeV pion beam



### Physics of charm hadrons

- Primarily single charm baryons, excited states
- Hidden charm baryons, pentaquark
- D, D\* mesons and excited states
- Charmed nuclei

Proposal approved and physics discussions are going

- What we can learn from charmed baryons
   Qqq: the simplest system with qq
- How much they are produced, in particular, excited states

## **Correlations in multiquarks**



#### Recent interests are triggered by **Exotic hadrons** A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964

anti-triplet as anti-quarks  $\bar{q}$ . Baryons can now be constructed from quarks by using the combinations ( $\bar{q}qq$ ), ( $\bar{q}qqq\bar{q}$ ), etc., while mesons are made out of ( $q\bar{q}$ ), ( $qq\bar{q}\bar{q}\bar{q}$ ), etc. It is assuming that the lowest baryon configuration (qqq) gives just the represen-



### LHCb found Pentaquarks

http://arxiv.org/abs/1507.03414

7-8 TeV pp collision —>  $\Lambda_b$ 



- What we can learn from charmed baryons Qqq: the simplest system with qq
- How much they are produced, in particular, excited states

- 2. Structure
- 3. Productions  $\pi + N \longrightarrow D^* + \Lambda^*$

2. Structure: *what do we expect to study?* 

# A heavy quark distinguish the fundamental modes $\lambda$ and $\varrho$ Place to look at qq dynamics



# Spectrum and WF's as $M_Q$ is varied

Roberts-Pervin, IJMPA, 23, 2817 (2008)

Yoshida, Sadato, Hiyama, Oka, Hosaka

• Model Hamiltonian  $H = \frac{p_1^2}{2m_q} + \frac{p_2^2}{2m_q} + \frac{p_3^2}{2M_Q} - \frac{P^2}{2M_{tot}} + V_{conf}(HO) + V_{spin-spin}(Color - magnetic) + \dots$ • Solved by the Gaussian expansion method Negative parity states — p-wave excitations - 1/2<sup>-</sup>, 3/2<sup>-</sup>



Negative parity states — p-wave excitations - 1/2<sup>-</sup>, 3/2<sup>-</sup>



Negative parity states — p-wave excitations - 1/2<sup>-</sup>, 3/2<sup>-</sup>



### 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 Heavy quark Mass [GeV]

Mixing of 
$$\Lambda(\text{phys}) = c_{\lambda} \Lambda(^2 \lambda) + c_{\rho} \Lambda(^2 \rho)$$

e.g.  $\lambda$ -mode dominant state: How much the other mode mixes?



## Intermediate summary

- Heavy quark spectroscopy will give more information on constituents
- Isotope shift may resolve two diquark modes

*collective* and *internal* 

- Λ baryons may have more chance to see the two modes separately
- HQ singlet, doublet are also useful
- Systematic study from strange to heavy is useful

# 3. Productions

### $\pi + N \rightarrow D^* + \Lambda_c$ reactions

Cross sections  $(Y_c/Y_s)$  and Ratios  $(Y_c^*/Y_c)$ 

### **Strategy:**

Forward peak (high energy)  $\rightarrow$  t-channel dominant Next figure

### We look at: (1) <u>Absolute values</u>

by  $(\Lambda_c/\Lambda_s)$  by the Regge model,  $K^*$ ,  $D^*$  Vector-Reggeon (2) Ratios of  $B_c^*(\lambda \text{ modes}) / B_c$ by a one step process of *Qd* picture for  $\lambda$ -mode

Pion-induced reaction  $\pi + p \rightarrow D^* + B_c^*$ 





### Vector Reggeon dominance Sang-Ho Kim, in preparation



- Angular dependence prefers vector-Reggeon
- Energy dependence seems
- There is some discrepancy in the very forward region





# Dynamical part ~ radial integral $q_{\rm eff}$ : the momentum transfer ~ Large GS $\langle B_c(\mathbf{S}\text{-wave}) | \vec{e}_{\perp} \cdot \vec{\sigma} e^{i\vec{q}_{eff} \cdot \vec{x}} | N(\mathbf{S}\text{-wave}) \rangle_{radial} \sim 1 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$ **Excited** states $\langle B_c(\mathbf{P}\text{-wave}) | \vec{e}_{\perp} \cdot \vec{\sigma} e^{i\vec{q}_{eff} \cdot \vec{x}} | N(\text{S-wave}) \rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^1 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$

$$\langle B_c(\mathbf{D}\text{-wave}) | \vec{e}_{\perp} \cdot \vec{\sigma} e^{i\vec{q}_{eff} \cdot \vec{x}} | N(\text{S-wave}) \rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^2 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

Transitions to excited states are not suppressed 22

### Results



Strange  $k_{\pi}^{CM} = 1.59 \text{ [GeV]}, k_{\pi}^{Lab} = 5.8 \text{ [GeV]}$ 

l = 0	$\Lambda\left(\frac{1}{2}^{+}\right)$	$\Sigma_{-}(rac{1}{2}^+)$	$\Sigma_{-}(\frac{3}{2}^+)$					
	1.00	0.067	0.44					
l = 1	$\Lambda_{-}(\frac{1}{2}^{-})$	$\Lambda_{-}(rac{3}{2}^{-})$	$\Sigma_{-}(\frac{1}{2}^{-})$	$\Sigma_{\pi}(\frac{3}{2}^{-})$	$\Sigma'(\frac{1}{2}^-)$	$\Sigma'_{\pm}(\frac{3}{2}^-)$	$\Sigma'_{-}(\frac{5}{2}^{-})$	
	0.11	0.23	0.007	0.01	0.01	0.07	0.067	
l = 2	$\Lambda_{-}(\frac{3}{2}^{+})$	$\Lambda_c(\frac{5}{2}^+-)$	$\Sigma_{-}(\frac{3}{2}^{+})$	$\Sigma_{\gamma}(\frac{5}{2}^+)$	$\Sigma_{-}^{\prime}(rac{1}{2}^{+})$	$\Sigma'_{\neg}(\frac{3}{2}^+)$	$\Sigma'_{-}(\frac{5}{2}^+)$	$\Sigma_{c}^{\prime}(rac{5}{2}^{+})$
	0.13	0.20	0.007	0.01	0.004	0.02	0.038	0.04

### Expected charm production spectrum



# Summary

• Charmed baryons

New platform to study quark dynamics

- J-PARC plans to study them
- Production rate: Charm/Strangeness: 10<sup>-4</sup> or less
- Abundant excited states
- **Decays** are also helpful to know the structure We are currently working for details

# 4. Decays



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### Pion emission – quark model --on going

Things to be looked at:

• Pion emission ~ very near the threshold



Place to look at the *two independent* operators



## Possible selection rules



## Possible selection rules

*o*-modes

### Decays of baryons = of diquarks



Two conditions must be satisfied for baryons and for diquarks

$$\Lambda_c(1/2^-,\rho) \to \Sigma_c(1/2^+,GS) + \pi$$
  

$$d({}^{3}P_0) \to d({}^{3}S_1) + \pi$$
 is not allowed





### Aoki Hatsuda Ishii, Phys.Rev.Lett. 99 (2007) 022001

HAL QCD data are consistent with the quark Pauli effects.S=0T. Inoue et al., (HAL QCD) PTP 124, 591 (2010)



Classification of SU(6) quark model



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### Baryon spectrum from the lattice, David Richard, Talk at YITP, HHIQCD, Feb. 2015



# X (3872)

Discovery by Belle in 2003, followed by D0, CDF, BaBar. BES



## What motivate us

- Quark model seem to work
- Multiquark configurations have been found
- How are they behave, and what are the **essential degrees of freedom** for hadrons?
- Charmed baryons Qqq are useful to study
- *qq*, yet another possible constituent Difficult to study because of colorful and confined nature

# 2. Charmed baryons





Negative parity states — p-wave excitations - 1/2<sup>-</sup>, 3/2<sup>-</sup>

