## Charmed baryons and their interactions

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

Contents

1. Introduction
2. Structure: How @d modes appear in the spectrum 3. Productions

## 1. Introduction Particle data book (PDG)

|  |  |  |  | $\beta_{31}$ | **** | $\underline{2}$ | $\rho_{1}$ | **** | $2^{\circ}$ | $P_{9}$ | **** | A: | **** |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Baryons |  |  |  | $\beta_{3}$ | *** | 2 | $\mathrm{ha}_{1}$ | **** | $\mathrm{E}^{+}$ | $P_{\text {a }}$ | **** | A, (2585)* | *** |
|  |  |  |  | $5{ }^{11}$ | **** | 1 | $\hat{R}_{12}$ | **** | 파530) | $P_{2}$ | **** | 有(2525)* | *** |
|  |  |  |  | $日_{4}$ | **** | 2[13s) | P12 | *** | -(1620) |  | * | (1, $(2248)^{4}$ | * |
|  |  |  |  | $\beta_{3}$ | * | 2 (1485) |  | * | 2(1500) |  | *** | A, (2000) ${ }^{*}$ | *** |
| N(10s0) | ${ }^{11}$ |  | A(1300) | $5_{11}$ | ** | I [1569] |  | ** | - -1320) $^{\text {a }}$ | $D_{13}$ | *** | (1, $(2740)^{*}$ | *** |
| $N(168)$ | $D_{15}$ | *** | A(190s) | Fin | **** | I (1585) | $a_{2}$ | ${ }^{*}$ | - 12950$)$ |  | *** | I, (20ss) | *** |
| N[1680) | Fis | *** | 4 (1910) | $P_{13}$ | **** | 2 [1620) | $\mathrm{SH}_{1}$ | ** | -(20)0] |  | *** | 2.(200) | *** |
| $N(1700)$ | $D_{13}$ | *** | $\Delta(1820)$ | $P_{3}$ | *** | 2 [1660] | $\mathrm{P}_{1}$ | *** | -(2120) |  | $\stackrel{ }{*}$ | L-(2000) | *** |
| $N(1710)$ | $P_{11}$ | ** | $4(1909)$ | Das | *** | I (1670) | $D_{13}$ | **** | - 422350$)$ |  | ** | $\because:$ | *** |
| N(1720) | $P_{11}$ | *** | $\Delta$ (1943) | $\mathrm{D}_{2}$ | ${ }^{*}$ | 2 [16\%) |  | ** | - [23m) |  | ** | $\pm$ | *** |
| $N(1000)$ | $P_{11}$ | ** | $\Delta(1809)$ | $F_{12}$ | **** | $\underline{T}(1750)$ | 51 | *** | - $2(2500)$ |  | * | $\because$ | *** |
| N(190] | $F_{17}$ | ${ }^{4 *}$ | $\Delta(2000)$ | Fs | ** | 2 (17ra) | $\mathrm{P}_{1}$ | * |  |  |  | IS | *** |
| $N(2000) \mid$ | $\mathrm{F}_{21}$ | ${ }^{* *}$ | $\Delta(2150)$ | $5{ }_{51}$ | * | I[7m] | D. | * $2 *$ | $5^{5}$ |  | **** | H. 12481 | *** |
| $N(2000)$ | $D_{13}$ | 4 | $\Delta(2300)$ | $G_{w}$ | $\stackrel{\square}{6}$ | I (1849) | $R_{1}$ | $\stackrel{ }{*}$ | ¢¢2asoy |  | *** | F, 1270] | *** |
| N[200] | $5{ }_{31}$ | 4 | $\Delta$ (2300) | $\mathrm{Hn}_{n}$ | ** | $\mathrm{E}_{\text {(2mes) }}$ | $\mathrm{P}_{1}$ | ** | ¢27noy |  | ** | -4, (2013) | *** |
| N[2100] | $P_{12}$ | * | $\Delta(2980)$ | $\mathrm{D}_{n}$ | * | 2 (1045) | ${ }_{\text {a }}$ | **** | [2.2475 |  | ** | $\mathrm{H}_{\text {(2909 }}$ | * |
| N[2190] | 6 | *** | $4(2300)$ | $\mathrm{F}_{3}$ | $\stackrel{ }{*}$ | $\underline{2}$ (1849) | $0_{3}$ | *** |  |  |  | -4, - $^{\text {ama }}$ | *** |
| N[2200] | 0 is | 8 | $\Delta$ [200) | $\mathrm{C}_{\mathrm{m}}$ | ** | $\underline{12005]}$ | St |  |  |  |  | (1)38s) | ** |
| $N[2230]$ | $\mathrm{He}_{0}$ | **** | $\Delta(2070)$ | $\mathrm{H}_{3}$ | *** | E (2005) | FII | **** |  |  |  | [-13000] | ** |
| N(23s) | 6 | *** | $\Delta(2790)$ | $\mathrm{I}_{1}$ | ** | 2 (2000) | ${ }^{3}$ | ** |  |  |  | E, (3123) | * |
| N(2000) |  | ** | $\Delta(2 \mathrm{Ha)}$ | $K_{\text {us }}$ | ** | $\underline{z}$ (00es) | 9 | ** |  |  |  | $\mathrm{F}_{5}$ | *** |
| N[2700] |  | ** |  |  |  | $\begin{aligned} & I(2109) \\ & I(2395) \end{aligned}$ | 61 |  |  |  |  | $\theta_{0}^{\prime}(2770)^{2}$ | *** |
|  |  |  | A N(1405) | 51 5 | *** | 2(2455) |  | ** |  |  |  |  |  |
|  |  |  | (1529) | $\mathrm{Da}_{3}$ | **** | 2 [200] |  | ** |  |  |  | \% | * |
|  |  |  | (1600) | P) | *** | $2(0005)$ |  | * |  |  |  |  | *** |
|  |  |  | (160) | $S_{10}$ | **** | [1970) |  | * |  |  |  |  | *** |
|  |  |  | (160) | Da | *** |  |  |  |  |  |  |  | 4 |
|  |  |  | (1800) | 51 | *** |  |  |  |  |  |  | $45_{8}^{5}$ | *** |
|  |  |  | (1835] | Pa | *** |  |  |  |  |  |  |  |  |
|  |  |  | (1895) | $F$ | **** |  |  |  |  |  |  |  |  |
|  |  |  | (1850] | $\mathrm{D}_{5}$ | **** |  |  |  |  |  |  |  |  |
|  |  |  | N106] | Rs | *35* |  |  |  |  |  |  |  |  |
|  |  |  | (2000) |  | * |  |  |  |  |  |  |  |  |
|  |  |  | N2005 |  | * |  |  |  |  |  |  |  |  |
|  |  |  | A2106] |  | **** |  |  |  |  |  |  |  |  |
|  |  |  | (2112) | $F_{58}$ | *** |  |  |  |  |  |  |  |  |
|  |  |  | N(2)25 |  | $\stackrel{ }{*}$ |  |  |  |  |  |  |  |  |
|  |  |  | (2350) | $\mathrm{Hm}_{0}$ | *** |  |  |  |  |  |  |  |  |
|  |  |  | N2sas |  | ** |  |  |  |  |  |  |  |  |


| timit umimoritu |  |  | $f\left(f^{c}\right)$ |  |  |  |  | $f\left(F^{\prime}\right)$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| N-NOMS |  |  |  | (f) |  | 49 |  | $\begin{aligned} & * 5(15) \\ & * / 4 /(19) \end{aligned}$ | $88^{4} 10^{-6}$ |
|  |  |  | 1-(2-+) | * $\kappa^{*}$ | 1/2( $20^{-}$) | + 0 | 90] |  | ${ }^{\circ}$ |
|  |  |  | $0^{-710}$ | * $\kappa^{*}$ | 1/210-1 |  | (il) | *x.109 |  |
|  |  |  | 17 | *к] | 1/20") |  | a0+1 |  |  |
| - 6 (100) | $0^{+}\left(D^{+}+1\right.$ | * (\%1700) | $1^{+1}$ | * $\kappa$ ] | 1/210") | * ${ }^{\text {duchasi }}+$ |  | * N(1) |  |
| *,(\%mbly | $\mathrm{I}^{+}\left(1^{--}\right)$ | *(1700) | $17\left(22^{+4}\right)$ | K5100] | 1/20+1 |  |  | *xil\| |  |
| * (172) | $0^{-18}$ | - (canay |  | * $\mathrm{K}^{\text {¢ }}$ (198) | 1/20) | *D. $8 \mathrm{sm} \mathrm{m}^{3}$ Buprasi+ |  | *- |  |
|  | $a^{2}\left(s^{-+}\right)$ | (1750) | $8^{*}(20+1$ | * Kin 12 m ) | 1/2( $\mathbf{1}^{+}$ |  |  | **i2S |  |
| * (6) ${ }^{(00)}$ | $\mathrm{g}^{+6+y^{++1}}$ | **(18x) | $\left.1710^{-+}\right)$ | *K.(1400) | $1 / 21^{*}$ ) | 804704 |  |  |  |
|  | $\left.\mathrm{l}^{-1 \mathrm{~s}^{++}}\right]$ |  | 0+0+ ${ }^{+}$ |  | 1/20 $1 / 70$ |  |  | *-150m |  |
|  | $0^{-}\left(10^{--7}\right.$ | x(las3) | $33^{\prime}\left(2^{-4}\right)$ | * K52430) 1/20*) |  |  |  |  |  |
| - M, ${ }^{\text {a }}$ | $0^{-11+-7}$ | *-41830] | $8^{-13}$ | * K $2140{ }^{\text {a }}$ | $1 / 22^{+}$ |  |  | д(\%ab) |  |
| * 5 (1273) | $1^{+}\left(11^{+-3}\right.$ | 2(103) | $8^{+}(2-+1$ | к(1)ev) | 1/210-) |  |  | x(1045 |  |
| * 2(1760) | $1-1 a^{+}+3$ $a^{+} 12++1$ | * Ninut | ¢-4\% ${ }^{\text {a }}$ | $\kappa(2 s \times 1)$ <br> $\kappa_{1}$ (159] | 1/20-1 |  |  | - 6 (1420) |  |
| * S [1270 | $a^{2}\left(12^{+}+1\right.$ $a^{2}(1)^{+}+1$ | (avom | $8^{*} 01^{-7}$ |  | $1 / 2\left(t^{\prime}\right)$ |  |  | - Wincum |  |
| * (123s) | $a^{2}\left(1^{++}\right)$ $a^{4}\left(10^{-+i}\right.$ | 60153) | $0^{4}(2++1$ $0^{+} 0+2$ |  |  |  | Auther tums <br> Vatisi Ved OKM Me tixtiencti |  |  |  |
| * = 0 (176) |  | - S0\%60) | $0^{+}\left(2^{++}\right)$ |  |  |  | $A(4) 50]$ |  |
|  | $\left.1^{-10^{-1}} 18^{-+}\right]$ | A(10m) | $8^{+}\left(3^{--}\right)$ | *K (1/n) <br> * K 91 nol | $\begin{aligned} & 1 / 22^{-}-1 \\ & \left.1 / 29^{-1}\right) \end{aligned}$ | $\operatorname{lin}_{00^{\prime}} 121^{-} \mid$ |  | - \|1048) |  |
| ( $+2(1100)$ | $1-12+*$ $a^{+} 18++1$ | * [0039) | $5^{*}\left(12^{+}+\right.$ $0^{4}+3+1$ |  |  | -tisrm Nim |  | $\square 5$ |  |
| - Cl1900 | $1-18$ $a^{2}\left(D^{+}+1\right.$ $1-10$ | - *(2000) | $0^{*}(2++)$ $1-(4++)$ | *K,(11 к(1) | $\begin{aligned} & 1 / 2(2-1 \\ & 1 / 20^{-7} \end{aligned}$ |  |  | 6(15) $0^{+}$ |  |
| * +, (1400) | $3^{-18-+7}$ | - (nowa) | $0^{+14+7}$ |  | 1/20+) |  |  |  |  | * T15) $5^{-1}(1)$ <br> *x.l\| $1 /$ - $8^{*}$ |  |
| * *165) | $a^{4}\left(\mathrm{~s}^{-+}\right)$ $\mathrm{a}^{+}\left(a^{++}\right)$ | $5(210)^{\text {a }}$ | $8^{-12-1}$ |  | $1 / x p^{+} 1$ |  |  |  |  |  |  |
| * C(1000) | $a^{+}\left(1^{++}\right)$ | (crise) |  |  |  | bot rom simanatin $-+1.5-811$ |  |  |  |  |  |
| * - (1479) | $a^{-11-7}$ | f(2150) | $0^{+} 02^{++1}$ $3+10$ | K, (025a) | $\begin{aligned} & 1 / 2 a^{-1} \\ & 1 / 7 y^{2}+1 \end{aligned}$ | * $0^{-1}$ |  | * Koill\| |  |  |  |
| - (180) | $9^{2} 13++7$ |  | ${ }^{*} \times 1$ |  |  | * 8 : | 817 | * 725) |  |  |  |
| *-2(160) | l- $1^{-10^{+}}+1$ $1^{4} 11^{-1}$ | ¢12780) |  |  | 1/29") | * $5,1 \mathrm{lmmP}$ 1/207) |  | ก10] |  |  |  |
|  | $1^{4}\left(1^{--7}\right.$ $a^{*}\left(5^{-+7}\right.$ | (0200) |  |  | $\begin{aligned} & 1 / 2\left(4^{-1}\right) \\ & i^{\prime}\left(r^{\prime \prime}\right) \end{aligned}$ | -5/Meso (1) |  | * - $_{\text {- }}$ |  |  |  |
|  | a $a^{*}\left(s^{-+~}\right.$ $a^{*}\left(5^{++}\right)$ | (17230) | $5^{*} 12$ |  |  |  |  | * $*$ (09\% |  |  |  |
| 5 (18s) | $0^{3}\left(11^{+4}\right)$ | ค(280) | $\begin{aligned} & 3^{4} 6=-7 \\ & 0^{2} 6++1 \end{aligned}$ | Convo |  |  |  | * 71 15 <br> *T145) <br> * 71\|amid <br> - T7.1003\| |  |  |  |
| (1358) | $a^{+}(2++)$ | (2100) | $s^{+}(4++)$ |  |  | * $0_{5}^{1}$ | 407 |  |  |  |  |
| A8931 | $3^{4}\left(3^{-7}-7\right.$ | Camol | $s^{4} 6$ |  |  |  |  |  |  |  |
| ¢ (250) | $0^{-}\left(1 a^{+}-7\right.$ | - [0]saj) | (2) |  |  |  |  |  |  |  |
| $* *,(1600)$ $*-(150)$ | $1-$ | A(2ma) |  |  |  | FON $4 T$ CANEL DAITS |  |  |  |  |
| 2,(164) $6(16409$ |  | Allenal | $8^{+}(6++1$ |  |  |  |  |  |  |  |  |  |
| **(1043) | $a^{4}\left(2 z^{-+}\right)$ |  |  |  |  |  |  |  |  |  |  |  |
| * *(1) | - | futher Stats |  |  |  |  |  |  |  |  |  |  |
| * - ¢ (157) | $0^{-(3--)}$ |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |

- Most baryons are light flavored qqq, mesons as q $\bar{q}$
- Can we see more heavy baryons, exotics?
- How multiquarks of new exotics behave?


## J-PARC 50 GeV proton $\rightarrow 30 \mathrm{GeV}$ 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<br>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 (qqq), qqqqq), etc., while mesons are made out of $(q \bar{q}),(q q \bar{q} \bar{q})$ etc. It is assuming that the lowest baryon configuration (qqq) gives just the represen-

## Baryons

## Mesons

qqq qqqqव̄
$q \bar{q}$ $q q \bar{q} \bar{q}$


## LHCb found Pentaquarks

http://arxiv.org/abs/1507.03414
7-8 TeV pp collision $\longrightarrow \Lambda_{b}$
$\Lambda_{b} \longrightarrow J / \psi, p, K^{-}$



- 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 $\pi+N->D^{*}+\Lambda^{*}$
4. Structure: what do we expect to study?

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


## Spectrum and WF's as $M_{Q}$ is varied

$$
\begin{aligned}
& \text { Roberts-Pervin, IJMPA, 23, } 2817 \text { (2008) } \\
& \text { Yoshida, Sadato, Hiyama, Oka, Hosaka }
\end{aligned}
$$

- Model Hamiltonian

$$
\begin{aligned}
H= & \frac{p_{1}^{2}}{2 m_{q}}+\frac{p_{2}^{2}}{2 m_{q}}+\frac{p_{3}^{2}}{2 M_{Q}}-\frac{P^{2}}{2 M_{\text {tot }}} \\
& +V_{\text {conf }}(H O)+V_{\text {spin-spin }}(\text { Color }- \text { magnetic })+\ldots
\end{aligned}
$$

- Solved by the Gaussian expansion method

Negative parity states - p-wave excitations - $1 / 2^{-}, 3 / 2^{-}$


Negative parity states - p-wave excitations - $1 / 2^{-}, 3 / 2^{-}$

| $M=m_{s}$ |  | $------\Sigma \Sigma\left(3 / 2^{-}\right)$ |
| :---: | :---: | :---: |
|  | 0.7 | $\begin{array}{r} -\quad \Sigma\left(1 / 2^{-}\right) \\ \cdots----\quad \Lambda\left(3 / 2^{-}\right) \\ - \\ \hline \end{array}\left(1 / 2^{-}\right)$ |
| ------3 | $-0.6$ |  |
| $\overline{-------1}$ |  |  |
|  | -0.4 |  |

$M=m_{c}$



Negative parity states -p -wave excitations $-1 / 2^{-}, 3 / 2^{-}$


## Wave function

## Mixing of $\quad \Lambda($ phys $)=c_{\lambda} \Lambda\left({ }^{2} \lambda\right)+c_{\rho} \Lambda\left({ }^{2} \rho\right)$

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


SU(3)
Heavy quark

## Intermediate summary

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


## collective and internal

- $\Lambda$ 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

$$
\pi+N \rightarrow \quad D^{*}+\Lambda_{c} \text { reactions }
$$

Cross sections $\left(Y_{c} / Y_{S}\right)$ and Ratios $\left(Y_{\mathrm{c}}{ }^{*} / Y_{\mathrm{c}}\right)$

## Strategy:

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

## We look at:

(1) Absolute values
by $\left(\Lambda_{\mathbf{c}} / \Lambda_{s}\right)$ by the Regge model, $\boldsymbol{K}^{*}, \boldsymbol{D}^{*}$ Vector-Reggeon (2) Ratios of $B_{c}^{*}(\lambda$ modes $) / B_{c}$
by a one step process of $Q d$ picture for $\lambda$-mode

Pion-induced reaction

$$
\pi+p \rightarrow \quad D^{*}+B_{c}{ }^{*}
$$




## Vector Reggeon dominance <br> Sang-Ho Kim, in preparation





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


## D* meson productions



## Relative rates of $\left(B_{\mathrm{c}}{ }^{*} / B_{\mathrm{c}}\right)$

One step process for $Q d \lambda$-mode


$$
t_{f i} \sim \vec{k}_{\pi} \times \vec{e} \cdot \vec{J}_{f i}
$$

$$
\sim\left\langle B_{c}^{*}\right| \vec{e}_{\perp} \cdot \vec{\sigma} e^{i \bar{q}_{f f} \cdot \vec{x}}|N\rangle=\text { (Geometric) } \times \text { (Dynamic) }
$$

$$
D^{*} \sim \text { Transverse }
$$

## Dynamical part ~ radial integral


$\mathrm{GS}\left\langle B_{c}(\mathrm{~S}\right.$-wave $\left.)\right| \vec{e}_{\perp} \cdot \vec{\sigma} e^{i \vec{q}_{e f f} \cdot \vec{x}} \mid N(\mathrm{~S}$-wave $\left.)\right\rangle_{\text {radial }} \sim 1 \times \exp \left(-\frac{q_{e f f}^{2}}{4 A^{2}}\right)$
Excited states

$$
\begin{aligned}
& \left.\left\langle B_{c}(P \text {-wave })\right| \vec{e}_{\perp} \cdot \vec{\sigma} e^{i_{e f f} \cdot \vec{x}} \mid N(\mathrm{~S} \text {-wave })\right\rangle_{\text {radial }} \sim\left(\frac{q_{e f f}}{A}\right)^{1} \times \exp \left(-\frac{q_{e f f}^{2}}{4 A^{2}}\right) \\
& \left.\left\langle B_{c}(D \text {-wave })\right| \vec{e}_{\perp} \cdot \vec{\sigma} e^{i \bar{q}_{e f f} \cdot \vec{x}} \mid N(\text { S-wave })\right\rangle_{\text {radial }} \sim\left(\frac{q_{e f f}}{A}\right)^{2} \times \exp \left(-\frac{q_{e f f}^{2}}{4 A^{2}}\right)
\end{aligned}
$$

## Results

Charm $\quad k_{\pi}^{C M}=2.71[\mathrm{GeV}], k_{\pi}{ }^{L a b}=16[\mathrm{GeV}]$

|  | $\begin{gathered} \Lambda_{c}\left(\frac{1}{2+}\right) \\ 1.00 \end{gathered}$ | $\begin{gathered} \hline \Sigma_{c}\left(\frac{1}{2}^{+}\right) \\ 0.02 \end{gathered}$ | $\begin{gathered} \Sigma_{c}\left(\frac{3^{+}}{}\right) \\ 0.16 \end{gathered}$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\underline{l=1}$ | $\Lambda_{c}\left(\frac{1}{2}{ }^{-}\right)$ | $\Lambda_{c}\left(\frac{3^{-}}{}{ }^{-}\right)$ | $\Sigma_{c}\left(\frac{1}{2}{ }^{-}\right)$ | $\Sigma_{c}\left(\frac{3}{2}{ }^{-}\right)$ | $\Sigma_{c}^{\prime}\left(\frac{1}{2}{ }^{-}\right)$ | $\Sigma_{c}^{\prime}\left(\frac{3^{-}}{}{ }^{-}\right)$ | $\Sigma_{c}^{\prime}\left(\frac{5}{2}\right)$ |  |
|  | 0.90 | 1.70 | 0.02 | 0.03 | 0.04 | 0.19 | 0.18 |  |
| $\underline{l=2}$ | $\Lambda_{c}\left(\frac{3}{2}{ }^{+}\right)$ | $\Lambda_{c}\left(\frac{5}{2}-\right)$ | $\Sigma_{c}\left(\frac{3}{2}{ }^{+}\right)$ | $\Sigma_{c}\left(\frac{5}{2}{ }^{+}\right)$ | $\Sigma_{c}^{\prime}\left(\frac{1}{2}{ }^{+}\right)$ | $\Sigma_{c}^{\prime}\left(\frac{3^{+}}{}{ }^{+}\right)$ | $\Sigma_{c}^{\prime}\left(\frac{5}{2}\right)$ | $\Sigma_{c}^{\prime}\left(\frac{5}{2}{ }^{+}\right)$ |
|  | 0.50 | 0.88 | 0.02 | 0.02 | 0.01 | 0.03 | 0.07 | 0.07 |

Strange $\quad k_{\pi}^{C M}=1.59[\mathrm{GeV}], k_{\pi}{ }^{L a b}=5.8[\mathrm{GeV}]$


## Expected charm production spectrum



## Summary

- Charmed baryons

New platform to study quark dynamics

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


## 4. Decays



## 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

$$
\begin{aligned}
& \bar{q} \gamma_{5} q \phi_{\pi}, \bar{q} \gamma^{\mu} \gamma_{5} q \partial_{\mu} \phi_{\pi} \\
& \vec{\sigma} \cdot \vec{p}_{i}, \vec{\sigma} \cdot \vec{p}_{f}(\vec{\sigma} \cdot \vec{q})
\end{aligned}
$$

## Possible selection rules

$\varrho$-modes
Decays of baryons $=$ of diquarks


## Possible selection rules

$\varrho$-modes
Decays of baryons $=$ of diquarks


Two conditions must be satisfied for baryons and for diquarks

$$
\begin{array}{ll}
\Lambda_{c}\left(1 / 2^{-}, \rho\right) \rightarrow \Sigma_{c}\left(1 / 2^{+}, G S\right)+\pi & \text { is not allowed } \\
d\left({ }^{3} P_{0}\right) \rightarrow d\left({ }^{3} S_{1}\right)+\pi
\end{array}
$$

## Radiative decay: $1 / 2^{-} \rightarrow \quad 1 / 2^{+}$E1



## Radiative decay: $5 / 2^{-} \rightarrow 1 / 2^{+}$M2, E3

$\lambda$ mode
${ }^{3} \mathrm{~S}_{1}$ diquark $1^{+}$

$\varrho$ mode
${ }^{3} \mathrm{P}_{2}$ diquark $2^{-}$


Aoki Hatsuda Ishii, Phys.Rev.Lett. 99 (2007) 022001
\# HAL QCD data are consistent with the quark Pauli effects.

| $\mathrm{S}=0$ |  | T. Inoue et al., (HAL QCD |
| :---: | :---: | :---: |
| 1 | [33] |  |
| 8 s | [51] |  |
| 27 | [33], [51] |  |
| $\mathrm{S}=1$ |  |  |



| 8a | $[33],[51]$ |
| :---: | :---: |
| 10 | $[33],[51]$ |
| $10 *$ | $[33],[51]$ |




Classification of SU(6) quark model



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



## X (3872)

## Discovery by Belle in 2003, followed by DO, CDF, BaBar. BES


$X$ as a Hadronic molecule




Fermi Lab



## 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



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Negative parity states - p-wave excitations - $1 / 2^{-}, 3 / 2^{-}$

$M=m_{c}$


