Nuclear and Hadron Physics in Japan
Heavy Baryons: Structure, Productions and Decays

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Modern Problems in Nuclear and Elementary Particle Physics
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Contents

• Physics in Japan/RCNP
  Cyclotron, LEPS, J-PARC, Supercomputer, etc
  Education

• Heavy Baryons: Structure, Productions and Decays
Physics in Japan/RCNP
Facilities in Japan

Spring-8

KEK

RCNP

RIKEN

J-PARC

Jul. 2-6, 2012
Grant-in-Aid for Scientific Research Priority Areas
~ Since 2007, 5 years with a few million dollars/year

2007-2012: Computational science for particle-nuclear-astro physics
2008-2013: Elucidation of New Hadrons with a Variety of Flavors
            Cosmological Inflation and Dark Matter
2009-2014: Topological Quantum Phenomena
2010-2015: Tera scale Physics @ LHC
2012-2017: Astrophysics by Gravitational Waves
            Nuclear Matter in Neutron Star
2013-2018: Neutrino Science Frontier
2014-2019: Underground Nuclear and Particle Physics
Elucidation of new hadrons with variety of flavors (2009 - 2013)
About 30 regular members were involved (staffs, postdocs)
Research Center for Nuclear Physics

The only Lab for collaboration of nuclear physics made in a university

• The largest cyclotron
• Working with other facilities; SPring-8, J-PARC <— Noumi
• Super computer
RCNP Cyclotron Facility

- **Architectural Layout**
  - **RI Beam**: Mono-energetic neutron, Since 1973
  - **Ultra Cold Neutron source**: Since 1992
  - **Ring Cyclotron**: K=400 MeV, Since 1992
  - **AVF Cyclotron**: K=140 MeV, Since 1973
  - **Grand Raiden**: MuSIC, Muon science
  - **MuSIC**: Muon science
  - **Ultra Cold Neutron source**: 基礎科学
  - **RI Beam**: 原子核物理

The facility is equipped with various beam lines and experimental setups for research in nuclear and particle physics.
Osaka University Undertaking by cooperation among RCNP and Graduate School of Medicine and Science

Graduate School of Medicine

- Radio therapy
- PET&SPECT inspection

Graduate School of Science

- RI separation and synthesis
- Nuclear data
- Diagnostics

RCNP

- Heavy-particle gantry
- Next generation BNCT
- High intensity compact accelerator

Medical and clinical applications of accelerator science, nuclear physics, radiation physics

Training of medical physicists by higher education using accelerators

Nuclear physics Accelerator

Organic chemistry

Nuclear chemistry
LEPS AND LEPS2 @SPring-8

120 km distance from RCNP

Super Photon ring -8 GeV

- Third-generation synchrotron radiation facility
- Circumference: 1436 m
- 8 GeV, 100 mA
- 62 beamlines (Max)
LEPS facility

8 GeV electron Collision

Recoil electron

Backward-Compton scattering

SSD + Sc phodoscope
ScFi + Sc phodoscope

Inverse Compton $\gamma$-ray of 3 GeV

Laser light of 3 eV

Beam intensity
$< 2.5 \times 10^6$ for 1.5 GeV ~ 2.4 GeV (355 nm laser)
$< 2.0 \times 10^5$ for 1.5 GeV ~ 2.9 GeV (266 nm laser)

Only forward spectrometer

a) SPring-8 SR ring

b) Laser hutch

c) Experimental hutch

Energy spectrum of BCS photons

Bremsstrahlung
Vector meson $\phi$ photoproduction

A peaking structure is seen in $d\sigma/dt$ near $E_\gamma=2$ GeV, which has not been explained by a simple model calculation.

A peak is dominated by natural parity exchange

$\sim$ Pomeron like

$$\frac{d\sigma}{dt} = \left( \frac{d\sigma}{dt} \right)_{t=-|t|_{\text{min}}} \exp(b(t+|t|_{\text{min}}))$$

Curve: Pomeron + Pseudo scalar exchange model

(A. Titov et. al, PRC 67, 065205)
Search for penta-quark $\Theta^+$

Its existence is still controversial!
LEPS2 with a new laser beam and a detector (from BNL)
Physics with LEPS2

- **Unique features**
  - High intensity beam, Polarized beam (Linearly/Circularly) ($\sim 10^7/s @ E_{\text{max}} = 2.4\ \text{GeV}$, $\sim 10^6/s @ E_{\text{max}} = 2.9\ \text{GeV}$)
  - Large acceptance for charged particles / photons
    - Reaction (missing mass) & Decay (invariant mass)
    - Kinematical constraint, Coplanarity
    - Angular distribution

- **Physics objectives**
  - $\Theta^+$ study
  - $\Lambda(1405)$ with K* photo-production
  -Modification of mesons in nucleus
  - Missing resonance search
  - $K$-NN search
  - Hyperon-nucleon interaction

High priority

More idea welcome!
Theory

Hadrons and Nuclei
Supercomputer

• Cooperating **SX-ACE (NEC)** vector processor ~ 393 TF
• Spend about 20 million yen (~ 0.2 million dollar)/year
• ~ 100 users (about 10 foreign uses), ~ 30 active users
• Lattice QCD, Nuclear structure, Few-body, Supernova
• About 10-20 publications/year

**Role in the community = HPCI**

H**igh** P**erformance** C**omputer** I**nfra**

with the Japan largest supercomputer, KEI
Kei computer (京) at Kobe
~ billion dollars
HAL QCD data are consistent with the quark Pauli effects.

$S=0$

1 $^8[33]$

27 $^8[33], [51]$

$S=1$

8a $^8[33], [51]$

10 $^{10}[33], [51]$

10* $^{10}[33], [51]$


T. Inoue et al., (HAL QCD) PTP 124, 591 (2010)
Nuclear Transmutation studies

*Impulsing Paradigm Change through Disruptive Technologies Program*

- Launched FY2014 and 12 programs approved.
- will end at Dec. 31, 2018.
- Keyword: high risk and high impact

Reduction and Resource Recycle of High Level Radioactive Wastes with Nuclear Transmutation (PM: Reiko Fujita)

*Microscopic Effective Reaction Theory*  
Kazuyuki Ogata
Extraction genuine data w/ MERT

*Microscopic Effective Reaction Theory*

Kazuyuki Ogata

- Model space is determined by analysis of alternative reaction data.
- Structural information is given by Tsukuba group (or others).
- MERT generates the objective reaction data.

\[
A(d,n)B \quad A + n \rightarrow B
\]

*from neutron pickup to neutron capture*
International Physics Course (IPC): theoretical physics and experiments at Osaka University

http://www.rcnp.osaka-u.ac.jp/~ipc/
Program concept and design of the IPC

- Offers **Master** and **Ph.D.** programs (not undergraduate programs)
- Organized inside the **Department of Physics** but includes groups at the **Institute of Laser Engineering**, the **Research Center for Nuclear Physics**, and the **Department of Earth Science and Astronomy**
- Students can work from the start as **active members of international collaborations** in theory or experiment
- Students can work with our own large-scale facilities, including **high-power lasers** and **high-energy accelerators**
- Education and research program conducted in **English**

See  [http://www.rcnp.osaka-u.ac.jp/~ipc/](http://www.rcnp.osaka-u.ac.jp/~ipc/)
Education at the IPC

1: **broad** knowledge and abilities

Lectures

Electrodynamics
Quantum Mechanics
Mathematics for Physics

Condensed Matter Theory
Fluid and Plasma Physics
Field Theory
Nuclear and Particle Physics
General Relativity
Optical Properties of Matter
Quantum Field Theory
Solid State Theory
Quantum Many-Body Systems
...

2: **deep** knowledge and abilities in one subject

Advanced seminars on frontier topics
and special intensive lectures

See [http://www.rcnp.osaka-u.ac.jp/~ipc/](http://www.rcnp.osaka-u.ac.jp/~ipc/)
Heavy Baryons: Structure, Productions and Decays

Baryons with heavy quark(s) may disentangle light quark dynamics

Atsushi Hosaka, RCNP, Osaka

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

Contents
1. Introduction
2. Structure: How $q\lambda$ modes appear in the spectrum
3. Productions
4. Decays
1. Introduction

Quark model and **EXOTICS**: Now 51 years old

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 $(qqq)$, $(qqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q})$, etc. It is assuming that the lowest baryon configuration $(qqq)$ gives just the representations $1$, $8$, and $10$ that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just $1$ and $8$.

But no colors ~ glues
X (3872)

Discovery by Belle in 2003, followed by D0, CDF, BaBar, BES, Fermi Lab, SLAC, LHC, LHCb, CMS.

And more recently also by LHCb, CMS.
Quarks bonding differently at LHCb $Z^+(4430)$


So until last week there were two known types of hadron.

......

LHCb has just confirmed what data from other experiments had already led us to suspect. There is a third way.

Phys. Rev. Lett. 112, 222002
Near and above the threshold

Meson-like

Diquarks

- \( \bar{q}q \) creation and rearrangement of multiquarks
- Correlations \( \bar{q}q \) \( qq \) (diquarks)
- Are heavy quarks useful to know it?
2. Charmed baryons

\[ S = \frac{1}{2}, \frac{3}{2} \]

\[
\begin{array}{cccc}
\Xi^+_{cc} & \Xi^+_{cs} & \Xi^+_{css} & \Xi^+_{css}
\end{array}
\]

\[
\begin{array}{cccc}
\Lambda_c & \Sigma_c & \Omega_c & \Omega_c
\end{array}
\]

[Energy levels diagram with states labeled]
2. Charmed baryons

More to come from J-PARC

S=3/2

S=1/2

$1/2^+ + \Xi_C^{'} + \Omega_C$
What do we expect to study?

A heavy quark may distinguish the fundamental modes $\lambda$ and $\rho$

$\Rightarrow$ place to look at diquark correlations

Isotope-shift: Copley-Isgur-Karl, PRD20, 768 (1979)

$m_Q = m_{u,d}$ Degenerate

Mixing of $\lambda$ and $\rho$

$m_Q \rightarrow \infty$ Distinguished
Spectrum and WF's as $M_Q$ is varied

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

Yoshida, Sadato, Hiyama, Oka, Hosaka

- Model Hamiltonian

$$H = \frac{p_1^2}{2m_q} + \frac{p_2^2}{2m_q} + \frac{p_3^2}{2M_Q} - \frac{P^2}{2M_{tot}} + V_{conf}(HO) + V_{spin-spin}(Color - magnetic) + \ldots$$

- Solved by the Gaussian expansion method
Negative parity states — p-wave excitations - $1/2^-$, $3/2^-$

\[ M = m \quad M = m_s \quad M = m_c \]

\[ \Sigma(3/2^-) \quad \Sigma(1/2^-) \quad \Lambda(3/2^-) \quad \Lambda(1/2^-) \]
Negative parity states — p-wave excitations - $1/2^-$, $3/2^-$
Wave function

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?

\[ \Lambda_{c*} \text{ is almost pure } \lambda \text{ mode} \]

Reflect more \(qq\) nature

\[ \Lambda \text{ solid} \]

\[ \Sigma \text{ dashed} \]

\[ |c|_2 \text{ Probability} \]

\[ M_Q \text{ [GeV]} \]

\[ \text{SU(3)} \quad \text{Heavy quark} \]
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

• Systematic study from strange to heavy is useful
3. Productions

\[ \pi + N \rightarrow D^* + \Lambda_c \] reactions

Production rate \((\Lambda_c / \Lambda)\) and Ratios \((B_c^* / B_c)\)
Strategy:
Forward peak (high energy) $\rightarrow$ t-channel dominant

Next figure

We look at:
(1) **Absolute values**
by $(\Lambda_c/\Lambda_s)$ by the Regge model, $D^*$ 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*
$\pi + p \rightarrow D^* + B_c^*$
$p_{\pi, \text{Lab}} = 4.5 \text{ GeV}$

D.J. Krennel et al
PRD6, 1220 (1972)
Absolute values

Regge model (Sang-Ho Kim, in preparation)

We have examined:
• $K^*$ (strange) productions
• $K^*$ ($D^*$) Reggeon dominance
• Angular dependence
• Small $u$-channels
  ~ Baryon Regge
• Normalizations
Vector Reggeon dominance

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

\[ \pi^- p \rightarrow (K^{*0}\Lambda & D^{*-}\Lambda_c^+) \]

\[ \sigma \text{ [\mu b]} \]

\[ s/s_{th} \]

\[ 10^{-6} \quad 10^{-4} \quad 10^{-2} \quad 10^{0} \quad 10^{2} \]

\[ 1 \quad 2 \quad 4 \quad 8 \]

K^{*0}\Lambda

D^{*-}\Lambda_c^+

10^{-4}

[Regge]
Relative rates of \( \frac{B_c^*}{B_c} \)

One step process for \( Qd \) \( \lambda \)-mode

\[
\begin{align*}
\pi & \quad D^* \\
N \quad \{ & d \quad \lambda \quad \} \quad B_c^* \\
\{ & N \quad d \quad \lambda \quad \} \quad B_c^* \\
\end{align*}
\]

\[
t_{fi} \sim \mathbf{k}_\pi \times \mathbf{e} \cdot \mathbf{J}_{fi}
\]

\[
\sim \left\langle B_c^* \left| \mathbf{e}_\perp \cdot \mathbf{\sigma} e^{i\tilde{q}_{\text{eff}} \cdot \tilde{x}} \right| N \right\rangle = \text{(Geometric)} \times \text{(Dynamic)} \times \text{CG coefficients}
\]

\( D^* \sim \text{Transverse} \)
Dynamical part $\sim$ radial integral

$q_{\text{eff}}$: the momentum transfer $\sim$ Large

GS \[ \left\langle B_c (\text{S-wave}) \right| \bar{e}_\perp \cdot \bar{\sigma} e^{i q_{\text{eff}} \cdot \vec{x}} \left| N(\text{S-wave}) \right\rangle_{\text{radial}} \sim 1 \times \exp \left( -\frac{q_{\text{eff}}^2}{4 A^2} \right) \]

Excited states

\[ \left\langle B_c (\text{P-wave}) \right| \bar{e}_\perp \cdot \bar{\sigma} e^{i q_{\text{eff}} \cdot \vec{x}} \left| N(\text{S-wave}) \right\rangle_{\text{radial}} \sim \left( \frac{q_{\text{eff}}}{A} \right)^1 \times \exp \left( -\frac{q_{\text{eff}}^2}{4 A^2} \right) \]

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

Transitions to excited states are not suppressed
## Results

### Charm

\[ k_{\pi}^{CM} = 2.71 \ [\text{GeV}], \ k_{\pi}^{Lab} = 16 \ [\text{GeV}] \]

<table>
<thead>
<tr>
<th>( l = 0 )</th>
<th>( \Lambda_c(\frac{1}{2}^+) )</th>
<th>( \Sigma_c(\frac{1}{2}^+) )</th>
<th>( \Sigma_c(\frac{3}{2}^+) )</th>
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<td>1.00</td>
<td>0.02</td>
<td>0.16</td>
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<th>( \Sigma_c'(\frac{1}{2}^+) )</th>
<th>( \Sigma_c'(\frac{3}{2}^+) )</th>
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<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
<td>0.07</td>
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</table>

### Strange

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

<table>
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<th>( \Sigma_c(\frac{3}{2}^+) )</th>
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<td>0.067</td>
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<th>( \Lambda_c(\frac{3}{2}^-) )</th>
<th>( \Sigma_c(\frac{1}{2}^-) )</th>
<th>( \Sigma_c(\frac{3}{2}^-) )</th>
<th>( \Sigma_c'(\frac{1}{2}^-) )</th>
<th>( \Sigma_c'(\frac{3}{2}^-) )</th>
<th>( \Sigma_c'(\frac{5}{2}^-) )</th>
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<td>0.007</td>
<td>0.01</td>
<td>0.01</td>
<td>0.07</td>
<td>0.067</td>
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<th>( l = 2 )</th>
<th>( \Lambda_c(\frac{3}{2}^+) )</th>
<th>( \Lambda_c(\frac{5}{2}^-) )</th>
<th>( \Sigma_c(\frac{3}{2}^+) )</th>
<th>( \Sigma_c(\frac{5}{2}^+) )</th>
<th>( \Sigma_c'(\frac{1}{2}^+) )</th>
<th>( \Sigma_c'(\frac{3}{2}^+) )</th>
<th>( \Sigma_c'(\frac{5}{2}^+) )</th>
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<td>0.004</td>
<td>0.02</td>
<td>0.038</td>
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</table>
Expected charm production spectrum

Ground state

Excited states

Counts/5 MeV

Missing Mass [GeV/c²]

1/2⁺

1/2⁻

3/2⁻

HQ doublet

3/2⁺

5/2⁺

1 : 2

3 : 2

Expected charm production spectrum
4. Decays

\[ \lambda\text{-mode} \]

\[ \rho\text{-mode} \]
Pion emission – quark model --on going

Things to be looked at:
• Pion emission $\sim$ very near the threshold

$\Lambda_c^*(2625, 3/2^-)$  \hspace{1cm} $\Sigma_c^*(2520, 3/2^+)$
$\Lambda_c^*(2595, 1/2^-)$  \hspace{1cm} $\Sigma_c(2455, 1/2^+)$

Place to look at the **two independent** operators

$\bar{q}\gamma_5 q\phi_\pi$, $\bar{q}\gamma^\mu \gamma_5 q \partial_\mu \phi_\pi$

$\vec{\sigma} \cdot \vec{p}_i$, $\vec{\sigma} \cdot \vec{p}_f (\vec{\sigma} \cdot \vec{q})$

\[ \Lambda_c^* \left\{ \vec{p}_i, \vec{p}_f \right\} \Sigma_c^* \]
Possible selection rules

$q$-modes

Decays of baryons = of diquarks

$J^P \rightarrow J'^P + \pi(0^-, l_\pi)$
Possible selection rules

$q$-modes

Decays of baryons = of diquarks

Two conditions must be satisfied for baryons and for diquarks

\[ \Lambda_c(1/2^-,\rho) \rightarrow \Sigma_c(1/2^+,GS) + \pi \]

\[ d(3P_0) \rightarrow d(3S_1) + \pi \]

is not allowed
Radiative decay: $1/2^- \rightarrow 1/2^+ E_1$

**λ mode**

- Good diquark $0^+$
- $l_\lambda = 1$

**φ mode**

- 3P0 diquark $0^-$
- $l_\phi = 1$

0$^- \rightarrow 0^+$ is forbidden
Radiative decay: $5/2^- \rightarrow 1/2^+ \text{ M2, E3}$

$\lambda$ mode

$^3S_1$ diquark $1^+$

$\ell_\lambda = 1$

Both M2 E3

$\rho$ mode

$^3P_2$ diquark $2^-$

$\ell_\rho = 1$

$2^- \rightarrow 0^+$ is only M2

Good diquark $0^+$
Summary

• Charmed baryons: there are many open issues
• J-PARC plans to study them

• Production rate: Charm/Strangeness: $10^{-4}$ or less
• Abundant production of excited states

• Decay selection rules are helpful
Energy dependence of the NN interaction

\[ |t(q=0)| \text{ (MeV fm}^3\text{)} \]

- \( t_0^c \)
- \( t_{\sigma}^c \)
- \( t_\tau^c \)

400 MeV
Kei computer 京都 at Kobe

Famous screening for government driven projects

Why No. 1!! not No. 2!!

Machine

HPCI consortium

Users office

Users
Harmonic oscillator

\[ H = \frac{p_1^2}{2m} + \frac{p_2^2}{2m} + \frac{p_3^2}{2M} + \frac{k}{2} \left( (x_1 - x_2)^2 + (x_2 - x_3)^2 + (x_3 - x_1)^2 \right) \]

\[ = \frac{p_{\rho}^2}{2m_{\rho}} + \frac{p_{\lambda}^2}{2m_{\lambda}} + \frac{k_{\rho} \rho^2}{2} + \frac{k_{\lambda} \lambda^2}{2} \]

\[ m_{\rho} = \frac{m}{2}, \quad m_{\lambda} = \frac{2mM}{M + 2m} \]

\[ k_{\rho} = \frac{3}{2} k, \quad k_{\lambda} = 2k \]

\[ \omega_{\rho} = \sqrt{3}\omega > \omega_{\lambda} = \sqrt{\frac{M + 2m}{M}} \omega \]
World best resolution

$^{58}\text{Ni}(p,n)$

$IUCF$

$\Delta E \approx 400\text{keV}$

$^{58}\text{Ni}(^3\text{He},t)$

$E_{^3\text{He}} = 140\text{MeV/u}, 0\text{-deg}$

$2001 \text{RCNP}$

$\Delta E = 35\text{keV}$
Beamline map of SPring-8