Hyperon-Hyperon Interactions and Searches for Exotic Di-Hyperons in Nuclear Collisions

February 29 – March 2, 2012

Organizers: Anthony Baltz, Rainer Fries, Huan Zhong Huang,
John Millener and Zhangbu Xu

RIKEN BNL Research Center

Building 510A, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

DISCLAIMER

This work was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002 and again in 2007. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consists of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~100 graduates of which 29 theorists and 15 experimenters have attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. In most cases all the talks are made available on the RBRC website. In addition, highlights to each speaker's presentation are collected to form proceedings which can therefore be made available within a short time after the workshop. To date there are over one hundred proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSF, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998. The next generation computer in this sequence, QCDCQ (400 Teraflops), is expected to be fully operational in early 2012.

N. P. Samios, Director
February 2012

CONTENTS

Preface to the Series	
Introduction	i
H-dibaryon from Full QCD Lattice Simulations	
Takashi Inoue	1
Possible Existence and Detection of Strangeness - 4 Dibaryon States	
Gerald Miller	7
Exotic Hadrons Production in Heavy Ion Collisions	
Che-Ming Ko.....	13
Resonance Production and Search for Exotica with ALICE at the LHC	
Benjamin Doenigus	19
Study of Lambda-Lambda Correlations with the STAR Detector at RHIC	
Neha Shah.....	25
Lambda-Lambda Correlation in (K^-K^+) Reaction and Heavy-ion Collisions	
Akira Ohnishi	31
Hyperon Physics at Hall B, Jefferson Lab	
Lei Guo.....	37
Femtoscopic Correlations and Final State Interactions	
Richard Lednicky	43
Baryon-Baryon Interactions for $S=0,-1,-2,-3,-4$	
Thomas Rijken.....	49
Recent Topics in Hypernuclear Physics and Perspective at J-PARC	
Tomofumi Nagae.....	55
Latest Results on Hypernuclear Physics from the FINUDA Experiment	
Elena Botta	61
Recent Results from the HypHI Project at GSI	
Takehiko Saito.....	69
Omega Baryon Interactions with Lattice QCD	
Joseph Wasem	75
YN (and YY) Interactions from Hypernuclei	
John Millener.....	81
Exploring Strange Matters	
Juergen Schaffner-Bielich	87
The H-dibaryon from Lattice QCD	
Silas Beane	95
Future Perspectives on STAR Exotic Searches	
Aihong Tang.....	101
Future J-PARC Experiment to Search for H Particle	
Susumu Sato	107
Summary Lecture	
Berndt Mueller.....	113
List of Registered Participants.....	119
Agenda.....	121
Additional RIKEN BNL Research Center Proceeding Volumes	123
Contact Information	

INTRODUCTION

This workshop, held on February 29 through March 2, 2012 at Brookhaven National Laboratory, was dedicated to the study of hyperon-hyperon interactions and searches for exotic di-hyperons in nuclear collisions. We brought together the heavy ion and hyperon physics communities to explore new physics opportunities arising from the large number of multiple hyperons produced in heavy ion collisions.

In heavy ion collisions many hyperons (Lambda, Xi, Omega and their anti-particles) are produced in each collision as a result of coalescence or recombination processes from strangeness equilibrated dense partonic matter. This provides a unique opportunity to study hyperon-hyperon interactions through their correlations in heavy ion collisions. The investigation of multi-strangeness hyperon-hyperon interactions with high statistics is not feasible in any other laboratory setting. This is a potentially very rich physics area that the heavy ion community has not fully explored yet. For example, the STAR experiment can reconstruct more than several tens of thousands of Lambda-Lambda pairs, more than a few tens of thousands Xi-Xi pairs and a sizable number of Omega-Omega pairs from TPC data in one year of RHIC running for Au+Au collisions. A large data volume of hyperon samples is also expected from the ALICE experiment at LHC. Such a large amount of hyperon pairs will also provide unprecedented sensitivity on exotic di-hyperon searches.

The workshop program covered both recent theoretical progress and experimental results. Exciting talks were presented at the workshop on:

- a) latest lattice QCD calculations on the hypothetical H particle
- b) model calculations on nucleon-nucleon, nucleon-hyperon and hyperon-hyperon interactions and the possible existence of stable di-hyperons
- c) hypernuclear physics and astrophysics, an
- d) experimental reports from STAR, ALICE, JLab and JPARC experiments.

Hyperon physics in heavy ion collisions is a promising, and so far underutilized, opportunity for the heavy ion research community. It could add an important dimension to the scientific research portfolio at RHIC/LHC in this decade. Recent RHIC results include the discovery of antimatter hypertriton in 2010 and anti-alpha in 2011, which have already demonstrated the vitality of such a research program. These proceedings will provide a snapshot of the current research status in this area and stimulate future exploration.

The workshop was sponsored by the RIKEN BNL Research Center and the STAR Collaboration. We thank Nick Samios, Larry McLerran, Nu Xu and James Dunlop for their support of the workshop. The Carl Dover Memorial Lecture was delivered by Professor Juergen Schaffner-Bielich and supported by family and friends of late Carl Dover, who was a pioneer in hypernuclear physics and calculations of exotic particle formation via coalescence in heavy ion collisions. We gratefully acknowledge Ms. Pamela Esposito's assistance as the workshop coordinator whose arrangement for the workshop operation has been greatly appreciated by all attendees of the workshop.

Organizers: Anthony Baltz (BNL)
Rainer Fries (TAMU)
Huan Zhong Huang (UCLA)
John Millener (BNL)
Zhangbu Xu (BNL)

H-dibaryon from Full QCD Lattice Simulations

Takashi Inoue, Nihon Univ.
for HAL QCD Collaboration

- ★ We've carried out full QCD lattice simulations for the H.
 - $32^3 \times 32$ lattice, $L=3.87$ [fm], Iwasaki gauge, clover quark
- ★ We've found a bound=stable H-dibaryon
 - in flavor SU(3) symmetric world at $M_{PS} = 470$ [MeV] – 1.17 [GeV]
 - its binding energy is 20 – 50 [MeV] depending on the quark mass
- ★ We've estimated H-dibaryon in the real world.
 - w/ phenomenological SU(3)_F breaking, H may be a resonance.

Multi-hadron system in LQCD

- Conventional : use energy eigenstate (eigenvalue)
 - Lüscher's finite volume method for phase-shift
 - Infinite volume extrapolation to get bound state energy
- HAL : utilize the potential $V(r) + \dots$ from the NBS w.f.
 - ie. an effective theory which reproduce T matrix from QCD
 - Advantages
 - No need to separate E eigenstate. Just need to measure the NBS w.f. Then, potential can be extracted.
 - Demand a minimal lattice volume. No need to extrapolate to $V=\infty$.
 - Can output many observables.

★ We can probe the H in this approach!

As far as H has BB component.

Observables in 1_F

T. I. et al [HALQCD collaboration]
Nucl. Phys. A in print, arXiv 1112.5926

- Left: scattering phase shift v.s. E_{cm}
 - shows existence of one discrete state below threshold.
- Right: obtained ground state
 - which is 20 - 50 MeV below from free BB ie. $3q-3q$.
 - This means that there is a 6-quark bound state in the 1_F channel.
 - A stable(bound) H -dibaryon exists in these $SU(3)_F$ limit world!

HHI in $S=-2, I=0$ sector

- $\Lambda\Lambda - N\Xi - \Sigma\Sigma$ coupled. Left: diagonal. Right: Off-diagonal.
- This sector is flavor symmetric (spin singlet), and involves $1F_7$.
- Channel coupling interactions are comparable to diagonal ones, except for small $\Lambda\Lambda - N\Xi$ transition (sign change must be artifact).
- Interaction is most attractive in $N\Xi$ channel, although it has not much meaning because channel coupling is strong.

Phase-shifts of BB in $S=-2, I=0, {}^1S_0$

- In the Stapp parametrization, the bar-phase-shifts are defined as

$$S_{ii}^{l=0} = \eta_i e^{2i\bar{\delta}_i}$$

- H approaches the $\Lambda\Lambda$ threshold from below and go through it.

$\Lambda\Lambda$ invariant-mass-spectrum

- Invariant-mass-spectrum of $\Lambda\Lambda$ calculated in S-wave dominance.

$$\rho_{\Lambda\Lambda}(\sqrt{s}) = |1 - S_{\Lambda\Lambda}^{l=0}|^2 / k$$

- We may have a chance to find H in experiments counting two Λ .

Possible Existence and Detection of Strangeness - 4 Dibaryon States

Gerald A. Miller,
Physics Department, Box 35-1595
University of Washington
Seattle, Wa. 98195-1560

Summary: This talk is basically a review of the paper, nucl-th/0607006, placed on the archive about 6 years ago. Given the nearly bound state nature of the 1S_0 np system, and the details of SU(3) flavor symmetry, one expects that the $\Xi\Xi$ system would be bound in that channel. This state could be detected at RHIC. The state interesting because it has $S=-4$, its existence would show the power of SU(3) flavor symmetry in QCD, and would improve the understanding of calculations of the properties of strange nuclear matter.

Outline

- SU(3) flavor $\longrightarrow$ $\Xi\Xi$ bound 1S_0 state
- NN, $\Xi\Xi$ each in {27} dim. rep of SU(3)
- np: 1S_0 nearly bound state $a_{np} = -24$ fm
- Increase nucleon mass 10%, **same** interaction get bound state
- $\Xi\Xi$, np 1S_0 states in same irrep of SU(3)
- 1S_0 state: NN, $\Xi\Xi$ similar, increased mass causes bound state
- 3 simplest models predict bound states
- why interaction not depend on quark masses? 6 detailed Nijmegen models predict bound states
- lattice calculation Beane et al 1109.2889 gives bound state
- detection at RHIC

NN, Ξ N, $\Xi \Xi$ interactions

- Evaluate Lagrangian e.g. Savage and Wise

$$\mathcal{L}^{(2)} \rightarrow \left(c_1 + c_3 + (c_2 + c_6) \frac{1}{2} \right) \left((\Xi^\dagger \Xi)^2 + (N^\dagger N)^2 \right) + (c_2 + c_6) \frac{1}{2} \left(\Xi^\dagger \sigma \Xi \cdot \Xi^\dagger \sigma \Xi + N^\dagger \sigma N \cdot N^\dagger \sigma N \right) \\ + 2(c_3 + c_4 \frac{1}{2}) \Xi^\dagger N^\dagger N \Xi + 2c_4 \frac{1}{2} \left(\Xi^\dagger \sigma N \cdot N^\dagger \sigma \Xi \right)$$

$\Xi \Xi$ short range potential same as NN

1S_0 channel – OPEP is small for NN

NN scattering length $a \approx -17.3$ fm

If $\Xi \Xi$ 1S_0 POTENTIAL same as for NN:

Same irrep of SU(3)

Nijmegen

there will be a BOUND STATE dibaryon $S=-4$, decays

weakly $\Xi \Lambda \pi$

np 1S_0 state

Zero energy, 0 potential, wave function: $u(r) = 1 - r/a$

Unbound $a < 0$

Bound $a > 0$

A little more attraction would give 1S_0 bound state

$$-\frac{d^2u}{dr^2} + MVu = k^2u \quad \text{Increase mass } M, \text{ increases attraction}$$

Three simple two-parameter potentials

- Square well, delta shell, separable
- Fit parameters to experimental np scattering length a , effective range r_e

$$k \cot \delta = -\frac{1}{a} + \frac{1}{2} r_e k^2$$

- Change nucleon mass (940 MeV) to Cascade mass (1315 MeV): 40% increase in attraction
- Each model $\Xi\Xi$ bound 1S_0 state $B=7.0$, 0.7, 0.6 MeV, see also Nijmegen potentials

Finding $\Xi\Xi$ bound states

- $\gamma D \rightarrow (\Xi\Xi)$ 4K threshold
 photon energy 5 GeV (thanks
 to R Jones) Cross sections small
 due to high momentum transfer
 at relevant kinematics
- $K D \rightarrow (\Xi\Xi)$ 3K ?
- RHIC (Huang) can detect decay
 products $\Xi\Lambda$ Energy is sufficient

Exotic hadrons production in heavy ion collisions

Che-Ming Ko
Texas A&M University

- Exotic hadrons studies in HIC
- Thermal vs coalescence production
- Pentaquark $\Theta^+(udud\bar{s})$
- Diomega $(\Omega\Omega)_0$
- $D_{sJ}(2317)$: diquark or tetraquark
- Charmed tetraquark mesons and pentaquark baryons
- Other exotic mesons, baryons and dibaryons

Supported by US National Science Foundation and the Welch Foundation

Exotic hadron studies in HIC

- $\Theta^+(udud\bar{s})$
 - Randrup, PRC 68, 031903 (2003); statistical model
 - Letessier et al., PRC 68, 061901(R) (2003); statistical model
 - Chen et al., PLB 601, 34 (2004); coalescence model
 - Nonaka et al., PRC 69, 031902 (2004); coalescence model, elliptic flow
 - Not observed by STAR and PHENIX
- Diomega $(\Omega\Omega)_0$
 - Zhang et al., PRC 61, 065204 (2000); based on chiral quark model
 - Pal et al., PLB 624, 210 (05); hadronic transport model
- $D_{sJ}: (c\bar{s})$ or $(c\bar{s}q\bar{q})$
 - Chen et al., PRC 76, 064903 (2007); coalescence model
- $\Theta_{cs}^+(udus\bar{c})$ and $T_{cc}(ud\bar{c}\bar{c})$
 - Lee et al., Eur. J. Phys. C 54, 259 (08); coalescence model
- Exotic mesons (8), baryons (8), and dibaryons (6)
 - Cho et al. [ExHIC Collaboration], PRL 106, 212001 (2011); PRC 84, 064910 (2011); coalescence model

Exotic mesons, baryons and dibaryons

Cho, Furumoto, Hyodo, Jido, Ko, Lee, Nielsen, Ohnishi, Sekihara, Yasui, and Yazaki [ExHIC Collaboration],
PRL 106, 212001 (2011); PRC 84, 064910 (2011)

Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.	$\omega^{\text{Mol.}}$ (MeV)	decay mode
Mesons									
$f_0(980)$	980	1	0	0^+	$q\bar{q}, s\bar{s} (L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\pi\pi$ (strong decay)
$a_0(980)$	980	3	1	0^+	$q\bar{q} (L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\eta\pi$ (strong decay)
$K(1460)$	1460	2	$1/2$	0^-	$q\bar{s}$	$q\bar{q}q\bar{s}$	$\bar{K}KK$	69.0(R)	$K\pi\pi$ (strong decay)
$D_s(2317)$	2317	1	0	0^+	$c\bar{s} (L=1)$	$q\bar{q}c\bar{s}$	DK	273(B)	$D_s\pi$ (strong decay)
T_{cc}^{1+}	3797	3	0	1^+	—	$qq\bar{c}\bar{c}$	$\bar{D}\bar{D}^*$	476(B)	$K^+\pi^- + K^+\pi^- + \pi^-$
$X(3872)$	3872	3	0	$1^+, 2^-^*)$	$c\bar{c} (L=2)$	$q\bar{q}c\bar{c}$	$\bar{D}D^*$	3.6(B)	$J/\psi\pi\pi$ (strong decay)
$Z^+(4430)^{+}$	4430	3	1	$0^-^*)$	—	$q\bar{q}c\bar{c} (L=1)$	$D_1\bar{D}^*$	13.5(B)	$J/\psi\pi$ (strong decay)
T_{cb}^0	7123	1	0	0^+	—	$qq\bar{c}\bar{b}$	$\bar{D}B$	128(B)	$K^+\pi^- + K^+\pi^-$
Baryons									
$\Lambda(1405)$	1405	2	0	$1/2^-$	$qqq (L=1)$	$qqqs\bar{q}$	$\bar{K}N$	20.5(R)-174(B)	$\pi\Sigma$ (strong decay)
$\Theta^+(1530)^{+}$	1530	2	0	$1/2^+^*)$	—	$qqqq\bar{s} (L=1)$	—	—	KN (strong decay)
$\bar{K}KN^{+}$	1920	4	$1/2$	$1/2^+$	—	$qqqs\bar{s} (L=1)$	$\bar{K}KN$	42(R)	$K\pi\Sigma, \pi\eta N$ (strong decay)
$\bar{D}N^{+}$	2790	2	0	$1/2^-$	—	$qqqq\bar{c}$	$\bar{D}N$	6.48(R)	$K^+\pi^-\pi^- + p$
$\bar{D}^*N^{+}$	2919	4	0	$3/2^-$	—	$qqqq\bar{c} (L=2)$	$\bar{D}^*N$	6.48(R)	$\bar{D} + N$ (strong decay)
Θ_{cs}^{+}	2980	4	$1/2$	$1/2^+$	—	$qqqs\bar{c} (L=1)$	—	—	$\Lambda + K^+\pi^-$
BN^{+}	6200	2	0	$1/2^-$	—	$qqqq\bar{b}$	BN	25.4(R)	$K^+\pi^-\pi^- + \pi^+ + p$
B^*N^{+}	6226	4	0	$3/2^-$	—	$qqqq\bar{b} (L=2)$	B^*N	25.4(R)	$B + N$ (strong decay)
Dibaryons									
H^{+}	2245	1	0	0^+	$qqqqss$	—	ΞN	73.2(B)	$\Lambda\Lambda$ (strong decay)
$\bar{K}NN^{+}$	2352	2	$1/2$	$0^-^*)$	$qqqqqs (L=1)$	$qqqqq\bar{s}q$	$\bar{K}NN$	20.5(T)-174(T)	ΛN (strong decay)
$\Omega\Omega^{+}$	3228	1	0	0^+	$ssssss$	—	$\Omega\Omega$	98.8(R)	$\Lambda K^- + \Lambda K^-$
H_c^{++}	3377	3	1	0^+	$qqqqsc$	—	$\Xi_c N$	187(B)	$\Lambda K^-\pi^+\pi^+ + p$
$\bar{D}NN^{+}$	3734	2	$1/2$	0^-	—	$qqqqq\bar{q}c$	$\bar{D}NN$	6.48(T)	$K^+\pi^- + d, K^+\pi^-\pi^- + p + p$
BNN^{+}	7147	2	$1/2$	0^-	—	$qqqqq\bar{q}\bar{b}$	BNN	25.4(T)	$K^+\pi^- + d, K^+\pi^- + p + p$

Exotic hadron yields at RHIC and LHC

TABLE V. Exotic hadron yields in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC and in central Pb + Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV at LHC from the quark coalescence ($2q/3q/6q$ and $4q/5q/8q$) and the hadron coalescence (Mol.), as well as from the statistical model (Stat.)

	RHIC				LHC			
	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.
Mesons								
$f_0(980)$	3.8, 0.73($s\bar{s}$)	0.10	13	5.6	10, 2.0 ($s\bar{s}$)	0.28	36	15
$a_0(980)$	11	0.31	40	17	31	0.83	1.1×10^2	46
$K(1460)$	—	0.59	3.6	1.3	—	1.6	9.3	3.2
$D_s(2317)$	1.3×10^{-2}	2.1×10^{-3}	1.6×10^{-2}	5.6×10^{-2}	8.7×10^{-2}	1.4×10^{-2}	0.10	0.35
T_{cc}^{1a}	—	4.0×10^{-5}	2.4×10^{-5}	4.3×10^{-4}	—	6.6×10^{-4}	4.1×10^{-4}	7.1×10^{-3}
$X(3872)$	1.0×10^{-4}	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	1.7×10^{-3}	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}
$Z^+(4430)^b$	—	1.3×10^{-5}	2.0×10^{-5}	1.4×10^{-5}	—	2.1×10^{-4}	3.4×10^{-4}	2.4×10^{-4}
T_{cb}^{0a}	—	6.1×10^{-8}	1.8×10^{-7}	6.9×10^{-7}	—	6.1×10^{-6}	1.9×10^{-5}	6.8×10^{-5}
Baryons								
$\Lambda(1405)$	0.81	0.11	1.8–8.3	1.7	2.2	0.29	4.7–21	4.2
Θ^{+b}	—	2.9×10^{-2}	—	1.0	—	7.8×10^{-2}	—	2.3
$\bar{K}KN^a$	—	1.9×10^{-2}	1.7	0.28	—	5.2×10^{-2}	4.2	0.67
$\bar{D}N^a$	—	2.9×10^{-3}	4.6×10^{-2}	1.0×10^{-2}	—	2.0×10^{-2}	0.28	6.1×10^{-2}
$\bar{D}^*N^a$	—	7.1×10^{-4}	4.5×10^{-2}	1.0×10^{-2}	—	4.7×10^{-3}	0.27	6.2×10^{-2}
Θ_{cs}^a	—	5.9×10^{-4}	—	7.2×10^{-3}	—	3.9×10^{-3}	—	4.5×10^{-2}
BN^a	—	1.9×10^{-5}	8.0×10^{-5}	3.9×10^{-5}	—	7.7×10^{-4}	2.8×10^{-3}	1.4×10^{-3}
B^*N^a	—	5.3×10^{-6}	1.2×10^{-4}	6.6×10^{-5}	—	2.1×10^{-4}	4.4×10^{-3}	2.4×10^{-3}
Dibaryons								
H^a	3.0×10^{-3}	—	1.6×10^{-2}	1.3×10^{-2}	8.2×10^{-3}	—	3.8×10^{-2}	3.2×10^{-2}
$\bar{K}NN^b$	5.0×10^{-3}	5.1×10^{-4}	0.011–0.24	1.6×10^{-2}	1.3×10^{-2}	1.4×10^{-3}	0.026–0.54	3.7×10^{-2}
$\Omega\Omega^a$	3.2×10^{-5}	—	1.5×10^{-5}	6.4×10^{-5}	8.6×10^{-5}	—	4.4×10^{-5}	1.9×10^{-4}
H_c^{++a}	3.0×10^{-4}	—	3.3×10^{-4}	7.5×10^{-4}	2.0×10^{-3}	—	1.9×10^{-3}	4.2×10^{-3}
$\bar{D}NN^a$	—	2.9×10^{-5}	1.8×10^{-3}	7.9×10^{-5}	—	2.0×10^{-4}	9.8×10^{-3}	4.2×10^{-4}
BNN^a	—	2.3×10^{-7}	1.2×10^{-6}	2.4×10^{-7}	—	9.2×10^{-6}	3.7×10^{-5}	7.6×10^{-6}

^aParticles that are newly predicted by theoretical model.

^bParticles that are not yet established.

■ Most yields are sufficient large ($>10^{-5}$)

Ratio of exotic hadron yields from coalescence and statistical models

Coalescence / Statistical model ratio at RHIC

Coalescence / Statistical model ratio at LHC

- Multiquark hadrons are suppressed while hadronic molecules are enhanced in coalescence model, compared to the statistical model predictions

Summary

- Expected yield of $\Theta^+(\text{udud}\bar{s})$ in HIC is large but it is not observed.
- Possible existence of tetraquark meson $T_{cc}(\text{ud}\bar{c}\bar{c})$ and pentaquark baryon $\Theta_{cs}(\text{udus}\bar{c})$ due to attractive diquark spin-spin interaction
- HIC allows for the study of $\Omega\Omega$ interaction and possible existence of $(\Omega\Omega)_{0+}$
- Yield of D_{sj} (2317) in HIC is sensitive to its quark structure
- Yields of exotic hadrons are appreciable in HIC ($>10^{-5}$)
- In the coalescence model, yields of exotic hadrons are sensitive to their structures with molecular-state configurations enhanced and multiquark configurations suppressed relative to statistical production

Resonance production and search for exotica with ALICE at the LHC

Benjamin Dönigus^{1,2} for the ALICE collaboration

¹ Research Division and ExtreMe Matter Institute EMMI, GSI
Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

² Helmholtz Research School H-QM, Frankfurt, Germany

Summary

We shortly described the ALICE setup and the running conditions of the first years data taking. We presented results on the hyperon production (Λ, Ξ, Ω) in pp collisions at 7 TeV and in Pb-Pb collisions at 2.76 TeV. We further discussed the production of resonances in pp and finally showed first results for the search of exotica with ALICE, namely the $\Xi^- \rightarrow \Xi^- \pi^+$ and $H^0 \rightarrow \Lambda p \pi^-$.

Resonances

- ALICE is well suited to do a broad search thanks to excellent particle Identification
- Rich resonance program for pp and Pb-Pb on mesonic and baryonic resonances

Multi-strange baryon production comparing Pb-Pb to pp

- Enhancements with respect to pp collisions confirm the hierarchy based on the strangeness content of the particle
- Comparison with lower energy data shows enhancement decreasing for increasing energy (same trend observed from SPS to RHIC)

HHI workshop - Benjamin Dönigus/ALICE

Anti-Matter production

In the statistics from 2010 Pb-Pb we identified four anti-alphas

The anti-hypertriton was also detected using the 2010 Pb-Pb data

→ 2011 statistics will enhance the yields significantly

Both first observed by the STAR experiment
Science 328, 58 (2010) and Nature 473, 353 (2011)

HHI workshop - Benjamin Dönigus/ALICE

Exotica

ALICE:
There is no indication for the
(dsds $\bar{u}$) pentaquark in pp 7 TeV

NA49:
Claimed “evidence” for the Ξ^{--} (dsds $\bar{u}$) pentaquark
in pp 17.2 GeV PRL 92 (2004) 042003

Experiment	Yield of $\Xi(1530)^0$	Yield of $\Xi(1860)^{--}$	Ratio of Yields
NA49	150	36	4.2
COMPASS	1700	< 79	>21.5
ALEPH	322	<24	>13.4
ALICE	26164	< 846	>31

HHI workshop - Benjamin Dönigus/ALICE

H-Dibaryon

Using the data from 2010, no signal is observed in $\Lambda p \pi^- / \Lambda\Lambda$

HHI workshop - Benjamin Dönig/ALICE

Study of Λ - Λ correlations with the STAR detector at RHIC

Neha Shah

For the STAR collaboration

University of California Los Angeles

Correlation Function for $\Lambda\Lambda$

➤ Purity corrected correlation functions for 0-40 % Au+Au collisions at $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV

➤ Statistical error only

Model fit to Correlation Function for $\Lambda\Lambda$

Model Fit → A. Ohnishi and T. Furumoto (WPCF 2011, Japan)

$\Lambda p \pi$ mass spectrum

- $\Lambda p \pi$ mass spectrum after placing cuts one by one
- Details about the cuts can be found at [arXiv:1112.0590](https://arxiv.org/abs/1112.0590)

Summary

- The Λ - Λ interaction is attractive
- Quark model interaction (FSS2) describes the data fairly for small ΞN coupling as well as without ΞN coupling $\Rightarrow$ consistent with Nagara event
- ND46 shows strong suppression in the presence of ΞN coupling as compared to data
- Preliminary measurement of $\Lambda p \pi$ mass spectrum to look for H signal is presented

Lambda-Lambda Correlation in (K^-, K^+) Reaction and Heavy-Ion Collisions

Akira Ohnishi and Takenori Furumoto

Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

Hyperon-hyperon interaction and the search for the $S = -2$ dibaryon (H) are long standing as well as current interesting subjects. The first prediction of the existence of deeply bound H , 80 MeV below the $\Lambda\Lambda$ threshold, had a strong impact in quark-hadron sciences. While a deeply bound H is denied by the discovery of double hypernuclei, existence of H as a resonance is suggested from the invariant mass spectrum measured in the KEK-E522 experiment. In addition, recent lattice QCD calculations suggest possible existence of H pole around the $\Lambda\Lambda$ threshold [1]. Even if we do not have a pole of H , $\Lambda\Lambda$ interaction is important in order to understand baryon-baryon interaction picture (meson exchange or quark exchange), as well as to understand the EOS of dense neutron star matter, where Λ is considered to emerge abundantly.

The structure of H and $\Lambda\Lambda$ interaction may be probed via the $\Lambda\Lambda$ correlation in heavy-ion collisions (HIC). For example, we have recently demonstrated that the structure of H can be clarified by the production yield in HIC [2]; if the H has a compact $6q$ structure, coalescence of 6 particles in a small volume is suppressed and the H production yield is calculated to be on order smaller than the statistical model estimate. If H has a loosely bound hadronic molecule structure, two hadron coalescence results in the production yield comparable to the statistical model estimate. Another important observable is $\Lambda\Lambda$ correlation. In $(K^-, K^+\Lambda\Lambda)$ reaction, the $\Lambda\Lambda$ invariant mass spectrum is found to be enhanced, and the steep and strong enhancement around $E_{\Lambda\Lambda} \simeq 10 - 20$ MeV cannot be explained by the final state interaction [3]. While the statistics is limited in $(K^-, K^+\Lambda\Lambda)$ reaction, we have a chance to observe $\Lambda\Lambda$ correlation in high-energy HICs with high statistics. We proposed to use $\Lambda\Lambda$ correlation in HICs to judge whether bound H exists or not [3], since the tail region of the wave functions is important to know the existence of a bound state and HICs have a large source size of hadrons.

Recently, STAR collaboration successfully measured the $\Lambda\Lambda$ correlation at RHIC [4]. We have analyzed the data based on a simple assumption of the Gaussian source, $S(\mathbf{r}) \propto \exp(-\mathbf{r}^2/R^2)$, and the correlation function formula. We also considered the feed effect from the decay of Σ^0 which decays into $\Lambda\gamma$ with 100 % branching ratio. The analyzed results are shown in the slide, and can be summarized as $1/a_0 \leq -1 \text{ fm}^{-1}$ and $r_{\text{eff}} > 3 \text{ fm}$ are the preferred condition for the $\Lambda\Lambda$ interaction. The preferred source size depends on the $\Lambda\Lambda$ interaction, but is roughly evaluated as $R \sim 2 \text{ fm}$. In a more detailed analysis, we need to perform coupled channel analysis with ΞN channel, but we have not considered it seriously since its effects may be small and the coupling interaction is uncertain.

We have also examined the preferred $\Lambda\Lambda$ interaction in the $^{12}\text{C}(K^-, K^+\Lambda\Lambda)$ reaction. In addition to cascade processes including quasi-free Ξ and Ξ^* production, heavy-meson production followed and decay [5] and various two step processes [6], Λ evaporation process is found to contribute to low q region [3]. With these in mind, we can conclude that the preferred $\Lambda\Lambda$ interactions in HICs are not inconsistent with the $\Lambda\Lambda$ invariant mass spectra in (K^-, K^+) reactions, except that the resonance H -like enhancement cannot be explained.

Further data on $\Lambda\Lambda$ correlations in HICs with higher statistics and $\Lambda\Lambda$ invariant mass spectrum in, for example, in $^{63}\text{Cu}(K^-, K^+)$ reactions as talked by S. Sato in this workshop, are decisive to pin down the $\Lambda\Lambda$ interaction and H particle.

References

- [1] C.J.Yoon et al.(KEK-E522 collab.), Phys. Rev. C **75** (2007), 022201(R).
- [2] S. Cho et al. (ExHIC collab.), Phys. Rev. Lett. **106** (2011), 212001; Phys. Rev. C **84** (2011), 064910.
- [3] A. Ohnishi, Y. Hirata, Y. Nara, S. Shimura, Y. Akaishi, Nucl. Phys. A **670** (2000), 297c; Few-Body Syst. Suppl. **12** (2000), 367; Nucl. Phys. A **684** (2001), 595c; *ibid* A **691** (2001), 242c.
- [4] Neha Shah et al.(STAR collab.), arXiv:1112.0590.
- [5] C. Gobbi, C. Dover, A. Gal, Phys. Rev. C **50** (1994), 1594.
- [6] Y. Nara, A. Ohnishi, T. Harada, A. Engel, Nucl. Phys. A **614** (1997), 433.

Lambda-Lambda correlation in (K-,K+) reactions and in HIC

Akira Ohnishi, Takenori Furumoto (YITP, Kyoto Univ.)

- Where is the S=-2 dibaryon (uuddss) “H” ?
 - Jaffe's prediction, Nagara Event, $\Lambda\Lambda$ inv. mass spec. (KEK-E522), Lattice QCD predictions,
 - $\Lambda\Lambda$ interaction and the Existence of H as a bound state or resonance is a current interesting problem.

■ $\Lambda\Lambda$ correlation in (K-, K+) reactions and Heavy-Ion Collisions

- Theoretical tool: Correlation function formula

$$C_{\Lambda\Lambda}(q) = \frac{\int dx_1 dx_2 S(x_1, p+q) S(x_2, p-q) |\psi^{(-)}(x_{12}, q)|^2}{\int dx_1 dx_2 S(x_1, p+q) S(x_2, p-q)}$$

$$\simeq 1 - \frac{1}{2} \exp(-q^2 R^2) + \frac{1}{2} \int dr S_{12}(r) (|\chi_0(r)|^2 - |j_0(qr)|^2) \quad (\text{HIC})$$

- Source: Gaussian (HIC), Cascade model results (K-,K+)
- Interaction: ND, NF, NSC89, NSC97, Ehime, fss2
- Other channel: $\Lambda\Lambda$ - ΞN couple channels, Σ^0 decay feed effects

How can we constrain $\Lambda\Lambda$ interaction from HIC data ?

- (1) Fix R from $C(q)$ at large q
- (2) Fix model par. from $C(q)$ at small q
- (3) Compare model predictions

Source size
 $R \sim 2.5$ fm

Σ^0 Decay Effects

- Feed from other particles would modify $\Lambda\Lambda$ corr.
(E.g. $\Lambda \rightarrow p \pi^-$ in pp corr., $\Sigma^0 \rightarrow \Lambda + \gamma$ in $\Lambda\Lambda$ corr.)
 - $Y(\Sigma^0) \sim 0.6 Y(\Lambda)$ (Stat. model) $\rightarrow$ MC results: $0.39 \times (C(q)-1)$
 - 10 % corr. in $\Lambda\Sigma, \Sigma\Sigma$ channel $\rightarrow$ 5 % in $C(q)$

Source size $R \sim 2$ fm

Preferred $\Lambda\Lambda$ Interaction and $\Lambda\Lambda$ corr. in $(K^-, K^+ \Lambda\Lambda)$

- STAR (preliminary) data choose some of the $\Lambda\Lambda$ interaction
 $\rightarrow 1/a_0 < -1 \text{ fm}^{-1}$, $r_{\text{eff}} > 3 \text{ fm}$ seems to be preferred.
- These $\Lambda\Lambda$ interactions are consistent (not inconsistent) with $\Lambda\Lambda$ invariant mass spectrum in $^{12}\text{C}(K^-, K^+ \Lambda\Lambda)$ reaction (E224, E522), while we cannot explain the enhancement at 10-25 MeV.

Questions and Answers

- Why do you use potential models rather than analyzing with scattering length (a_0) and effective range (r_{eff}) ? As far as the interaction range is much smaller than the source size, these are enough to explain the correlation. (Schaffner-Bielich, Lednicky)
 - For hadronic interactions with strangeness, couple channel effects are generally important for complete analysis. Toward this, we use potential models as a whole including coupling potentials.
- What happens when $\Lambda\Sigma^0$ correlation is strong ? (Rijken)
 - $\Lambda\Lambda$ correlation is modified, and we have to judge the interaction model as a whole. In principle, experiments can fix $\Lambda\Sigma$ - interaction from correlations.
- What happens when $\Lambda\Lambda$ - ΞN coupling is strong ? (Ko)
 - Coupling acts as the imaginary part, and suppresses $C(q)$ at low q .
- How $C(q)$ is related to a_0 ? (Miller)
 - If int. range $\ll$ source size, we get $C(Q \rightarrow 0) \simeq \frac{1}{2} - \frac{2}{\sqrt{\pi}} \frac{a_0}{R} + \left(\frac{a_0}{R}\right)^2$
Existence of loose bound state leads to strong suppression.

Hyperon Physics at Hall B, Jefferson Lab

Lei Guo

Florida International University
for the CLAS Collaboration

March 7, 2012

Abstract

In the past decade, tremendous amount of data have been collected by the CLAS Collaboration on hyperon physics. For the $S=-1$ hyperons, various differential and total cross sections have been measured for Λ , Σ , and other excited $S=-1$ hyperons in both photoproduction and electroproduction on nucleon targets. The decay of nucleon resonances into kaon and hyperons are believed to be an important component of the N^* program at CLAS. In addition to the N^* component, the polarization observable also offers unique perspective into the production mechanisms of the hyperons. Furthermore, CLAS has proved that photon beam is a useful alternative to kaon beam for Ξ production. The $\Xi^-(1320)$ cross section has been measured for photon energies up to 4.8 GeV, and its polarization are also being investigated in photoproduction experiments with and without beam polarization. As part of the Jefferson Lab 12GeV upgrade effort, the CLAS12 will be able to produce copious data on hyperons with $S=-1$ to $S=-3$, including excited Λ 's, Σ 's, Ξ 's and Ω , providing a unique opportunity to discover unobserved resonances, particularly in the Ξ sector.

Λ Polarization: Photoproduction

R. Bradford *et al.*, Phys. Rev. C **75**, 035205 (2007).

$$R \equiv \sqrt{P^2 + C_x^2 + C_z^2}$$

$$\bar{R} = 1.01 \pm 0.01$$

- consistent with unity
- 100% polarization with circularly polarized beam
- Unexpected by hadrodynamic models

Induced polarization of Λ in $\gamma p \rightarrow K^+/K^{*+}\Lambda$

$K^+/K^{*+}\Lambda$ contribution to N^* are
 comparable
 Λ recoil polarization shows 0-crossing
 in both channels

Recent CLAS6 results on Ξ

E_γ : 2.8-3.8 GeV

Guo et al, Phys.Rev.C76:025208 (2007)

- Non-dedicated data, low beam energy, no vertex detector ...
- First high statistics exclusive γp experiment
- Future dedicated program at JLAB feasible and promising

- Data qualitatively consistent with t-channel hyperon production
- High spin hyperon resonances needed ($J \geq 3/2$)

Ξ^- induced polarization in photoproduction

This data (2004, 2.8-3.8GeV): No beam/target polarization

New data (2008: 3.6-5.4GeV): Circularly polarized photon beam.

Ongoing

The only direction Ξ can be polarized is out of plane

(Parity conservation)

CLAS12 (with FT): polarization transfer for Ξ^-

P_γ (10-70%), known on a event by event basis

Summary

- Many results for $S=-1$ hyperons have been published by CLAS
 - KY contribution to N^* being determined
 - Polarization observables yield many interesting, and sometimes unexpected results
- CLAS12 could be a factory for the underexplored Ω/Ξ baryons
 - Ω^- : Cross section can be measured
production mechanism can be investigated
 - Excited cascade resonances:
Spin-Parity can be determined
- $\Xi(1320)$ polarization: Insight to the production mechanisms
- Λ/Ξ polarization measurement in target fragmentation region possible at CLAS12
- More exciting hyperon results to come from CLAS6/CLAS12

Femtoscopic Correlations and Final State Interactions

R. Lednický @ JINR Dubna & IP ASCR Prague

- History
- Assumptions
- Correlation study of strong interaction
- Conclusions

29.2.2012

RBK Hyperon Workshop, BMJ 2012

1

QS symmetrization of production amplitude
 → momentum correlations of identical particles are
 sensitive to space-time structure of the source

Final State Interaction

Similar to Coulomb distortion of β -decay $\langle \psi_{-k}(r) |^2 \rangle$

$\Rightarrow$ FSI is sensitive to source size r and scattering amplitude f

It complicates CF analysis but makes possible

- $\rightarrow$ Femtoscopy with nonidentical particles $\pi^+\pi^0, \pi^+\pi^+\pi^-, \pi^+\pi^+\pi^+\pi^-, \dots$ & Coalescence $\pi^+\pi^0, \pi^+\pi^+\pi^-, \pi^+\pi^+\pi^+\pi^-, \dots$
- $\rightarrow$ Study “exotic” scattering $\pi^+\pi^0, \pi^+\pi^+\pi^-, \pi^+\pi^+\pi^+\pi^-, \dots$
- $\rightarrow$ Study relative space-time asymmetries $\pi^+\pi^0, \pi^+\pi^+\pi^-, \pi^+\pi^+\pi^+\pi^-, \dots$

Assumptions to derive “Fermi” formula for CF

$$CF = \langle |\psi_{k^*}(r^*)|^2 \rangle$$

- two-particle approximation (small freezeout PS density f)
 $\sim OK, \langle f \rangle \ll 1$? low p_t
- smoothness approximation: $\langle \Delta p \rangle \gg \langle q \rangle_{\text{correl}} \Leftrightarrow R_{\text{emitter}} \ll R_{\text{source}}$
 $\sim OK$ in HIC, $R_{\text{source}}^2 \gg 0.1 \text{ fm}^2 \approx p_t^2$ -slope of direct particles usually OK
- equal time approximation in PRF
 $t_{\text{freeze}} \approx t_{\text{freeze}}^* \rightarrow \text{eq. time condition } |t^*| \ll \mu r^2 \text{ to several \%}$
- $t_{\text{FSI}} = d\delta/dE \gg t_{\text{prod}}$
 $t_{\text{FSI}} (\text{s-wave}) = \mu f_0/k^* \Rightarrow k^* = 1/2 q \ll \text{hundreds MeV/c}$
 $\approx \text{typical momentum transfer in the production process}$
- & account for coupled channels within the same isomultiplet only:
 $\pi^+ \pi^- \leftrightarrow \pi^0 \pi^0, \pi^+ p \leftrightarrow \pi^0 n, K^+ K^- \leftrightarrow K^0 \bar{K}^0, \dots$
- $t_{\text{FSI}} (\text{resonance in any L-wave}) = 2/\Gamma \Rightarrow \Gamma \ll \text{hundreds MeV/c}$

Pair purity problem for CF(pΛ)@STAR

Particle	Identification	Fraction Primary
p	$76 \pm 7\%$	$52 \pm 4\%$
$\bar{p}$	$74 \pm 7\%$	$48 \pm 4\%$
Λ	$86 \pm 6\%$	$45 \pm 4\%$
$\bar{\Lambda}$	$86 \pm 6\%$	$45 \pm 4\%$

⇒ **PairPurity ~ 15%**

Assuming no correlation for misidentified particles and particles from weak decays

$$\rightarrow C_{measured}^{corr}(k^*) = \frac{C_{measured}(k^*) - 1}{\text{PairPurity}} + 1$$

← Fit using RI-Lyuboshitz'82 (for np)

$$C(k^*) = 1 + \sum_s \rho_s \left[\frac{1}{2} \left| \frac{f^s(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0^s}{2\sqrt{\pi}r_0} \right) + \frac{2\Re f^s(k^*)}{\sqrt{\pi}r_0} F_1(Qr_0) - \frac{2\Im f^s(k^*)}{r_0} F_2(Qr_0) \right],$$

where $F_1(z) = \int_0^z dx e^{x^2 - z^2}/z$ and $F_2(z) = (1 - e^{-z^2})/z$.

$$f^s(k^*) = \left(\frac{1}{f_0^s} + \frac{1}{2} d_0^s k^{*2} - i k^* \right)^{-1}$$

Pairs	Fractions (%)
$p_{\text{prim}} - \Lambda_{\text{prim}}$	15
$p_{\Lambda} - \Lambda_{\text{prim}}$	10
$p_{\Sigma^{+-}} - \Lambda_{\text{prim}}$	3
$p_{\text{prim}} - \Lambda_{\Sigma^0}$	11
$p_{\Lambda} - \Lambda_{\Sigma^0}$	7
$p_{\Sigma^{+-}} - \Lambda_{\Sigma^0}$	2
$p_{\text{prim}} - \Lambda_{\Xi}$	9
$p_{\Lambda} - \Lambda_{\Xi}$	5
$p_{\Sigma^{+-}} - \Lambda_{\Xi}$	2

← but, there can be residual correlations for particles from weak decays requiring knowledge of $\Lambda\Lambda$, $p\Sigma$, $\Lambda\Sigma$, $\Sigma\Sigma$, $p\Xi$, $\Lambda\Xi$, $\Sigma\Xi$ correlations

Summary

- Assumptions behind femtoscopy theory in HIC seem OK at $k \rightarrow 0$. At $k > \sim 100$ MeV/c, the **r-k correlation** requires a generalization of the usual smoothness approximation.
- Wealth of data on correlations of various particle species ($\pi^\pm, K^\pm, p^\pm, \Lambda, \Xi$) is available & gives unique space-time info on production characteristics including collective flows.
- Info on two-particle strong interaction: $\pi\pi$ & $\Lambda\Lambda$ & $\bar{p}\Lambda$ scattering lengths comes from HIC data at SPS and RHIC. Good perspective at RHIC and LHC (a problem of residual correlations is to be solved).
- An evidence on $\Lambda\Lambda$ potential core from LEP (however, a small source size questions the smoothness approximation).

Baryon-Baryon Interactions for
 $S=0,-1,-2,-3,-4$
Recent Nijmegen Extended-Soft-Core
ESC08-models

Hyperon-Hyperon Interactions and Searches for
Exotic D-Hyperons in Nuclear Collisions

BNL, February 29 - March 2, 2012

Th.A. Rijken, M.M. Nagels , Y. Yamamoto

IMAPP, University of Nijmegen

2 Role BB-interaction Models

Particle and Flavor Nuclear Physics

- Concepts:

QCD: Colored quarks + gluons
Confinement $SU_c(3)$
Strong coupling $g_{QCD} \approx 1$
Lattice QCD: flux-tubes/strings
Flavor SU_f -symmetry
Spontaneous CSB

BB-interaction
models

Principle: "Experientia ac ratione"

(Christiaan Huygens 1629-1695)

Experiments:

NN-scattering
YN- & YY-scattering
Nuclei & Hypernuclei
Nuclear- & Hyperonic matter
Neutron-star matter

3 Nijmegen ESC-models

Recent Baryon-baryon ESC Interactions

- Extended-soft-core Baryon-baryon Model ESC04/08
- Recent publications ESC-model:
 - I, Nucleon-nucleon Interactions,
Rijken, Phys.Rev. C73, 044007 (2006)
 - II, Hyperon-nucleon Interactions,
Rijken & Yamamoto, Phys.Rev. C73, 044008 (2006)
 - III, $S = -2$ Hyperon-hyperon/nucleon Interactions,
Rijken & Yamamoto, arXiv:nucl-th/060874 (2006)
 - IV, Baryon-Baryon Interactions and Hypernuclei,
Rijken & Nagels & Yamamoto, P.T.P. Suppl. 185 (2011)
 - V, $S = 0, -1, -2$ Nucleon-/nucleon/hyperon Interactions,
Rijken & Nagels & Yamamoto, to be published (2012)
 - VI, $S = -3, -4$ Nucleon-/nucleon/hyperon Interactions,
Rijken & Nagels, to be published (2012)

-
-
- ESC08 = ESC04 + quark-core effects + ALS-corrections.

4 ESC-model, dynamical contents

ESC08c: Soft-core $NN + YN + YY$ ESC-model

- extended ESC04-model, PRC73 (2006)
- NN: 20 free parameters: couplings, cut-off's, meson mixing and F/(F+D)-ratio's
- meson nonets:
 - $J^{PC} = 0^{-+}$: π, η, η', K ; $= 1^{--}$: ρ, ω, ϕ, K^*
 - $= 0^{++}$: $a_0(962), f_0(760), f_0(993), \kappa_1(900)$
 - $= 1^{++}$: $a_1(1270), f_1(1285), f_0(1460), K_a(1430)$
 - $= 1^{+-}$: $b_1(1235), h_1(1170), h_1(1380), K_b(1430)$
- soft TPS: two-pseudo-scalar exchanges,
- soft MPE: meson-pair exchanges: $\pi \otimes \pi, \pi \otimes \rho, \pi \otimes \epsilon, \pi \otimes \omega$, etc.
- pomeron/odderon exchange $\Leftrightarrow$ multi-gluon / pion exchange
- quark-core effects,
- gaussian form factors, $\exp(-\mathbf{k}^2/2\Lambda_{B'BM}^2)$
- Simultaneous NN+YN Data (constrained) fit, 4301 NN-data, 52 YN-data:
 1. Nucleon-nucleon: $pp + np, \chi_{dpt}^2 = 1.08(!)$
 2. Hyperon-nucleon: $\Lambda p + \Sigma^\pm p, \chi_{dpt}^2 \approx 1.00$

5 QPC: ${}^3S_1 + {}^3P_0$ -model and ESC08c

ESC08c Couplings and ${}^3S_1 + {}^3P_0$ -Model Description

Meson	$r_M [fm]$	γ_M	3S_1	3P_0	QPC	ESC08c
$\pi(140)$	0.23	5.51	$g=-3.54$	$g=+7.40$	3.87 (4.07)	3.64
$\eta(957)$	0.71	2.22	$g=-2.83$	$g=+5.93$	3.10 (3.72)	3.07
$\rho(770)$	0.71	2.37	$g=-0.24$	$g=+0.99$	0.75 (0.92)	0.73
$\omega(783)$	0.71	2.35	$g=-1.10$	$g=+4.60$	3.50 (3.45)	3.51
$a_0(962)$	0.81	2.22	$g=+0.28$	$g=+0.58$	0.86 (0.90)	0.89
$\epsilon(760)$	0.71	2.37	$g=+1.42$	$g=+2.96$	4.38 (4.37)	4.36
$a_1(1270)$	0.61	2.09	$g=-0.20$	$g=-0.84$	-1.05 (-1.06)	-1.10
$f_1(1420)$	0.61	2.09	$g=-0.72$	$g=-3.03$	-3.76 (-3.25)	-0.91

- Weights ${}^3S_1/{}^3P_0$ are $A/B = 0.323/0.677 \approx 1 : 2$.
- SU(6)-breaking: (56) and (70) irrep mixing, $\varphi = -22^\circ$.
- QCD pair-creation constant: $\gamma(\alpha_s = 0.30) = 2.19$.
- QCD cut-off: $\Lambda_{QCD} = 244.3 \text{ MeV}$, QQG form factor: $\Lambda_{QQG} = 986.2 \text{ MeV}$.
- ESC08c: Pseudoscalar and axial mixing angles: -13° and $+50^\circ$.

6 Conclusions and Status YN-interactions

Conclusions and Prospects

1. High-quality Simultaneous Fit/Description $NN \oplus YN$,
OBE, TME, MPE meson-exchange dynamics.
 $SU_f(3)$ -symmetry, (Non-linear) chiral-symmetry.
2. NN, YN, YY : Couplings $SU_f(3)$ -symmetry, 3P_0 -dominance QPC,
Quark-core effect: $^3S_1(\Sigma N, I = 3/2)$ is strongly repulsive,
3. Scalar-meson nonet structure $\Leftrightarrow$ Nagara $\Delta B_{\Lambda\Lambda}$ values.
4. NO $S=-1$ Bound-States, NO $\Lambda\Lambda$ -Bound-State,
5. Prediction: $D_{\Xi N} = \Xi N(I = 1, ^3S_1)$ B.S.!, $D_{\Xi\Xi} = \Xi\Xi(I = 1, ^1S_0)$ B.S. (?)

Status meson-exchange description of the YN/YY-interactions:

- a. ESC08: Excellent G-matrix predictions for the $U_\Lambda, U_\Sigma, U_\Xi$ well-depth's,
 ΛN spin-spin and spin-orbit, and Nagara-event okay.
- b. Similar role tensor-force in 3S_1 NN -, $\Lambda/\Sigma N$ -, ΞN -, and $\Lambda/\Sigma\Xi$ -channels.
- c. Neutron Star mass $M/M_\odot = 1.44 \Leftrightarrow$ Multi-Pomeron Repulsion.

- JPARC, FINUDA, FAIR: new data Hypernuclei, $\Sigma^+ P, \Lambda P$!!

Recent topics in Hypernuclear physics and Perspective at J-PARC

Tomofumi NAGAE

Kyoto University

- Introduction to Strangeness Nuclear Physics
- Recent Topics and Perspective in Strangeness Nuclear Physics
 - $S=-1$ Baryon Systems
 - $S=-2$ Baryon Systems
 - Kaonic Nuclei
- Summary

Hadron Experimental Hall @J-PARC

World highest intensity Kaon beams!

First beam in Feb. 2009

Beam recovery in Feb. 2012 after the Earthquake

60m x 56m

Success of (π^+, K^+) Spectroscopy

H. Hotchi et al., PRC 64, 044302(2001)

▪ Λ single-particle energy

→ $U_{\Lambda} = 28 \text{ MeV}$

Hypernuclear Gamma-rays

by H. Tamura

Spectroscopic Study of Ξ -Hypernucleus, $^{12}_{\Xi}\text{Be}$, via the $^{12}\text{C}(K^-, K^+)$ Reaction

J-PARC E05
 T. Nagae et al.

- Discovery of Ξ -hypernuclei
- Measurement of Ξ -nucleus potential depth and width of $^{12}_{\Xi}\text{Be}$ $S=-1$

K⁻pp search experiments at J-PARC

- ${}^3\text{He}(\text{K}^-, n)$ reaction at 1 GeV/c: E15
- $d(\pi^+, \text{K}^+)$ reaction at 1.5 GeV/c: E27

- ▶ $\text{K}^- + {}^3\text{He} \rightarrow n + (\text{K}^-\text{pp})$
- ▶ $(\text{K}^-\text{pp}) \rightarrow \Lambda + p$

mass resolution for K⁻pp

invariant mass
 $\sigma = 19 \text{ MeV}/c^2$ ($\sigma_{\text{CDC}} = 250 \mu\text{m}$)

missing mass
 $\sigma = 12 \text{ MeV}/c^2$ ($\sigma_{\text{ToF}} = 150 \text{ ps}$)

Latest results on Hypernuclear Physics from the FINUDA Experiment

E. Botta^{a,b},

^a*INFN Sez. di Torino, via P. Giuria 1, Torino, Italy*

^b*Dip. di Fisica, Università di Torino, via P. Giuria, 1 Torino, Italy*

Abstract

An overview of the most recent results obtained by the FINUDA Collaboration is presented. The FINUDA experiment collected data to study the production of hypernuclei on different nuclear targets. The hypernucleus formation occurred through the strangeness-exchange reaction $K_{stop}^- + {}^A Z \rightarrow {}_\Lambda^A Z + \pi^-$. From the analysis of the momentum of the emerging π^- , binding energies and formation probabilities of ${}^7\text{Li}$, ${}^9\text{Be}$, ${}^{13}\text{C}$ and ${}^{16}\text{O}$ have been measured and are here discussed.

The FINUDA experiment has also completed an extensive study of the weak decay of p -shell Λ -Hypernuclei including both Mesonic and Non-Mesonic modes. Charged Mesonic Decay rates have been determined based on the analysis of π^- kinetic energy spectra, never measured before. The study of proton spectra from Non-Mesonic Weak Decay for p -shell Hypernuclei, both single and in coincidence with a neutron, has triggered the investigation of the two nucleon-induced $\Lambda NN \rightarrow nNN$ decay channel: its weight has been evaluated to be $\Gamma_2/\Gamma_{NM} = 0.21 \pm 0.07_{\text{stat}} \pm 0.03_{\text{sys}}$. A direct experimental evidence of the occurrence of the weak reaction $\Lambda np \rightarrow nnp$ in nuclei is presented for the first time. Three events have been found which can be attributed to ${}^7_\Lambda\text{Li}$ and ${}^9_\Lambda\text{Be}$ two nucleon-induced Non Mesonic Weak Decay.

Finally, evidence for the neutron-rich hypernucleus ${}^6_\Lambda\text{H}$ has been obtained by studying (π^+, π^-) pairs in coincidence from the $K_{stop}^- + {}^6\text{Li} \rightarrow {}^6_\Lambda\text{H} + \pi^+$ production reaction followed by ${}^6_\Lambda\text{H} \rightarrow {}^6\text{He} + \pi^-$ weak decay. The production rate of ${}^6_\Lambda\text{H}$ is determined to be $(5.9 \pm 4.0) \cdot 10^{-6}/K_{stop}^-$. Its binding energy, evaluated jointly from production and decay, is $B_\Lambda({}^6_\Lambda\text{H}) = (4.0 \pm 1.1)$ MeV with respect to the ${}^5\text{H} + \Lambda$ unbound system.

1. Introduction

FINUDA (acronym for FIsica NUcleare a DAΦNE) was a hypernuclear physics experiment installed at one of the two interaction regions of the DAΦNE e^+e^- collider, the INFN-LNF Φ(1020)-factory. A detailed description of the experimental apparatus can be found in Ref. [1]. The layout figured a cylindrical symmetry arrangement; here we briefly sketch its main components moving outwards from the beam axis: the *interaction/target region*, composed by a barrel of 12 thin scintillator slabs (TOFINO), surrounded by an octagonal array of Si microstrips (ISIM) facing eight target tiles; the *tracking device*, consisting of four layers of position sensitive detectors (a decagonal array of Si microstrips (OSIM), two octagonal layers of low mass drift chambers (LMDC) and a stereo system of straw tubes (ST)) arranged in coaxial geometry; the *external time of flight detector* (TOFONE), a barrel of 72 scintillator slabs. The whole apparatus was placed inside a uniform 1.0 T solenoidal magnetic field; the tracking volume was immersed in He atmosphere to minimize the multiple scattering effect.

The main features of the apparatus were the thinness of the target materials needed to stop the low energy (~ 16 MeV) K^- 's from the $\Phi \rightarrow K^- K^+$ decay channel ($\sim 49\%$), the high transparency of the FINUDA tracker and the very large solid angle ($\sim 2\pi$ sr) covered by the detector ensemble; accordingly, the FINUDA apparatus was suitable to study simultaneously the formation and the decay of Λ hypernuclei by means of high resolution magnetic spectroscopy of the emitted charged particles. Moreover, since the K^+ decays more abundantly into a $\mu^+ + \nu_\mu$ with a well known branching ratio, this reaction, occurring at rest in the targets, provides in FINUDA a unique reference both for energy and absolute rate measurements. It must also be underlined that the possibility of housing up to eight different targets simultaneously allows to have a high degree of flexibility, while avoiding possible systematic errors in comparing the properties of different Hypernuclei.

The main items of the FINUDA scientific program are the study of both the structure of hypernuclei produced by the strangeness-exchange reaction, $K_{stop}^- + {}^A Z \rightarrow {}^A_\Lambda Z + \pi^-$, and their weak decay modes; the mesonic decay (MWD) is studied in the charged mode ${}^A_\Lambda Z \rightarrow ({}^{A+1})Z + \pi^-$ and the non mesonic decay (NMWD), in the charged one-nucleon induced ${}^A_\Lambda Z \rightarrow ({}^{A-2})(Z-1) + p + n$ and in the two-nucleon induced ${}^A_\Lambda Z \rightarrow ({}^{A-3})(Z-1) + p + n + n$ modes.

FINUDA collected data in two different periods. The data discussed in the following were collected mainly in the second data taking lasted from November 2006 to June 2007 with an integrated luminosity of 966 pb^{-1} . The targets were two of ${}^6\text{Li}$, two of ${}^7\text{Li}$, two of ${}^9\text{Be}$, one of ${}^{13}\text{C}$ and one of D_2O . In the following results coming from the first data taking in 2003-2004, with an integrated luminosity of $\sim 220 \text{ pb}^{-1}$, concerning three targets of ${}^{12}\text{C}$ are also discussed.

2. p-shell Hypernuclei structure

The FINUDA Collaboration published recently [2] new data on the spectroscopy of ${}^7_\Lambda\text{Li}$, ${}^9_\Lambda\text{Be}$, ${}^{13}_\Lambda\text{C}$ and ${}^{16}_\Lambda\text{O}$ produced by K^- at rest. The measured pattern of excited states is similar to that obtained with the (π^+, K^+) reaction at 1.05 GeV/c (KEK - E336); this agreement is expected since the two experiment feature a comparable energy resolution

and a comparable momentum transfer (300 MeV/c) to the produced Λ hyperon. As an example, the spectrum obtained with the ^{16}O target is shown by Fig. 1 left. The only

Fig. 1. Left: excitation energy spectrum of ^{16}O obtained with the $(K_{\text{stop}}^-, \pi^-)$ reaction by FINUDA [2]. In the inset the binding energy distribution for a sample free from the K^- in flight decay background is shown. Right: formation probabilities from FINUDA (a) and cross section from E336 (b) for bound states. In (c) the ratio between the two is shown. From Ref. [2].

disagreement was found for the binding energy of the ground state of $^{16}_{\Lambda}\text{O}$, 13.4 ± 0.4 MeV, to be compared with 12.42 ± 0.05 MeV obtained at KEK. In spite of the larger error, the value from FINUDA can be considered more reliable since it agrees with a previous measurement with stopped K^- (12.9 ± 0.4 MeV) and with a recent result on the $(e, e'K^+)$ electroproduction reaction on ^{16}O leading to the formation of $^{16}_{\Lambda}\text{N}$ (13.76 ± 0.16 MeV). Furthermore, FINUDA had the advantage of a continuous self-calibrating control on the stability on the absolute value of the momenta of the spectroscopied pions by means of the monochromatic μ^+ from the $K_{\mu 2}$ decay. For full details see [2].

To draw from the data on K^- capture probabilities of formation a simple A -dependence for the examined p -shell Hypernuclei only well defined Hypernuclides were considered, by choosing only excited states with energy below the threshold for the decay by nucleon emission. Fig. 1 right (a) shows a plot of the capture rates chosen following the above criterion as a function of A . A smoothly decreasing behavior appears, with the exception of a strong enhancement corresponding to the formation of $^{12}_{\Lambda}\text{C}$ bound states. Fig. 1 right (b) shows for comparison the differential cross section integrated in the forward direction (2° – 14°) for the production of the same states observed with the (π^+, K^+) reaction and Fig. 1 right (c) the ratio between the two values. This ratio shows a distinct A -dependence for the two reactions, K^- capture at rest and in-flight (π^+, K^+) . The strong A -dependence of the $(K_{\text{stop}}^-, \pi^-)$ rates with respect to the weak dependence of the (π^+, K^+) differential cross sections reflects the sizable difference between the strongly attractive K^- -nuclear interaction at threshold and the weakly repulsive K^+ -nuclear interaction. This remark was the starting point for an attempt to determine the value of

Re V_{K-} , quite important for several items of K-nuclear Physics. Theoretical approaches varying from shallow potentials (40-60 MeV) at threshold to very deep density dependent potentials (150-200) MeV were in fact proposed. The comparison of the experimental formation rates with the calculations performed with a shallow or deep potential slightly favored the second one.

3. p-shell Hypernuclei Weak Decay

The study of the Weak Decay of Hypernuclei requires the detection of pions and nucleons, produced in the MWD and NMWD decay modes respectively, in coincidence with the π^- signalling the formation of the ground state or of a low-lying excited state of the Hypernucleus.

In particular, for the study of MWD, ${}^A_\Lambda Z \rightarrow ({}^{A+1})Z + \pi^-$, the low momentum decay π^- (80-110 MeV/c) has to be searched in coincidence within a quite tight window (6-12 MeV/c) in the production π^- spectrum. The FINUDA experiment performed a systematic study of the charged mesonic weak decay channel of p-shell Λ -hypernuclei [3]. Negatively charged pion spectra from mesonic decay were measured with magnetic analysis for the first time for ${}^7_\Lambda\text{Li}$, ${}^9_\Lambda\text{Be}$, ${}^{11}_\Lambda\text{B}$ and ${}^{15}_\Lambda\text{N}$. The shape of the π^- spectra was interpreted through a comparison with pion distorted wave calculations that take into account the structure of both hypernucleus and daughter nucleus (see [3] for full details). Branching ratios $\Gamma_{\pi^-}/\Gamma_{tot}$ were derived from the measured spectra and converted to π^- decay rates Γ_{π^-} by means of known or extrapolated total decay widths Γ_{tot} of p-shell Λ -hypernuclei. Based on these measurements, the spin-parity assignment $1/2^+$ for ${}^7_\Lambda\text{Li}$ and $5/2^+$ for ${}^{11}_\Lambda\text{B}$ ground-state are confirmed and a spin-parity $3/2^+$ for ${}^{15}_\Lambda\text{N}$ ground-state has been assigned for the first time. The systematic study performed by FINUDA on p-shell Hypernuclei MWD had thus allowed to demonstrate the correctness of the hypotheses underlying the spectroscopic calculations and to affirm that the spectroscopy of MWD π^- can be used as a tool for the study of the hypernuclear structure complementary to the γ -ray spectroscopy of their low-lying state de-excitation.

For the study of NMWD, ${}^A_\Lambda Z \rightarrow ({}^{A-2})(Z-1) + p + n$, in a first step, a proton was searched in coincidence within the same tight window (6-12 MeV/c) in the production π^- spectrum. In FINUDA the proton momentum was measured by magnetic analysis, with an excellent resolution and without distortion of the spectra due to the target thickness. A further advantage of FINUDA was its lower energy threshold (15 MeV). In a first analysis proton energy spectra coming from NMWD of ${}^5_\Lambda\text{He}$, ${}^7_\Lambda\text{Li}$ and ${}^{12}_\Lambda\text{C}$ were studied [4]. All of them show a quite similar shape, i.e. a peak at around 80 MeV, with a low energy rise, due to Final State Interaction (FSI) and 2N-induced weak decays ($\Lambda + (np) \rightarrow n + n + p$, $\Lambda + (pp) \rightarrow n + p + p$). If the low energy rises were predominately due to FSI effect one should naturally expect that the broad peak structure at 80 MeV (coming from clean $\Lambda p \rightarrow np$ weak processes broadened by the Fermi motion of nucleons) were smeared out for the heavier nuclei. Concerning the 2N-induced NMWD, if the weak decay Q-value is shared by three nucleons, a low-energy rise may exist even for the very light s-shell Hypernuclei. The first FINUDA data, thus, seem to indicate a substantial contribution of the two-nucleon induced NMWD. Triggered by this observation, proton spectra for all other p-shell hypernuclei were studied. These spectra feature a similar behaviour, i.e., the presence of a structure around 80 MeV even for ${}^{16}_\Lambda\text{O}$.

A technique was devised to disentangle the contribution coming from the two-nucleon induced decays, from the one-nucleon induced decays with FSI [1]. The systematics in the mass number range $A = 5 - 16$, covered by FINUDA was exploited. Each spectrum was fitted, for a proton kinetic energy from 80 MeV onwards, with a Gaussian function to determine, through its mean value, the energy corresponding to the maximum of the one-proton induced contribution. The spectrum was then divided in two parts, one below the mean value, with area A_{low} , and one above it, with area A_{high} . It was assumed the first part to be populated by one-proton induced decays, two-nucleon induced decays and FSI processes, while the second part has contributions from one-proton induced decays and FSI, neglecting the two-nucleon induced decays, which, above 70 MeV, accounts for only 5% of the total two-nucleon induced strength.

With the assumption that the FSI effects are proportional to A and that the Γ_2/Γ_p is constant in the $A = 5 - 16$ Hypernuclear mass range, we found [1]:

$$\frac{\Gamma_2}{\Gamma_p} = 0.43 \pm 0.25 . \quad (1)$$

In order to determine $\Gamma_2/\Gamma_{\text{NM}}$, the average of the values of Γ_n/Γ_p from KEK experiments was used. The result is:

$$\frac{\Gamma_2}{\Gamma_{\text{NM}}} = 0.24 \pm 0.10 . \quad (2)$$

This value is in agreement with the theoretical predictions and the latest KEK experimental results. See [1] for full details.

A similar approach was used later by FINUDA to extract the $\Gamma_2/\Gamma_{\text{NM}}$ ratio for $A = 5-16$ Hypernuclei using np coincidence spectra [5]. We selected (π^-, n, p) coincidence events with a π^- in the momentum region corresponding to the formation of a ground state hypernucleus, and a proton with a kinetic energy more than 20 MeV lower than the mean value μ of the Gaussian function determined in [1], $E_p < (\mu - 20 \text{ MeV})$, and an opening angle between the two emitted nucleons, $\cos\theta(np) \geq -0.8$. These selections enhanced the contribution of two nucleon-induced weak decays.

Also in this case we applied the same considerations on the A -dependence of FSI and Γ_2/Γ_p used for the study of the single proton spectra, obtaining finally:

$$\frac{\Gamma_{np}}{\Gamma_p} = 0.39 \pm 0.16_{\text{stat}} \begin{smallmatrix} +0.04 \text{ sys} \\ -0.03 \text{ sys} \end{smallmatrix} . \quad (3)$$

The obtained Γ_{np} width can be used to evaluate $\Gamma_2/\Gamma_{\text{NM}}$; moreover, assuming again the same Γ_n/Γ_p value used in (2) we found:

$$\frac{\Gamma_2}{\Gamma_{\text{NM}}} = 0.21 \pm 0.07_{\text{stat}} \begin{smallmatrix} +0.03 \text{ sys} \\ -0.02 \text{ sys} \end{smallmatrix} , \quad (4)$$

where the error is reduced with respect to that of Ref. [1]. It is worthwhile to notice that the two values obtained by FINUDA are not independent from each other, since the proton required in coincidence with a π^- in Ref. [1] and with a (π^-, n) pair in Ref. [5] belongs to the same experimental sample. To compare with the KEK-E508 determination, the FINUDA value affected by a smaller error [5], can be used: the two results are completely compatible within errors.

Finally, thanks to the large solid angle coverage of the FINUDA apparatus ($\sim 2\pi$ sr) and to its detection efficiency for neutrons and for protons with low kinetic energy, it has been possible to find three events [6] in which also the second neutron from pn -induced NMWD, ${}^A_\Lambda Z \rightarrow ({}^{A-3})(Z-1) + p + n + n$, was detected, two of them originating from ${}^7\text{Li}$ and one from ${}^9\text{Be}$ targets. From the kinematical analysis it is possible to conclude that they can be safely attributed to 2N-induced NMWD of ${}^7_\Lambda\text{Li}$ and ${}^9_\Lambda\text{Be}$.

4. ${}^6_\Lambda\text{H}$ observation

Hypernuclei with a neutron or proton excess are suitable systems for studying the ΛN effective interaction, the Λ -nucleus mean field potential and the behaviour of the Λ hyperon in a low density neutron or proton halo matter. Relevant contributions of the coherent ΛN - ΣN coupling and the associated ΛNN three-body interaction are predicted for Hypernuclei with a neutron excess. Studies of neutron-rich Hypernuclei could thus put constraints on the ΛNN interaction.

Very recently, the full statistics collected by FINUDA on ${}^6\text{Li}$ was analyzed to look for ${}^6_\Lambda\text{H}$ production, through the double charge exchange reaction $K^- + {}^6\text{Li} \rightarrow {}^6_\Lambda\text{H} + \pi^+$, by requiring a coincidence between the π^+ signaling the formation of ${}^6_\Lambda\text{H}$ and its subsequent decay into ${}^6\text{He} + \pi^-$ within a very tight energy window [7]. This approach was possible thanks to the very good energy resolution and instrumental stability of the detectors. Three events were found, corresponding unambiguously to the formation and subsequent decay of ${}^6_\Lambda\text{H}$. A very careful analysis showed that they could not be ascribed to possible instrumental or physical backgrounds, mainly coming from the reaction chain $K^- + p \rightarrow \Sigma^+ + \pi^-$, $\Sigma^+ \rightarrow n + \pi^+$. The mass of ${}^6_\Lambda\text{H}$ deduced from the above events was found to be 5801.4 ± 1.1 MeV, corresponding to a Λ binding energy $B_\Lambda = 4.0 \pm 1.1$ MeV with respect to the mass of the unbound ${}^5\text{H} + \Lambda$. Fig. 2 shows the energy level scheme for the ground state of ${}^6_\Lambda\text{H}$ deduced by FINUDA and theoretical calculations. From this experiment, which

Fig. 2. Energy level scheme for ${}^6_\Lambda\text{H}$ ground state. The dotted box around ${}^6_\Lambda\text{H}$ mass the represents the error on the mass mean value obtained by FINUDA [7], the dashed box around ${}^5\text{H}$ indicates its width.

provides the first observation of the hyperheavy hydrogen ${}^6_\Lambda\text{H}$, we may not conclude that the ΛNN force, leading to the ground state mass of 5799.64 MeV, is negligible but only that its influence looks lower than predicted. The production rate of ${}^6_\Lambda\text{H}$, is $(5.9 \pm 4.0) \cdot 10^{-6}$ / stopped K^- , about three orders of magnitude lower than the production rates for bound Λ -Hypernuclei, as expected. For full details see [7].

References

- [1] M. Agnello, et al., Phys. Lett. B 685 (2010) 247.
- [2] M. Agnello, et al., Phys. Lett. B 698 (2011) 219.
- [3] M. Agnello et al., Phys. Lett. B 681 (2009) 139.
- [4] M. Agnello et al., Nucl. Phys. A 804 (2008) 151.
- [5] M. Agnello et al., Phys. Lett. B 701 (2011) 556.
- [6] M. Agnello et al., accepted for publication on Nucl. Phys. A, doi: 10.1016/j.nuclphysa.2012.01.024.
- [7] M. Agnello et al., Phys. Rev. Lett. 108 (2012) 042501.

Recent results of from the HypHI project at GSI

Take R. Saito

*GSI Helmholtz Center for Heavy Ion Research, Darmstadt, Germany
Institute of Nuclear Physics, Johannes Gutenberg-University Mainz,
Mainz, Germany
Helmholtz Institute Mainz (HIM), Mainz, Germany*

The HypHI project aims to perform precise hypernuclear spectroscopy by means of heavy ion induced reactions on a fixed target. In contrast to the other hypernuclear spectroscopy with central heavy ion collisions such as STAR and ALICE, hypernuclei are produced peripheral collisions with fragmentation reactions, therefore, there is now limitation in principle on the mass number of produced hypernuclei. Furthermore, hypernuclei at extreme isospin values can be produced due to the mechanism of the fragmentation reactions. In the HypHI experiments, hypernuclei are produced and identified in the projectile rapidity region, and a large Lorentz boost in the produced hypernuclei enables to select events with hypernuclear displaced decay vertex by using a secondary vertex trigger in the data taking.

We have already performed the Phase 0 experiment with ${}^6\text{Li}$ projectiles at 2 A GeV on a carbon target in order to prove the experimental principle of the HypHI project by producing and identifying light hypernuclei with reconstructions of π^- mesonic weak decay channels. In the presentation, analyses both without and with a drift chamber in front of the bending magnet, BDC, have been discussed. Clear signals of ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$ as well as Λ hyperon have been observed. Furthermore, signals in the $d + \pi^-$ and $t + \pi^-$ invariant mass distributions have been observed.

The analysis on the Phase 0 experiment is about to be completed, and the analysis of the second experiment (Phase 0.5) with ${}^{20}\text{Ne}$ projectiles at 2 A GeV on a carbon target is in progress.

Detection principle

C. Rappold, PhD thesis

Hypnuclear landscape with HypHI

Phase 1 (2012-2018) at GSI
Proton rich hypernuclei

Phase 2 (2018-) at R3B/FAIR
Neutron rich hypernuclei

Known hypernuclei
10⁴ /week
10³ /week
With hypernuclear separator

Phase 3 (202X-) at FAIR
Hypernuclear separator

HypHI Phase 0 in October 2009

- The goal of the Phase 0 experiments
 - To demonstrate the feasibility of precise hypernuclear spectroscopy with ^6Li primary beams at 2 A GeV : Mesonic decay $\Lambda \rightarrow \pi^- + p$

Funding

- Helmholtz-University Young Investigators Group VH-NG-239, 2006-2012
- DFG grant SA1696/1-1 2007-2009, TOF detectors

Analysis with BDC

E. Kim, PhD thesis, NPA in press

Analysis with BDC

E. Kim, PhD thesis

Omega Baryon Interactions with Lattice QCD

Joseph Wasem^{a,†}, Michael I. Buchoff[‡], and Thomas C. Luu[§]

*Physical Sciences Directorate
Lawrence Livermore National Laboratory
Livermore, California 94550, USA
LLNL-JRNL-522761*

Abstract

We discuss the interactions of the two- Ω^- baryon system in multiple spin channels with lattice QCD. Lattice QCD is the only known technique for calculating low-energy hadronic observables directly from the underlying theory of QCD. In addition to being an interesting hyperonic system in its own right, the two- Ω^- system also provides an ideal laboratory for exploring the interactions of multi-baryon systems with minimal dependence on light quark masses. Previous model calculations of the two- Ω^- system have obtained conflicting results, which can be resolved by lattice QCD. The lattice calculations are performed using two different volumes with $L \sim 2.5$ and 3.9 fm at $m_\pi \sim 390$ MeV with a lattice spacing of $a_s \sim 0.123$ fm. Using multiple interpolating operators from a non-displaced source, we present scattering information for two ground state Ω^- baryons in both the $S=0$ and $S=2$ channels. For $S=0$, $k \cot \delta$ is extracted at two volumes, which leads to an extrapolated scattering length of $a_{S=0}^{\Omega\Omega} = 0.16 \pm 0.22$ fm, indicating a weakly repulsive interaction. Additionally, for $S=2$, two separate highly repulsive states are observed.

^a Speaker

[†] wasem2@llnl.gov

[‡] buchoff1@llnl.gov

[§] luu5@llnl.gov

Lattice QCD calculations have advanced to the point that scattering phenomena for multi-hadron systems can be reliably calculated from first principles. Calculations performed with analysis of two or more hadrons in a finite volume allow for phase shifts and potential bound states to be studied non-pertubatively[1, 2]. In this proceeding, we discuss the $\Omega^- \Omega^-$ system, which is poorly understood experimentally due to the large mass and relatively short lifetime of the Ω^- . Lattice QCD calculations can predict phenomena in these systems and pinpoint signals for heavy ion scattering experiments, such as STAR or ALICE. The $\Omega\Omega$ system has not received as much theoretical attention as its lighter hyperon counterparts, however within the last decade this system was studied in the context of the chiral quark model[3], where it was found to prefer a bound ground state with a binding energy of 116 MeV. A conflicting analysis[4] using the quark dislocation model finds the system to be weakly repulsive. A model-independent lattice QCD calculation can address this debate[5].

An attractive aspect of studying the $\Omega\Omega$ system on the lattice is the fact that the system is believed to primarily depend on the physical strange quark mass as opposed to the unphysically large light quark masses with which these lattice calculations are performed[6], implying a calculation at the physical point should rely less on chiral extrapolations. Also, calculations involving only the heavier strange quark are less computationally expensive and have better signal-to-noise. For these reasons, the multi- Ω^- system is the ideal laboratory for understanding nuclear interactions (including tensor forces and s-wave three-baryon forces[7, 8]) directly from the lattice.

Lattice calculations are performed in Euclidean space, where the usual LSZ formalism only holds at kinematic threshold[9]. As a result, scattering information has to be extracted by analyzing energy shifts of hadrons in finite volume. For two hadrons (A and B) in a finite volume, the interaction momenta k at a given volume ($V = L^3$) can be related to the two-particle interaction energy ΔE and the scattering phase shifts $\delta(k)$ by[1, 2]

$$\begin{aligned} E &= \sqrt{k^2 + m_A^2} + \sqrt{k^2 + m_B^2} = \Delta E + m_A + m_B \\ k \cot \delta(k) &= \frac{1}{\pi L} S \left(\left(\frac{kL}{2\pi} \right)^2 \right) = -\frac{1}{a} + \frac{1}{2} r k^2 + \dots \\ S(\eta) &= \sum_{\substack{|\mathbf{j}| < \Lambda \\ \mathbf{j} \neq 0}} \frac{1}{|\mathbf{j}|^2 - \eta} - 4\pi\Lambda \end{aligned} \quad (1)$$

where the value of $k \cot \delta(k)$ extracted then has the normal effective range expansion.

The discretized lattice calculations with periodic boundary conditions also break the continuum $O(3)$ rotational symmetry to an octahedral subgroup. The spin-3/2 Ω^- fermionic modes map on to the lattice irrep H^+ ($S = 3/2$). In this irrep, the interpolating operator overlapping the Ω^- baryon is given by[10]

$$\bar{\Omega}_{\alpha\beta\gamma} = \epsilon_{abc} \bar{s}_\alpha^a \bar{s}_\beta^b \bar{s}_\gamma^c, \quad (2)$$

where a, b , and c are color indices and α, β , and γ are spinor indices. Linear combinations of $\bar{\Omega}_{\alpha\beta\gamma}$ will produce Ω^- interpolating operators in the correct irreducible representations of the octahedral group. For non-displaced sources, and following Ref. [10], there are two embeddings of the Ω^- particle in the H^+ irrep. In the non-relativistic limit, the first embedding maps onto the upper two spinor components in the Dirac-Pauli basis, while the second maps onto the lower two components. As such, one expects larger overlap with ground state

systems when dealing with the first embedding. The s-wave states of the two Ω^- system can be formed from a tensor product of the ground state lattice irreps, and by forcing the system of two H^+ baryons to be in a relative s-wave the angular momentum of the resulting state will be entirely determined by the spin combinations allowed. With the additional condition for an anti-symmetric wavefunction the two Ω^- baryons in an s-wave state can only have two non-trivial spin channels: $S=0$ (the A_1^+ irrep) and $S=2$ (the E^+ and T_2^+ irreps).

Due to the three degenerate valance quarks, the Ω^- interpolating operator has the property that exchanging two quarks leads to both a minus sign from permuting Grassman number and a minus sign from exchanging indices in the epsilon tensor, which cancel, giving all Wick contractions the same relative sign. It can be shown using this property that all contractions of the two- Ω^- fall into two distinct forms: ‘direct’ and ‘exchange’, as shown in Fig. 1. This drastically reduces the computational cost due to matrix multiplication, decreasing the $6!=720$ possible contractions of two- Ω system by an order of magnitude.

FIG. 1. Quark contractions types used in the calculation including the (a) direct contributions and the (b) exchange contributions.

For each correlation function, different source/sink smearing combinations are put through a matrix-Prony algorithm as detailed in Ref. [11], which partially removes excited state contamination. Further enhancement of the ground state is accomplished by averaging different combinations of embeddings. We also suppress excited states by projecting the momentum of individual particle sinks to zero independently, which will remove excited states with nonzero back-to-back momentum[12]. A fully correlated χ^2 minimizing fit is then performed in the plateau region to extract the ground state energy with errors.

Using Chroma[13], the configurations used were generated on uBGL while the propagator inversions and contractions were performed on the Edge cluster with the QUDA GPU library[14], both at LLNL. The configurations were anisotropic Wilson lattices using the tuning parameters defined in Ref. [15]. The ensembles used were $20^3 \times 256$ ($L \sim 2.5$ fm) and $32^3 \times 256$ ($L \sim 3.9$ fm) with $m_\pi \approx 390$ MeV, $a_s \sim .1227$ fm, and $a_s/a_t \sim 3.5$.

The three lowest embedding combinations of the H^+ irrep have significant overlap with the ground state Ω^- , and the effective mass plot for the sum of the three lowest embedding combinations is shown in Fig. 2 for both the $20^3 \times 256$ and the $32^3 \times 256$ lattices. The lowest embedding combinations for the $S = 0$ system result in the effective mass plots in Fig. 3. The fit results for each data set are shown in Table I.

The effective mass plots for the $S = 2$ states are shown in Fig. 4. One can see that the two $S = 2$ irreps achieve statistically separate lowest energy states, despite coupling to states with the same set of quantum numbers, indicating that at least one (and possibly both) are failing to achieve the correct ground state of the $S = 2$ two Ω^- system. In both cases, the states achieved are at a significantly higher energy level than for the $S = 0$ case.

FIG. 2. Effective mass plots for the H^+ ($S=\frac{3}{2}$) Ω^- baryon calculated using (a) $20^3 \times 256$ and (b) $32^3 \times 256$ lattices.

FIG. 3. Effective mass plots for the A_1^+ ($S=0$) two Ω^- system calculated using (a) $20^3 \times 256$ and (b) $32^3 \times 256$ lattices.

implying a much more repulsive channel, as expected from Pauli exclusion arguments.

TABLE I. Fit values and Energy Shifts for the Ω^- systems (in dimensionless units, $a_t \bar{E}$).

Irrep	Lattice Size	$a_t E$	$\sigma_{E,stat.}$	$\sigma_{E,sys.}$	χ^2/dof	Q	$a_t \Delta E$	$\sigma_{\Delta E,stat.}$
H^+	$20^3 \times 256$	0.291501	0.000457	+0.000099 -0.000268	1.003	0.460		
	$32^3 \times 256$	0.290001	0.000804	+0.000418 -0.000001	0.850	0.708		
A_1^+	$20^3 \times 256$	0.586235	0.000843	+0.000091 -0.000348	1.105	0.327	0.00323	0.00124
	$32^3 \times 256$	0.583224	0.002002	+0.000577 -0.000680	1.086	0.350	0.00322	0.00257
T_2^+	$20^3 \times 256$	0.642961	0.007136	+0.002502 -0.005120	0.925	0.514	0.05996	0.00719
E^+	$20^3 \times 256$	0.67256	0.00293	+0.00013 -0.00329	0.500	0.916	0.08956	0.00307

In the $S = 0$ two Ω^- system, the data from two different volumes in Table I will allow for

FIG. 4. Effective mass plots of the (a) E^+ and (b) T_2^+ irreps (the $S = 2$ two Ω^- system) calculated using the $20^3 \times 256$ lattice.

two applications of Eq. 1 and, in combination with the effective range expansion, an extraction of the scattering length a . In principle the range parameter r will also be extracted, however it will be contaminated by higher order terms and is unreliable. For the $S = 0$ system the results are shown in Fig. 5(a) along with the systematic and statistical errors. A distribution of the parameter a is generated and shown in Fig. 5(b), with a resulting scattering length in the $S=0$ channel of

$$a_{S=0}^{\Omega\Omega} = 0.16 \pm 0.22 \text{ fm}. \quad (3)$$

Note that the distribution fit to the data is that of a Lorentz distribution, where use of a normal distribution would result in the quotation of too large an uncertainty.

FIG. 5. Plot of (a) $k \cot \delta$ (with central value, statistical error (thick line), and statistical plus systematic error (thin line)) and (b) the distribution of scattering lengths a for the $S = 0$ two Ω^- system with a Lorentz distribution.

From Fig. 5(a) one can see that the central value of k^2 observed does not change appreciably between the two different volumes, and in Fig. 5(b) the distribution of the extracted scattering length is strongly peaked at very small values, indicating a very weakly repulsive

system. Indeed, assuming natural sizes for the higher order range parameters the Lorentz distribution for the scattering length provides a 79.5% chance that the system is repulsive and a 20.5% chance that it is attractive. Additionally, the ΔE values in Table I are positive (repulsive) and small for both $20^3 \times 256$ and $32^3 \times 256$ lattices. Thus, from our current calculations, we find evidence that the system is consistent with the weakly repulsive scenario in Ref. [4] and inconsistent with the deeply bound state found in Ref. [3]. Ultimately, more calculations are required to acquire a full systematic error budget, but for the $\Omega\Omega$ system these are expected to be small due to weak light quark dependence.

These results provide an interesting complement to previous studies[12, 16–18] of hyperon interactions, where many of the interactions have been found to be attractive and contain bound states at $m_\pi \sim 390$ MeV. The difference between the evidence for other bound hyperon states and the conclusion in this work of a weakly repulsive $\Omega\Omega$ state may simply reflect a much stronger influence of light-quark dynamics in the valence sector of the $\Lambda\Lambda$ and $\Xi\Xi$ systems. Further studies at different pion masses approaching the physical point are needed to gain a better understanding of the similarities and differences of each of these systems.

This work was performed under the auspices of the U.S. DOE by LLNL under Contract No. DE-AC52-07NA27344 and the UNEDF SciDAC Grant No. DE-FC02-07ER41457, and was partially supported by LLNL LDRD 10-ERD-033.

-
- [1] M. Luscher, Commun. Math. Phys. **105**, 153 (1986).
 - [2] M. Luscher, Nucl.Phys. **B354**, 531 (1991).
 - [3] Z. Y. Zhang, Y. W. Yu, C. R. Ching, T. H. Ho, and Z.-D. Lu, Phys. Rev. **C61**, 065204 (2000).
 - [4] F. Wang, J.-l. Ping, G.-h. Wu, L.-j. Teng, and J. T. Goldman, Phys. Rev. **C51**, 3411 (1995), arXiv:nucl-th/9512014.
 - [5] M. I. Buchoff, T. C. Luu, and J. Wasem, (2012), arXiv:1201.3596 [hep-lat].
 - [6] J. Bulava *et al.*, Phys. Rev. **D82**, 014507 (2010), arXiv:1004.5072 [hep-lat].
 - [7] S. R. Beane, W. Detmold, T. C. Luu, K. Orginos, A. Parreno, *et al.*, Phys.Rev. **D80**, 074501 (2009), arXiv:0905.0466 [hep-lat].
 - [8] T. Yamazaki, Y. Kuramashi, A. Ukawa, and f. t. P.-C. Collaboration, Phys.Rev. **D81**, 111504 (2010), arXiv:0912.1383 [hep-lat].
 - [9] L. Maiani and M. Testa, Phys. Lett. **B245**, 585 (1990).
 - [10] S. Basak *et al.* (Lattice Hadron Physics (LHPC)), Phys. Rev. **D72**, 074501 (2005), arXiv:hep-lat/0508018.
 - [11] S. R. Beane *et al.*, Phys. Rev. **D79**, 114502 (2009), arXiv:0903.2990 [hep-lat].
 - [12] S. R. Beane *et al.* (NPLQCD), Phys. Rev. **D81**, 054505 (2010), arXiv:0912.4243 [hep-lat].
 - [13] R. G. Edwards and B. Joo (SciDAC), Nucl. Phys. Proc. Suppl. **140**, 832 (2005), arXiv:hep-lat/0409003.
 - [14] M. A. Clark, R. Babich, K. Barros, R. C. Brower, and C. Rebbi, Comput. Phys. Commun. **181**, 1517 (2010), arXiv:0911.3191 [hep-lat].
 - [15] H.-W. Lin *et al.* (Hadron Spectrum), Phys. Rev. **D79**, 034502 (2009), arXiv:0810.3588 [hep-lat].
 - [16] S. R. Beane *et al.* (NPLQCD), (2010), arXiv:1012.3812 [hep-lat].
 - [17] T. Inoue *et al.* (HAL QCD), Phys. Rev. Lett. **106**, 162002 (2011), arXiv:1012.5928 [hep-lat].
 - [18] S. R. Beane *et al.* (NPLQCD), (2011), arXiv:1109.2889 [hep-lat].

YN (and YY) interactions from hypernuclei

John Millener

Brookhaven National Laboratory

- The ΛN interaction is attractive and generates a well depth of about 30 MeV in nuclei. Λ single-particle states are known from (K^-, π^-) , (π^+, K^+) , and $(e, e'K^+)$ reactions on nuclear targets up to Pb. Review: Hashimoto and Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564
- The weak-decay lifetimes of Λ hypernuclei are around 200 ps.
- The addition of a Λ raises all particle thresholds by about 1 MeV/mass.no. of the emitted particle in p-shell hypernuclei.
- Hypernuclear γ -ray spectroscopy with Ge detectors (Hyperball) $(\pi^+, K^+ \gamma)$ at KEK and $(K^-, \pi^- \gamma)$ at BNL with $\sim$ keV resolution.
- Interpreted using shell-model calculations that include the mixing of both Λ - and Σ -hypernuclear configurations.

Slides

1. Parametrization of the YN interaction for p-shell hypernuclei
2. Model of $\Lambda - \Sigma$ coupling for $A=4$ hypernuclei
3. Spectra of p-shell hypernuclei determined from Γ -ray spectroscopy. The $\Lambda\Sigma$ columns show the theoretical contributions of $\Lambda - \Sigma$ coupling to the binding energy.
4. Breakdown of contributions to doublet spacings and comparison between theory and experiment.

Future Hypernuclear γ -ray Spectroscopy

- Hyperball-J at J-PARC (Tamura)
- $(K^-, \pi^- \gamma)$ $p_K = 1.1$ or 1.5 GeV/c
- Larger spin-flip amplitudes - test case ${}^4_{\Lambda}\text{He } 1^+ \rightarrow 0^+$
- p-shell and light sd-shell nuclei as targets. First ${}^{19}\text{F}$
- $(K^-, \pi^0 \gamma)$ also possible

$$V_{\Lambda N} = V_0(r) + V_\sigma(r) \, s_N \cdot s_\Lambda + V_{LS}(r) \, l_{N\Lambda} \cdot (s_\Lambda + s_N) + V_{ALS}(r) \, l_{N\Lambda} \cdot (s_\Lambda - s_N) + V_T(r) \, S_{12}$$

$$V_0 = 1/4 \, {}^1V_C + 3/4 \, {}^3V_C \quad V_\sigma = {}^3V_C - {}^1V_C$$

$$\text{For } p_N s_Y \quad V_{\Lambda N} = \bar{V} + \Delta \, s_N \cdot s_\Lambda + S_\Lambda \, l_N \cdot s_\Lambda + S_N \, l_N \cdot s_N + T \, S_{12}$$

Parameters in MeV					
	$\bar{V}$	Δ	S_Λ	S_N	T
$N\Lambda$ - $N\Lambda$ $A = 7 - ?$		0.430	-0.015	-0.390	0.030
$A = 11 - 16$		0.330	-0.015	-0.350	0.024
$N\Lambda$ - $N\Sigma$	1.45	3.04	-0.085	-0.085	0.157

$\Lambda - \Sigma$ coupling for ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$

Y. Akaishi et al., PRL 84 (2000) 3539

$$|{}^4_{\Lambda}\text{He}(T = 1/2)\rangle = \alpha s^3 s_{\Lambda} + \beta s^3 s_{\Sigma}$$

From $\Lambda\text{N}-\Sigma\text{N}$ g matrix for $0s$ orbits

$$v = \langle s^3 s_{\Lambda} | g | s^3 s_{\Sigma} \rangle, \quad \Delta E \sim 80 \text{ MeV} \quad \begin{array}{ll} {}^3g_{ss} = 4.8 & {}^1g_{ss} = -1.0 \\ \bar{V} = 3.35 & \Delta = 5.8 \end{array}$$

$$0^+ \quad v = \frac{3}{2} {}^3g_{ss} - \frac{1}{2} {}^1g_{ss} = \bar{V} + \frac{3}{4}\Delta \quad \text{Admixture} \sim -v/\Delta E$$

$$1^+ \quad v = \frac{1}{2} {}^3g_{ss} + \frac{1}{2} {}^1g_{ss} = \bar{V} - \frac{1}{4}\Delta \quad E^{shift} \sim v^2/\Delta E$$

$$\text{NSC97f: for } 0^+ \quad v \sim 7.7 \text{ MeV} \Rightarrow E^{shift} \sim 0.74 \text{ MeV}$$

Doublet spacings in p-shell hypernuclei

	J_u^π	J_l^π	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE^{th}	ΔE^{exp}
${}^7_\Lambda\text{Li}$	$3/2^+$	$1/2^+$	72	628	-1	-4	-9	693	692
${}^7_\Lambda\text{Li}$	$7/2^+$	$5/2^+$	74	557	-32	-8	-71	494	471
${}^8_\Lambda\text{Li}$	2^-	1^-	151	396	-14	-16	-24	450	(442)
${}^9_\Lambda\text{Li}$	$5/2^+$	$3/2^+$	116	530	-17	-18	-1	589	
${}^9_\Lambda\text{Li}$	$3/2_2^+$	$1/2^+$	-80	231	-13	-13	-93	-9	
${}^9_\Lambda\text{Be}$	$3/2^+$	$5/2^+$	-8	-14	37	0	28	44	43
${}^{11}_\Lambda\text{B}$	$7/2^+$	$5/2^+$	56	339	-37	-10	-80	267	264
${}^{11}_\Lambda\text{B}$	$3/2^+$	$1/2^+$	61	424	-3	-44	-10	475	505
${}^{12}_\Lambda\text{C}$	2^-	1^-	61	175	-12	-13	-42	153	161
${}^{15}_\Lambda\text{N}$	$3/2_2^+$	$1/2_2^+$	65	451	-2	-16	-10	507	481
${}^{16}_\Lambda\text{O}$	1^-	0^-	-33	-123	-20	1	188	23	26
${}^{16}_\Lambda\text{O}$	2^-	1_2^-	92	207	-21	1	-41	248	224

Exploring Strange Matters

Jürgen Schaffner-Bielich

Institute for Theoretical Physics and
Heidelberg Graduate School for Fundamental Physics and
ExtreMe Matter Institute EMMI

RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

Carl Dover Memorial Lecture

Brookhaven National Laboratory, New York, USA, March 1, 2012

Carl B. Dover 1941–1996

(from Carl Dover memorial issue, Nucl. Phys. A 625 (1997))

Carl B. Dover and Strange Hadronic Matter (abridged)

- his first talk ever on dibaryons:
first hypernuclear meeting in Heidelberg 1982
(Avraham Gal, private communication)
- work on producing the H-dibaryon with hadronic
reactions (PRL 1982 with Aerts)
- work on production of dibaryons in heavy-ion
collisions (1989 with P. Koch and M. May)
- organizing the summer program on strangeness in
Seattle 1992 (where we first met)
- joint work on strange hadronic matter 1993, 1994
(with Gal, Millener, C. Greiner, Stöcker and myself)

Weak Decays of Dibaryon $\Xi^0 \Xi^-$ (JSB, Mattiello, Sorge PRL 2000)

- predicted to be bound by Nijmegen model NSC97 and Chiral EFT
- can be seen by $(\Xi^0 \Xi^-)_b \rightarrow \Xi^- + \Lambda$ in $\Xi^- \Lambda$ mass plots
- branching ratio is only a few percent

Production of hypernuclei in heavy-ion collisions

(Armstrong, Dover et al. (E864 collaboration) 2004)

- production of ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ seen!
- decay modes: ${}^3_{\Lambda}\text{H} \rightarrow {}^3\text{He} + \pi^-$, ${}^4_{\Lambda}\text{H} \rightarrow {}^4\text{He} + \pi^-$
- last paper of Carl Dover!

The charming world of exotic states

- talk given by Carl at the HIPAGS meeting 1990 (BNL-44520) on: 'Production of rare composite objects in relativistic heavy-ion collision'
- discusses antimatter, hypernuclei, strangelets, H-dibaryon, charmed pentaquark and tetraquark state with bottom quark
- probability for forming charmed states at RHIC à la Carl:

$$P(A, C) \approx \left(\frac{\sigma_{c\bar{c}}}{\sigma_{total}} \right)^{|C|} \times \left(\frac{N_N}{N_\pi} \right)^A \times N_\pi \approx 10^{3-2|C|-2A}$$

- gives about 0.1 deuterons, 0.1 Λ_c , 10 D-mesons
- for a sensitivity of 10^{-n} : $2A + 2|C| < 3 + n$
- able to find charmed hexaquark states?

(JSB and Vischer 1998)

The heritage of Carl B. Dover

(BNL Science and Technology Award 1994,
courtesy: Tony Baltz)

the exploration of
strange matter lives
on
the scientific heritage
of Carl!
thanks Carl!

The H-dibaryon from Lattice QCD

Silas Beane

95

BNL

3/2/2012

Deuteron binding still ambiguous..

Evidence for binding

$$B_H^{\text{quadratic}} = 7.4 \pm 2.1 \pm 5.8 \text{ MeV}$$

EE bound!!

Soon will be competitive with EFT and models!

Conclusion

- A Golden Age for nuclear physics is imminent! But need to run big machines a long time to do nuclear physics!
- Few-hadron systems are currently under intense investigation. Calculation of deuteron properties is a major outstanding benchmark. The H-dibaryon and $\Xi\Xi$ systems are bound at unphysical quark masses. Results on hyperon-nucleon scattering are forthcoming.
- Naive chiral extrapolation of the existing lattice data indicate that at 2-sigma level H can be unbound or independent of the quark masses: need $m_\pi \sim 200 - 250$ MeV AND smaller lattice spacing to claim control of continuum limit!

Future Perspectives on STAR Exotic Searches

Summary

- RHIC is an ideal machine for exotic/antimatter production.
- STAR is in excellent position for exotic/antimatter/rare-decay search.
- STAR has made important discoveries. With more proposed upgrades (HLT, DAQ10k, phase II pp2pp etc.), STAR will significantly broaden its search range for new/exotic phenomena.
- Together, we can expand RHIC's research horizon.

Aihong Tang for the STAR Collaboration

1

Exotic/Rare Particle Search in STAR

Push the boundary of Standard Model

- Dibaryon at midrapidity
- Strangelet search at forward region

Look for new physics beyond Standard Model

- Rare decays
- Antimatter

Atom/parton chemistry test ground

- Atomcules
- Muonic Atoms
- Glueball

Extension and beyond RHIC-II

- Potentials at EIC

Aihong Tang

The H^0 -Dibaryon : How to trigger

Trigger on secondary decay topologies (with GPU acceleration) $\rightarrow$ potential for new discoveries

Aihong Tang

3

Antimatter

Figure 2.52: Left panel: ${}^3\overline{He}$ EMC energy vs TPC $\sqrt{m^2 + p^2}$. Right panel: same for 3He .

Trigger on antimatter with BEMC
Look for possible heavier antimatter and enrich
samples for (anti)hypernuclei studies.

Creating First Antinucleus Atomcules

Metastable antiproton-helium atom discovered at KEK: Iwasaki, PRL 67 (1991); nature 361 (1993) 238

Mass difference: $p\text{-}p\bar{p} < 2 \times 10^{-9}$; Hori, PRL 96 (2006);

measurement of baryon mass and magnetic moment for CPT test at LEAR/CERN

<http://asacusa.web.cern.ch/ASACUSA/index-e.html>

What if we replace antiproton with antiDeuteron, antiTriton or antiHelium3 ?

Only RHIC can address this question with enough antimatter nuclei.

Measure Antinucleus mass (CPT test)

Antinucleus-nucleus annihilation

Rare Decays

[Park et al. HyperCP Collab. PRL94(2005)021801]

$\Sigma \rightarrow p l^+ l^-$

$\eta \rightarrow l^+ l^-$

Search for traces of New Physics beyond the standard model.

These decays usually involve EM or weak coupling which can be calculated to high accuracy.

STAR has high rate capability and excellent lepton ID at low momentum.

Aihong Tang

Future J-PARC experiment to Search for H particle

Contents

- o Introduction
 - H-dibaryon, Theoretical expectation, Observation
- o Letter of intent
 - Proposed setup at J-PARC, Prototype, Expected yield
- o Progress on accelerator of J-PARC
 - Improvement of Spill, Intensity
- o Summary

“RBRC workshop on hyperon interaction and di-hyperon searches”

BNL, Feb29- Mar2, 2012

Letter of Intent

- We prepared LOI and Proposal to meet coming rapid increase of J-PARC intensity for K-beam.
- Handed in to J-PARC PAC, in Jul 2011, J.K. Ahn, K. Imai, et al. "Search for H-Dibaryon with a Large Acceptance Hyperon Spectrometer".
- Intra-nuclear cascade model calculations developed by Y.Nara, A.Ohnishi T. Harada, et al. e.g. arXiv: nucl-th/9608017v1 are the theoretical pilot of the letter .

KEK-J-PARC-PAC2011-03

Letter of Intent for 50 GeV Proton Synchrotron

Search for H-Dibaryon with a Large Acceptance Hyperon Spectrometer

J.K.Ahn*, B.H.Choi, S.H.Hwang, S.H.Kim,
S.Y.Kim, J.K.Lee, J.Y.Park, S.Y.Ryu
Pusan National University, Korea

S.Hasegawa, R.Honda, Y.Ichikawa, K.Imai*, R.Kiuchi, H.Sako,
S.Sato, K.Shirotori, H.Sugimura, K.Tanida
Japan Atomic Energy Agency (JAEA), Japan

H.Fujioka, T.Nagae, M.Niiyama
Kyoto University, Japan

R.Kiuchi, K.Tanida
Seoul National University, Korea

M.Ieiri, K.Ozawa, H.Takahashi, T.Takahashi
High Energy Accelerator Research Organization (KEK), Japan

K.Nakazawa, M.Sumihama
Gifu University

B.Bassalleck
University of New Mexico, USA

(* indicate contact persons)
6 July, 2011

Proposed Spectrometer

- Larger acceptance in the Helmholtz-type (super conducting, T-class) magnet.
- 3-D tracking with higher rate (upto 10^6 Kaon beam, highest in J-PARC) with gating performance.

Prototype

TPC 20cm drift x 10cm x 10 cm square,

(1) 7 kV $\rightarrow$ 16 kV for TPC field,

(2) $\pm 0.7V$ for gating field,

(3) 3 kV for 3 planes GEM + drift space

HV module is capable independent voltage setting.

R&D items at RCNP in 2011 Nov/Dec

(i) GEM with read out 2D pad (width 2, 3, 4 mm)

To reduce ch.#

More items to be tested at test bench.

(i) muPIC (1D+1D) readout (with 0.4mm pitch)

(ii) Gating wire with a field guide plane ($\pm 150V$) up to $10E6$.

To reduce gate noise
(ii) gating operation at GEM ($\pm$ few 10 V)

(iii) Gas (P10, CF4+Ar)

Expected Statistics

[↓] 90% C.L. upper limits on the direct H production cross section on 12 C and 3He. The dashed line shows a theoretical calculation for 12C and 3He based on the model of Aerts and Dover (PRD28(1983)450)

Many experiment is performed and excluded H dibaryon mass upto 2200 MeV, But the experiments were not sensitive to this cross section if H-dibaryon mass is near $\Lambda\Lambda$ threshold because of large tail of quasi-free Ξ^- production.

Parameters	Values
K^- beam	$10^6 K^-$ per spill (6 second)
Cu target	4.25×10^{22}
$d\sigma/d\Omega_{\Lambda}^{\Lambda\Lambda}$	$14.6 \mu\text{b/sr}$
$\Delta\Omega$	0.11 sr
Branching ratio ($\Lambda \rightarrow p\pi^-$)	0.64
Detection efficiency of K^+ with Kurama	0.5
Detection efficiency of two Λ with TPC	0.5
Yield	0.007 event / spill

3300 $\Lambda\Lambda$ -events $\leftrightarrow$ 0.007 events / spill

If $d\sigma_{\text{H}}/d\Omega = 0.2 \mu\text{b/sr}$, in 100shifts (3 shift / day), 46 H-events are expected

For J-PARC power

LINAC ACS upgrade (181MeV->400MeV)

N.Ohuchi (J-PARC) ATAC report 2011

Hyperon-Hyperon Interactions Workshop: Summary Lecture

Berndt Müller

Department of Physics, Duke University, Durham, NC 27708, USA

The summary lecture presented a review of the various lectures given at the workshop. Main topics include an overview of the original theoretical ideas, a survey of the status of the relevant experimental investigations, the existing plans for improved measurements during the coming decade, the status of theoretical analysis and predictions, and a reminder why it is important to quantitatively determine the interactions among hyperons, including the possible existence of multi-strange bound states.

Why Nuclear Collisions?

- Nuclear collisions at RHIC and LHC equilibrate s-quarks thermally and chemically.
 - All possible hadronic states made of (u, d, s) quarks should be produced “copiously”.
 - Production of hadrons from deconfined (QGP) phase should facilitate production of non-molecular multi-quark states, if they exist.
 - Study of two-particle interactions should be possible, because hadron pairs of all kinds are produced copiously within a small volume.
 - Large and growing datasets exist.
 - Powerful detectors with excellent particle-ID are available.

➤ The scattering length (a_0) and the effective range (r_{eff}) with no, weak, medium, and strong coupling to ΞN :

	a_0 (fm)	r_{eff} (fm)
No coupling	-2.42	-6.36
weak (Set.A)	-2.47	-6.65
medium (Set.B)	-2.98	-13.53
strong (Set.C)	-2.27	-2.61

➤ Current fit gives indication towards non-existence of strong bound state of $\Lambda\Lambda$

H-Dibaryon

Using the data from 2010, no signal is observed in $\Lambda\pi^-/\Lambda\Lambda$

H Di-baryon in LGT

$$B_H^{\text{quadratic}} = 7.4 \pm 2.1 \pm 5.8 \text{ MeV}$$

How $\Xi\Xi$ would help

$$NN: (ud)u \leftrightarrow (ud)d$$

$$\Xi\Xi: (ss)u \leftrightarrow (ss)d$$

We cannot change the u/d quark masses, but we can replace u/d by s !

Exploring the $\Xi\Xi$ interaction is as close as we will ever get to verifying theoretical predictions for the quark mass dependence of nuclear forces.

Hyperon-Hyperon Interactions and Searches for Exotic Di-Hyperons in Nuclear Collisions

February 29 – March 2, 2012

Organizers: Anthony Baltz (BNL), Rainer Fries (Texas A&M), Huan Zhong Huang (UCLA),
John Millener (BNL) and Zhangbu Xu (BNL)

Participant List

Name	Affiliation	E-Mail Address
Hidemitsu Asano	Kyoto University	h.asano@scphys.kyoto-u.ac.jp
Anthony Baltz	RBRC and BNL	baltz@bnl.gov
Silas Beane	University of New Hampshire	silas@physics.unh.edu
Peter Bond	BNL	bond@bnl.gov
Elena Botta	INFN-Torino and Torino University	botta@to.infn.it
Xiangli Cui	BNL	cuixl@rcf.rhic.bnl.gov
Benjamin Dönigus	GSi Helmholtzzentrum fuer Schwerionenforschung	b.doenigus@gsi.de
James Dunlop	BNL	dunlop@bnl.gov
Rainer Fries	Texas A&M University	rfries@comp.tamu.edu
Lei Guo	Florida International University	lguo@jlab.org
Lixin Han	BNL	hanlixin@sinap.ac.cn
Bingchu Huang	BNL	huangbc@bnl.gov
Huan Huang	UCLA	huang@physics.ucla.edu
Takashi Inoue	Nihon Univ College of Bioresource Sciences	inoue.takashi@nihon-u.ac.jp
Sid Kahana	BNL	kahana@bnl.gov
Zhongbo Kang	RBRC	zkang@bnl.gov
Hongwei Ke	Central China Normal University	kehwa@bnl.gov
Che-Ming Ko	Texas A&M University	ko@comp.tamu.edu
Ramona Lea	University of Trieste and INFN Trieste	ramona.lea@ts.infn.it
Richard Lednicky	JINR Dubna	lednicky@fzu.cz
Yu-Gang Ma	Shanghai Inst of Applied Physics (SINAP), CAS	yigma@sinap.ac.cn
Larry McLerran	RBRC and BNL	mclerran@bnl.gov
John Millener	BNL	millener@bnl.gov
Gerald Miller	University of Washington	miller@uw.edu
Berndt Mueller	Duke University	mueller@phy.duke.edu
Tomofumi Nagae	Kyoto University	nagae@scphys.kyoto-u.ac.jp
Akira Ohnishi	Yukawa Inst for Theoretical Physics, Kyoto Univ	ohnishi@yukawa.kyoto-u.ac.jp
Philip Pile	BNL	pile@bnl.gov
Jianwei Qiu	BNL	jqu@bnl.gov
Thomas Rijken	IMAP, Radboud-University	t.rijken@science.ru.nl
Lijuan Ruan	BNL	ruan@bnl.gov
Jai Salzwedel	Ohio State University	Jai.Salzwedel@cern.ch
Takehiko Saito	GSi	t.saito@gsi.de
Nick Samios	RBRC and BNL	samios@bnl.gov
Susumu Sato	JAEA	susumu.sato@j-parc.jp
Juergen Schaffner-Bielich	Heidelberg University	schaffner-bielich@uni-heidelberg.de
Neha Shah	UCLA	neha@physics.ucla.edu
Qiye Shou	BNL	qyshou@rcf.rhic.bnl.gov
Aihong Tang	BNL	aihong@bnl.gov
Zebo Tang	University of Science and Technology of China	zbtang@ustc.edu.cn
Fuqiang Wang	Purdue University	fqwang@purdue.edu
Joseph Wasem	Lawrence Livermore National Laboratory	wasem2@llnl.gov
Nu Xu	LBL	nxu@lbl.gov
Zhangbu Xu	BNL	xzb@bnl.gov
Chi Yang	BNL	chiyang@mail.ustc.edu.cn
Guo Yi	University of Science and Technology of China	yiguo@rcf.rhic.bnl.gov
Feng Zhao	UCLA	fengzhao@physics.ucla.edu
Yuhui Zhu	BNL	yhzhu.sinap@gmail.com

Hyperon-Hyperon Interactions and Searches for Exotic Di-Hyperons in Nuclear Collisions

Hamilton Seminar Room
Chemistry Department, Bldg. 555
February 29 – March 2, 2012

Wednesday, February 29, 2012

Chair: Huan Zhong Huang

08:30 – 09:00		<i>Registration/Coffee</i>
09:00 – 09:10	Larry McLerran	Welcome
09:10 – 09:40	Takashi Inoue	H-dibaryon from Full QCD Lattice Simulations
09:40 – 10:10	Gerald Miller	Possible Existence and Detection of Strangeness - 4 Dibaryon States
10:10 – 10:40	Che-Ming Ko	Exotic Hadrons Production in HIC
10:40 – 11:00		<i>Coffee</i>

Chair: James Dunlop

11:00 – 11:30	Benjamin Doenigus	Resonance Production and Search for Exotica with ALICE at the LHC
11:30 – 12:00	Neha Shah	Measurement of Lambda-Lambda Correlations with STAR
12:00 – 02:00		<i>Lunch</i>

Chair: John Millener

02:00 – 02:30	Akira Ohnishi	Lambda-Lambda Correlation in (K-,K+) Reaction and Heavy-ion Collisions
02:30 – 03:00	Lei Guo	Hyperon Physics at CLAS
03:00 – 03:30		<i>Coffee</i>

Chair: Jianwei Qiu

03:30 – 04:00	Richard Lednický	Femtoscopic Correlations and Final State Interactions
04:00 – 04:30	Tom Rijken	Baryon-Baryon Interactions

Thursday, March 1, 2012

Chair: Phil Pile

09:00 – 09:30	Tomo Nagae	Recent Topics in Hypernuclear Physics and Perspective at J-PARC
09:30 – 10:00	Elena Botta	Latest Results on Hypernuclear Physics from the FINUDA Experiment
10:00 – 10:30	Takai Saito	Recent Results from the HypHI Project at GSI
10:30 – 11:00		<i>Coffee</i>

Chair: Yugang Ma

11:00 – 11:30	Joseph Wasem	Omega Baryon Interactions with Lattice QCD
11:30 – 12:00	John Millener	YN (and YY) Interactions from Hypernuclei
12:00 – 02:00		<i>Lunch</i>

Chair: Rainer Fries

02:00 – 03:00	Rainer Fries	Discussions of Theoretical Issues (open to any who would like to share a few slides)
03:00 – 03:30		<i>Coffee</i>

Chair: Anthony Baltz

03:30 – 04:30	<i>Carl Dover Memorial Lecture, Juergen Schaffner-Bielich, "Exploring Strange Matters"</i>	
05:00 – 06:00	<i>Cocktail Hour in Conjunction with Carl Dover Memorial Lecture, Chemistry Department Lobby</i>	
06:15 – 08:00	<i>Workshop Dinner, Brookhaven Center South Room</i>	

Friday, March 2, 2012

Chair: Zhangbu Xu

09:00 – 09:30	Silas Beane	The H-dibaryon from Lattice QCD
09:30 – 10:00	Aihong Tang	Future Perspectives on STAR Exotic Searches
10:00 – 10:30	Susumu Sato	Future JPARC Exp to Search for H particle
10:30 – 11:00		<i>Coffee</i>

Chair: Nu Xu

11:00 – 12:00	Berndt Mueller	Workshop Summary and Outlook (End of Workshop)
---------------	----------------	--

Additional RIKEN BNL Research Center Proceedings:

- Volume 107 – Future Directions in High Energy QCD, October 20-22, 2011
- Volume 106 – Fluctuations, Correlations and RHIC Low Energy Runs, October 3-5, 2011 – BNL-96514-2011
- Volume 105 – Opportunities for Polarized He-3 in RHIC and EIC, September 28-30, 2011 – BNL-96418-2011
- Volume 104 – Brookhaven Summer Program on Quarkonium Production in Elementary and Heavy Ion Collisions, June 6-18, 2011 – BNL-96171-2011
- Volume 103 – Opportunities for Drell-Yan Physics at RHIC, May 11-13, 2011 – BNL-95236-2011-2011
- Volume 102 – Initial State Fluctuations and Final-State Particle Correlations, February 2-4, 2011 – BNL-94704-2011
- Volume 101 – RBRC Scientific Review Committee Meeting, October 27-29, 2010 – BNL-94589-2011
- Volume 100 – Summer Program on Nucleon Spin Physics, July 14-27, 2010 – BNL-96163-2011
- Volume 99 – The Physics of W and Z Bosons, June 24-25, 2010 – BNL-94287-2010
- Volume 98 – Saturation, the Color Glass Condensate and the Glasma: What Have we Learned from RHIC? – May 10-12, 2010 – BNL-94271-2010
- Volume 97 – RBRC Scientific Review Committee Meeting, October 21-22, 2009 – BNL-90674-2009
- Volume 96 – P- and CP-Odd Effects in Hot and Dense Matter, April 26-30, 2010 – BNL-94237-2010
- Volume 95 – Progress in High-pT Physics at RHIC, March 17-19, 2010 – BNL-94214-2010
- Volume 94 – Summer Program on Nucleon Spin Physics at LBL, June 1-12, 2009
- Volume 93 – PHENIX Spinfest School 2009 at BNL - July 1-31, 2009. BNL-90343-2009
Link: PHENIXSpinfestSchool2009@BNL
- Volume 92 – PKU-RBRC Workshop on Transverse Spin Physics, June 30 - July 4, 2008, Beijing, China – BNL-81685-2008
- Volume 91 – RBRC Scientific Review Committee Meeting, November 17-18, 2008 – BNL-81556-2008
- Volume 90 – PHENIX Spinfest School 2008 at BNL, August 4-8, 2008 – BNL-81478-2008
- Volume 89 – Understanding QGP through Spectral Functions and Euclidean Correlators, April 23-25, 2008 – BNL-81318-2008
- Volume 88 – Hydrodynamics in Heavy Ion Collisions and QCD Equation of State, April 21-22, 2008 – BNL-81307-2008
- Volume 87 – RBRC Scientific Review Committee Meeting, November 5-6, 2007 – BNL-79570-2007
- Volume 86 – Global Analysis of Polarized Parton Distributions in the RHIC Era, October 8, 2007 – BNL-79457-2007
- Volume 85 – Parity-Violating Spin Asymmetries at RHIC-BNL, April 26-27, 2007 – BNL-79146-2007
- Volume 84 – Domain Wall Fermions at Ten Years, March 15-17, 2007 – BNL 77857-2007
- Volume 83 – QCD in Extreme Conditions, July 31 - August 2, 2006 – BNL-76933-2006
- Volume 82 – RHIC Physics in the Context of the Standard Model, June 18-23, 2006 – BNL-76863-2006
- Volume 81 – Parton Orbital Angular Momentum (Joint RBRC/University of New Mexico Workshop) February 24-26, 2006 – BNL-75937-2006
- Volume 80 – Can We Discover the QCD Critical Point at RHIC?, March 9-10, 2006 – BNL-75692-2006
- Volume 79 – Strangeness in Collisions, February 16-17, 2006 – BNL-79763-2008
- Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, December 12-14, 2005 – BNL-76915-2006
- Volume 77 – RBRC Scientific Review Committee Meeting, October 10-12, 2005 – BNL-52649-2005
- Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005
- Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005
- Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005
- Volume 73 – Jet Correlations at RHIC, March 10-11, 2005 – BNL-73910-2005
- Volume 72 – RHIC Spin Collaboration Meetings XXXI (January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11, 2005) – BNL-73866-2005
- Volume 71 – Classical and Quantum Aspects of the Color Glass Condensate – BNL-73793-2005
- Volume 70 – Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic – BNL-73867-2005
- Volume 69 – RBRC Scientific Review Committee – BNL-73546-2004
- Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004
- Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures
- Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino Italy – BNL-73534-2004
- Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6, 2004) – BNL-73506-2004

Additional RIKEN BNL Research Center Proceedings:

- Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
- Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
- Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004
- Volume 61 – RIKEN-TODAI Mini Workshop on “Topics in Hadron Physics at RHIC”, March 23-24, 2004 – BNL-72336-2004
- Volume 60 – Lattice QCD at Finite Temperature and Density – BNL-72083-2004
- Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004
- Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
- Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004
- Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
- Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
- Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
- Volume 53 – Theory Studies for Polarized pp Scattering – BNL-71747-2003
- Volume 52 – RIKEN School on QCD “Topics on the Proton” – BNL-71694-2003
- Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
- Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
- Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
- Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
- Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
- Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
- Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
- Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
- Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
- Volume 42 – Baryon Dynamics at RHIC – BNL-52669
- Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
- Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
- Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
- Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
- Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
- Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
- Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
- Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641
- Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
- Volume 32 – RHIC Spin Physics V – BNL-52628
- Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
- Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
- Volume 29 – Future Transversity Measurements – BNL-52612
- Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
- Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
- Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
- Volume 25 – RHIC Spin – BNL-52581
- Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
- Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
- Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
- Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
- Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
- Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573

Additional RIKEN BNL Research Center Proceedings:

- Volume 18 - Event Generator for RHIC Spin Physics - BNL-52571
- Volume 17 - Hard Parton Physics in High-Energy Nuclear Collisions - BNL-52574
- Volume 16 - RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes - BNL-52569
- Volume 15 - QCD Phase Transitions - BNL-52561
- Volume 14 - Quantum Fields In and Out of Equilibrium - BNL-52560
- Volume 13 - Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration - BNL-66299
- Volume 12 - Quarkonium Production in Relativistic Nuclear Collisions - BNL-52559
- Volume 11 - Event Generator for RHIC Spin Physics - BNL-66116
- Volume 10 - Physics of Polarimetry at RHIC - BNL-65926
- Volume 9 - High Density Matter in AGS, SPS and RHIC Collisions - BNL-65762
- Volume 8 - Fermion Frontiers in Vector Lattice Gauge Theories - BNL-65634
- Volume 7 - RHIC Spin Physics - BNL-65615
- Volume 6 - Quarks and Gluons in the Nucleon - BNL-65234
- Volume 5 - Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density - BNL-65105
- Volume 4 - Inauguration Ceremony and Non-Equilibrium Many Body Dynamics - BNL-64912
- Volume 3 - Hadron Spin-Flip at RHIC Energies - BNL-64724
- Volume 2 - Perturbative QCD as a Probe of Hadron Structure - BNL-64723
- Volume 1 - Open Standards for Cascade Models for RHIC - BNL-64722

For information please contact:

Ms. Pamela Esposito
RIKEN BNL Research Center
Building 510A
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

Phone: (631) 344-3097
Fax: (631) 344-4067
E-Mail: pesposit@bnl.gov

Ms. Susan Foster
RIKEN BNL Research Center
Building 510A
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

(631) 344-5864
(631) 344-2562
sfoster@bnl.gov

Homepage: <http://www.bnl.gov/riken>

RIKEN BNL RESEARCH CENTER

Hyperon-Hyperon Interactions and Searches for Exotic Di-Hyperons in Nuclear Collisions

February 29 – March 2, 2012

Li Keran

*Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee*

Copyright©CCASTA

Speakers

Silas Beane
Lei Guo
Richard Lednicky
Berndt Mueller
Thomas Rijken
Juergen Schaffner-Bielich
Joseph Wasem

Elena Botta
Takashi Inoue
John Millener
Tomofumi Nagae
Takehiko Saito
Neha Shah

Benjamin Dönigus
Che-Ming Ko
Gerald Miller
Akira Ohnishi
Susumu Sato
Aihong Tang

Organizers: Anthony Baltz, Rainer Fries, Huan Zhong Huang, John Millener and Zhangbu Xu