The Hypernuclear Physics Program at Jefferson Lab

Patrick Achenbach

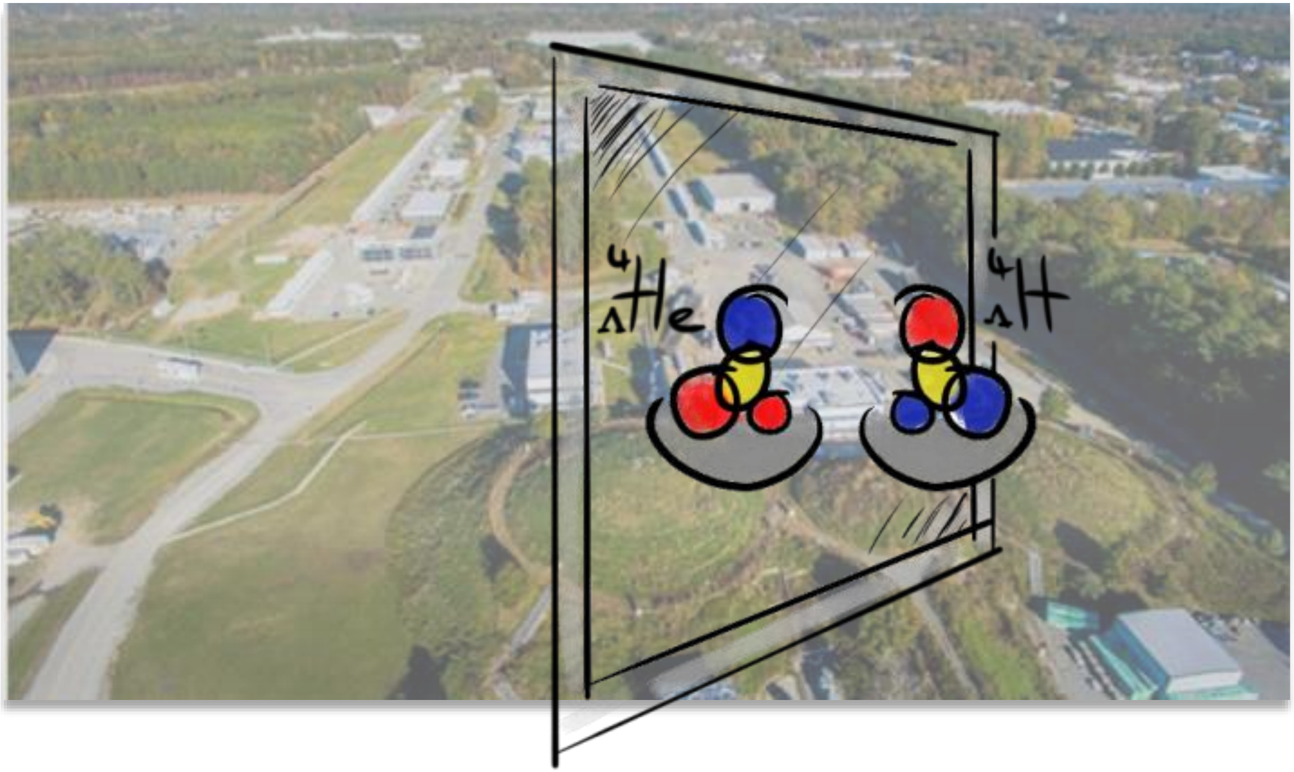
Jefferson Lab

June 2o23

Contents

– Jefferson Lab and how hypernuclear physics experiments fit in

– Current hypernuclear proposals and letters of intent to JLab PAC



Jefferson Lab and
How Hypernuclear Physics Experiments Fit In

CEBAF at Jefferson Lab

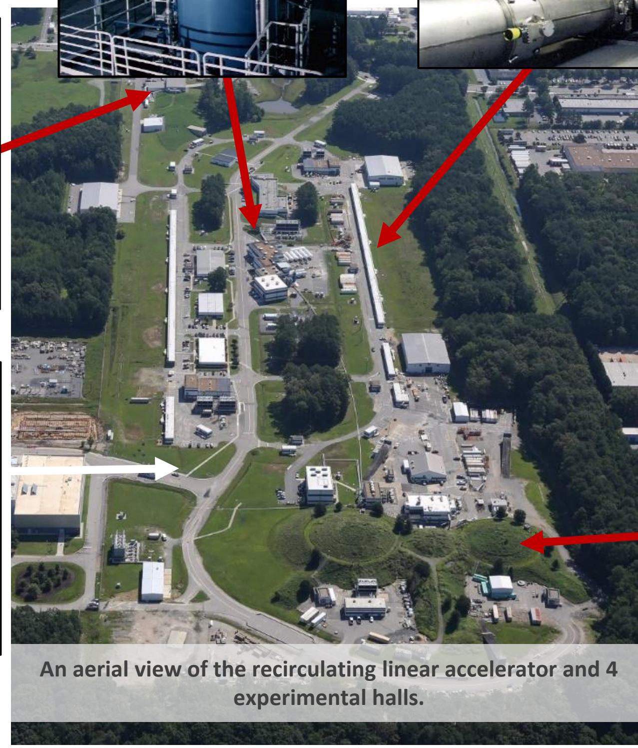
Cryogenic Refrigeration Plant

Cryomodules in the accelerator tunnel

Superconducting Niobium radiofrequency cavities

Hall D

Recirculation Arcs

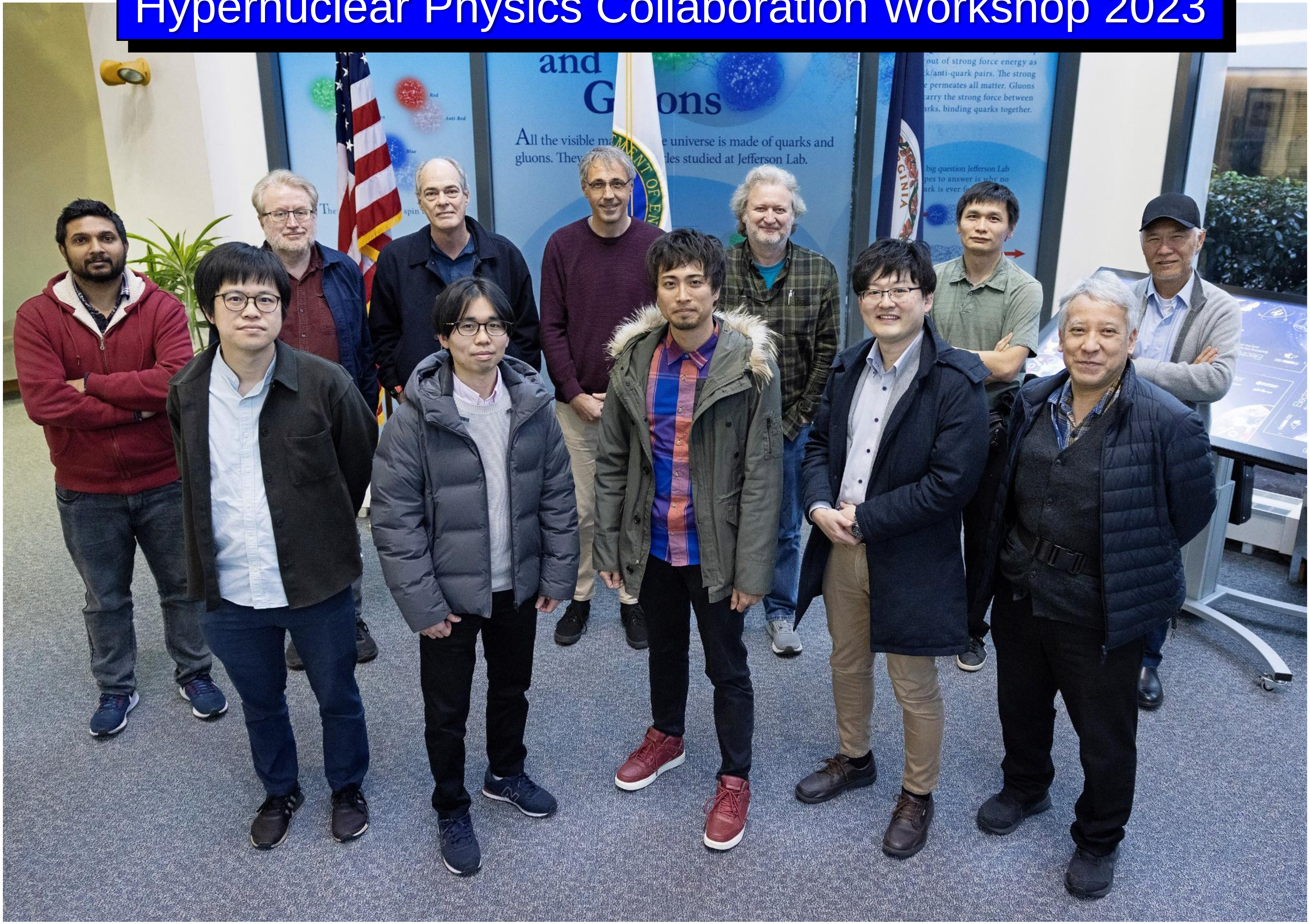


An aerial view of the recirculating linear accelerator and 4 experimental halls.

Hall C

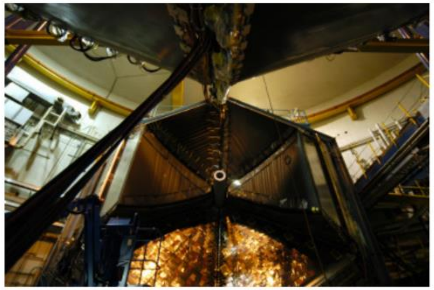
- How does QCD generate the masses of the baryons and mesons?
- Why is the spin of the nucleon ‘1/2’?
- What are emergent properties of dense systems of gluons?

Hypernuclear Physics Collaboration Workshop 2023



Connections Across Collaborations

TEASING STRANGE MATTER FROM THE ORDINARY



New insights from Jefferson Lab reveal details of how strange matter forms in ordinary matter

NEWPORT NEWS, VA – In a unique analysis of experimental data, nuclear physicists have made the first-ever observations of how lambda particles, so-called "strange matter," are produced by a specific process called semi-inclusive deep inelastic scattering (SIDIS). What's more, these data hint that the building blocks of protons, quarks and gluons, are capable of marching through the atomic nucleus in pairs called diquarks, at least part of the time. These results come from an experiment conducted at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility.

Daily Press

NEWS

How nuclear physicists at Jefferson Lab found something 'strange' in the ordinary

By Eliza Noe
Daily Press • Apr 25, 2023 at 7:32 am

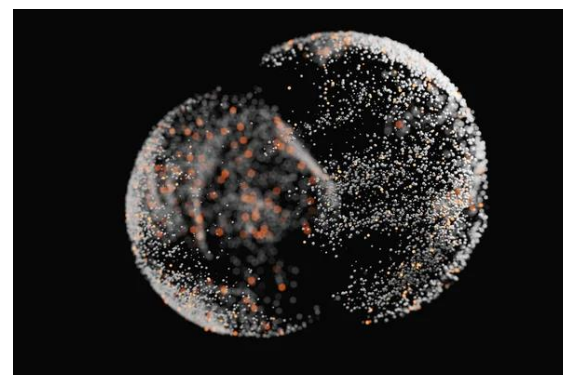
PARTICLE PHYSICS

Physicists See 'Strange Matter' Form inside Atomic Nuclei

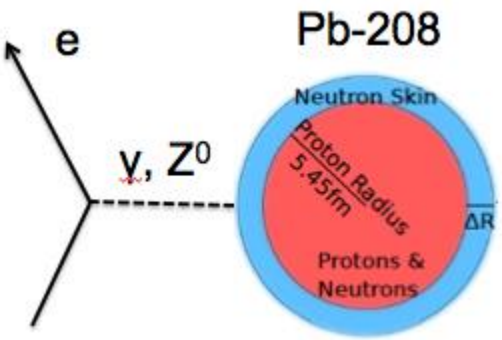
New research attempts to discern how bizarre particles of strange matter form in the nuclei of atoms

SCIENTIFIC AMERICAN

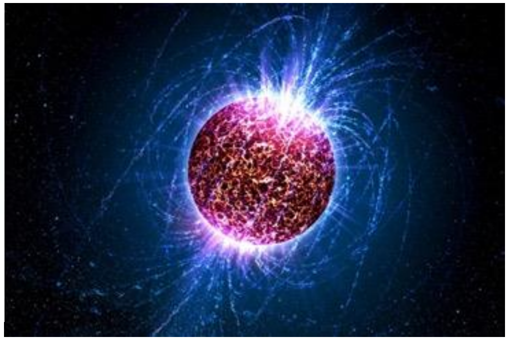
By Stephanie Pappas on April 27, 2023



Connections Across the Sciences

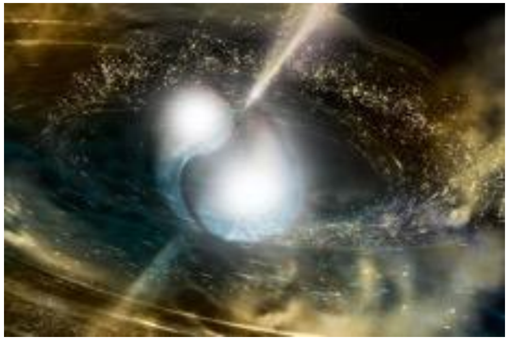


[PREX Collab., PRL 126, 172502 (2021)]



- JLab probes nuclear forces by electron scattering
- Neutron skin results lead to implication for neutron stars

- LIGO observes neutron star mergers
- Gravitational waves carry signatures of nuclear forces and nuclear matter



[Abbott et al., PRL 119, 161101 (2017)]

An Active and Unresolved Topic

Eur. Phys. J. A 13, 213–215 (2002)

THE EUROPEAN PHYSICAL JOURNAL A
© Società Italiana di Fisica Springer-Verlag 2002

Necessity of extra repulsion in hypernuclear systems: Suggestion from neutron stars

T. Takatsuka[1,a], S. Nishizaki[1,b], and Y. Yamamoto[2,c]

[1] Faculty of Humanities and Social Sciences, Iwate University Morioka 020-8550, Japan
[2] Physics Section, Tsuru University, Tsuru 402-0054, Japan

Eur. Phys. J. A (2019) 55: 207
DOI 10.1140/epja/i2019-12909-9

THE EUROPEAN PHYSICAL JOURNAL A

Letter

Impact of chiral hyperonic three-body forces on neutron stars

Domenico Logoteta[1,2], Isaac Vidaña[3,a], and Ignazio Bombaci[1,2]

[1] Dipartimento di Fisica "Enrico Fermi", Università di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy
[2] INFN, Sezione di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy
[3] INFN, Sezione di Catania, Dipartimento di Fisica "Ettore Majorana", Università di Catania, Via Santa Sofia 64, I-95123 Catania, Italy

Hyperon mixing and universal many-body repulsion in neutron stars

Y. Yamamoto,[1] T. Furumoto,[2] N. Yasutake,[3] and Th. A. Rijken[1,4]
[1]Nishina Center for Accelerator-Based Science, Institute for Physical and Chemical Research (RIKEN), Wako, Saitama 351-
[2]National Institute of Technology, Ichinoseki College, Ichinoseki, Iwate 021-8511, Japan
[3]Department of Physics, Chiba Institute of Technology, 2-1-1 Shibazono Narashino, Chiba 275-0023, Japan
[4]IMAPP, University of Nijmegen, Nijmegen, The Netherlands
(Received 9 June 2014; revised manuscript received 1 September 2014; published 30 October 2014)

Multi-Pomeron repulsion and the neutron-star mass

Y. Yamamoto,[1] T. Furumoto,[2] N. Yasutake,[3] and Th. A. Rijken[1,4]
[1]Nishina Center for Accelerator-Based Science, Institute for Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan
[2]Ichinoseki National College of Technology, Ichinoseki, Iwate 021-8511, Japan
[3]Department of Physics, Chiba Institute of Technology, 2-1-1 Shibazono Narashino, Chiba 275-0023, Japan
[4]IMAPP, University of Nijmegen, Nijmegen, The Netherlands
(Received 11 December 2012; revised manuscript received 4 March 2013; published 16 August 2013)

PRL 114, 092301 (2015) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2015

Hyperon Puzzle: Hints from Quantum Monte Carlo Calculations

Diego Lonardoni,[1] Alessandro Lovato,[1] Stefano Gandolfi,[2] and Francesco Pederiva[3,4]
[1]Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA
[2]Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[3]Physics Department, University of Trento, via Sommarive, 14 I-38123 Trento, Italy
[4]INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, I-38123 Trento, Italy
(Received 24 July 2014; published 6 March 2015)

Eur. Phys. J. A (2020) 56:175
https://doi.org/10.1140/epja/s10050-020-00180-2

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Theoretical Physics

Hyperon–nucleon three-body forces and strangeness in neutron stars

Dominik Gerstung, Norbert Kaiser[a], Wolfram Weise
Physics Department, Technical University of Munich, 85748 Garching, Germany

Three-Body Force as an "Extra Repulsion" Suggested from Hyperon-Mixed Neutron Stars

Tatsuyuki TAKATSUKA,[1,*)] Shigeru NISHIZAKI[1] and Ryozo TAMAGAKI[2,**)]

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

EPL, 94 (2011) 11002
doi: 10.1209/0295-5075/94/11002

Estimation of the effect of hyperonic three-body forces on the maximum mass of neutron stars

I. VIDAÑA[1(a)], D. LOGOTETA[1], C. PROVIDÊNCIA[1], A. POLLS[2] and I. BOMBACI[3]

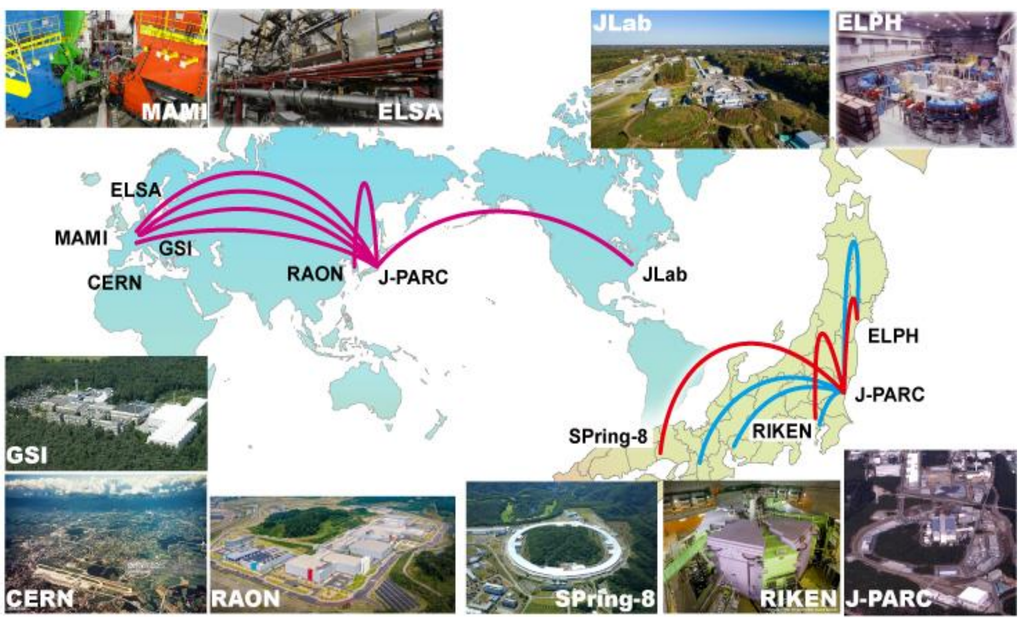
[1] Centro de Física Computacional, Department of Physics, University of Coimbra PT-3004-516, Coimbra, Portugal, EU
[2] Departament d'Estructura i Constituents de la Matèria and Institut de Ciències del Cosmos, Universitat de Barcelona - Avda. Diagonal 647, E-08028 Barcelona, Spain, EU
[3] Dipartimento di Fisica "E. Fermi", Università di Pisa, and INFN, Sezione di Pisa

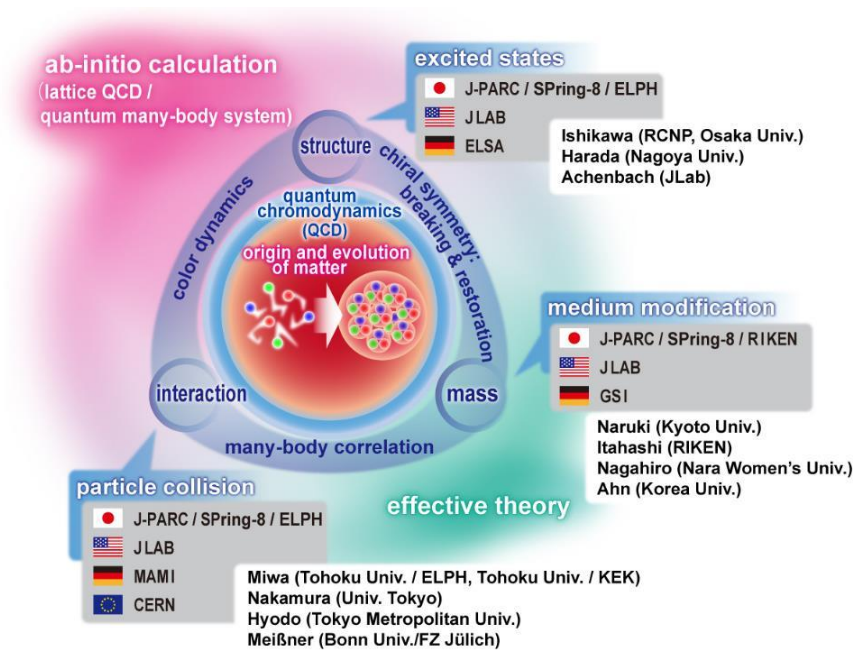
Constraints from Λ hypernuclei on the ΛNN content of the Λ-nucleus potential and the 'hyperon puzzle'

E. Friedman[1] and A. Gal*[1]
[1]Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel
(Dated: April 12, 2022)

Connections Across the World

- J-PARC is one of the key labs sharing the same objectives in understanding hadron physics, hadron structure, hadron interaction, and hadron mass
- Proposal for “International Leading Research” has been submitted in Feb 2023: Formation of baryons with multiple strange quarks; Λ-p interactions; Emergence of hadron mass

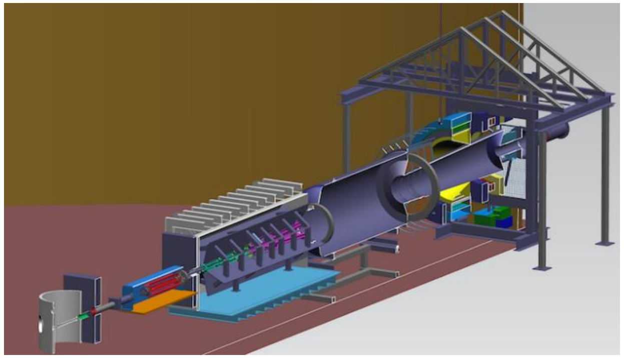




Hall A/C Plans Beyond 2025

Hall A

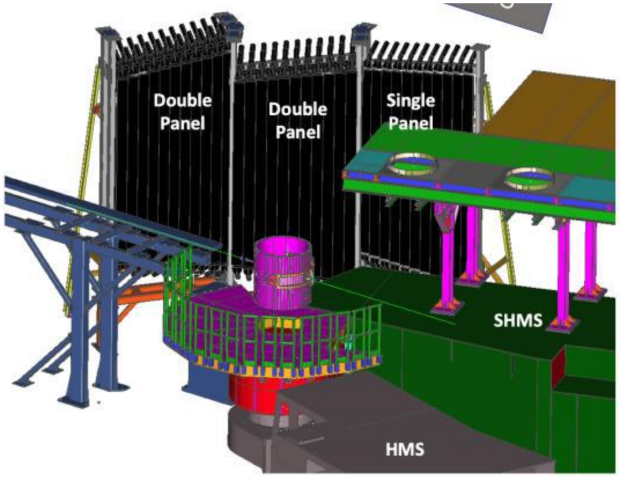
Jan 2025 – Jan 2026: Installation of MOLLER



Jan 2026 – 2029: Running of MOLLER

Hall C

Jul 2025 – Mar 2026: Standard SHMS/HMS experiments



Early in Jan 2026: Hypernuclear solid targets installation

Jul 2026 – Mar 2027: Running of hypernuclear experiments

[Mark Jones, Hypernuclear Workshop, Mar. 2023]

Jefferson Lab's Future Positron Program

12 GeV Ce⁺BAF : present high level goals

[Joe Grames, Positron Workshop, Mar. 2023]

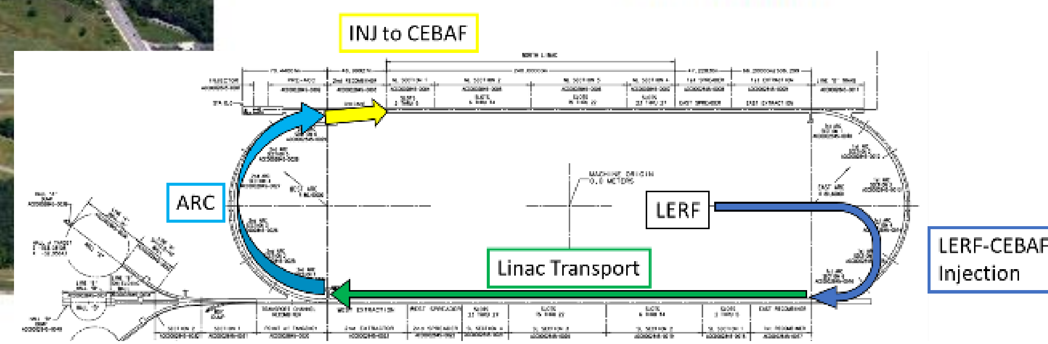
Machine Parameter	Electrons	Positrons
Hall Multiplicity	4	1 or more
Energy (ABC/D)	11/12 GeV	11/12 GeV
Beam Repetition	249.5/499 MHz	249.5/499/1497 MHz
Duty Factor	100% cw	100% cw
Unpolarized Intensity	170 μA	> 1 μA
Polarized Intensity	170 μA	> 50 nA
Beam Polarization	> 85%	> 60%
Fast/Slow Helicity Reversal	1920 Hz/Yes	1920 Hz/Yes

Hall multiplicity tied to intensity and rep rate

Cannot copy existing pulsed mode technology

Beam distributions are characteristically different

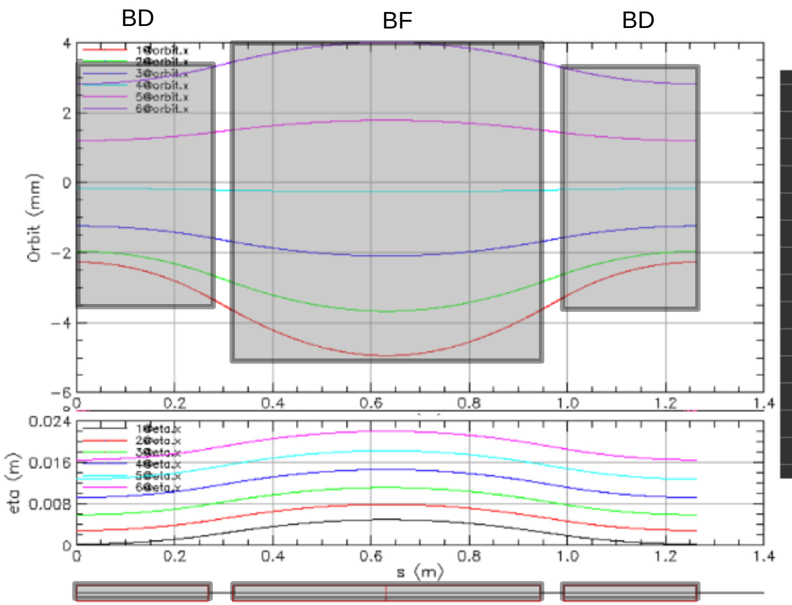
Few positrons with highest spin polarization

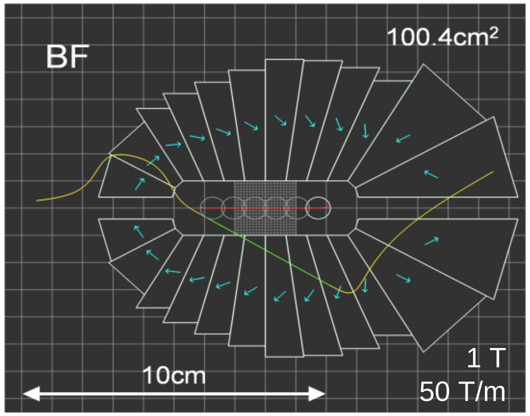


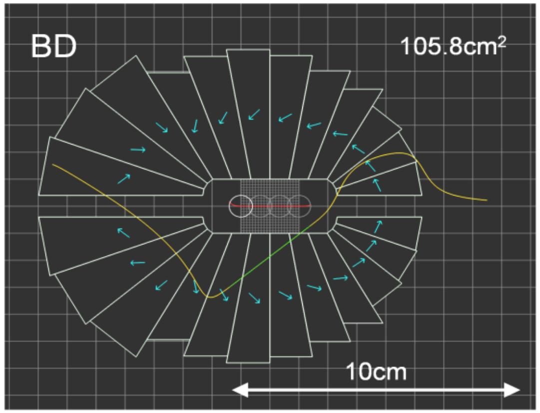
- Positrons (e+) in the LERF (former FEL) with transport to CEBAF
- Energy Upgrade for 650 MeV Electron (e-) Injection in the LERF

Beam Energy Doubling in CEBAF

- Large momentum acceptance fixed-field alternating-gradient (FAA) cells
- Transporting six beams with energies spanning a factor of two
- Through same string of relatively little expensive permanent magnets
- Closely spaced orbits for all six beams (~ 1 cm)
- CBETA demonstrated 42, 78, 114, and 150 MeV in common chamber







A CEBAF Energy Upgrade – The Big Picture

Addresses:

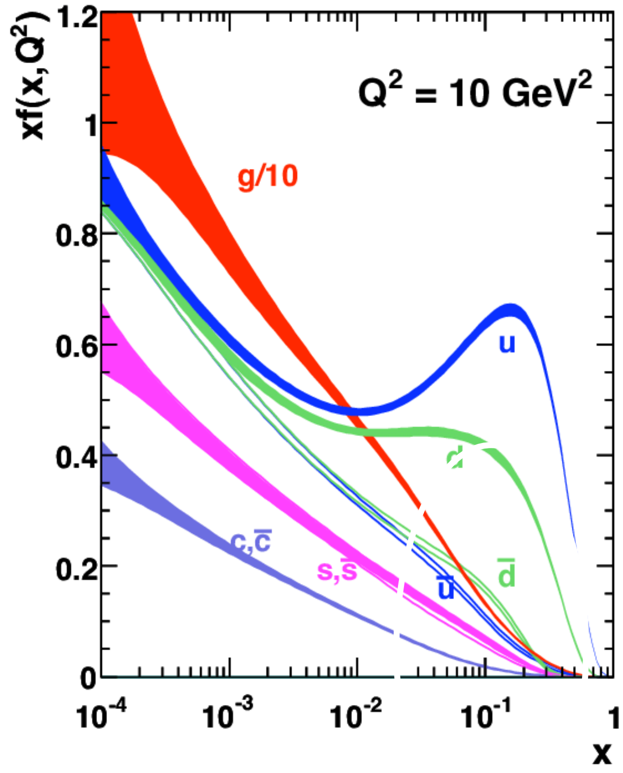
- Emergence of hadrons from QCD
- Quark-gluon dynamics
- Structure of hadrons
- Hadron-hadron interactions

Experimental approaches:

- Spectroscopy
- Excited states
- TMDs, GPDs
- Hadronization

Important aspects:

- Builds upon program of investigation in the valence region (x > ~0.1)
- Validation of QCD inspired models
- New opportunities in the charm sector

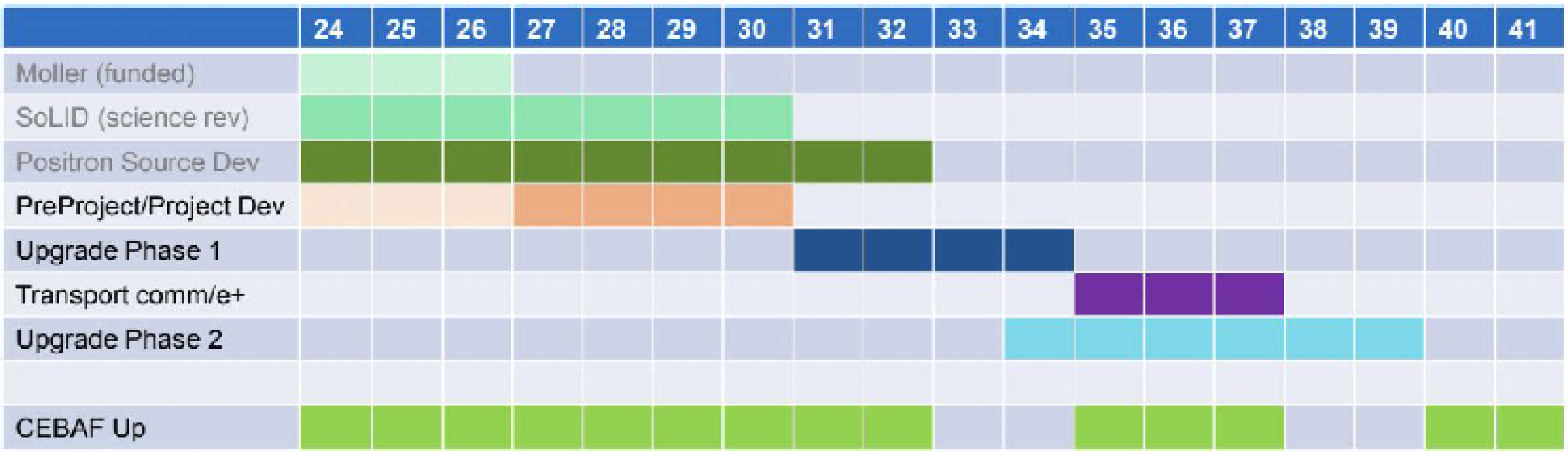


White paper in preparation: “Hadronic Structure at the Luminosity Frontier: JLab at 22 GeV”

Jefferson Lab's Long-Term Schedule

Notional CEBAF & upgrade schedule (FY24 – FY42)

- Accelerator/engineering team have worked up an early schedule and cost estimate
  - Schedule assumptions based on a notional timing of when funds might be available (near EIC ramp down based on EIC V3 profile)
  - For completeness, Moller and SoLID (part of 12 GeV program) are shown; early positron source development also shown



- JLab to run 12 GeV electron beam until 2032
- JLab to run 12 GeV positron beam 2035–37
- JLab to run 22 GeV electron beam from 2040

[Thia Keppel, Positron Workshop, Mar. 2023]

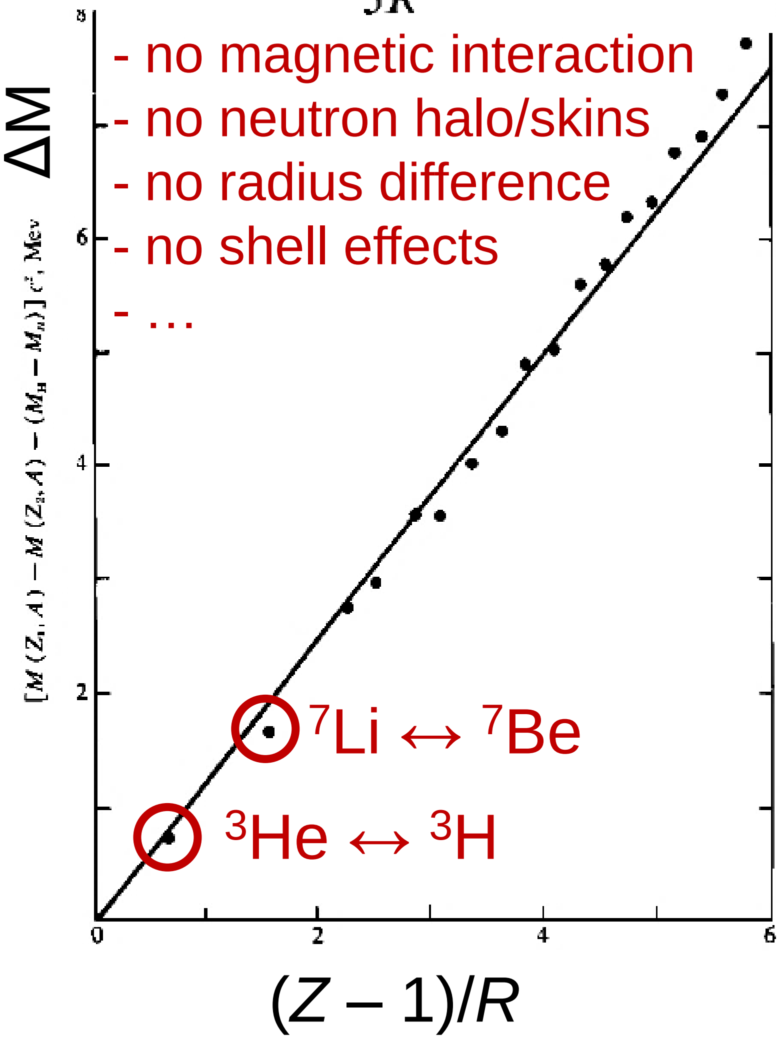
Hypernuclear Physics Proposals and LoIs to JLab PAC

E12-15-008 (In Jeopardy): An Isospin Dependence Study of the Lambda-N Interaction Through the High Precision Spectroscopy of Lambda Hypernuclei with Electron Beam

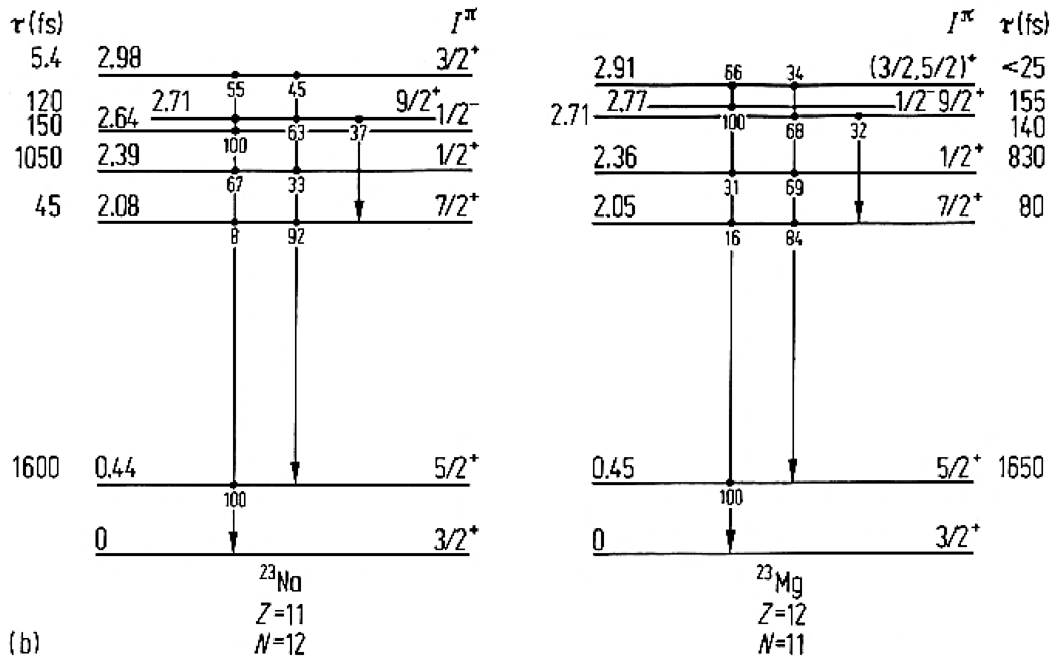
E12-20-013: Studying Λ interactions in nuclear matter with the ^{208}Pb($e,e'K+$) $^{208}_{\Lambda}$Tl reaction

The Role of Symmetries: Isospin

$$\Delta M = (Z_1 - 1)\frac{6e^2}{5R} + (M_H - M_n)c^2$$



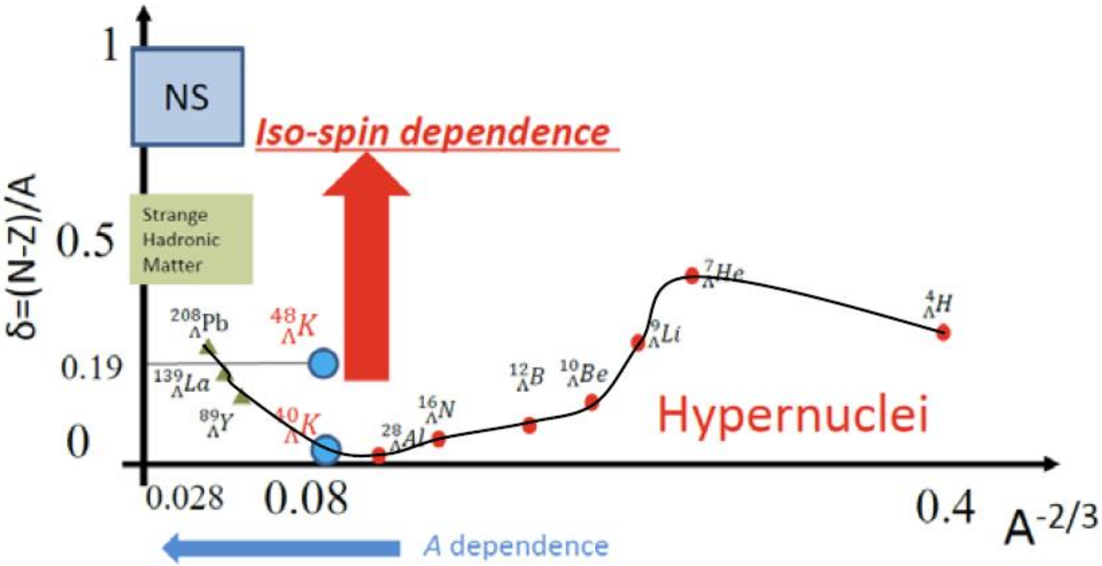
[Gleit et al., Nuclear Data Sheets 5 (1963)]

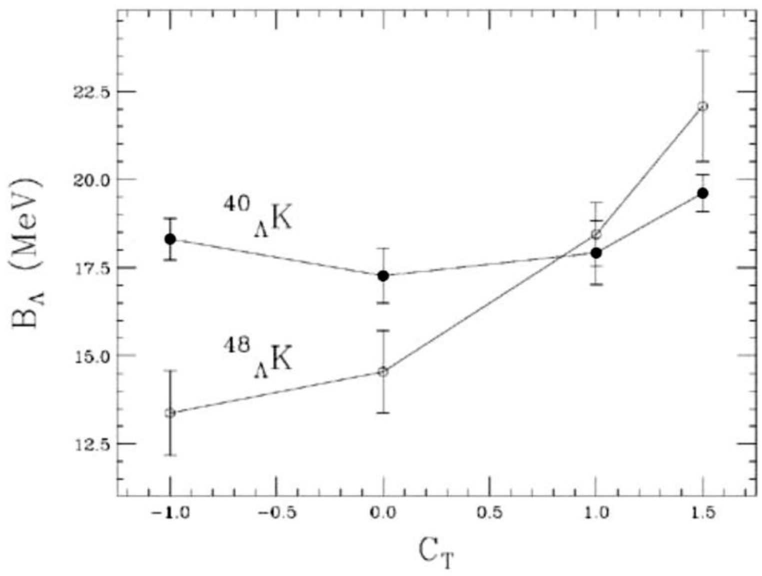


[Endt & van der Leun, NPA 310 (1978), 67]

- Symmetry in masses, binding energies and level schemes of mirror nuclei
- Strong force F independent of nucleon exchange: ($F_{p\text{-}p} = F_{n\text{-}n}$)

Study of Isospin-Dependence





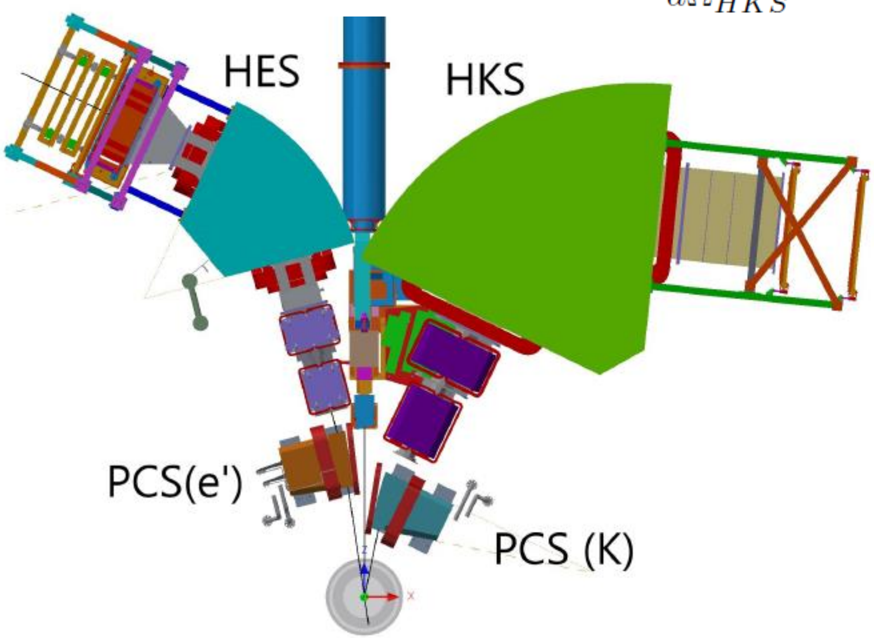
Current experimental information in this mass region cannot provide ANY information on the possible isospin dependence of hypernuclear forces

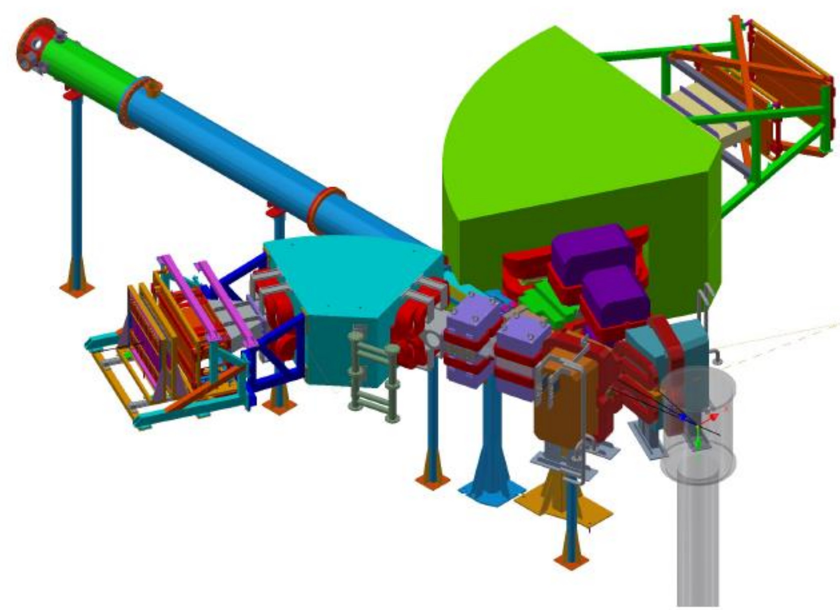
Experimental Setup

	Original	Updated
Experimental Hall	Hall-A	Hall-C
Beam Energy [/(GeV)]	4.532	2.240
Electron spectrometer	HRS	HES
Bending direction	Vertical	Horizontal
Central momentum [/(GeV/c)]	3.03	0.74
Kaon spectrometer	HKS	HKS
Bending direction	Horizontal	Horizontal
Central momentum [/(GeV/c)]	1.20	1.20

Beam	Energy E_e [/(GeV)]	2.240
	Energy stability $\Delta E_e/E_e$	3×10^{-5}
PCS + HES	Central momentum P_e [/(GeV/c)]	0.744
	Central angle $\theta_{e,e'}$ [/(deg)]	8
	Solid angle $\Delta\Omega_{e'}$ [/(msr)]	3.4
	Momentum resolution $\Delta P_{e'}/P_{e'}$	4.4×10^{-4}
PCS + HKS	Central momentum P_K [/(GeV/c)]	1.200
	Central angle θ_K [/(deg)]	15
	Solid angle $\Delta\Omega_K$ [/(msr)]	8.3
	Momentum resolution $\Delta P_K/P_K$	2.9×10^{-4}

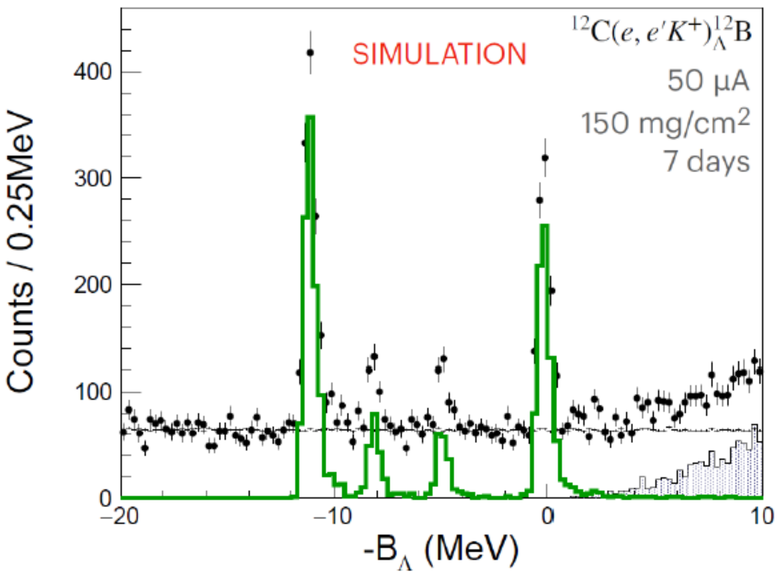
$$Y = N_t \times N_e \times \Gamma \times \frac{d\sigma}{d\Omega_{HKS}} \times \Delta\Omega_{HKS} \times \epsilon_{HES} \times \epsilon_{HKS} \times \epsilon_{decay}.$$

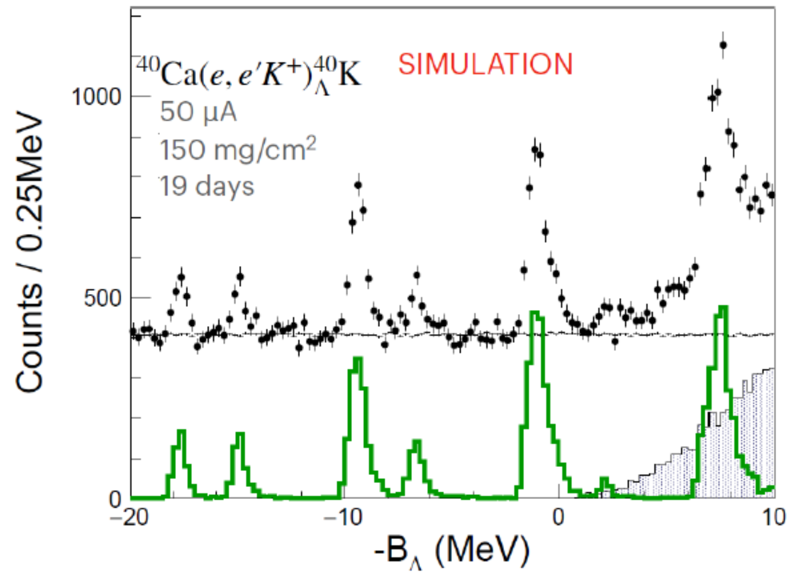




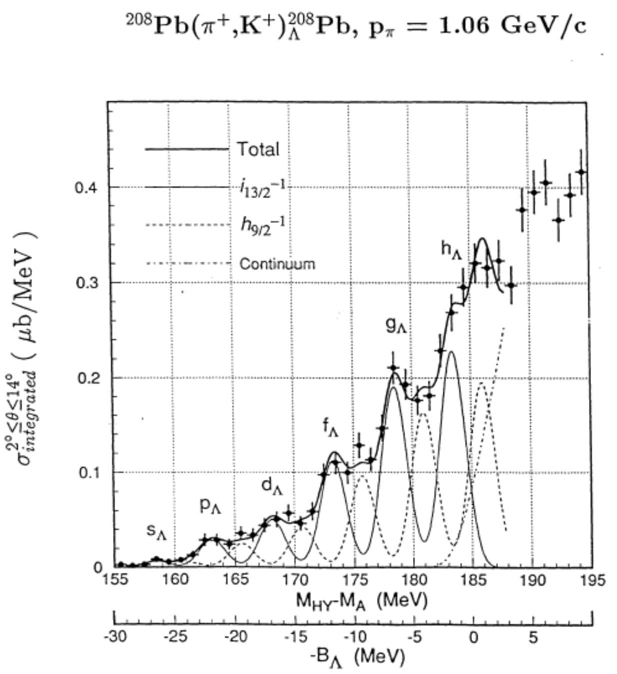
Study of Light and Medium-Mass Hypernuclei

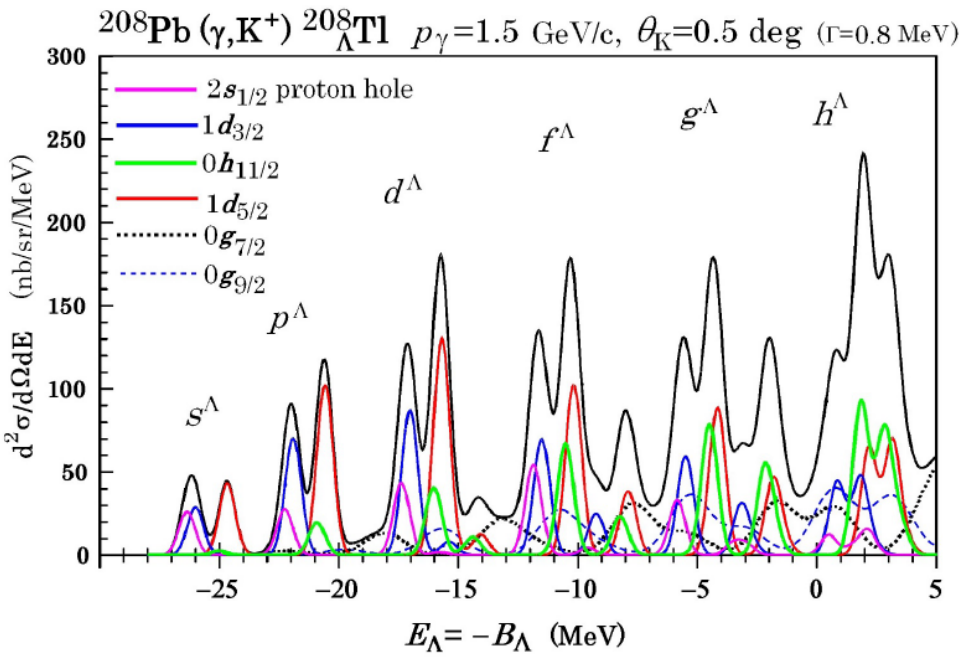
Target	CH_2	^{6}Li	^{9}Be	^{11}B	^{12}C	^{27}Al	^{40}Ca	^{48}Ca
Hyperon/Hypernucleus	Λ	$^{6}_{\Lambda}$He	$^{9}_{\Lambda}$Li	$^{11}_{\Lambda}$Be	$^{12}_{\Lambda}$B	$^{27}_{\Lambda}$Mg	$^{40}_{\Lambda}$K	$^{48}_{\Lambda}$K
Target thickness [/(mg/cm^2)]	500	150	150	150	150	150	150	150
Cross section [/(nb/sr)]	1000	10	10	30	90	60	50	50
Beam intensity [/(μA)]	2	50	50	50	50	50	50	50
Yield (g.s.) [/(/h)]	8.6	1.5	1.0	2.5	6.8	2.0	1.1	0.9
Acc. BG [/(/MeV/h)]	0.03	0.86	0.84	0.96	1.2	1.8	2.4	1.9





Study of Heavy Hypernuclei



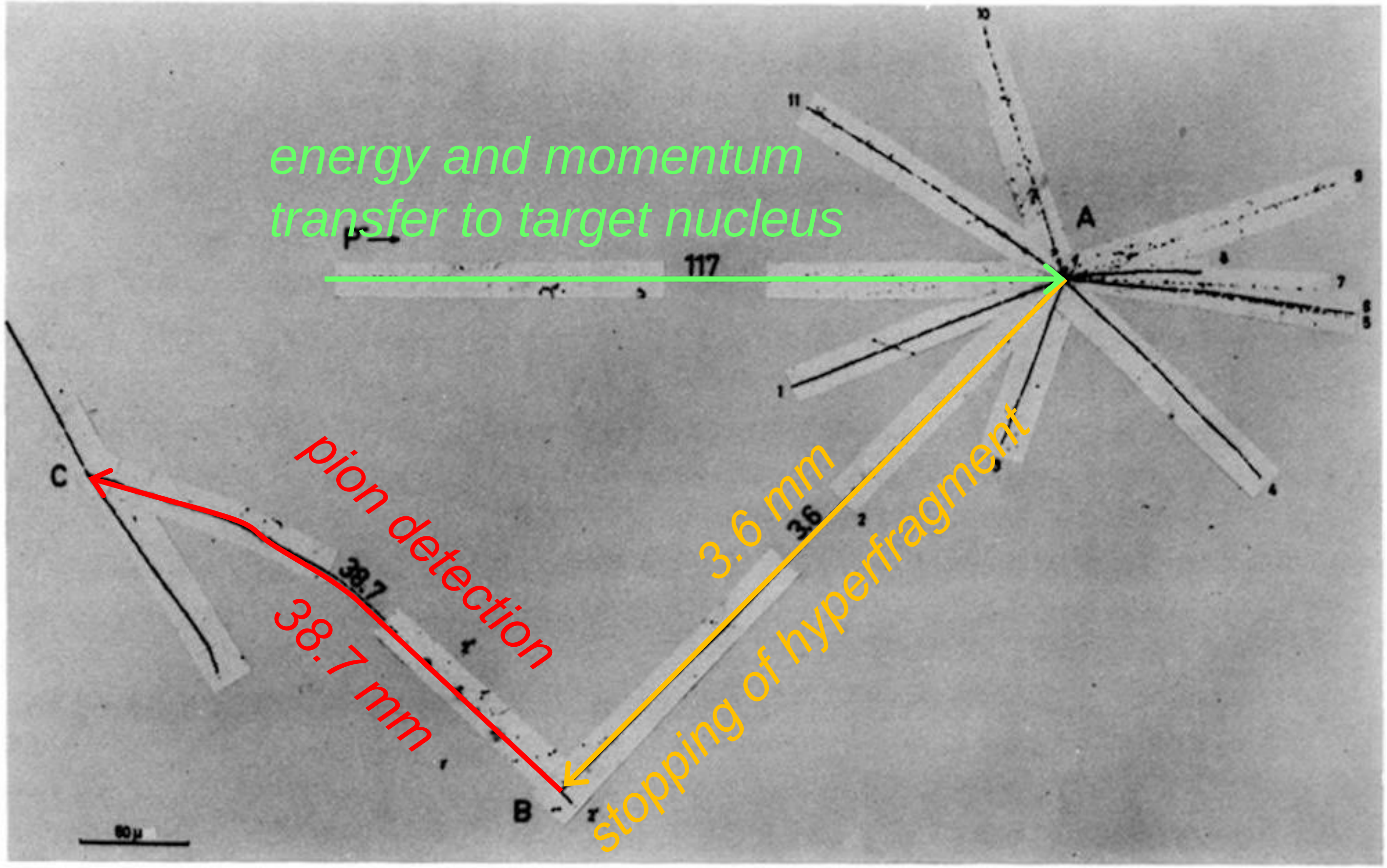


Due to extended region of constant density and large neutron excess heavy hypernuclei provide best available proxy of neutron star matter

Heavy hypernuclei provide an environment, in which three-body interactions are expected to play an important role

LOI12-23-011: High-resolution Spectroscopy of Light Hypernuclei with the Decay-Pion Spectroscopy

Hypernuclear Decay-Pion Spectroscopy in Emulsion

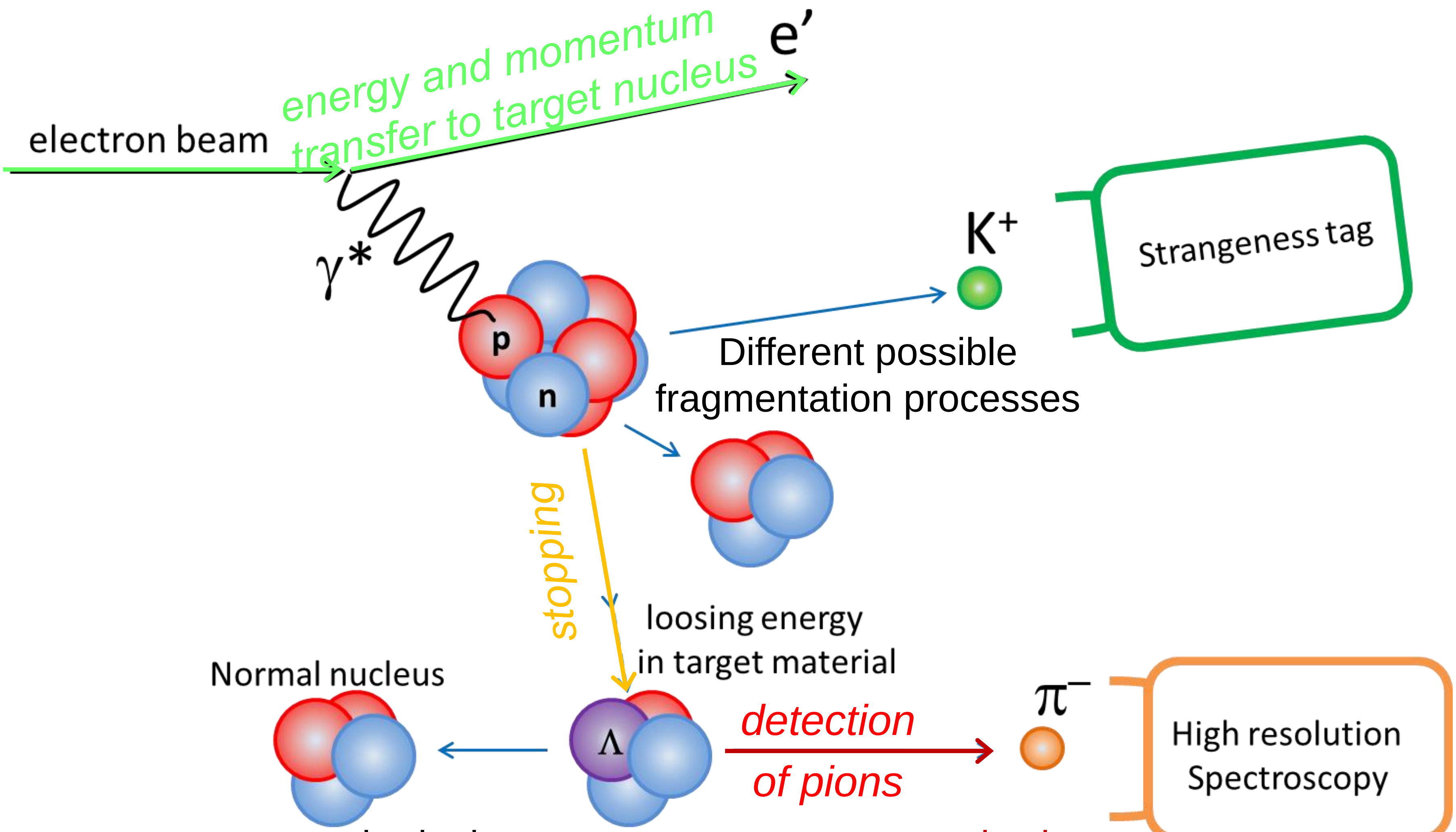


$$_{\Lambda}H^4 \rightarrow He^4 + \pi^- + Q,$$

where $Q = 54.6 \pm 1.0$ Mev.

[A.G. Ekspong et al., Phys. Rev. Lett. 3 (1959) 103]

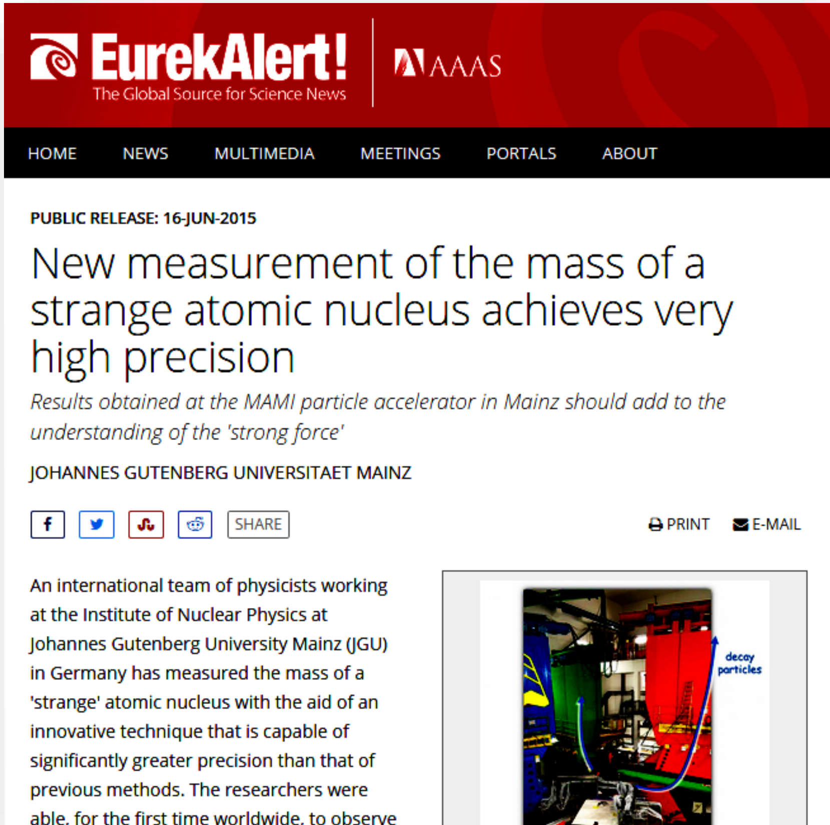
Hyperfragment Decay-Pion Spectroscopy with Electron Beams



two-body decay at rest ⇒ mono-energetic pions

$$M_{\mathrm{HYP}} = \sqrt{M_{\mathrm{ncl}}^2 + p_{\pi^-}^2} + \sqrt{M_{\pi^-}^2 + p_{\pi^-}^2}$$

Method Established at Mainz Microtron MAMI


EurekAlert! The Global Source for Science News | AAAS

HOME NEWS MULTIMEDIA MEETINGS PORTALS ABOUT

PUBLIC RELEASE: 16-JUN-2015

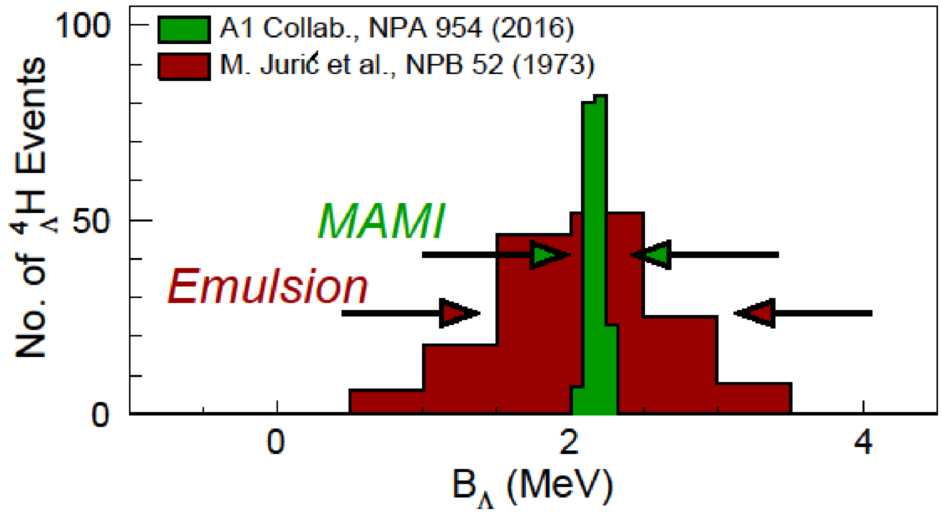
New measurement of the mass of a strange atomic nucleus achieves very high precision

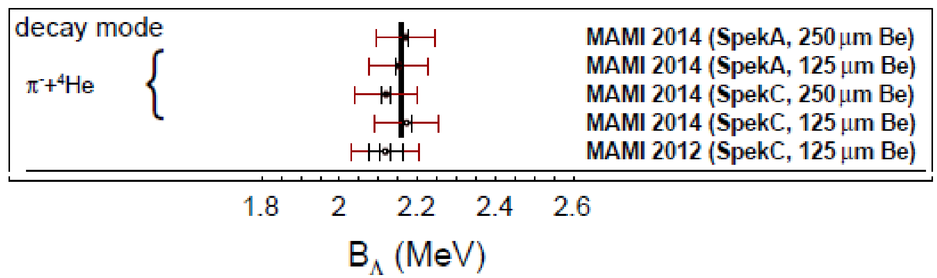
Results obtained at the MAMI particle accelerator in Mainz should add to the understanding of the 'strong force'

JOHANNES GUTENBERG UNIVERSITAET MAINZ

SHARE PRINT E-MAIL

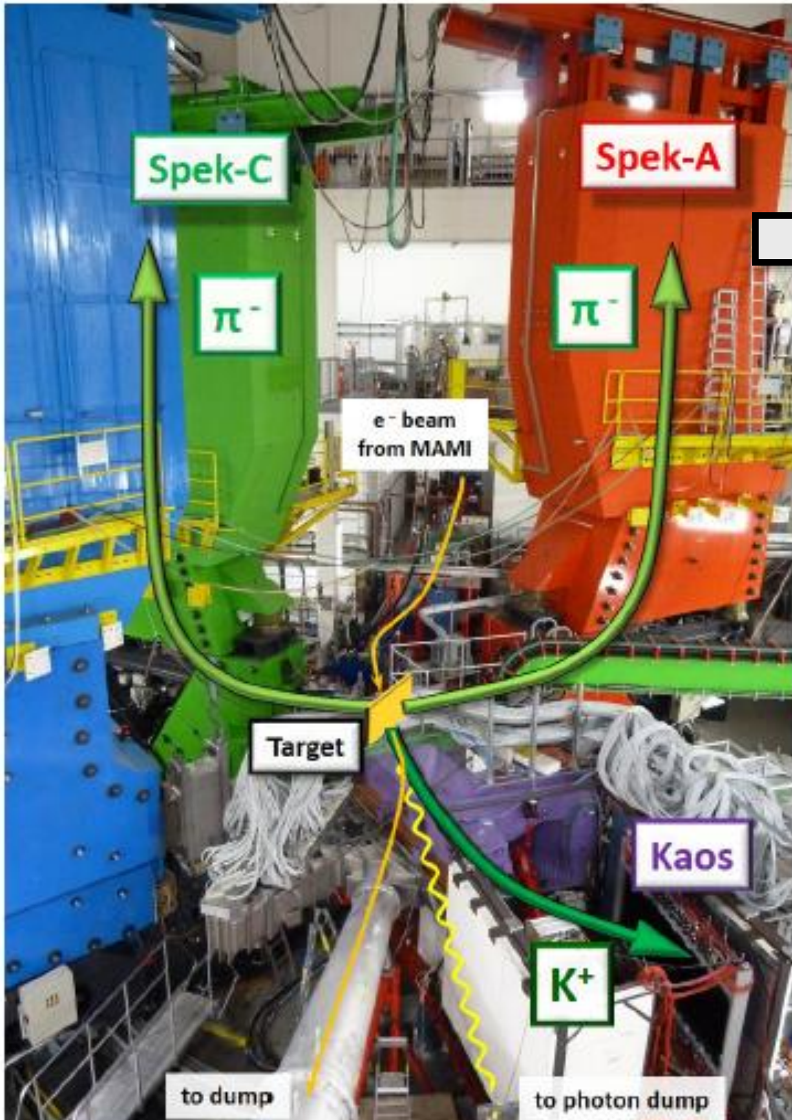
An international team of physicists working at the Institute of Nuclear Physics at Johannes Gutenberg University Mainz (JGU) in Germany has measured the mass of a 'strange' atomic nucleus with the aid of an innovative technique that is capable of significantly greater precision than that of previous methods. The researchers were able, for the first time worldwide, to observe

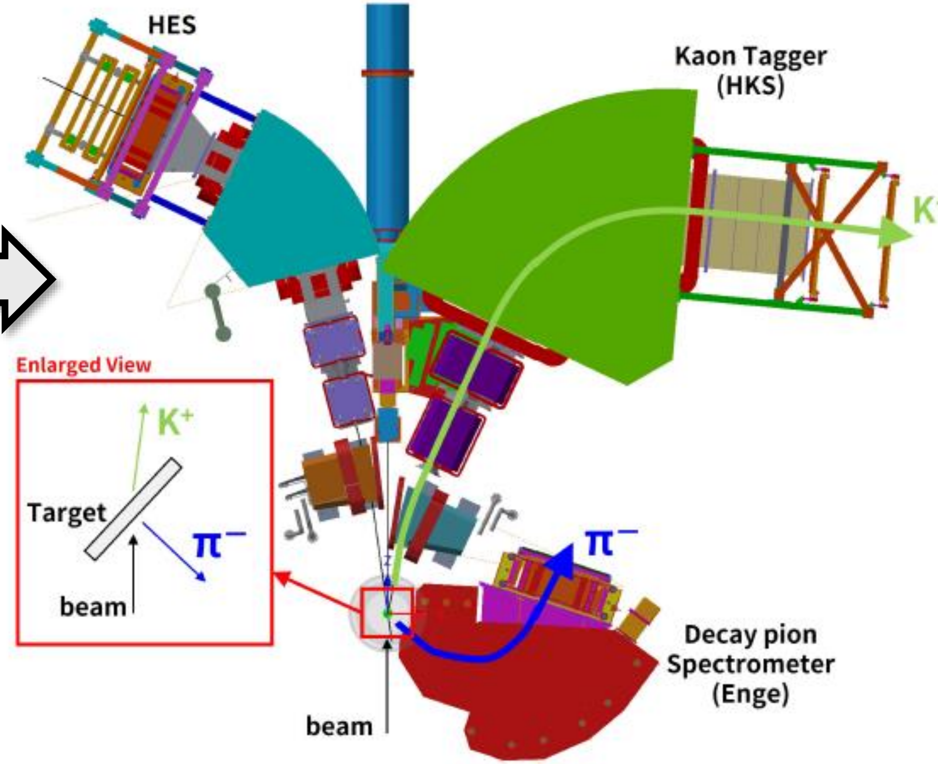




Binding energies of light hyperisotopes could be measured with improved precision by decay-pion spectroscopy

Continuation of Study at JLab

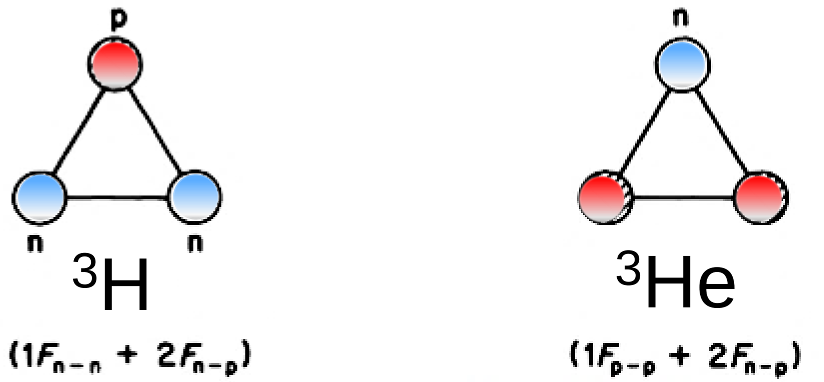


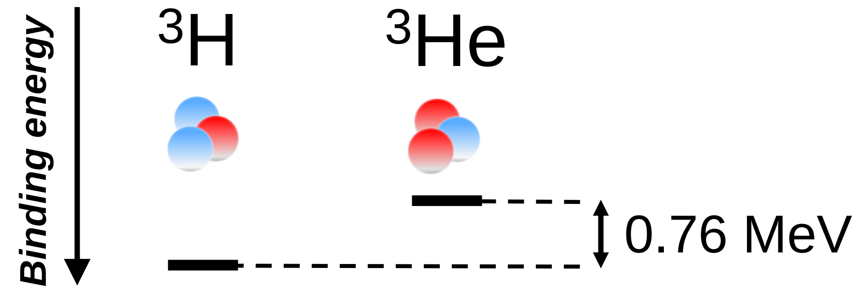


Target	Thickness (mm)	Thickness (mg/cm^2)	Hypernuclei
^{6}Li	2.8	150	$^{3,4}_{\Lambda}$H
^{9}Be	0.8	150	$^{3,4,6}_{\Lambda}$H, $^{7,8}_{\Lambda}$He, $^{7,8,9}_{\Lambda}$Li, $^{8}_{\Lambda}$Be
^{11}B	0.7	150	$^{3,4,6}_{\Lambda}$H, $^{7,8}_{\Lambda}$He, $^{7,8,9}_{\Lambda}$Li, $^{8}_{\Lambda}$Be
^{12}C	0.9	150	$^{3,4,6}_{\Lambda}$H, $^{7,8}_{\Lambda}$He, $^{7,8,9}_{\Lambda}$Li, $^{8}_{\Lambda}$Be, $^{9,10,11,12}_{\Lambda}$B
^{27}Al	0.6	150	s, p, sd-shell hypernuclei?
^{40,48}Ca	1.0	150	s, p, sd-shell hypernuclei?
^{208}Pb	0.13	150	s, p, sd-shell hypernuclei?

LOI12-23-013: Study of Charge Symmetry Breaking in *p*-Shell Hypernuclei

Charge Symmetry Breaking in Nuclei





$M(^3\mathrm{H}) =$	2808.921	$B(^3\mathrm{H}) =$	8.482
$M(^3\mathrm{He}) =$	2808.391	$B(^3\mathrm{He}) =$	7.718
$\Delta M^3 =$	−0.530	$\Delta B^3 =$	−0.764

… can be studied in mirror nuclei after correcting for Coulomb effects

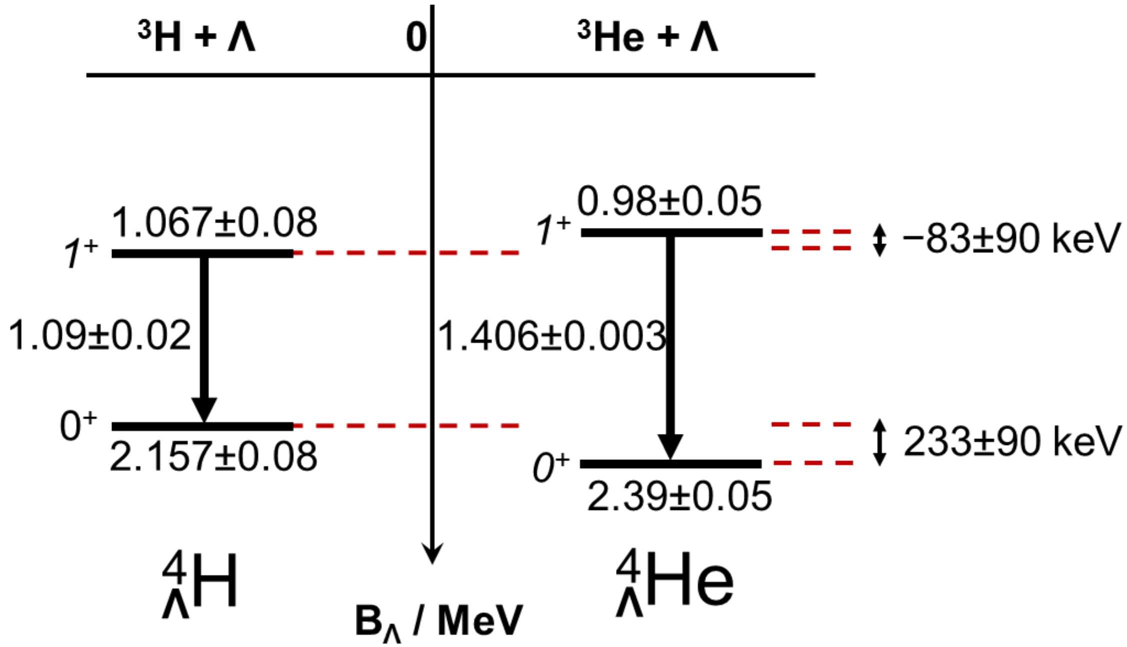
… is dominated by electromagnetic effects

… nuclear part very small, ~ 80 keV in case of ^{3}H - ^{3}He

… is well understood and reproduced by theory using ρ^0-ω mixing

[R. Machleit et al., Phys. Rev. C 63, 034005 (2001)]

Charge Symmetry Breaking in Hypernuclei



[F. Schulz et al. (A1 Collab.), NPA 954, 149 (2016)]

– Is CSB in the *A = 4* system a feature of spin-dependent interactions?

– Is CSB a general feature of SU(3) interactions in light systems?

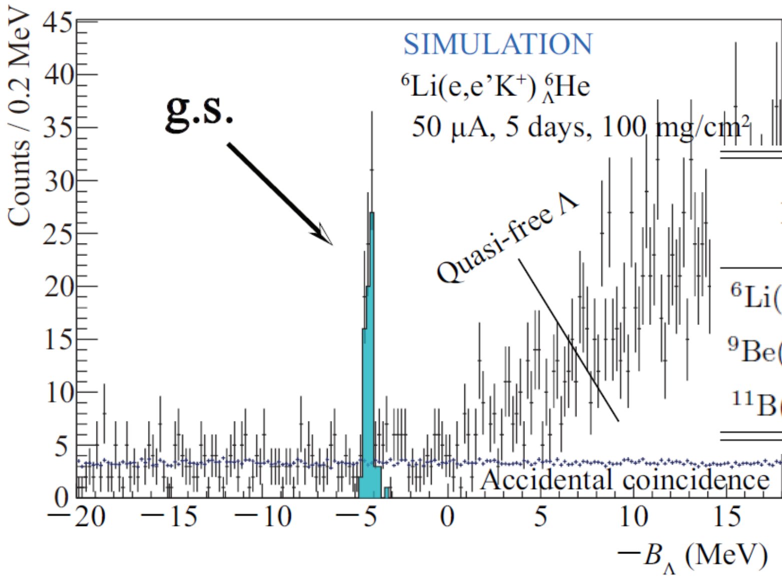
Answers can only be found in systematic studies across different nuclei

Hypernuclear Isospin Multiplets

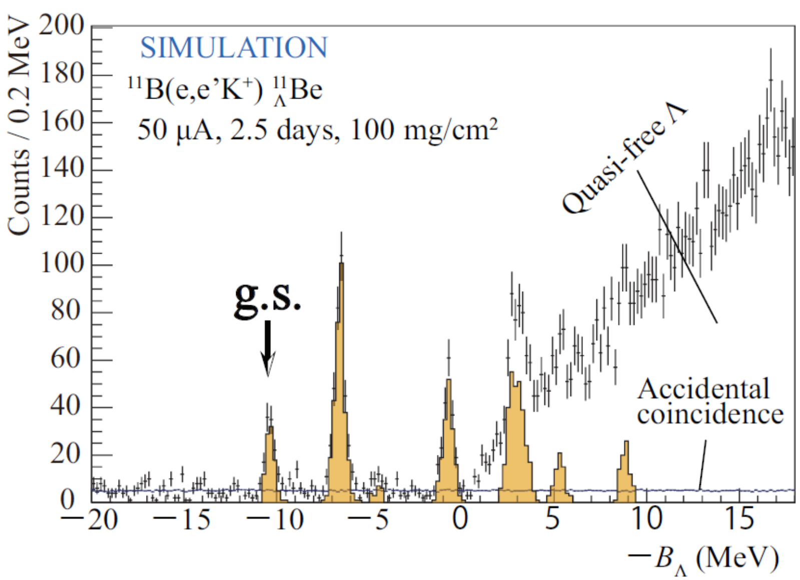
Electron-beam experiment at JLab — VP
Hadron-beam experiment at J-PARC — H
Emulsion experiment — E
γ-ray experiment — Y

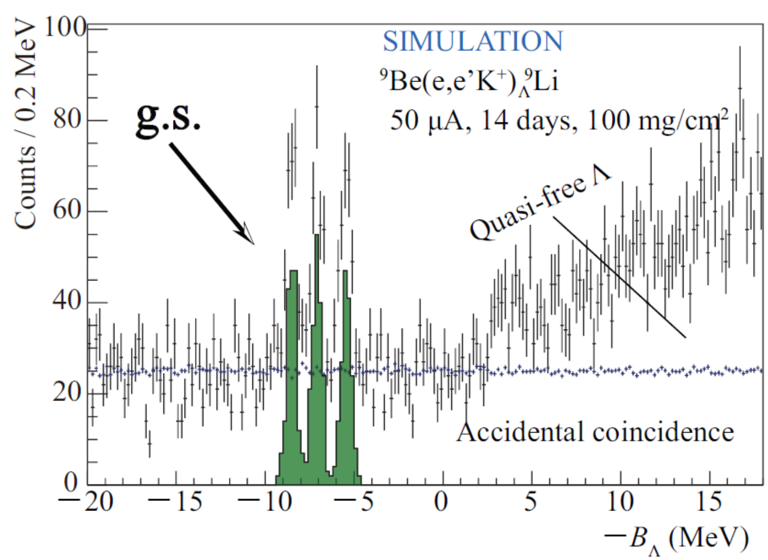
Hypernucleus		T<0	T=0	T>0
s-shell	d N Λ (0⁺) (1⁺)	${}^{4}_{\Lambda}\mathrm{H}$ (VP E Y H) *new*		${}^{4}_{\Lambda}\mathrm{He}$ (VP E Y H)
p-shell	α N Λ	${}^{6}_{\Lambda}\mathrm{He}$ *new*		${}^{6}_{\Lambda}\mathrm{Li}$ *new*
	α N N Λ	${}^{7}_{\Lambda}\mathrm{He}$	${}^{7}_{\Lambda}\mathrm{Li}^{*}$	${}^{7}_{\Lambda}\mathrm{Be}$
	α d N Λ	${}^{8}_{\Lambda}\mathrm{Li}$		${}^{8}_{\Lambda}\mathrm{Be}$
	α d N N Λ	${}^{9}_{\Lambda}\mathrm{Li}$ *new*	${}^{9}_{\Lambda}\mathrm{Be}$	${}^{9}_{\Lambda}\mathrm{B}$
	α α N Λ	${}^{10}_{\Lambda}\mathrm{Be}$		${}^{10}_{\Lambda}\mathrm{B}$ *new*
	α α N N Λ	${}^{11}_{\Lambda}\mathrm{Be}$ *new*	${}^{11}_{\Lambda}\mathrm{B}$ *new*	${}^{11}_{\Lambda}\mathrm{C}$
	α α d N Λ	${}^{12}_{\Lambda}\mathrm{B}$		${}^{12}_{\Lambda}\mathrm{C}$ *new*

Study of Partner States



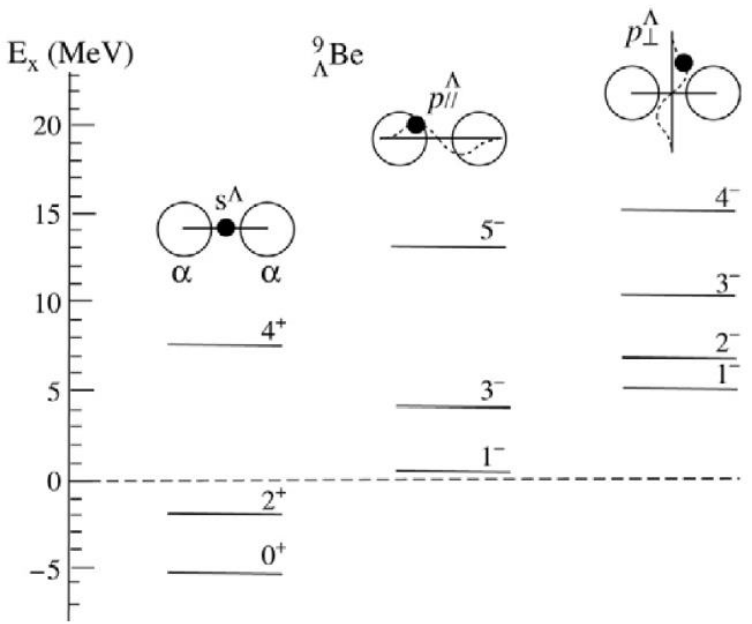
Reaction	Target thickness [/(g/cm²)]	Beam current (/μA)	Assumed cross section [/(nb/sr)]	Yield per day
$^{6}\mathrm{Li}(e,e'K^{+})^{6}_{\Lambda}\mathrm{He}$	100	50	10	24
$^{9}\mathrm{Be}(e,e'K^{+})^{9}_{\Lambda}\mathrm{Be}$			7.6	12
$^{11}\mathrm{B}(e,e'K^{+})^{11}_{\Lambda}\mathrm{B}$			30	39

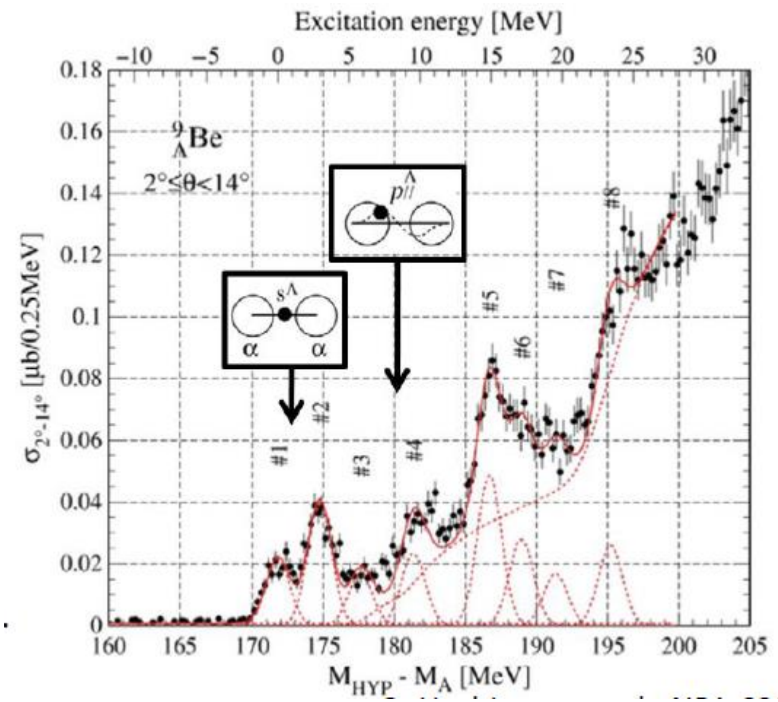




LOI12-23-016: Study of a Triaxially Deformed Nucleus Using a Lambda Particle as a Probe

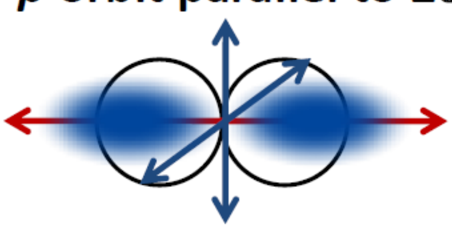
Genuine Hypernuclear States





Genuine hypernuclear states:

p orbit parallel to 2α (long axis)

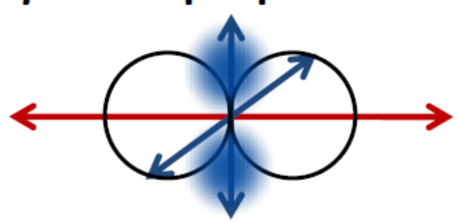


Large overlap

Deeply bound

^{9}Be analog states:

p orbit perpendicular to 2α (short axes)

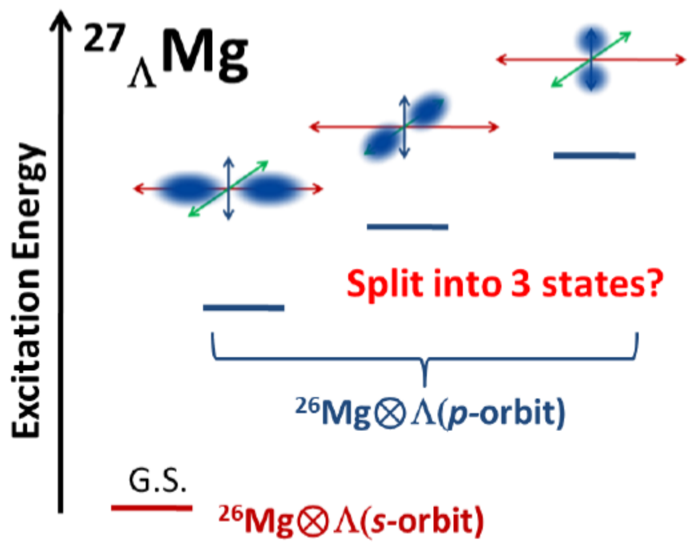


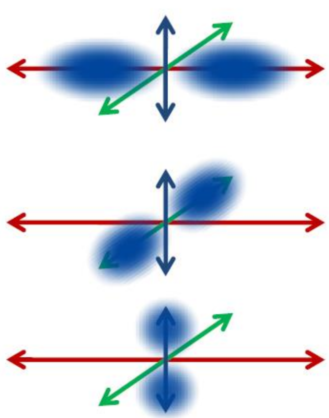
Small overlap

Shallowly bound

States in Triaxially Deformed Hypernuclei

Candidate: Mg hypernuclei

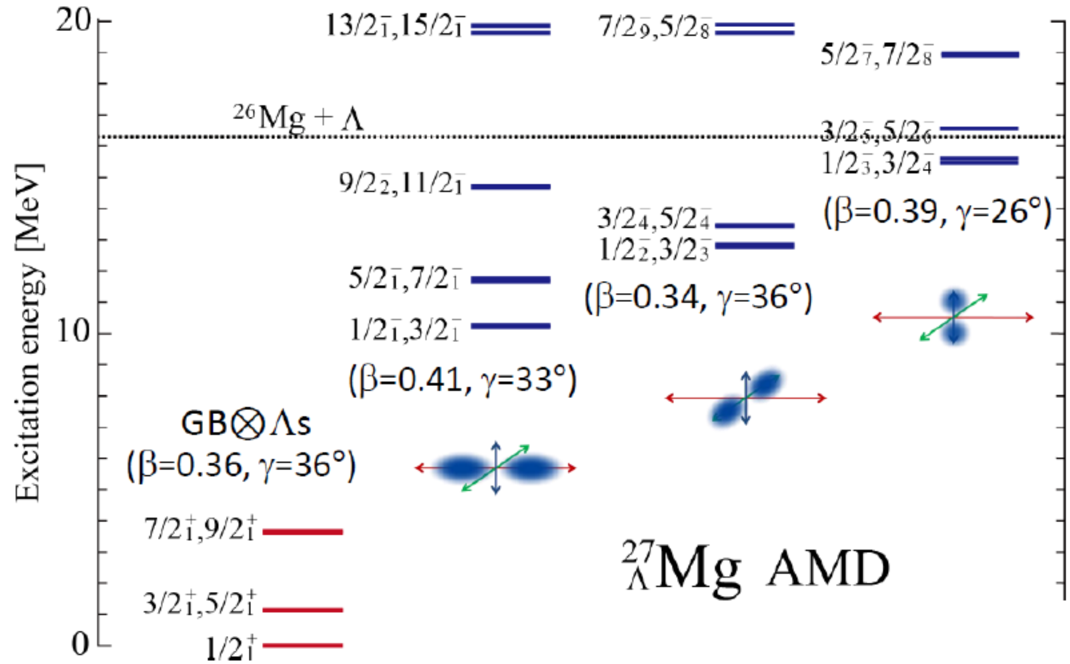


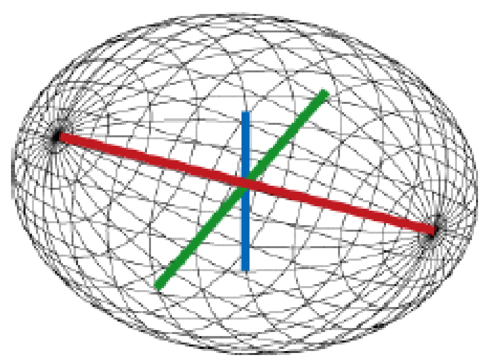


Large overlap
Deeply bound

Middle

Small overlap
shallow binding





Triaxial deformation

Summary

Strange meson & hypernuclear spectroscopy are now becoming a precision science

Study of isospin dependence is linked to understanding of *NN* and *ΛN* interactions

Study of charge symmetry breaking in hypernuclei uniquely reveals features of nuclear interactions

Study of coupling of Λ to deformed nuclei uniquely reveals cluster and shape structures

Research program will develop our knowledge of nuclear equation-of-state and stability of neutron stars