2025/5/15 @ JLab

THE UNIVERSITY OF TOKYO

QNSI

Quark Nuclear Science Institute, UTokyo

Isospin dependent Lambda-NN interaction and Triaxially Deformation Nuclear States

E12-24-013

An isospin dependence study of the Lambda-N interaction through the high precision spectroscopy of Lambda hypernuclei with electron beam

E12-24-011

Study of triaxially deformed nucleus using a Lambda particle as a probe

S.N.Nakamura Univ. of Tokyo

HYPERON Puzzle

Mystery of heavy Neutron Stars.

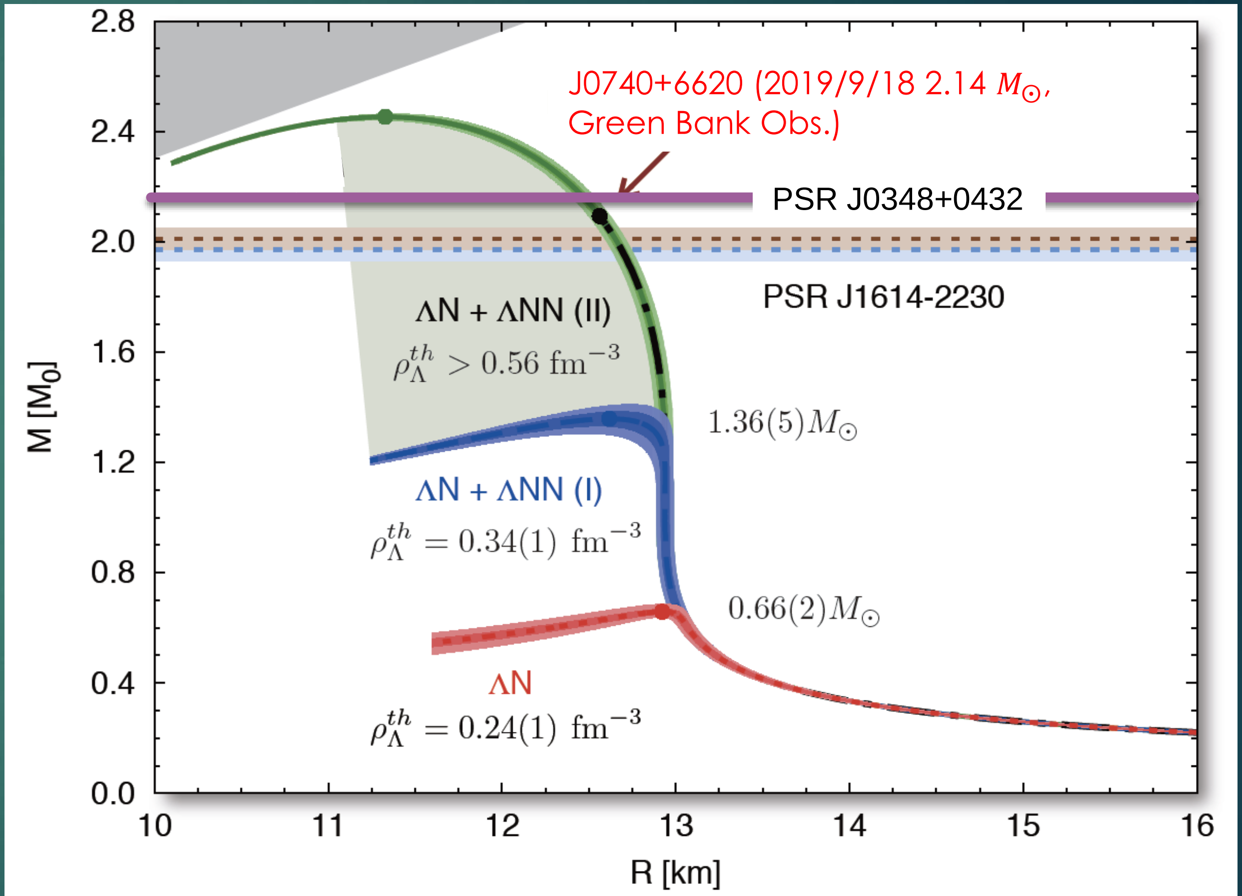
Based on our knowledge of baryonic force,
Hyperon naturally appear at high density $(\rho \sim 2,3\rho_0)$

Too soft EOS. **NS cannot support mass of 2 $M_\odot$**

Contradict to astronomical observations.

Need **additional repulsive force**
(ΛNN 3-body repulsive force)
Make stiffer EOS

Neutron star : **Large $(N-Z)/A \geq$ 0.9 and Large A**



2 solar mass NS

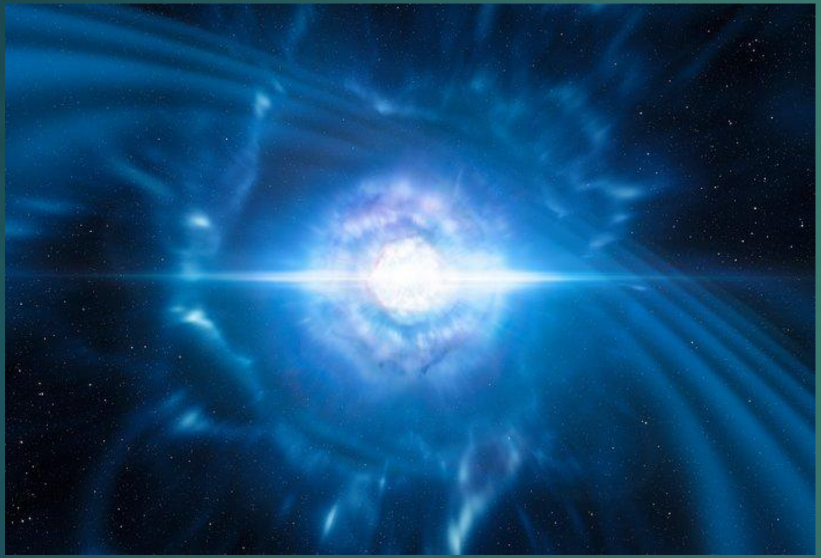
Iso-spin dependence
E12-24-014

A dependence
E12-24-003

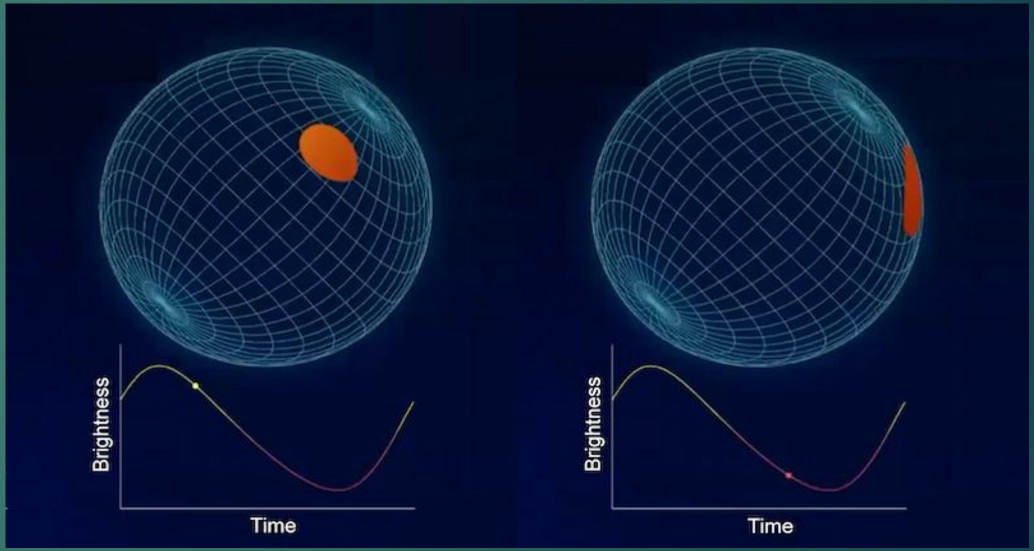
New astronomical observations

New Gravitational Waves from NS mergers and NICER (Neutron star Interior Compsition ExploreR)

CC4.0 ESO/L. Calçada/M. Kornmesser



Gravitation Wave from neutron star mergers
LIGO/Virgo PRL **119**, 161101 (2017)

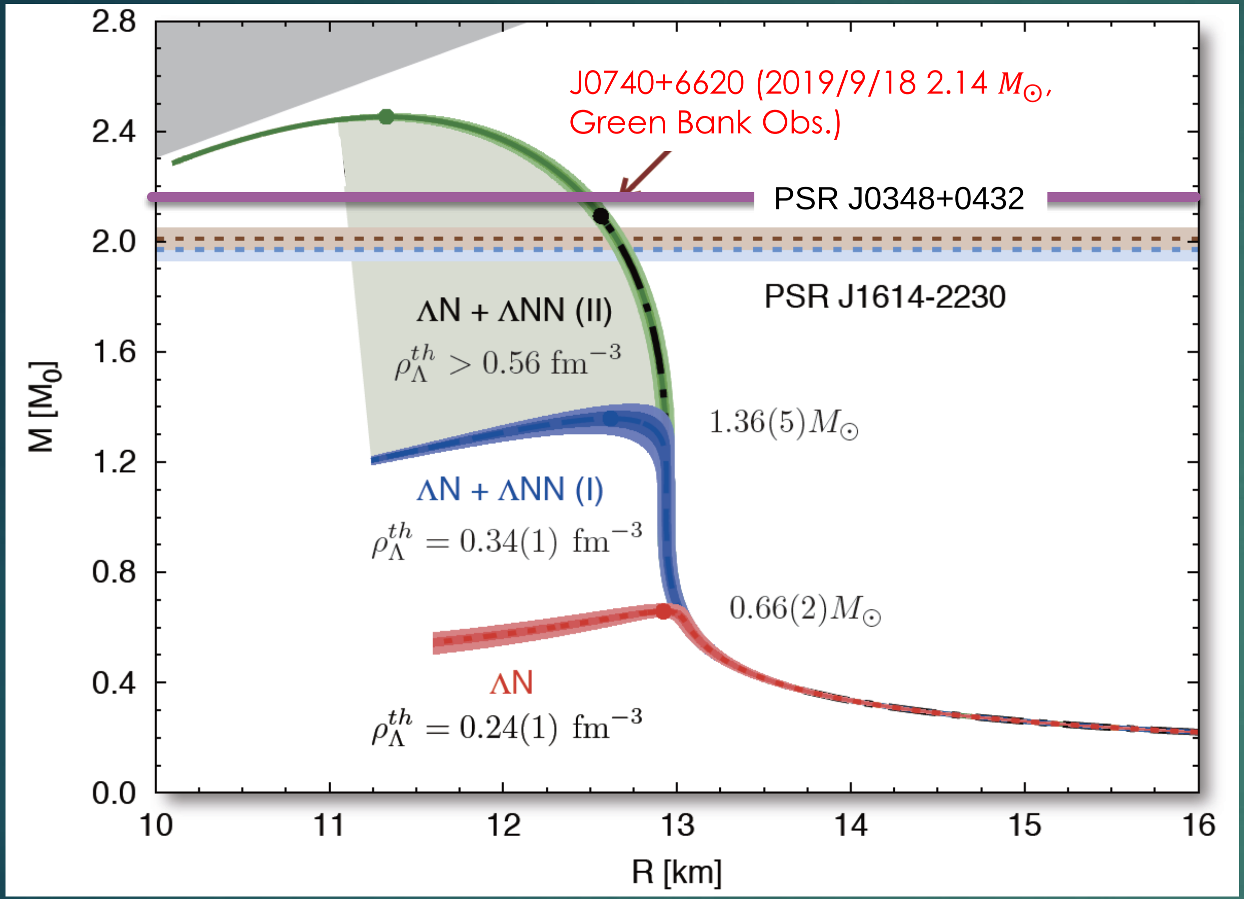


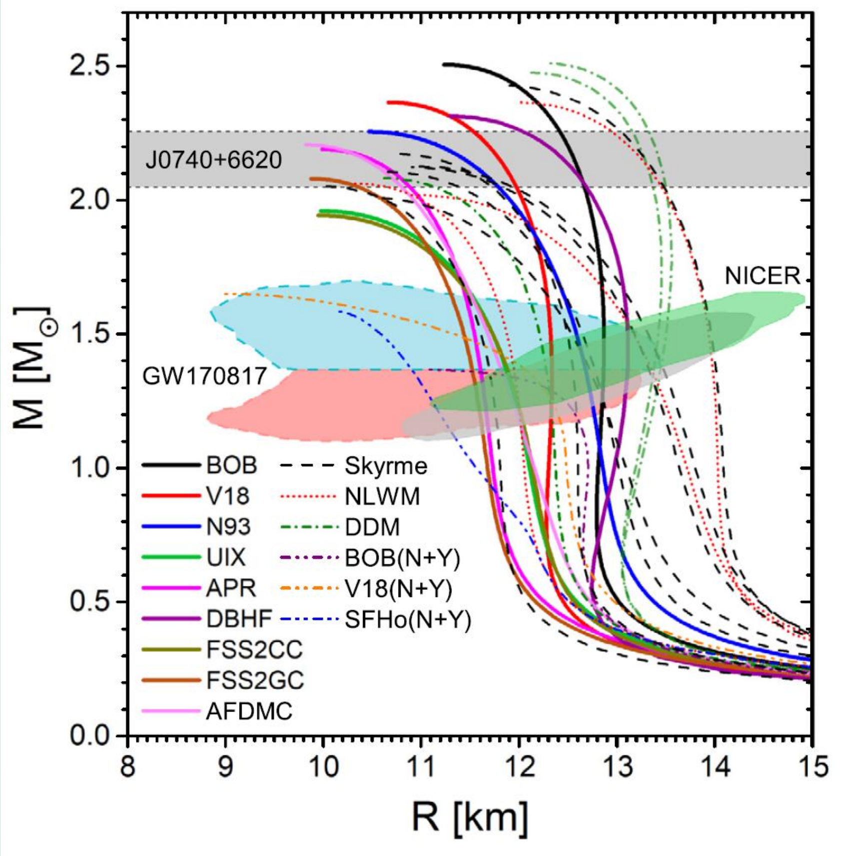
Goddard Space Flight Center

NICER : NS x-ray hot spot measurement
Physics 14, 64 (Apr. 29, 2021)

Macropscopic features of NS : Tidal deformability, Radius and Mass

New constrains from astronomical observations





Macroscopic understanding of NS made great progresses.
But we would like to know why NS is so heavy and large.

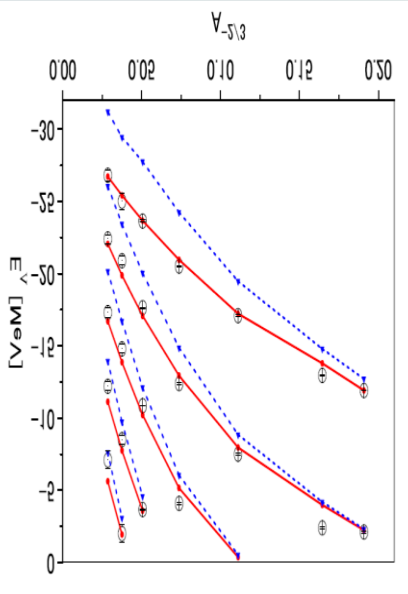
C.F.Burgio et al. Prog. Part. Nucl. Phys 120 (2021) 103879.

Microscopic study (nuclear physics exp) becomes more important than ever!

Today, Togashi-san will talk about recent theoretical progresses

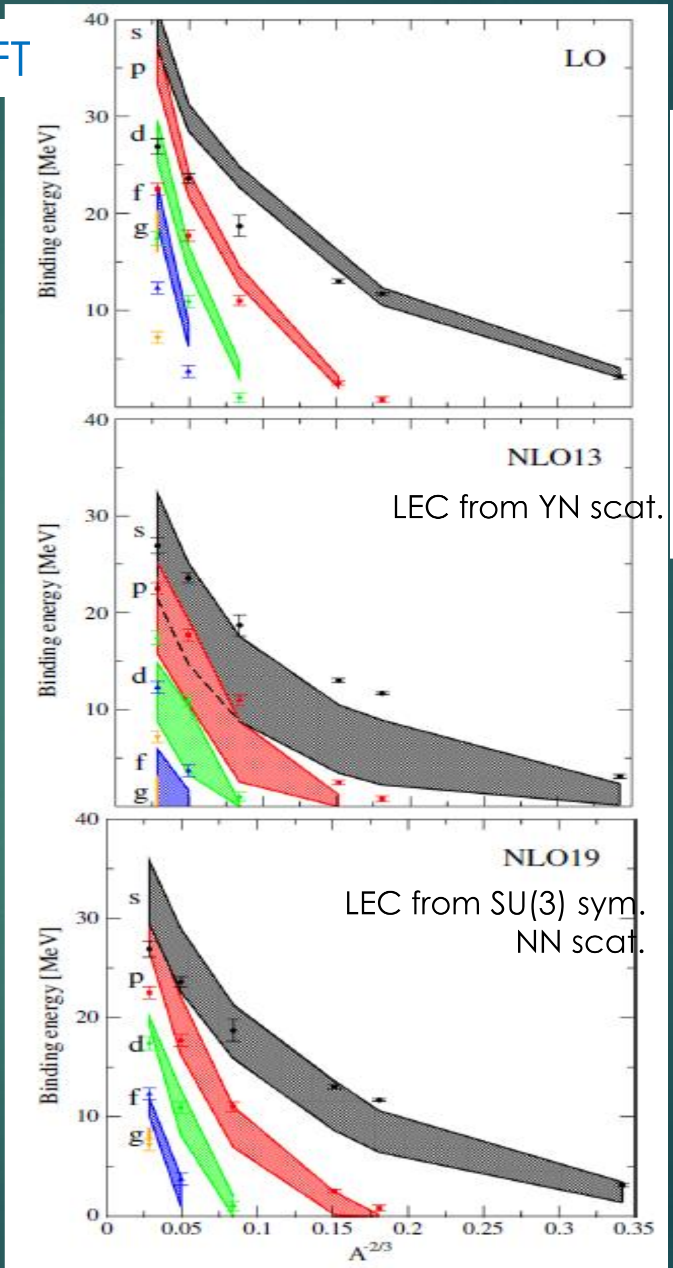
Λ Single Particle Energies of Λ Hypernuclei by Various Calculations

M.M. Nagels et al., PRC 99 (2019) 044003.



ESC16
ESC16+ (Inc. 3BF)
G-matrix

ChEFT

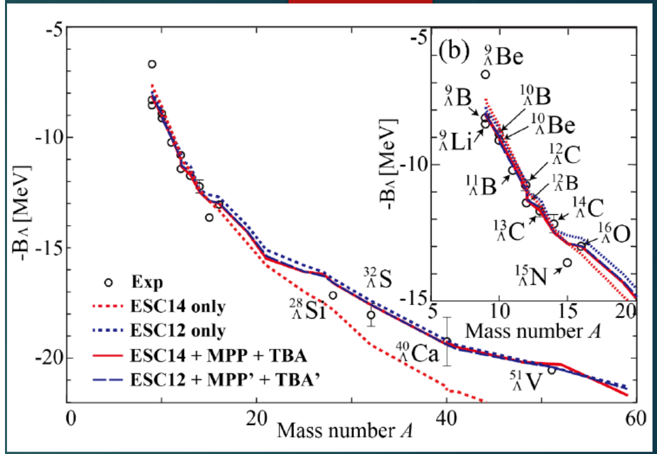


LEC from YN scat.

LEC from SU(3) sym.
NN scat.

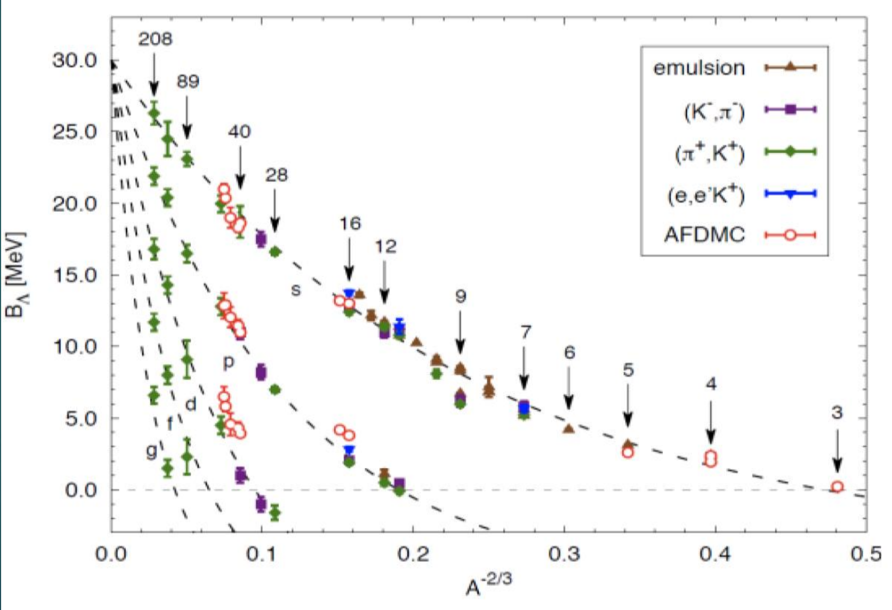
J.Haidenbauer, I.Vidana, EPJA (2020) 56:55.

Hyper-AMD



M.Isaka et al.,
PRC94, 044310 (2016),
PRC 95, 044308 (2017)

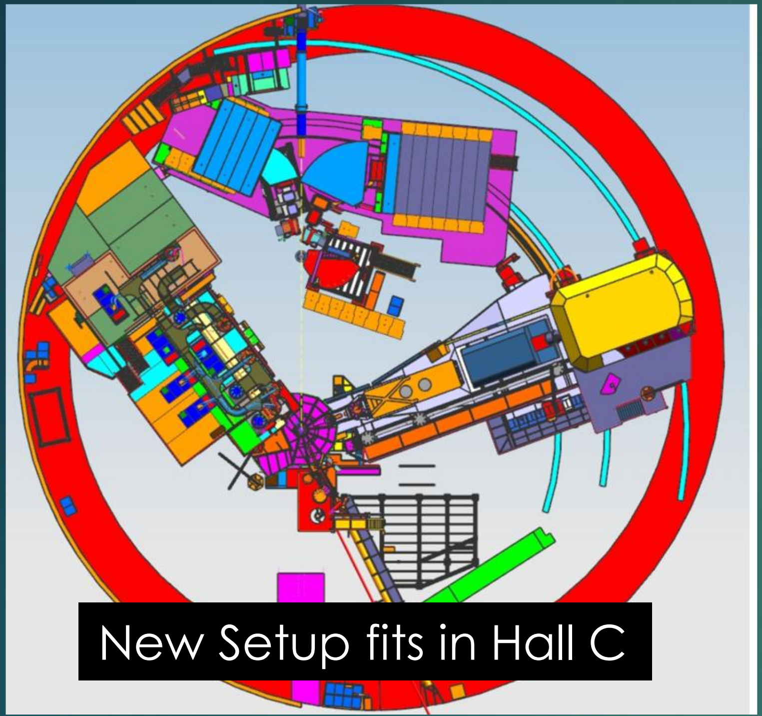
AFDMC



D.Lonardoni and F. Pederiva, arXiv:1711.07521.

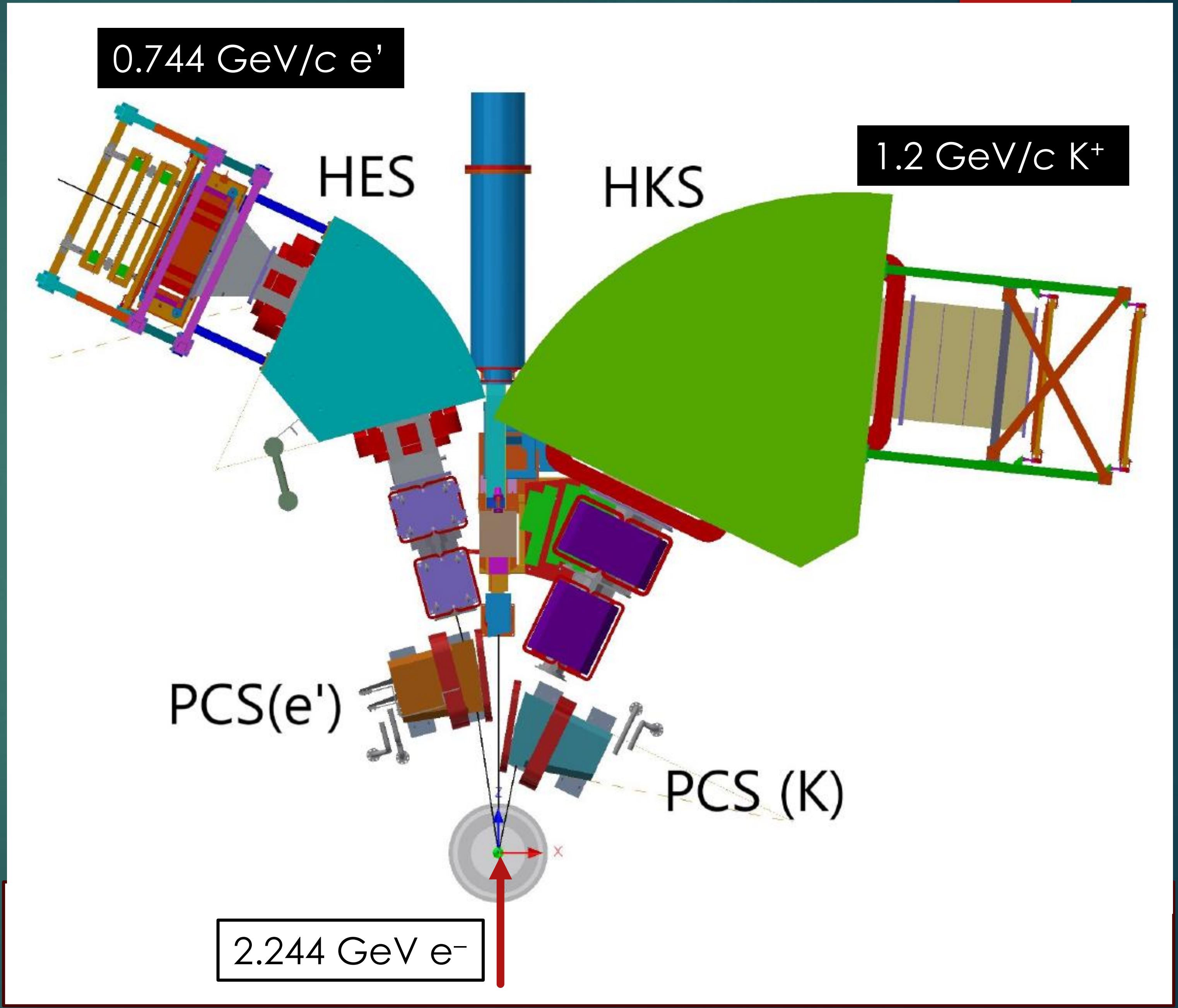
Jinno-san will talk about unified theoretical approach to study Hypernuclei, HI collision and hyperon puzzle

Setup in Hall-C



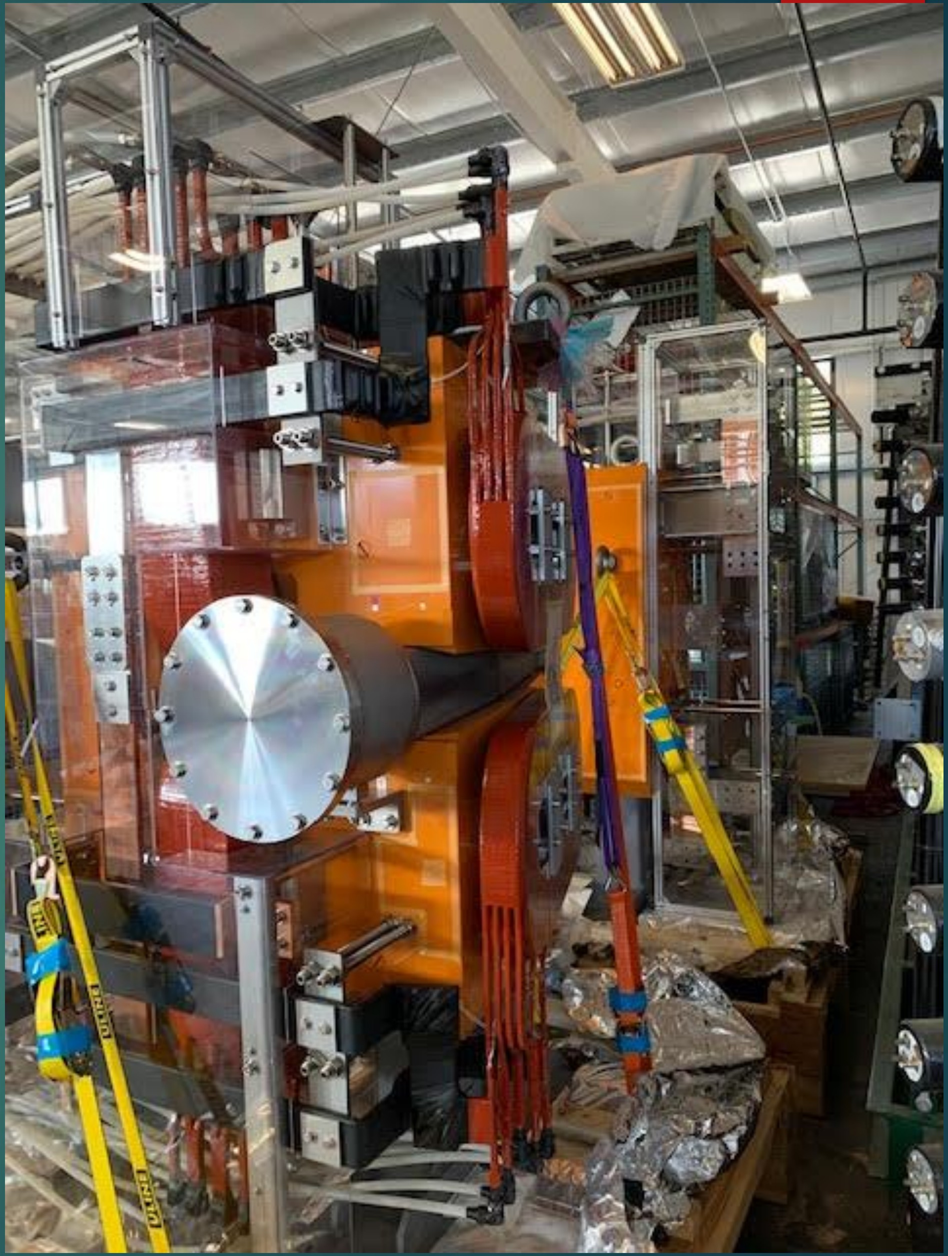
New Setup fits in Hall C

HKS-HES+SPL (E015-115)

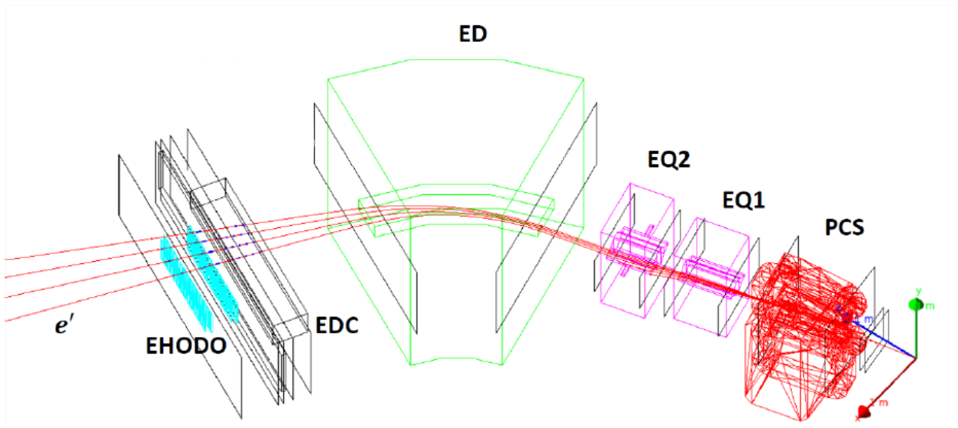


PCS magnets, newly developed major instrument, were already constructed and shipped to JLab

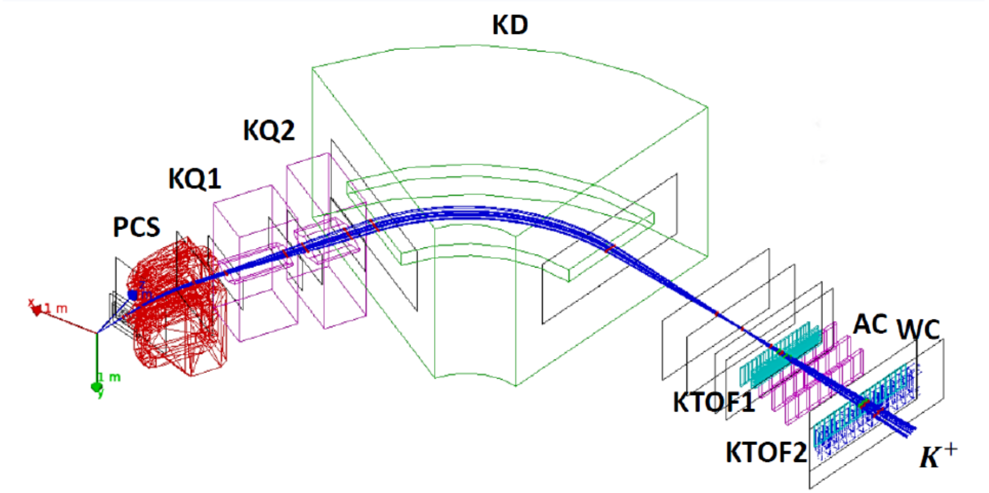
Newly constructed PCS magnets (TOKIN, 2020.3)



Delivered to JLab (2022.2 @ JLab)



(a) The model of HES implemented in GEANT4.

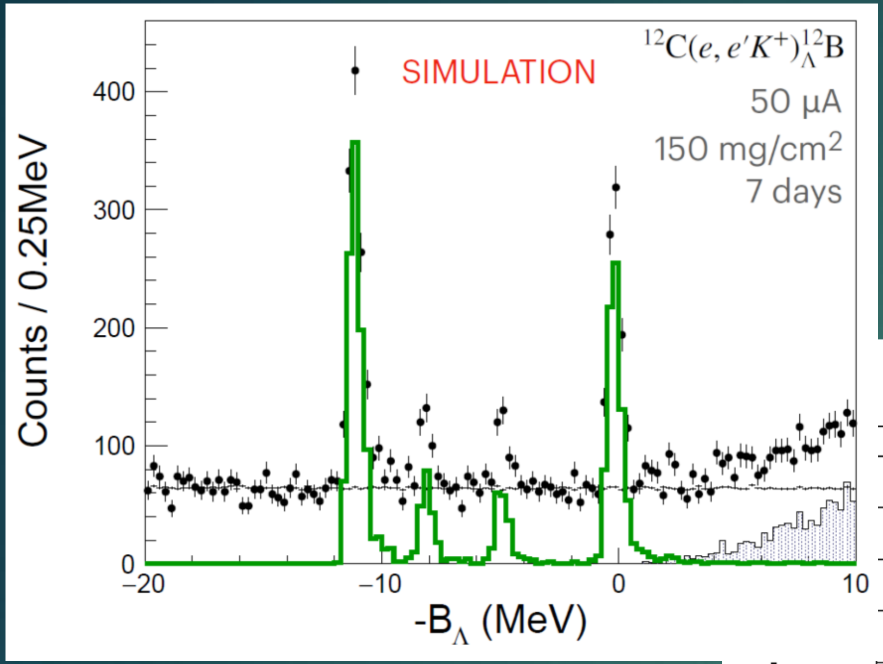


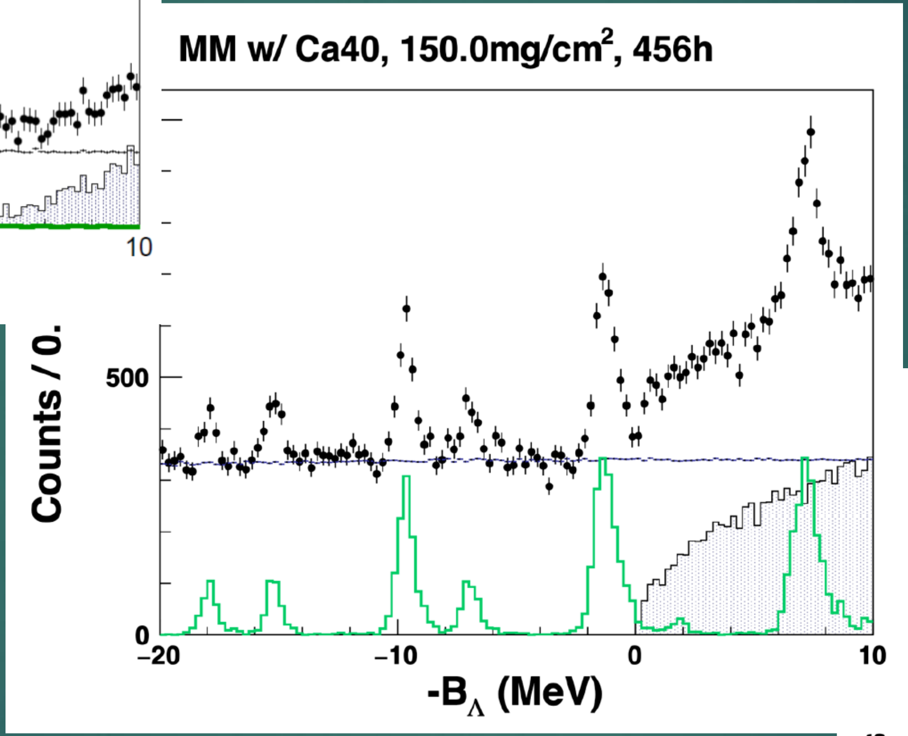
(b) The model of HKS implemented in GEANT4.

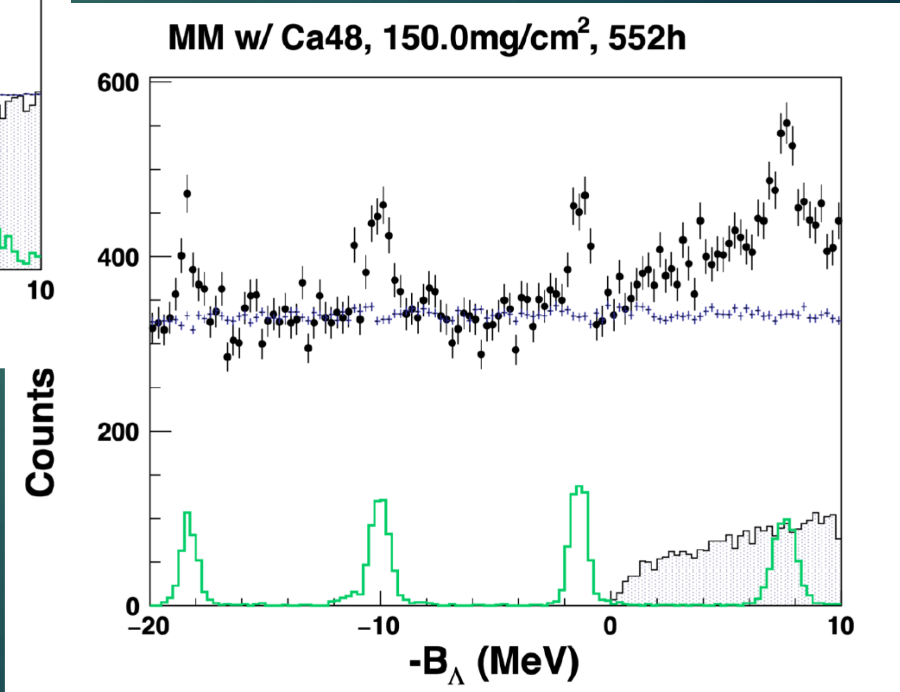
Beam	Energy E_e [/(GeV)]	2.240
	Energy stability $\Delta E_e/E_e$	$< 1 \times 10^{-4}$(FWHM)
PCS + HES	Central momentum P_e [/(GeV/c)]	0.744
	Central angle $\theta_{e,e'}$ [/(deg)]	8.5
	Solid angle $\Delta\Omega_{e'}$ [/(msr)]	3.4
	Momentum resolution $\Delta P_{e'}/P_{e'}$	4.3×10^{-4}(FWHM)
PCS + HKS	Central momentum P_K [/(GeV/c)]	1.200
	Central angle θ_K [/(deg)]	11.5
	Solid angle $\Delta\Omega_K$ [/(msr)]	7.0
	Momentum resolution $\Delta P_K/P_K$	2.9×10^{-4}(FWHM)
p $(e, e'K^+)$ Λ	W [/GeV]	1.912
	Q^2 [/(GeV/c)^2]	0.036
	$\theta_{\gamma^* K}$ (/deg)	7.35
	ϵ	0.59
	ϵ_L	0.0096

Detailed GEANT4 Simulation incl. PCS

Expected missing mass spectra for $^{12}_{\Lambda}\mathrm{B}$, $^{40}_{\Lambda}\mathrm{K}$, $^{48}_{\Lambda}\mathrm{K}$





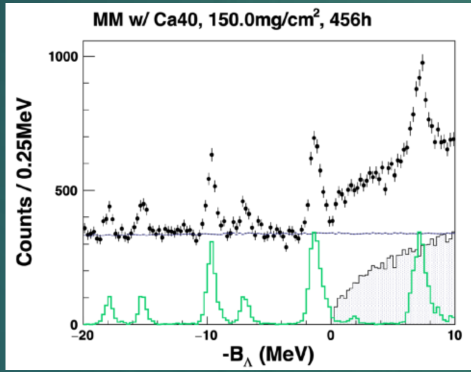


Expected resolution 0.6 MeV (FWHM)

Estimation of Necessary Beamtime

GEANT4 Simulation

Expected Spectra

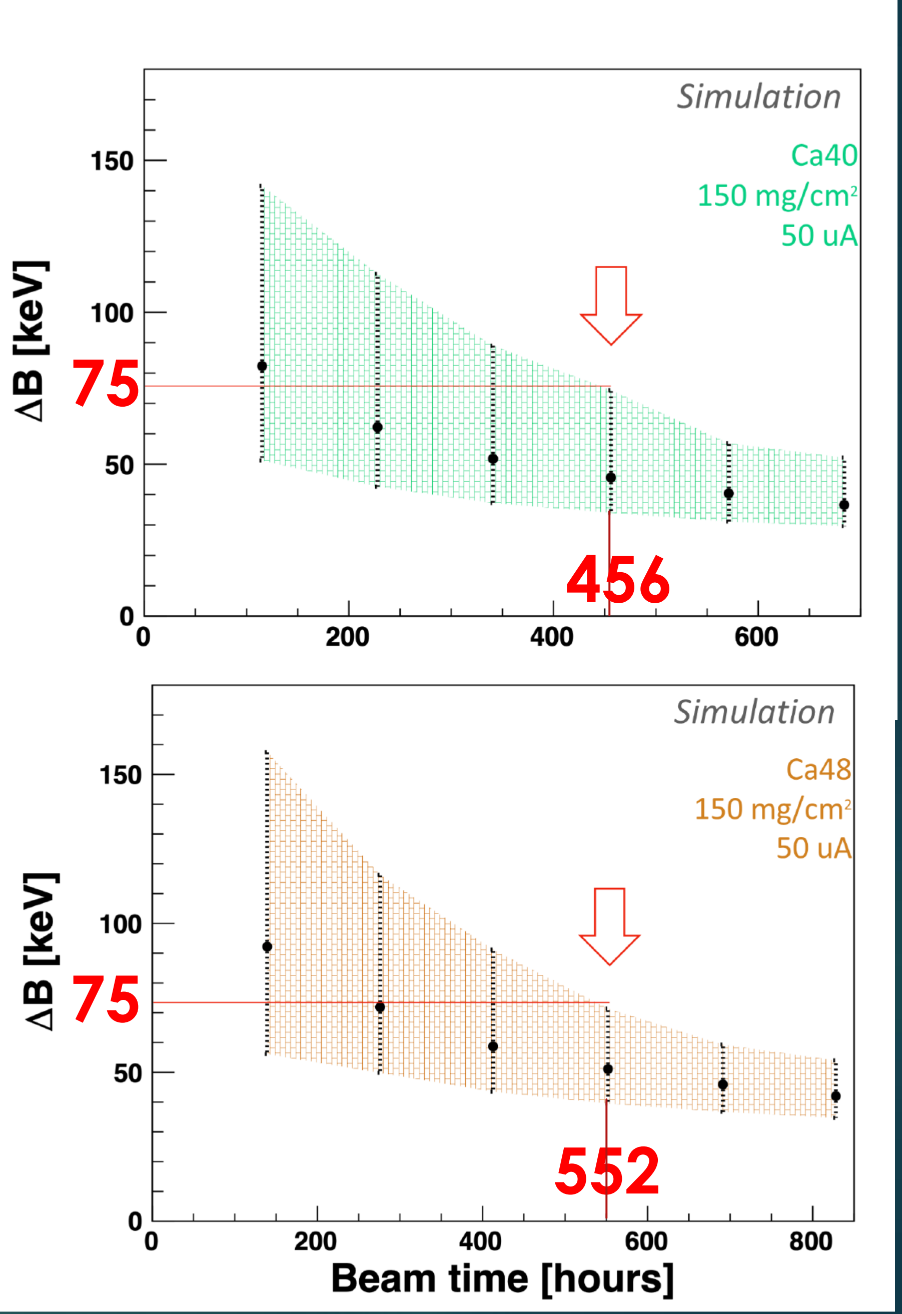


Mixed Event Analysis(BG subtraction)

Peak Fit

X 1000

Energy Determination Uncertainty ΔB



Summary of updated request of beamtime

Target (Hyper Nucleus)	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected yield (/h)	Num. of events	Req. beamtime (hours)	B.G. rate (/MeV/h)	S/N	Comments
CH_2 (Λ, Σ^0)	2	450	1000	6.12	890	144	0.02	475	Calibration
^{12}C ($^{12}_{\Lambda}$B)	50	150	90	5.39	900	168	0.85	8.4	Calibration
^{27}Al ($^{27}_{\Lambda}$Mg)	50	150	40 *	1.06	180	~~168~~	1.25	1.1	Calibration
Subtotal						480			Calibration
^{40}Ca ($^{40}_{\Lambda}$K)	50	150	50	0.90	410	456	1.70	0.7	Physics
^{48}Ca ($^{48}_{\Lambda}$K)	50	150	50	0.75	410	552	1.34	0.7	Physics
Subtotal						1008			Physics
Total						1488			

* for $0s^{\Lambda}$ $9/2^+, 7/2^+$ doublet.

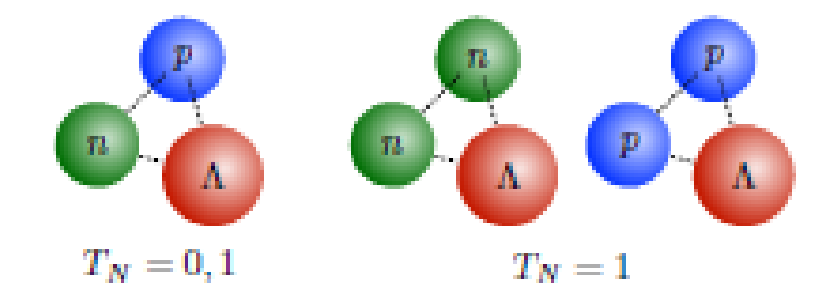
1488 hours (62 days) beamtime (28 days were already approved as E12-15-008 by PAC51)
7 days (168h) calibration can be absorbed in E12-24-011.

62- 7 = **55 PAC days** was approved by PAC52.

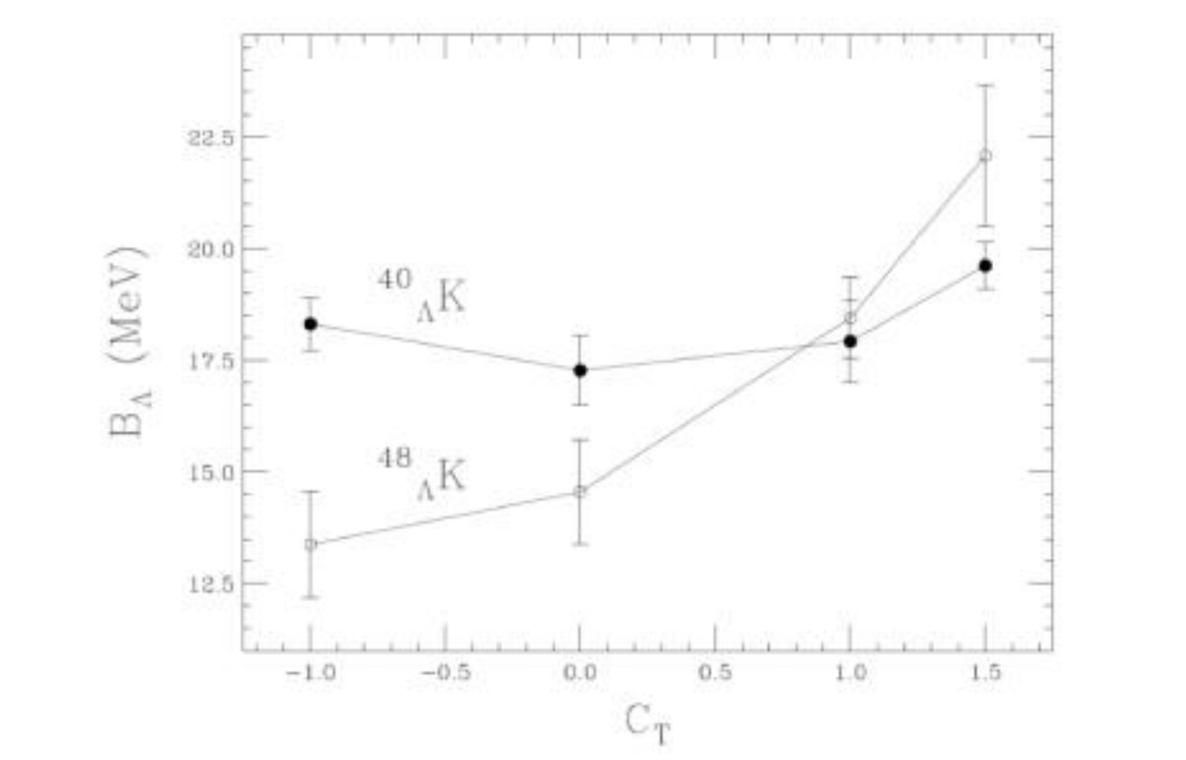
AFDMC calculation

Assumed Isospin dependent term of the ΛNN potential

$$v^T_{\lambda ij}\tau_i \cdot \tau_j = -3v^T_{\lambda ij}\mathcal{P}_{ij}^{T_N=0} + (1 + C_T)v^T_{\lambda ij}\mathcal{P}_{ij}^{T_N=1}.$$



D. Lonardoni and F. Pederiva (2018)



(b) Λ binding energies calculated by AFDMC for $^{40}_{\Lambda}$K and $^{48}_{\Lambda}$K as a funciton of C_T

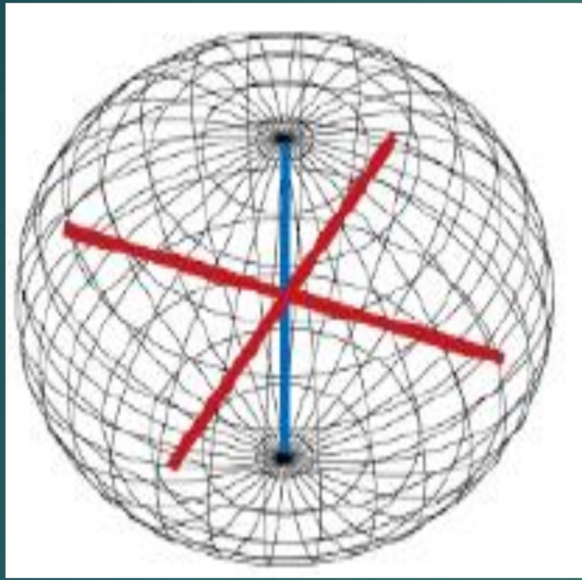
This calculation is somewhat dated.
Requires theoretical support reflecting the latest developments.

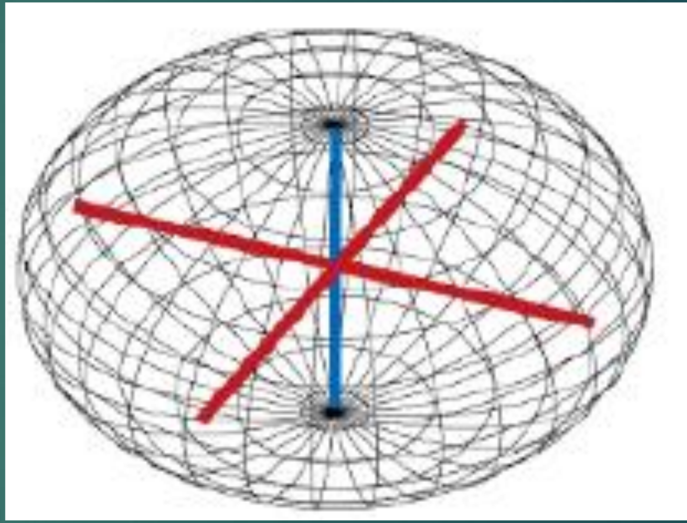
Summary for E12-24-013

- **High-precision hypernuclear spectroscopy is more important** now due to recent progresses of astronomical observations.
- **All necessary spectrometer including newly developed PCS magnets are ready in hands**.
- The last HKS experiment was conducted in 2009, and more than 15 years have since passed. Therefore, **a thorough re-check and update of the detectors is necessary**, and this work is currently underway.
- The experiment aims study **ΛNN 3-body force iso-spin dependence study**. It is essentially important to solve the hyperon puzzle.
- **Closer collaboration with theoretical physicists** is indispensable.

E12-24-011 Study of triaxially deformed nucleus using a Λ particle as a probe

Nucleus High density quantum many-body system



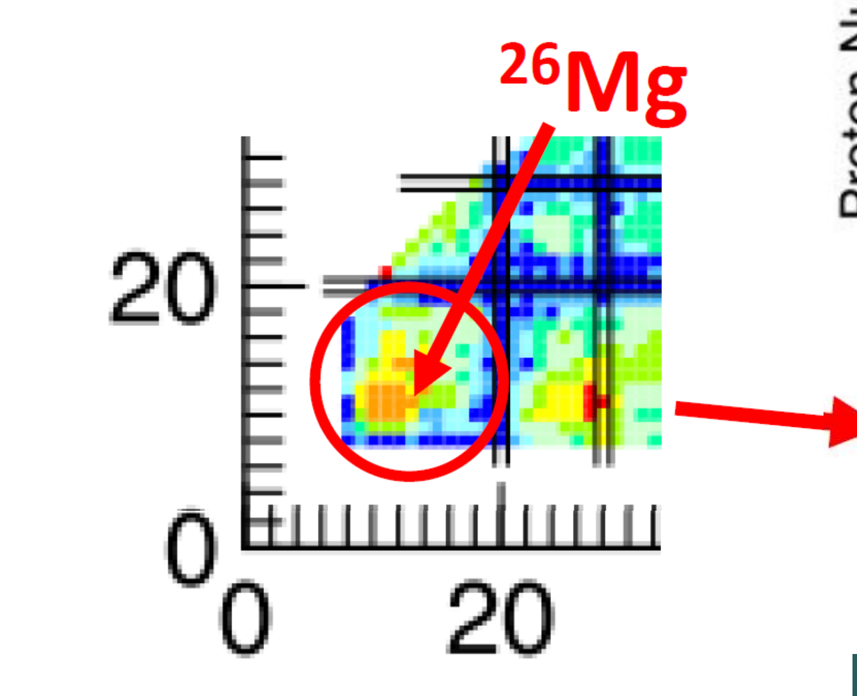


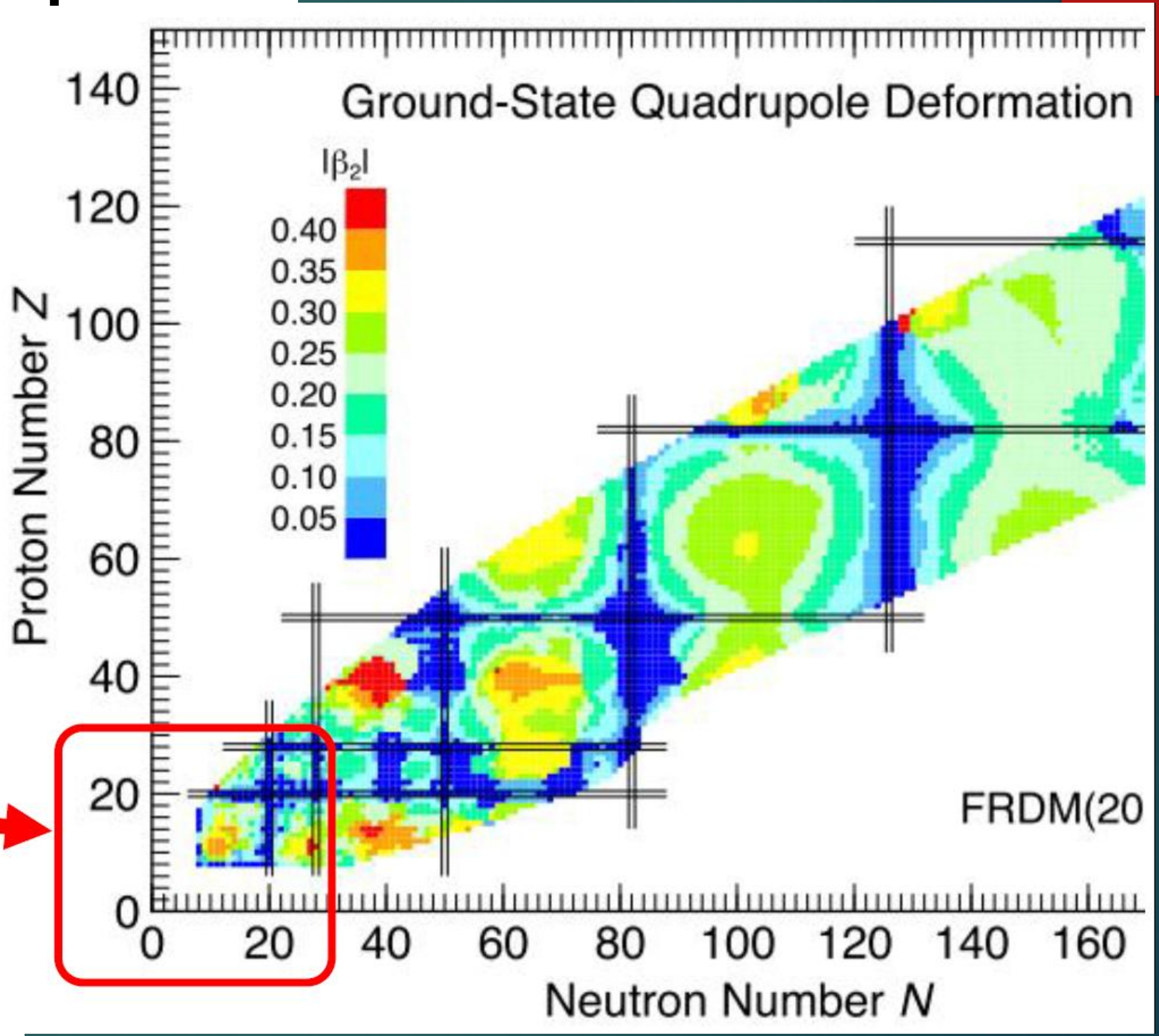
Extremely dense, but its shape can be changed with a relatively small energy.

Deformed nuclei are not special.

Gamma-ray measurement is usual experimental technique to study deformed nuclei

We proposed a totally new method



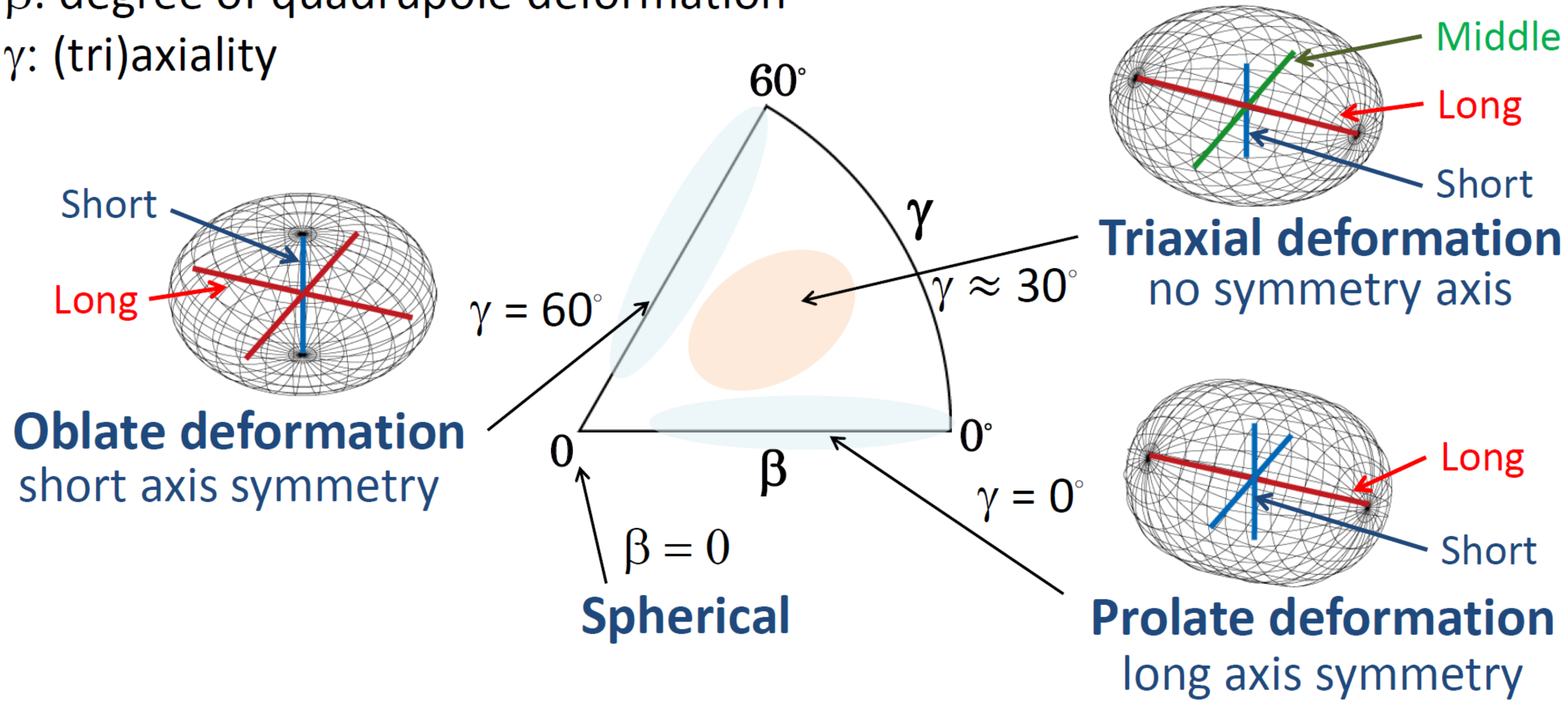


P. Möller, et al., Atomic Data and Nuclear Data Tables **109**(2016)

Parameters to describe deformation

Nuclear quadrupole deformation (β,γ)

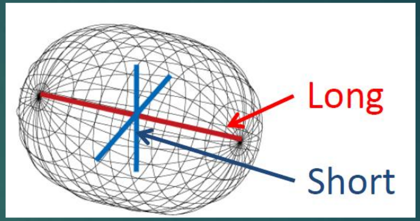
- β: degree of quadrupole deformation
- γ: (tri)axiality



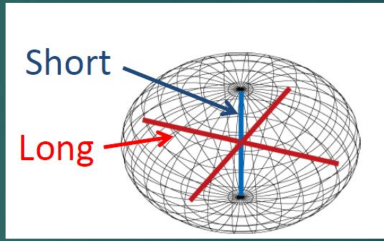
M.Isaka, Hypernuclear Physics Workshop 2023 at JLab

^{26}Mg is interesting candidate for triaxially deformed nucleus

Proton Z=12 Prolate



Neutron N=14 Oblate

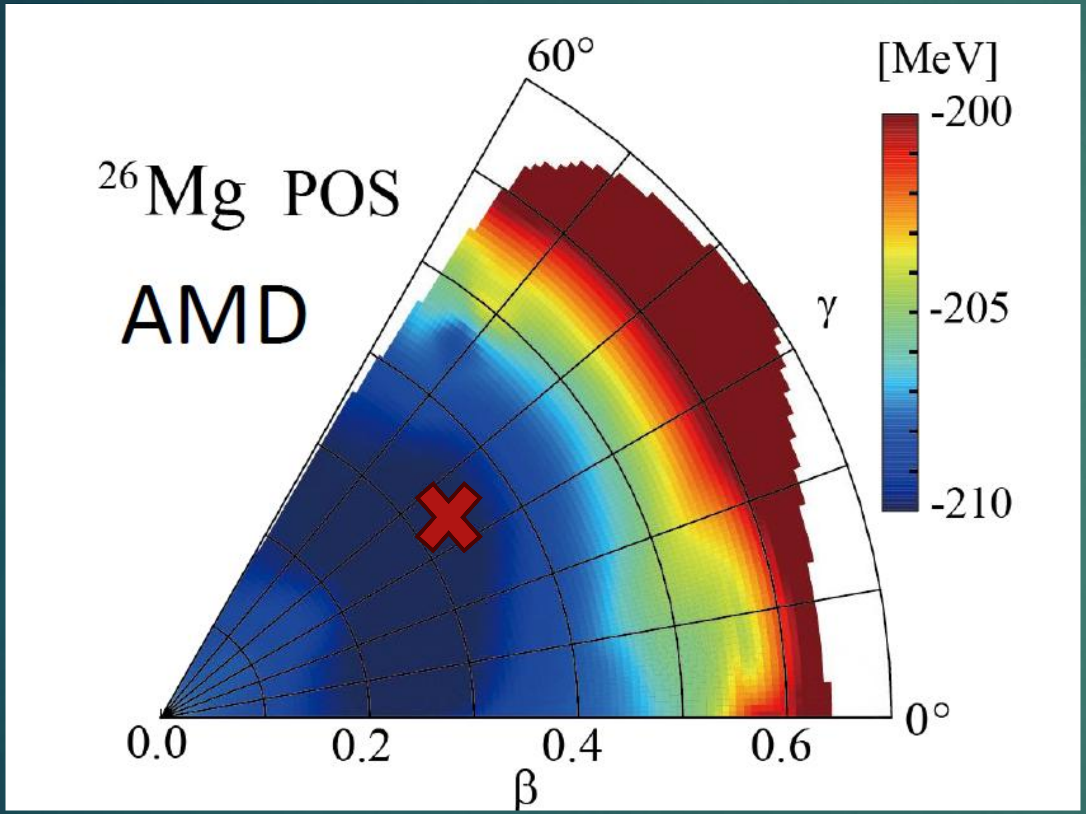


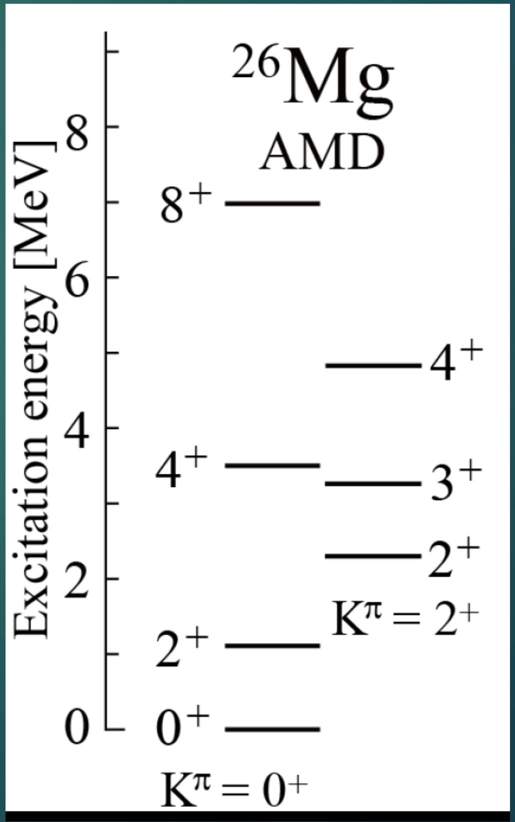
Co-existence of different deformations

Terasaki et al. NPA**621**(1997)
Rodrıguez-Guzman et al. NPA**709** (2002)
Peru et al PRC**77** (2008)
Hinohara, Kanada-En'yo PRC**83** (2011)

Recent theoretical calculation

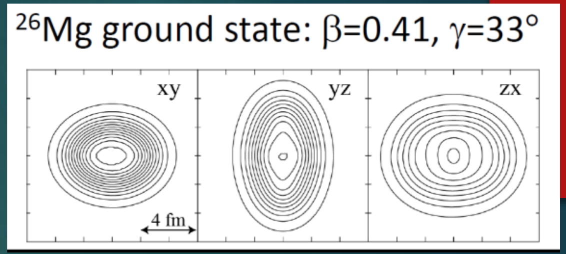
(Hyper)
Anti-symmetrized Molecular Dynamics
M. Isaka et al. PRC 83 (2011) 044323.
PRC 83 (2011) 054304.

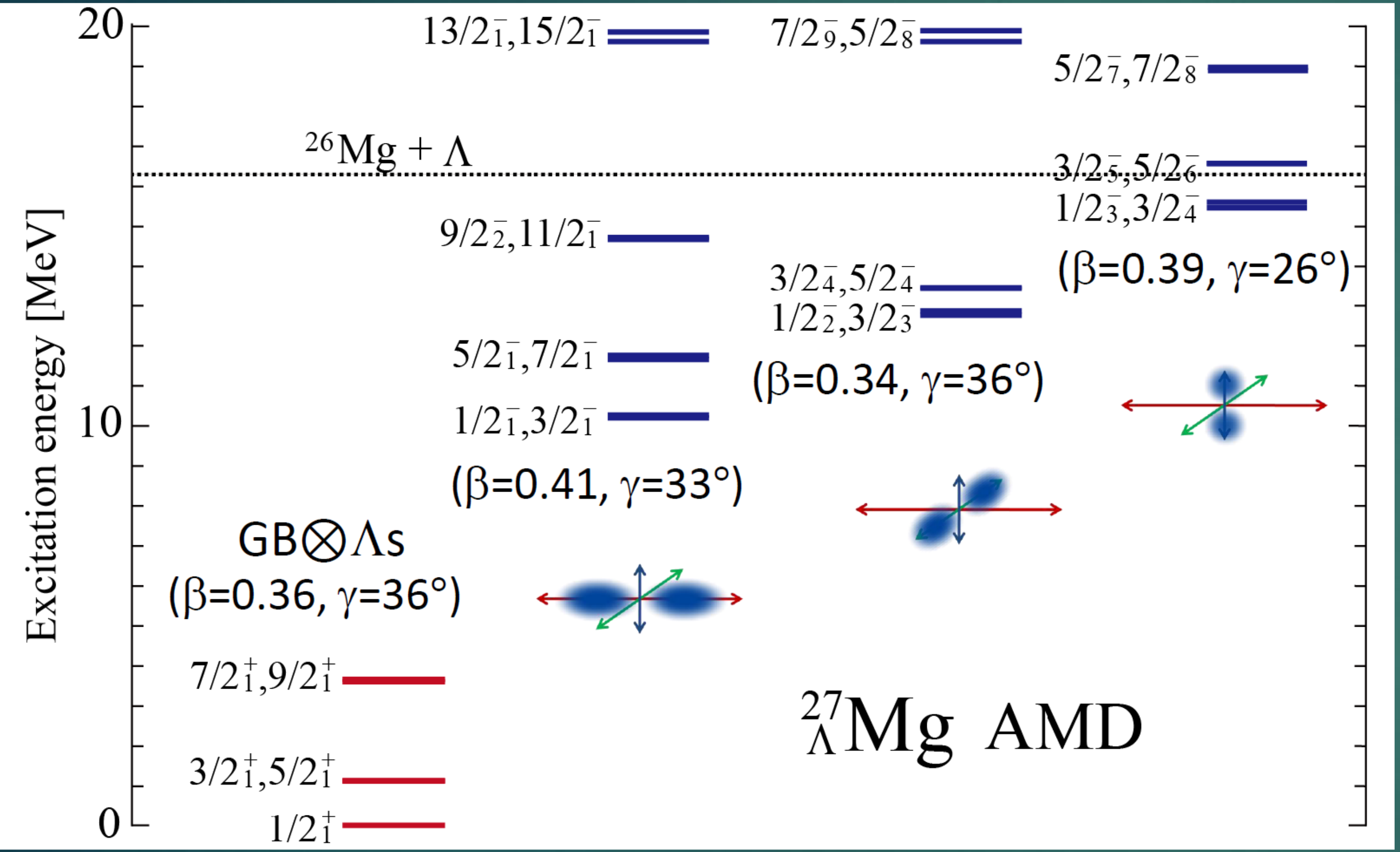




Adding a Λ particle

$$^{27}\mathrm{Al}(e,e'K^{+})^{27}_{\Lambda}\mathrm{Mg}$$



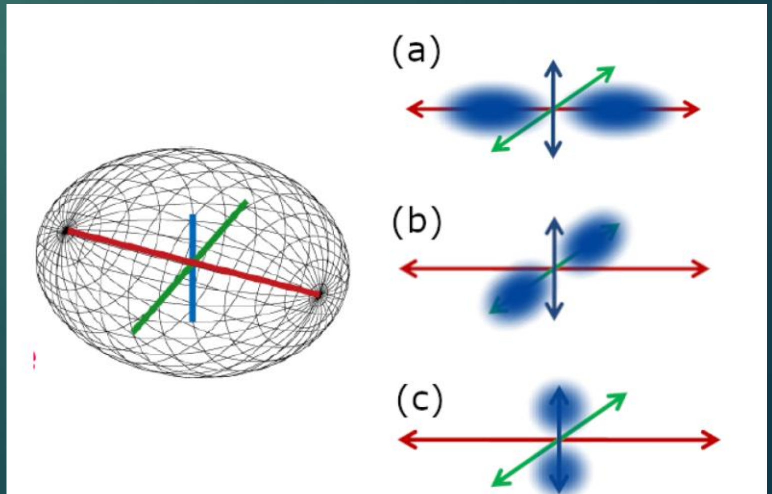


ΛN interaction is attractive

WF of Λ in p-orbit is straight

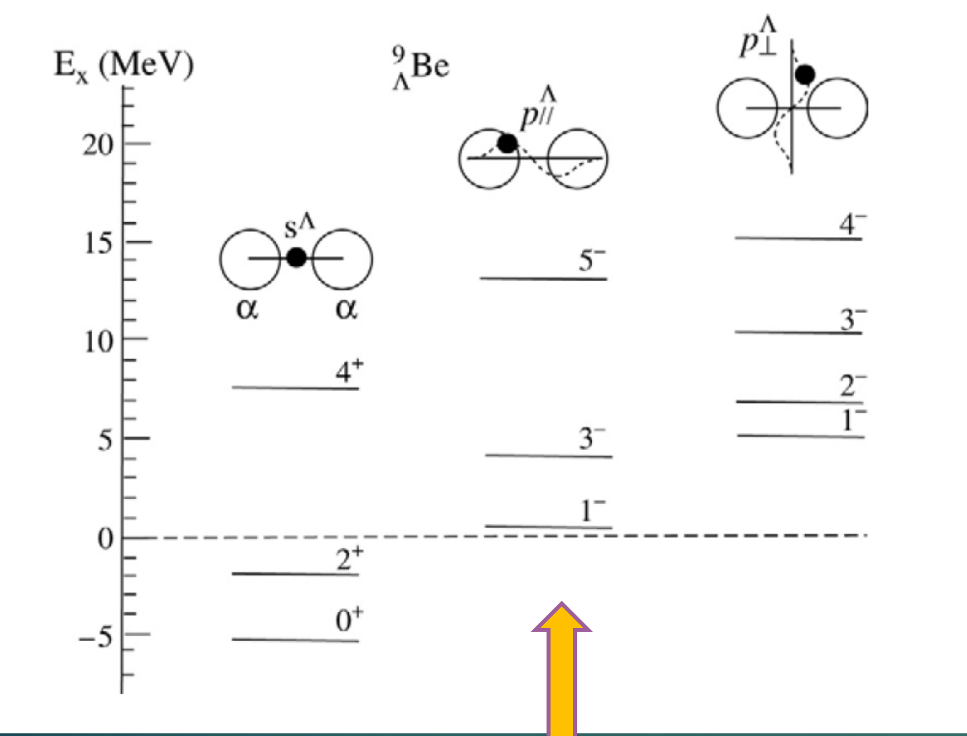
Overlap between Λ and ^{26}Mg core depends on axis direction

$^{26}\mathrm{Mg}\otimes\Lambda(p)$ splits in 3 states

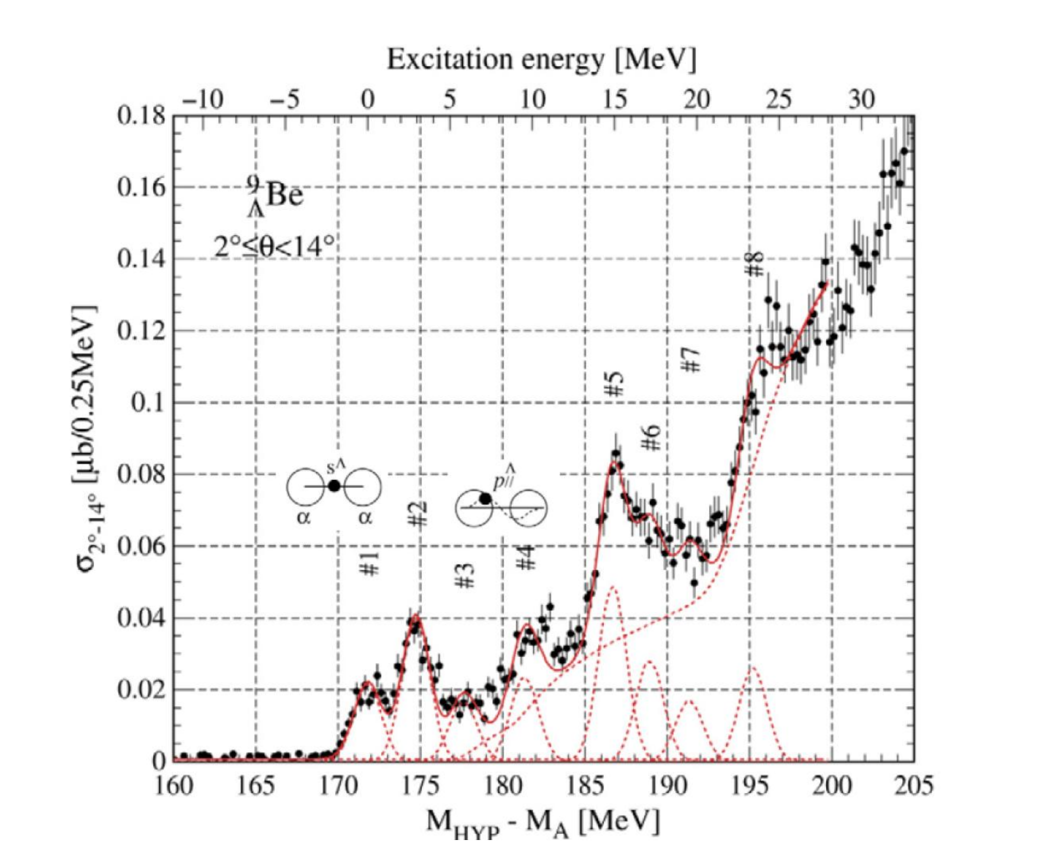


M.Isaka, Hypernuclear Physics Workshop 2023 at JLab

Genuine hypernuclear state : ${}^{9}_{\Lambda}\mathrm{Be}$



Impossible for normal nucleus due to Pauli blocking

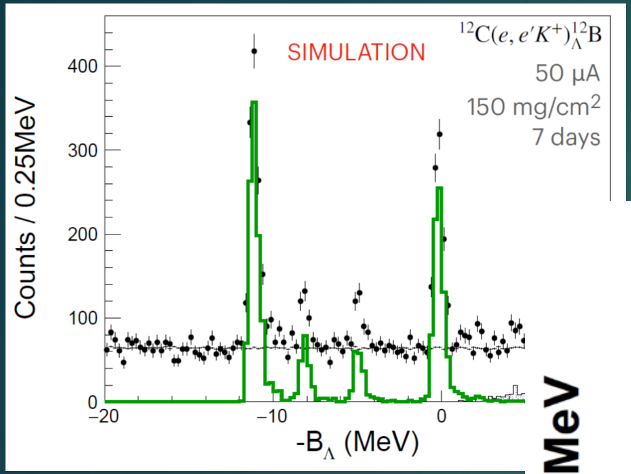


Energy spectrum obtained by the (π^+, K^+) reaction at KEK-PS

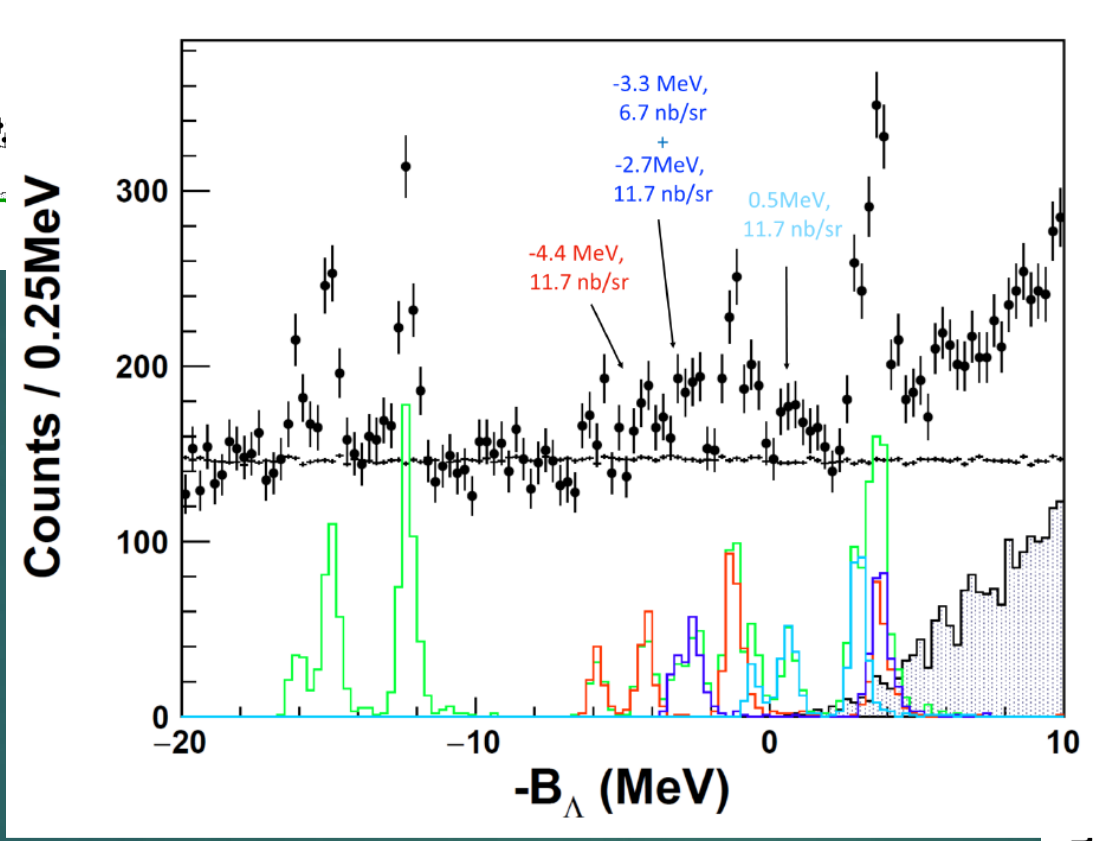
O. Hashimoto and H. Tamura, Prog. Part. and Nucl. Phys. **57** 564 (2006)

Expected missing mass spectra for ${}^{12}_{\Lambda}\mathrm{B}$, ${}^{27}_{\Lambda}\mathrm{Mg}$

Expected resolution 0.6 MeV (FWHM)

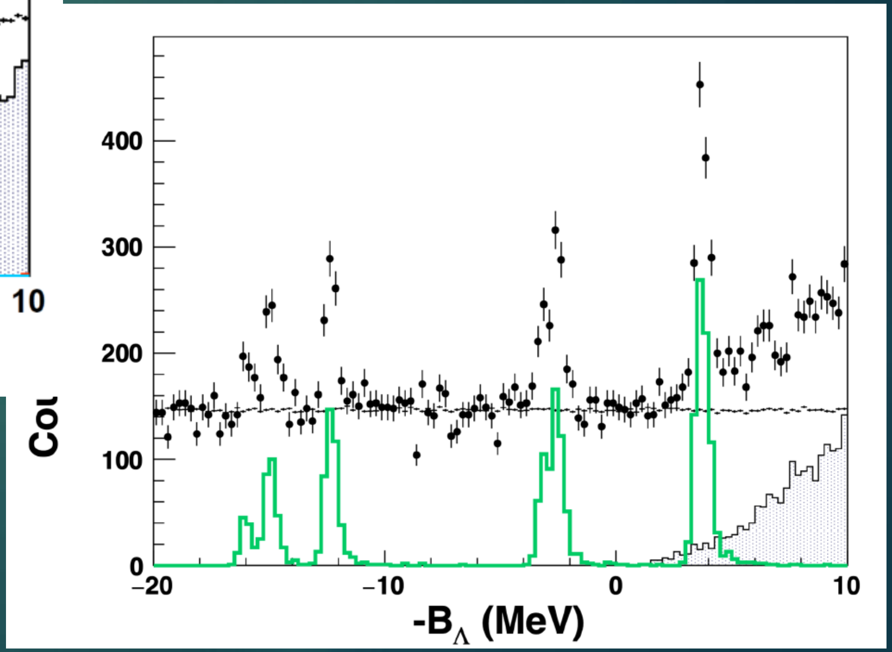


Triaxially deformed ${}^{27}_{\Lambda}\mathrm{Mg}$



Energy level : Hyper-AMD (Isaka)
Cross Section: Shell model (Umeya)

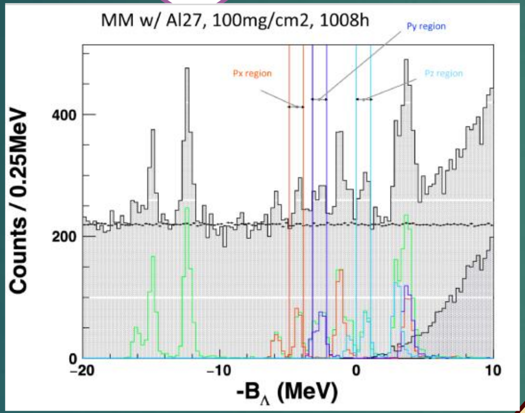
Sphere shape ${}^{27}_{\Lambda}\mathrm{Mg}$



Estimation of Necessary Beamtime

GEANT4 Simulation

Expected Spectra

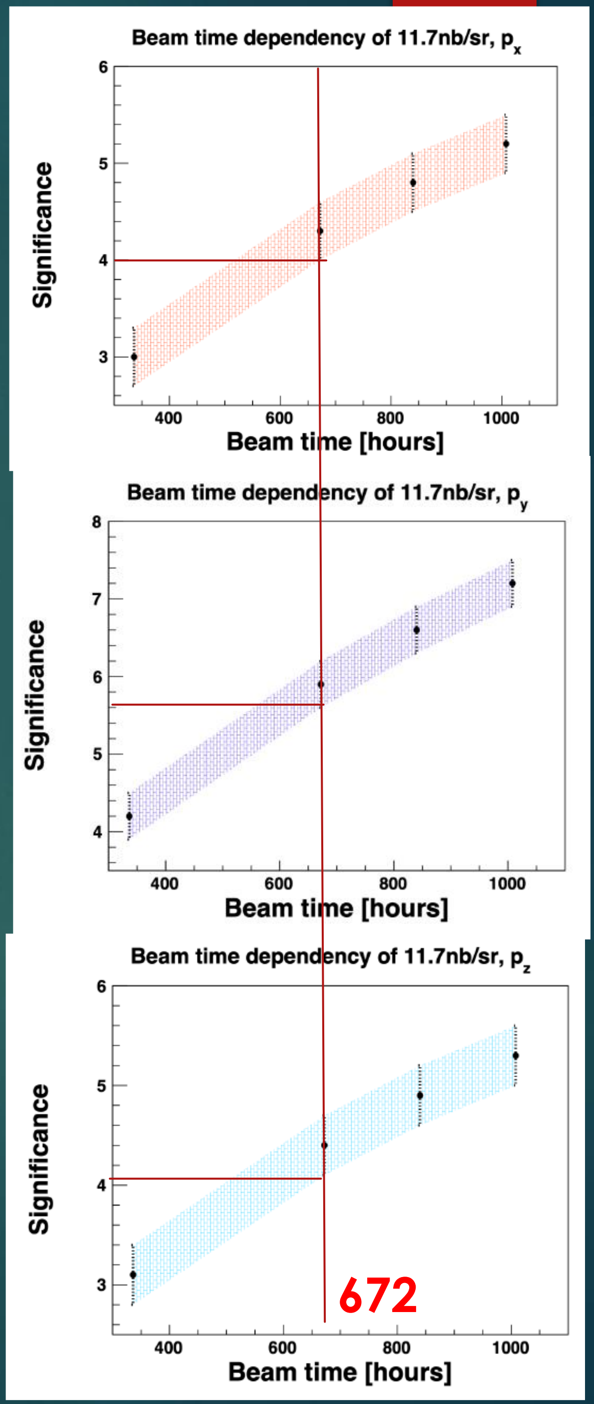


Mixed Event Analysis(BG subtraction)

X 1000

Peak Fit

Peak Significance $S/(S+N)^{1/2}$



Summary of request of beamtime

Target (Hyper Nucleus)	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected yield (/h)	Num. of events	Req. beamtime (hours)	B.G. rate (/MeV/h)	S/N	Comments
CH_2 (Λ, Σ^0)	2	450	1000	6.12	890	144	0.02	475	Calibration
^{12}C ($^{12}_{\Lambda}$B)	50	150	90	539	900	168	0.85	8.4	Calibration
Subtotal						—			Combined with E12-15-008
^{27}Al ($^{27}_{\Lambda}$Mg)	50	100	10 (p^{Λ})	0.18	120	672	0.55	0.4	Physics
Total						672			

28 PAC days

Calibration beamtime can be shared
with E12-15-008/PR12-24-013 and other campaign exps.

Summary

- **Λ particle in p-orbit can be used as a probe to study triaxially deformed nucleus, ^{26}Mg.**
- This is a **totally new** experimental technique to study triaxially deformed nuclei. We **request 672 hours (28 days) beamtime, calibration beam time (CH_2 and ^{12}C) can be shared with other hypernuclear experiments and Al calibration beamtime (7days) of E12-24-013 can be absorbed in this proposing experiment**.

This will open a possibility to use Lambda as a probe to study shape of various nuclei.