The WASA-FRS and beyond at NUSTAR

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Germany

Professor and group leader,
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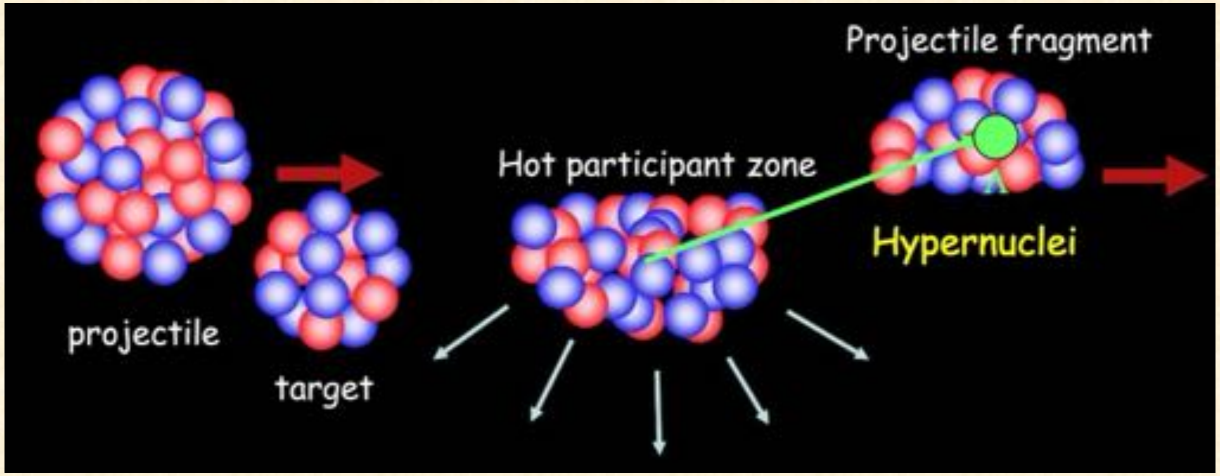
China

Hypernuclear production with heavy ion beams

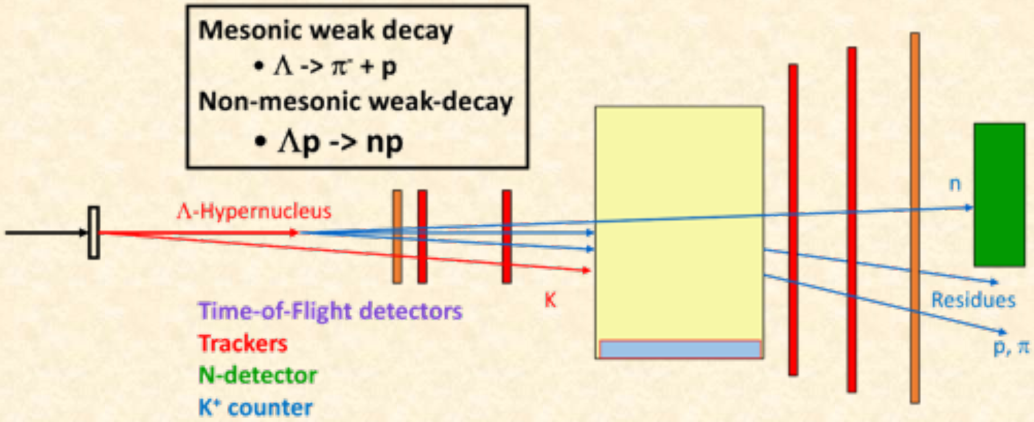


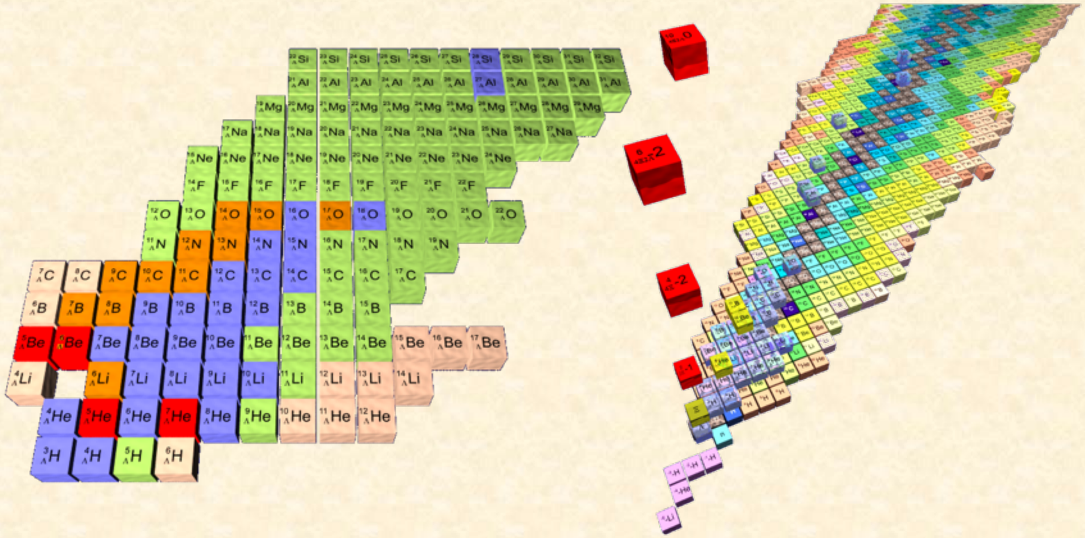
Stable Heavy Ion beams:

- 2 A GeV at GSI and 10 GeV at FAIR

Rare Isotope beams:

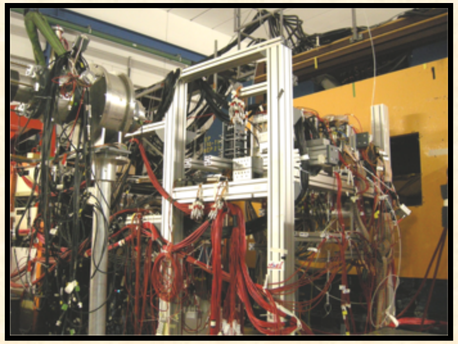
- Example: 3.2 A GeV for proton-rich ^{9}C

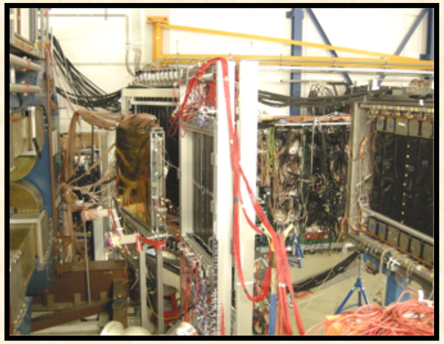


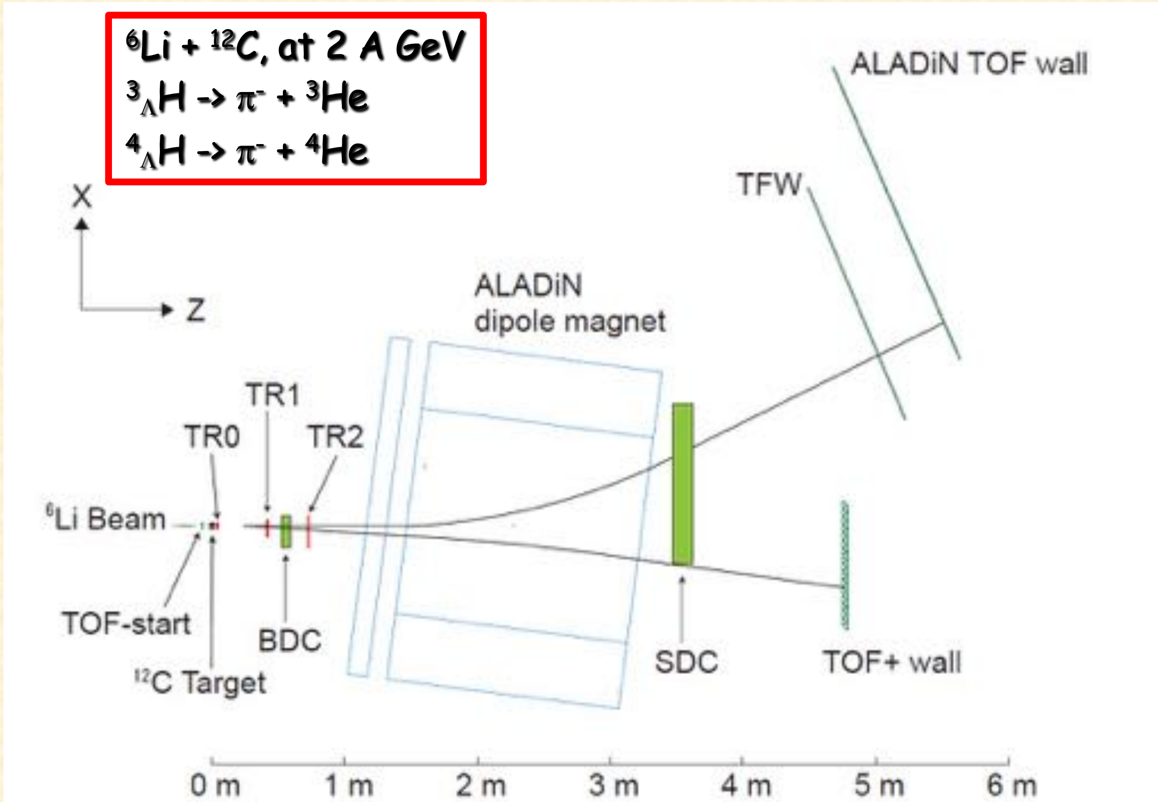


Pioneering experiment: HypHI Phase 0 (2009)

- To demonstrate the feasibility of precise hypernuclear spectroscopy with ^{6}Li primary beams at 2 A GeV on a carbon target







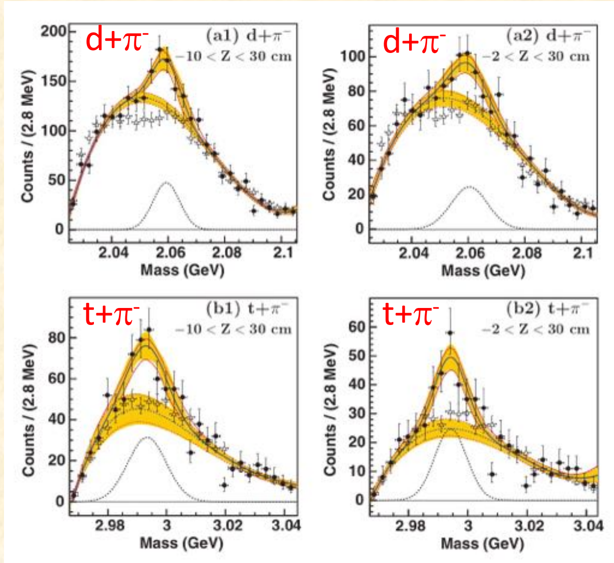
Two puzzles initiated by HypHI

Signals indicating nnΛ bound state

All theoretical calculations are negative

- E. Hiyama et al., Phys. Rev. C89 (2014) 061302(R)
- A. Gal et al., Phys. Lett. B736 (2014) 93
- H. Garcilazo et al., Phys. Rev. C89 (2014) 057001

and much more publication



C. Rappold et al., PRC 88 (2013) 041001

Short lifetime of $^{3}_{\Lambda}H$ C. Rappold et al., Nucl. Phys. A 913 (2013) 170

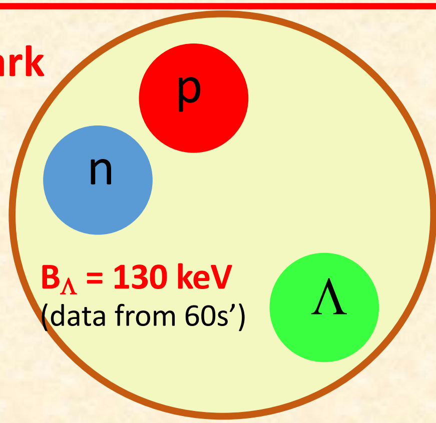
- HypHI Phase 0: 183^{+42}_{-32} ps
- STAR at RHIC: ~~155^{+25}_{-22} ps~~ **142^{+24}_{-21}**
- ALICE at LHC: ~~181^{+54}_{-39} ps~~ **237^{+33}_{-36}**

STAR Collaboration, Phys. Rev. C 97 (2018) 054909

ALICE Collaboration, Phys. Lett. B 797 (2019) 134905

No theories to reproduce the short lifetime

Benchmark



$\tau(^{3}_{\Lambda}H)$ should be equal to $\tau(\Lambda$, 263 ps)

Hot topics in hypernuclear and few-body physics

Also non-HI experiments: J-PARC, JLab, ELPH, MAMI

Very recent result from STAR

Measurements of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H Lifetimes and Yields in Au+Au Collisions in the High Baryon Density Region

M. S. Abdallah,[5] B. E. Aboona,[55] J. Adam,[6] L. Adamczyk,[2] J. R. Adams,[39] J. K. Adkins,[30] G. Agakishiev,[28] I. Aggarwal,[41] M. M. Aggarwal,[41] Z. Ahammed,[61] I. Alekseev,[3,35] D. M. Anderson,[55] A. Aparin,[28] E. C. Aschenauer,[6] M. U. Ashraf,[11] F. G. Atetalla,[29] A. Attri,[41] G. S. Averichev,[28] V. Bairathi,[53] W. Baker,[10] J. G. Ball Cap,[20] K. Barish,[10] A. Behera,[52] R. Bellwied,[20] P. Bhagat,[27] A. Bhasin,[27] J. Bielcik,[14] J. Bielcikova,[38] I. G. Bordyuzhin,[3] J. D. Brandenburg,[6] A. V. Brandin,[35] I. Bunzarov,[28] X. Z. Cai,[50] H. Caines,[64] M. Calderón de la Barca Sánchez,[8] D. Cebra,[8] I. Chakaberia,[31,6] P. Chaloupka,[14] B. K. Chan,[9] F-H. Chang,[37] Z. Chang,[6] N. Chankova-Bunzarova,[28] A. Chatterjee,[11] S. Chattopadhyay,[61] D. Chen,[10] J. Chen,[49] J. H. Chen,[18] X. Chen,[48] Z. Chen,[49] J. Cheng,[57] M. Chevalier,[10] S. Choudhury,[18] W. Christie,[6] X. Chu,[6] H. J. Crawford,[7] M. Csanád,[16] M. Daugherity,[1] T. G. Dedovich,[28] I. M. Deppner,[19] A. A. Derevschikov,[43] A. Dhamija,[41] L. Di Carlo,[63] L. Didenko,[6] P. Dixit,[22] X. Dong,[31] J. L. Drachenberg,[1] E. Duckworth,[29] J. C. Dunlop,[6] N. Elsey,[63] J. Engelage,[7] G. Eppley,[45] S. Esumi,[58] O. Evdokimov,[12] A. Ewigleben,[32] O. Eyser,[6] R. Fatemi,[30] F. M. Fawzi,[5] S. Fazio,[6] P. Federic,[38] J. Fedorisin,[28] C. J. Feng,[37] Y. Feng,[44] P. Filip,[28] E. Finch,[51] Y. Fisyak,[6] A. Francisco,[64] C. Fu,[11] L. Fulek,[2] C. A. Gagliardi,[55] T. Galatyuk,[15] F. Geurts,[45] N. Ghimire,[54] A. Gibson,[60] K. Gopal,[23] X. Gou,[49] D. Grosnick,[60] A. Gupta,[27] W. Guryn,[6] A. I. Hamad,[29] A. Hamed,[5] Y. Han,[45] S. Harabasz,[15] M. D. Harasty,[8] J. W. Harris,[64] H. Harrison,[30] S. He,[11] W. He,[18] X. H. He,[26] Y. He,[49] S. Heppelmann,[8] S. Heppelmann,[42] N. Herrmann,[19] E. Hoffman,[20] L. Holub,[14] Y. Hu,[18] H. Huang,[37] H. Z. Huang,[9] S. L. Huang,[52] T. Huang,[37] X. Huang,[57] Y. Huang,[57] T. J. Humanic,[39] G. Igo,[9,*] D. Isenhower,[1] W. W. Jacobs,[25] C. Jena,[23] A. Jentsch,[6] Y. Ji,[31] J. Jia,[6,52] K. Jiang,[48] X. Ju,[48] E. G. Judd,[7] S. Kabana,[53] M. L. Kabir,[10] S. Kagamaster,[32] D. Kalinkin,[25,6] K. Kang,[57] D. Kapukchyan,[10] K. Kauder,[6] H. W. Ke,[6] D. Keane,[29] A. Kechechyan,[28] M. Kelsey,[63] Y. V. Khyzhniak,[35] D. P. Kikoła,[62] C. Kim,[10] B. Kimelman,[8] D. Kincses,[16] I. Kisel,[17] A. Kiselev,[6] A. G. Knospe,[32]

A. N. Vasiliev,[43] I. Vassiliev,[17] V. Verkest,[63] F. Videbæk,[6] S. Vokal,[28] S. A. Voloshin,[63] F. Wang,[44] G. Wang,[9] J. S. Wang,[21] P. Wang,[48] X. Wang,[49] Y. Wang,[11] Y. Wang,[57] Z. Wang,[49] J. C. Webb,[6] P. C. Weidenkaff,[19] L. Wen,[9] G. D. Westfall,[34] H. Wieman,[31] S. W. Wissink,[25] R. Witt,[59] J. Wu,[11] J. Wu,[26] Y. Wu,[10] B. Xi,[50] Z. G. Xiao,[57] G. Xie,[31] W. Xie,[44] H. Xu,[21] N. Xu,[31] Q. H. Xu,[49] Y. Xu,[49] Z. Xu,[6] Z. Xu,[9] G. Yan,[49] C. Yang,[49]

ex] 18 Oct 2021

Using all the available experimental data, the average lifetimes of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H are 200 ± 13 ps and 208 ± 12 ps, respectively. These precise data clearly indicate that the $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H lifetimes are considerably lower than the free-Λ lifetime. We conclude that the $^{3}_{\Lambda}$H lifetime puzzle is resolved on the experimental side.

Q. Yang,[49] S. Yang,[45] Y. Yang,[37] Z. Ye,[45] Z. Ye,[12] L. Yi,[49] K. Yip,[6] Y. Yu,[49] H. Zbroszczyk,[62] W. Zha,[48] C. Zhang,[52] D. Zhang,[11] J. Zhang,[49] S. Zhang,[12] S. Zhang,[18] X. P. Zhang,[57] Y. Zhang,[26] Y. Zhang,[48] Y. Zhang,[11] Z. J. Zhang,[37] Z. Zhang,[6] Z. Zhang,[12] J. Zhao,[44] C. Zhou,[18] Y. Zhou,[11] X. Zhu,[57] M. Zurek,[4] and M. Zyzak[17]
(STAR Collaboration)

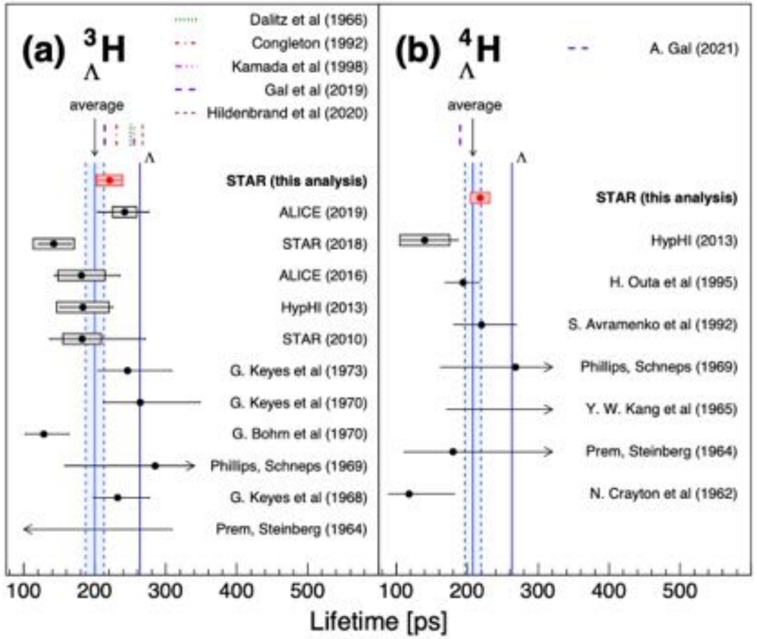


FIG. 2: $^{3}_{\Lambda}$H (a) and $^{4}_{\Lambda}$H (b) measured lifetime, compared to previous measurements [3–5, 7–11, 28–34], theoretical calculations [35–40] and the free-Λ lifetime [41]. Horizontal lines represent statistical uncertainties, while boxes represent systematic uncertainties. The experimental average lifetimes and the corresponding uncertainty of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H are also shown as vertical blue shaded bands.

HOWEVER, Binding energy of hypertriton

NATURE PHYSICS | VOL 16 | APRIL 2020 | 409–412 | www.nature.com/naturephysics

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LETTERS

https://doi.org/10.1038/s41567-020-0799-7

Check for updates

Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton

The STAR Collaboration*

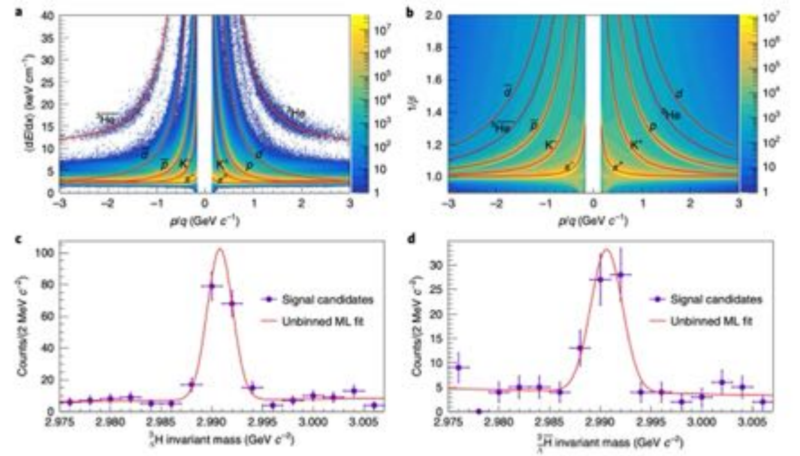


Fig. 2 | Particle identification and the invariant mass distributions for ${}^{3}_{\Lambda}$H and ${}^{3}_{\Lambda}\overline{\text{H}}$ reconstruction. a,b, (d*E*/d*x*) (mean energy loss per unit track length in the gas of the TPC) versus *p*/*q* (where *p* is the momentum and *q* is the electric charge in units of the elementary charge *e*) (**a**) and 1/*β* (where *β* is the speed of a particle in units of the speed of light) versus *p*/*q* (**b**). (d*E*/d*x*) is measured by the TPC and 1/*β* is measured by the TOF detector in conjunction with the TPC. In both cases, the coloured bands show the measured data for each species of charged particle, while the red curves show the expected values. Charged particles are identified by comparing the observed (d*E*/d*x*) and 1/*β* with the expected values. **c,d**, Utilizing both 2-body and 3-body decay channels, the invariant mass distributions of ${}^{3}_{\Lambda}$H (**c**) and ${}^{3}_{\Lambda}\overline{\text{H}}$ (**d**) are shown. The error bars represent statistical uncertainties (s.d.). The red curves represent a fit with a Gaussian function plus a linear background, using the unbinned maximum likelihood (ML) method.

The Λ binding energy, B_Λ, for ${}^{3}_{\Lambda}$H and ${}^{3}_{\Lambda}\overline{\text{H}}$ is calculated using the mass measurement shown in equation (1). We obtain

$$B_\Lambda = 0.41 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.})\ \text{MeV} \quad (3)$$

average value of 0.13 ± 0.05(stat.) MeV. When applied to our value of 0.41 ± 0.12(stat.) MeV it yields a significantly smaller value of $7.90^{+1.71}_{-0.93}$ fm. The larger B_Λ and shorter effective scattering length suggest a stronger YN interaction between the Λ and the relatively low-density nuclear core of the ${}^{3}_{\Lambda}$H (ref. [36]). This, in certain models, requires SU(3) symmetry breaking and a more repulsive YN interaction at high density, consistent with implications from the range of masses observed for neutron stars[5].

Former value by emulsion (data from 60's)

0.13 ± 0.05 MeV

Recent theoretical calculation

Revisiting the hypertriton lifetime puzzle

A. Pérez-Obiol,[1] D. Gazda,[2] E. Friedman,[3] and A. Gal[3,*]

[1] *Laboratory of Physics, Kochi University of Technology, Kami, Kochi 782-8502, Japan*
[2] *Nuclear Physics Institute, 25068 Řež, Czech Republic*
[3] *Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*

(Dated: July 9, 2020)

Concluding remarks. Reported in this work is a new microscopic three-body calculation of the ${}^{3}_{\Lambda}$H pionic two-body decay rate $\Gamma({}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He}+\pi^{-})$. Using the $\Delta I = \frac{1}{2}$ rule and a branching ratio taken from experiment to connect to additional pionic decay rates, the lifetime $\tau({}^{3}_{\Lambda}\mathrm{H})$ was deduced. As emphasized here $\tau({}^{3}_{\Lambda}\mathrm{H})$ varies strongly with the small, rather poorly known Λ separation energy $B_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})$; it proves possible then to correlate each one of the three distinct RHI experimentally reported values $\tau_{\mathrm{exp}}({}^{3}_{\Lambda}\mathrm{H})$ with a theoretical value $\tau_{\mathrm{th}}({}^{3}_{\Lambda}\mathrm{H})$ that corresponds to its own underlying $B_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})$ value. The $B_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})$ intervals thereby correlated with these experiments are roughly $B_{\Lambda} \lesssim 0.1$ MeV, $0.1 \lesssim B_{\Lambda} \lesssim 0.2$ MeV and $B_{\Lambda} \gtrsim 0.2$ MeV for ALICE, HypHI and STAR, respectively. New experiments proposed at MAMI on Li target [39] and at JLab, J-PARC and ELPH on ^{3}He target [40] will hopefully pin down precisely $B_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})$ to better than perhaps 50 keV, thereby leading to a unique resolution of the 'hypertriton lifetime puzzle'.

STAR, HypHI, ALICE: **from 121 to 270 ps**

Other recent theoretical works

For hypertriton:

<u>Effective field theory</u>

F. Hildenbrand et al., Phys. Rev. C 102, 064002 (2020)

- $R = \Gamma_{3He} / (\Gamma_{3He} + \Gamma_{pd})$ is sensitive to the binding energy

For nnΛ:

<u>Pionless effective field theory</u>

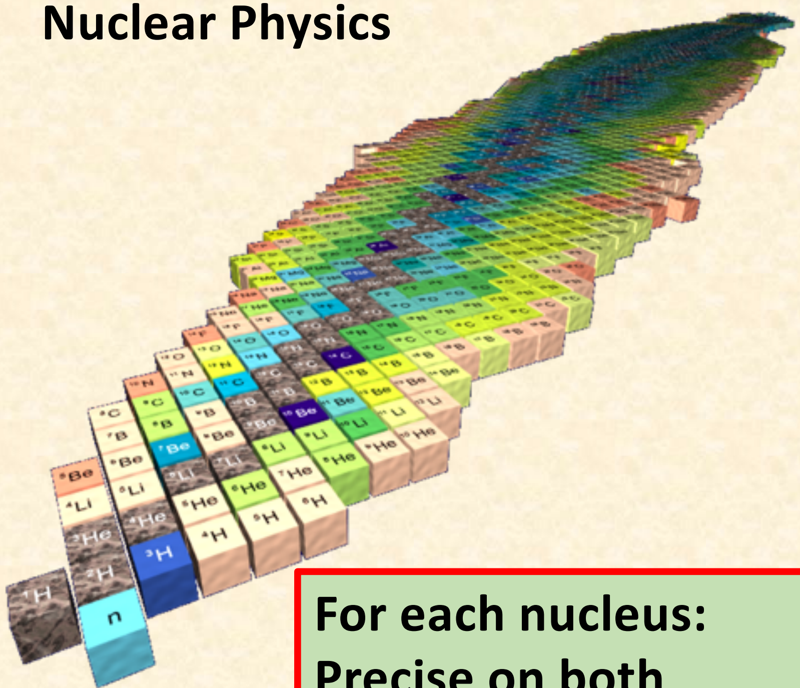
S.-I. Ando et al., Phys. Rev. C 92, 024325 (2015)

F. Hildenbrand et al., Phys. Rev. C 100 034002 (2019)

Not yet excluding the bound state

Nuclear physics v.s. Hypernuclear physics

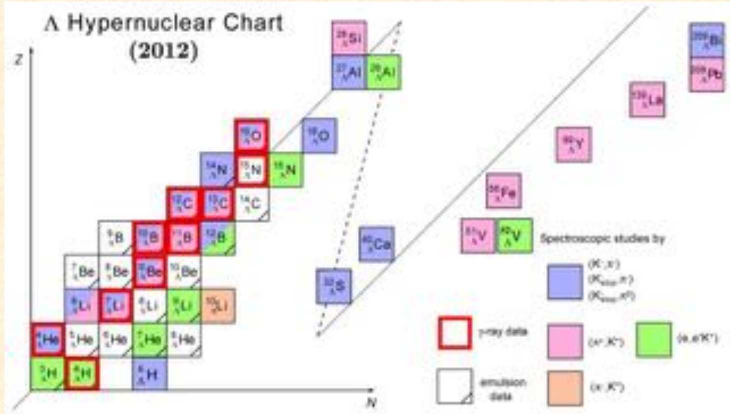
Nuclear Physics



For each nucleus:
Precise on both

- **Mass (binding energy)**
- **Lifetime**

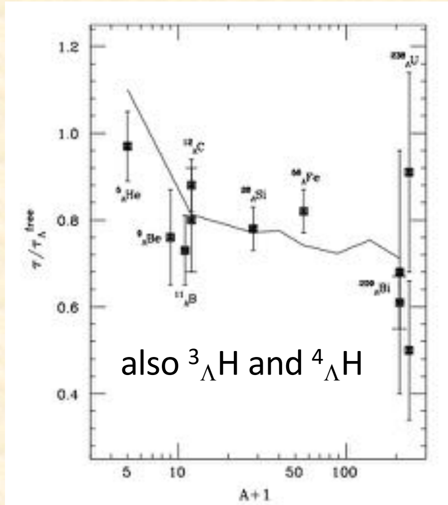
Hypernuclear Physics



For each hypernucleus:
Poor on both

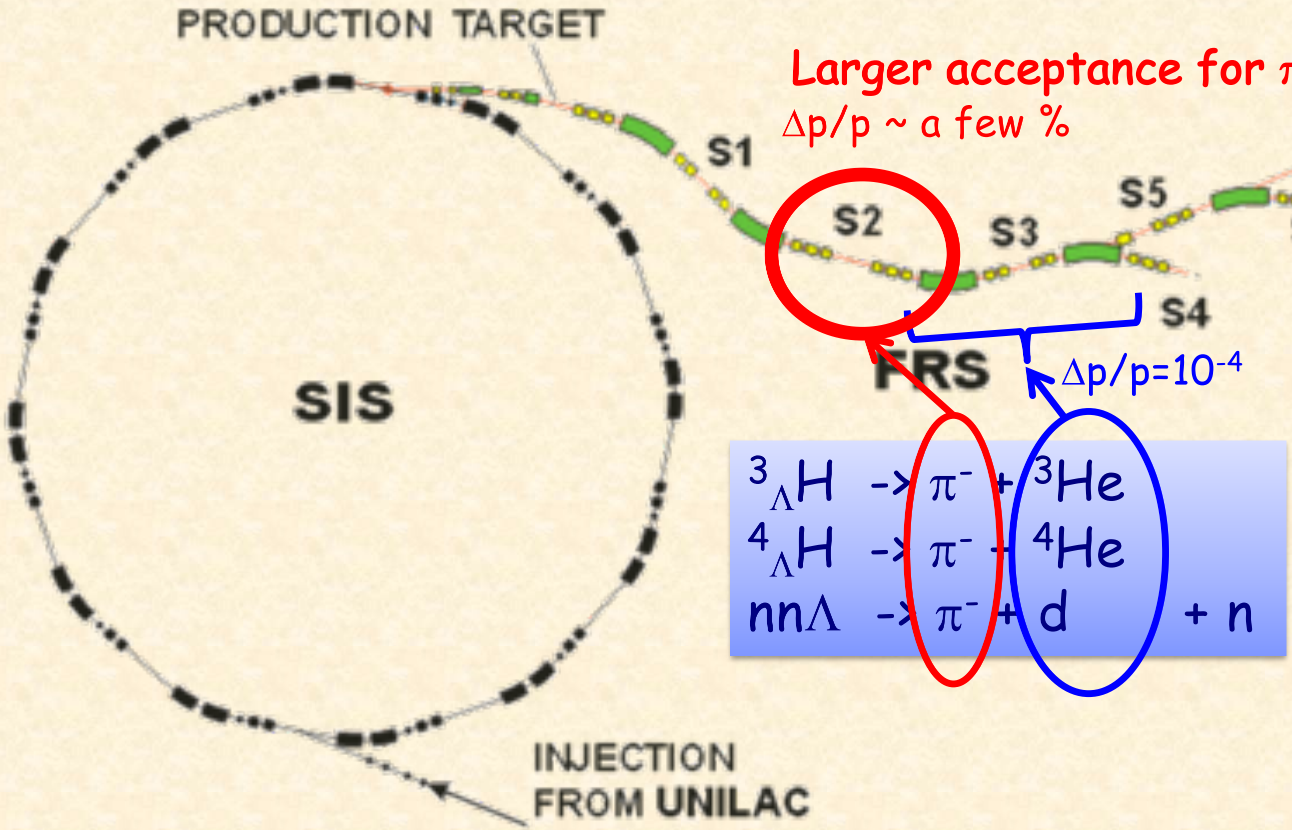
- **Mass (binding energy)**
- **Lifetime**

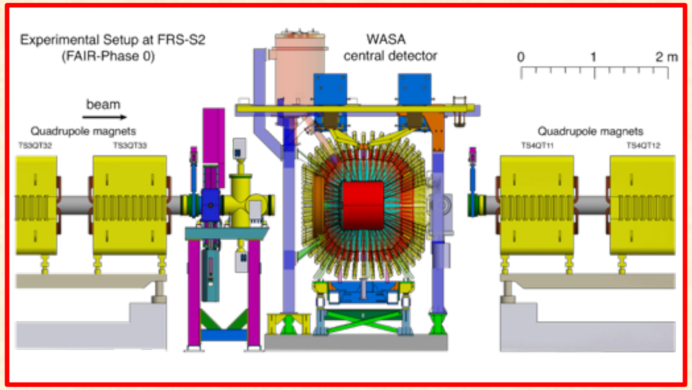
Starting with
the benchmarking $^{3}_{\Lambda}H$



Phys. Rep. 369 (2002) 1

The WASA-FRS experiment at FAIR Phase 0

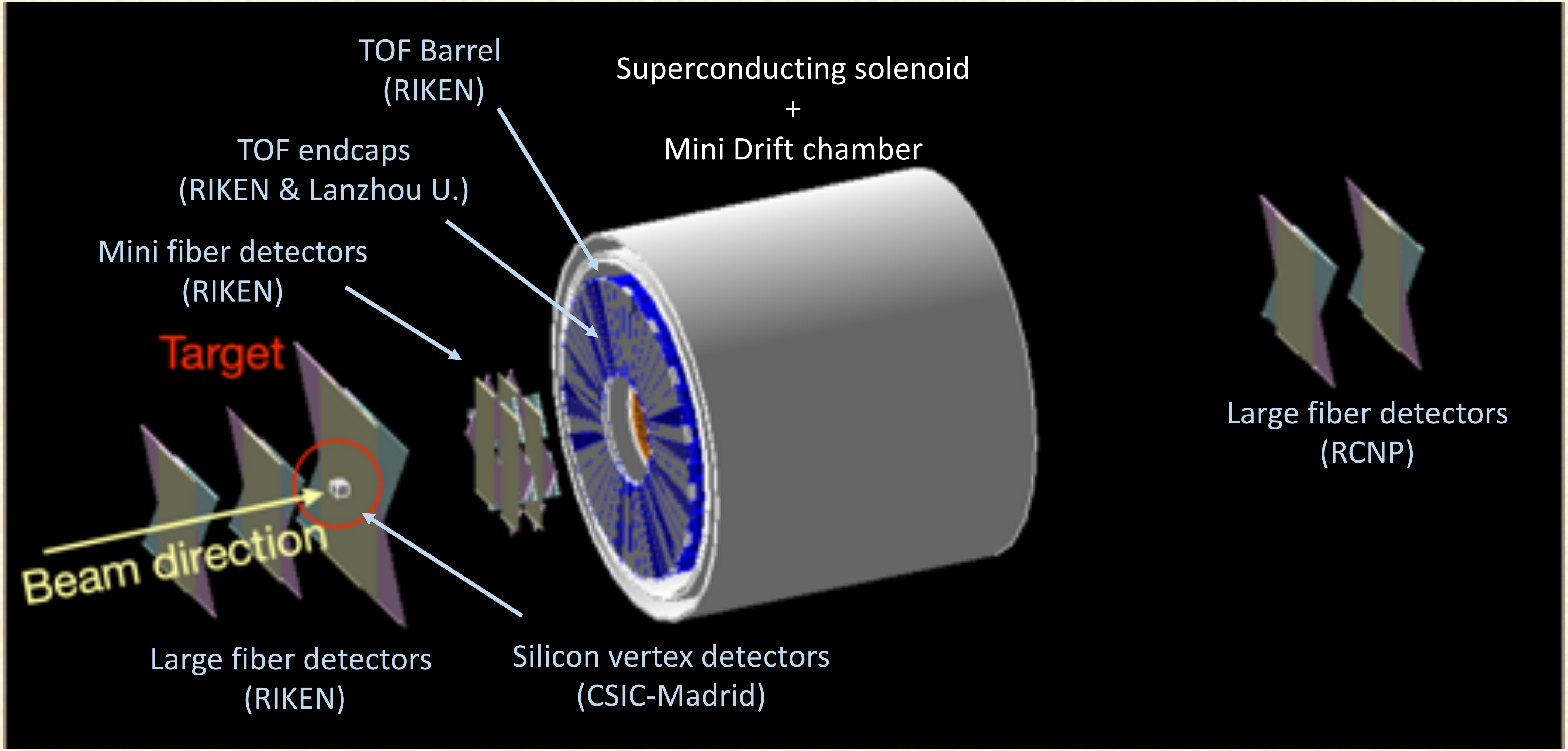




The WASA-FRS experiment at FAIR Phase 0

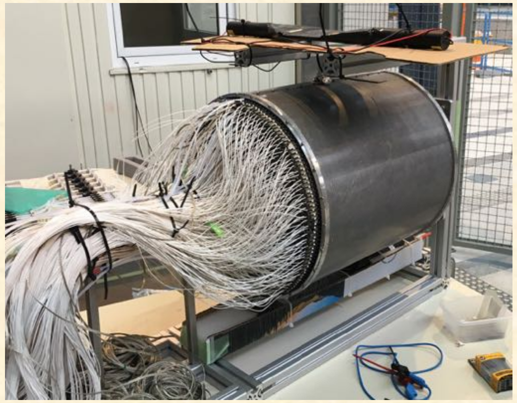
WASA already at GSI since March 2019

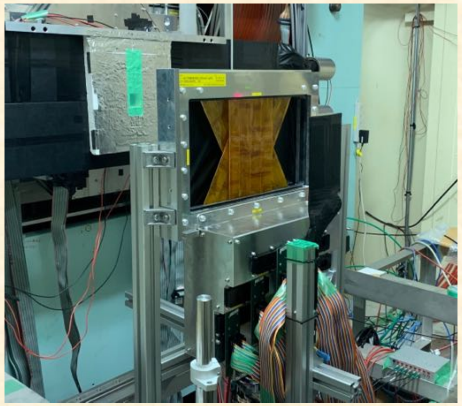
The WASA-FRS experiment at FAIR Phase 0

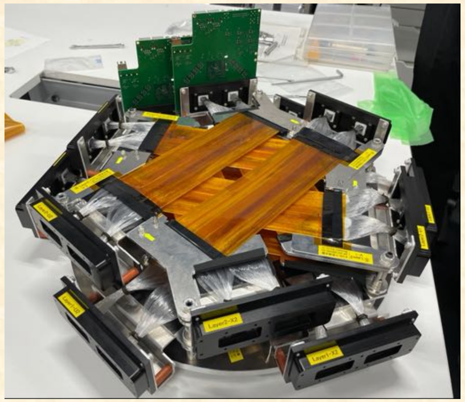


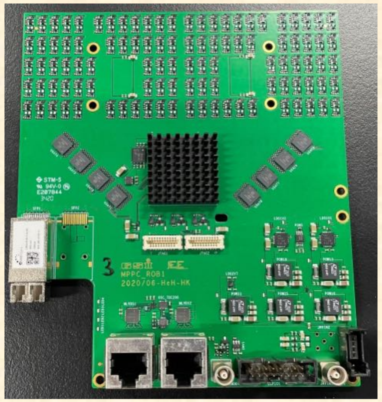
The WASA-FRS experiment at FAIR Phase 0

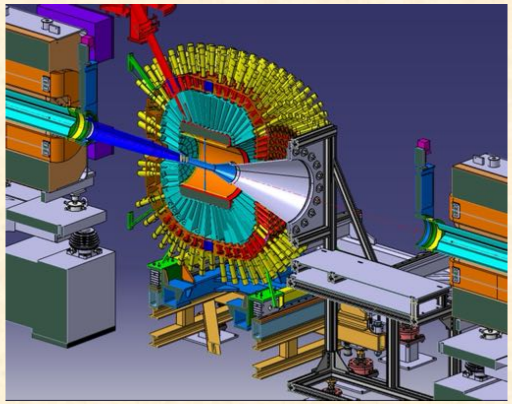
- Commissioning of
  - Mini drift chamber: **DONE**
  - Superconducting magnet: **already at 4K**
- Upgrading of
  - Time-of-Flight Barrel: in progress, **DONE**
  - TOF endcaps, **soon completed**
- Development and construction of
  - Large Scintillating fiber detectors: **DONE**
  - Mini fiber detector inside the iron yoke: **DONE**
  - Electronics for fiber detectors: in production, **Almost DONE**
  - New holding structures: **DONE and already installed**



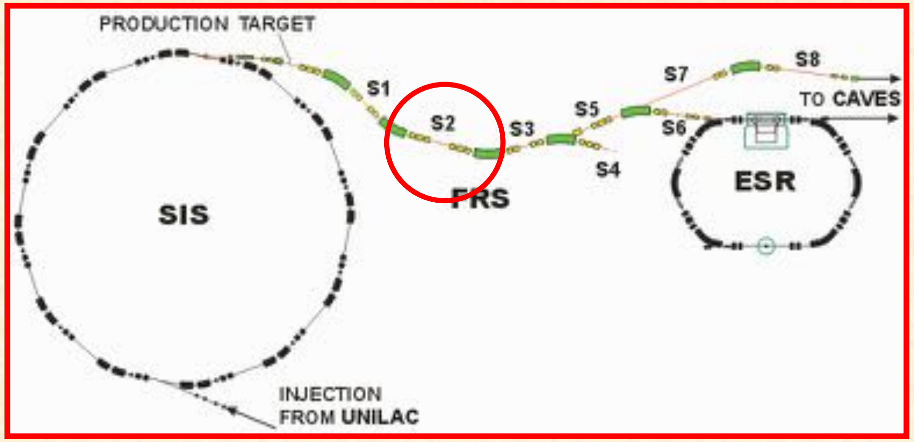








The WASA-FRS experiment at FAIR Phase 0



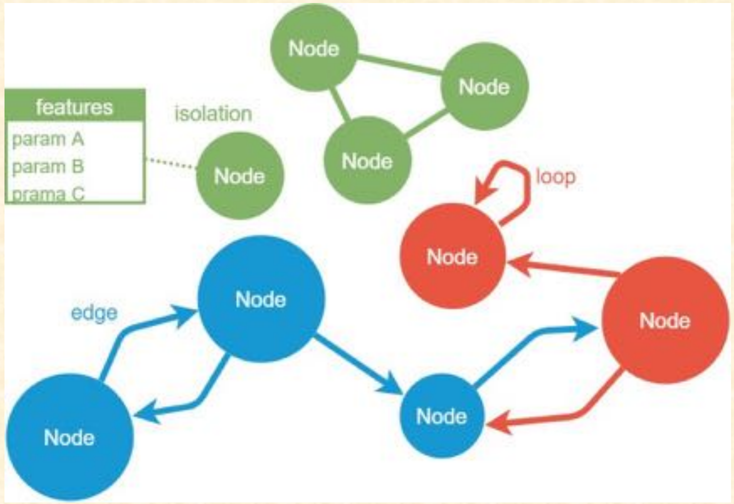
Scheduled in February – March, 2022

- Lifetime of ${}^{3}{}_{\Lambda}\mathrm{H}$ and ${}^{4}{}_{\Lambda}\mathrm{H}$
- Confirmation of nnΛ

The WASA-FRS experiment at FAIR Phase 0

Development of the machine learning model for data analyses

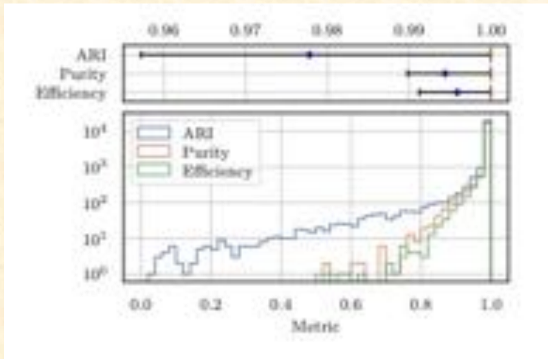
Graph Neural Network (GNN)

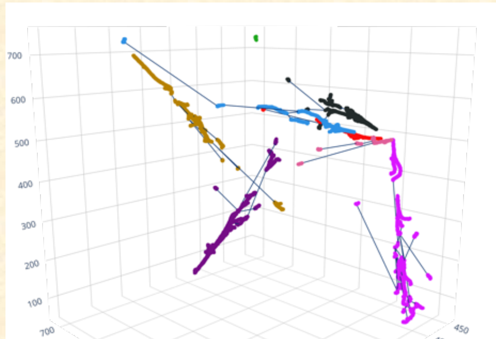


Graph
node : data point
edge : relation between nodes

node and edge can have features and a label

Clustering of Electromagnetic Showers and Particle Interactions with Graph Neural Networks in Liquid Argon Time Projection Chambers Data





arXiv:2007.01335v2 [physics.ins-det] 22 Sep 2020

The WASA-FRS experiment at FAIR Phase 0

Development of the machine learning model for data analyses

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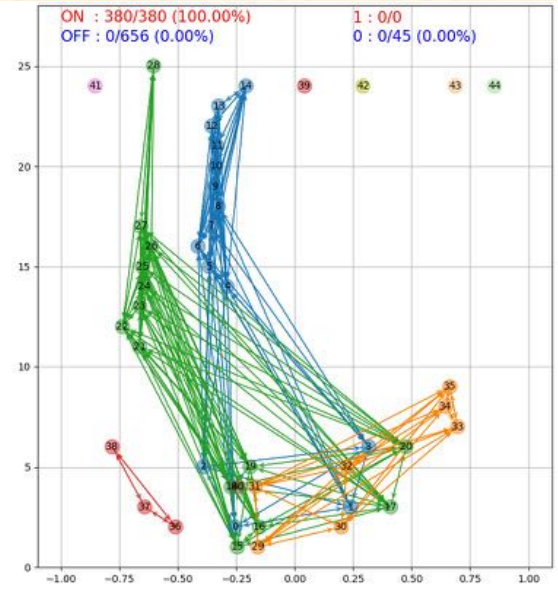
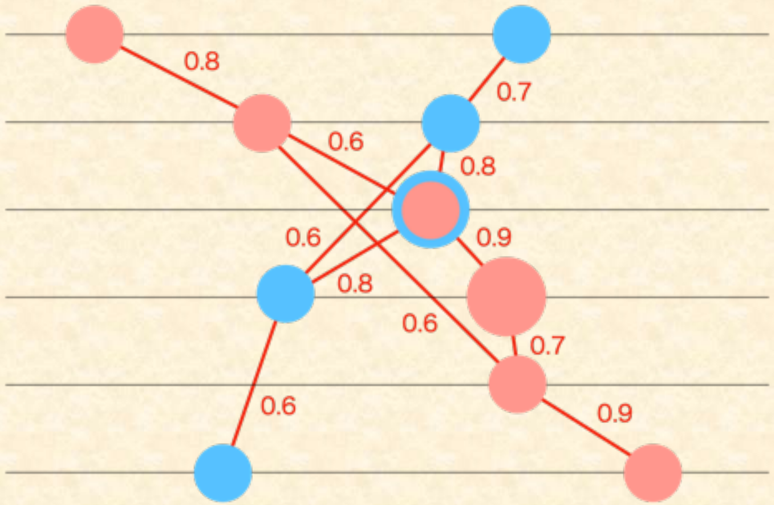


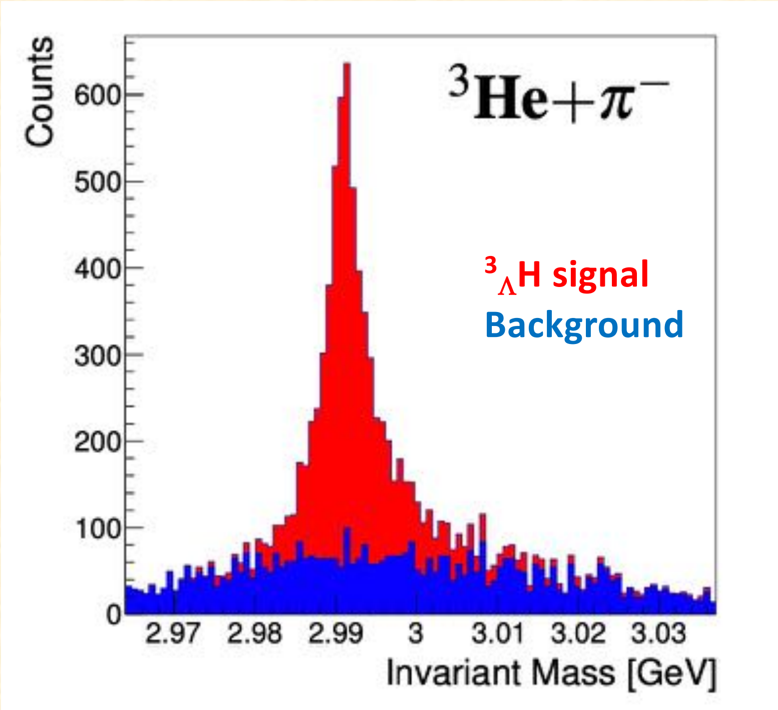


Dataset	π^- (perfect)	π^- (valid)	Other (perfect)	Other (valid)	Node AP(test)	Edge AP(test)
100k	96.31 %	99.77 %	95.12 %	98.66 %	0,94924	0,99932
300k	97.35 %	99.79 %	96.21 %	98.75 %	0,95876	0,99964
1M	98.09 %	99.92 %	97.05 %	99.07 %	0,97219	0,99980

H. Ekawa et al., To be submitted to Journal of Computational Physics

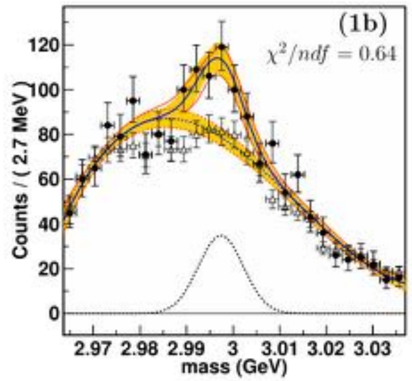
The WASA-FRS experiment at FAIR Phase 0

Expected results by updtated MC simulations



4 days measurement

Former HypHI (2012)



target position: z=25 cm
vertex z cut: 35 – 50 cm
#layer(MDC): > 6
cldst cut: < 0.3 cm

Mass resolution:

- 3.2 MeV/c^2 (1 T field)
- 1.5 times better than HypHI

Statistics

- About 5800 in the peak for 4 days
- 38 times more than HypHI
- 120 σ significance

Expected Lifetime accuracy

- **8 ps**
- 5 times better than HypHI

The existence or not of nnL will be confirmed with large confidence level

Scheduled in February – March, 2022

WASA-FRS in Nature Reviews Physics

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Perspective | Published: 14 September 2021

New directions in hypernuclear physics

Takehiko R. Saito, Wenbou Dou, Vasyl Drozd, Hiroyuki Ekawa, Samuel Escrig, Yan He, Nasser Kalantar-Nayestanaki, Ayumi Kasagi, Myroslav Kavatsyuk, Enqiang Liu, Yue Ma, Shizu Minami, Abdul Muneem, Manami Nakagawa, Kazuma Nakazawa, Christophe Rappold, Nami Saito, Christoph Scheidenberger, Masato Taki, Yoshiki K. Tanaka, Junya Yoshida, Masahiro Yoshimoto, He Wang & Xiaohong Zhou

Nature Reviews Physics (2021) | Cite this article

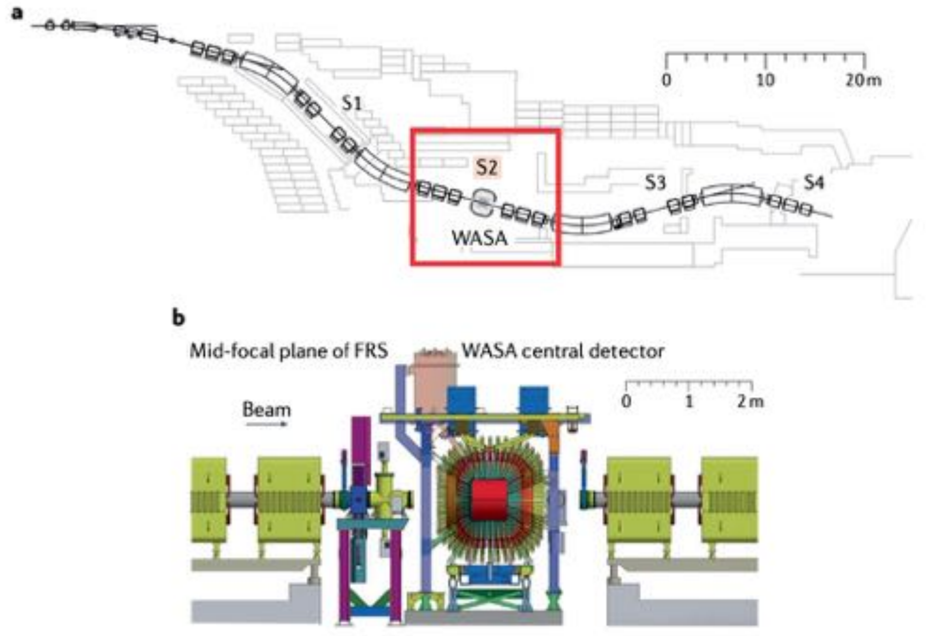
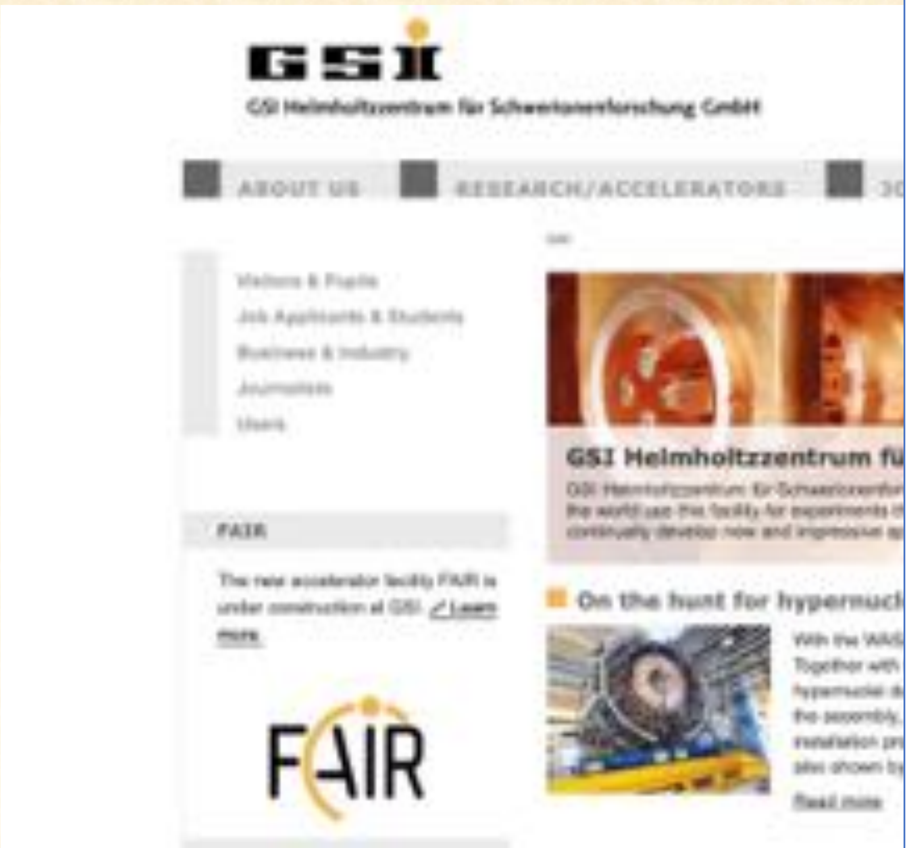
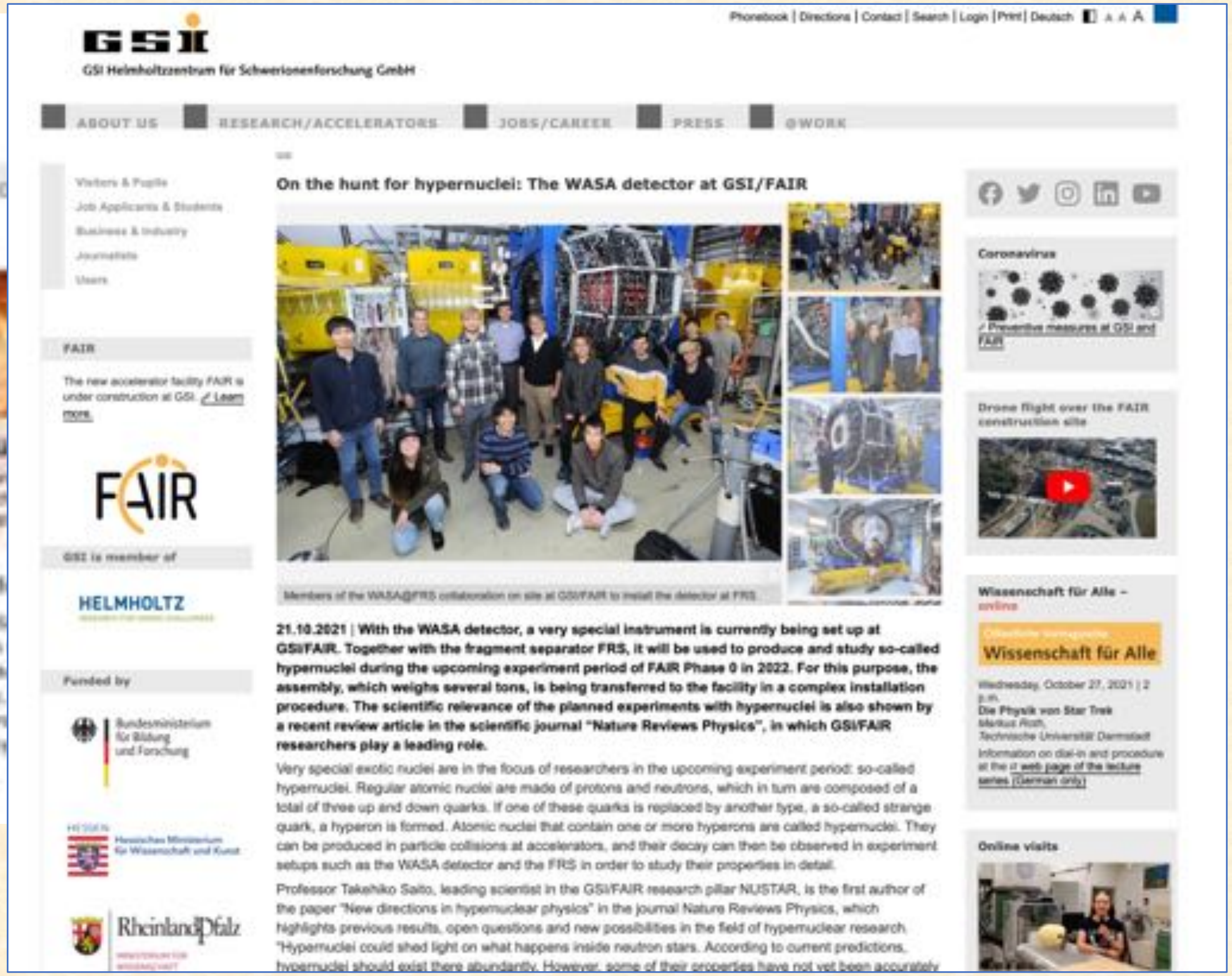


Fig. 1 | **The WASA-FRS hypernuclear experiment. a** | Schematic drawing of the fragment separator (FRS) at GSI. The ^{6}Li primary beams at 2 A GeV are delivered to the diamond target located at the mid-focal plane of the FRS, referred to as S2, to produce hypernuclei of interest. Residual nuclei of the π^- weak decays of hypernuclei are transported from S2 to S4 in the FRS, and measured precisely with a momentum-resolving power of 10^{-4}. The π^- mesons produced by the hypernuclear decays are measured at S2 by the Wide Angle Shower Apparatus (WASA) central detector. **b** | The WASA central detector. Panel **b** is adapted with permission from REF.[76].

DOI: https://doi.org/10.1038/s42254-021-00371-w
Cover of December 2021 issue

GSI press release on October 21st





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GSI Helmholtzzentrum für Schwerionenforschung GmbH

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On the hunt for hypernuclei: The WASA detector at GSI/FAIR

Members of the WASA@FRS collaboration on site at GSI/FAIR to install the detector at FRS

21.10.2021 | With the WASA detector, a very special instrument is currently being set up at GSI/FAIR. Together with the fragment separator FRS, it will be used to produce and study so-called hypernuclei during the upcoming experiment period of FAIR Phase 0 in 2022. For this purpose, the assembly, which weighs several tons, is being transferred to the facility in a complex installation procedure. The scientific relevance of the planned experiments with hypernuclei is also shown by a recent review article in the scientific journal "Nature Reviews Physics", in which GSI/FAIR researchers play a leading role.

Very special exotic nuclei are in the focus of researchers in the upcoming experiment period: so-called hypernuclei. Regular atomic nuclei are made of protons and neutrons, which in turn are composed of a total of three up and down quarks. If one of these quarks is replaced by another type, a so-called strange quark, a hyperon is formed. Atomic nuclei that contain one or more hyperons are called hypernuclei. They can be produced in particle collisions at accelerators, and their decay can then be observed in experiment setups such as the WASA detector and the FRS in order to study their properties in detail.

Professor Takehiko Saito, leading scientist in the GSI/FAIR research pillar NUSTAR, is the first author of the paper "New directions in hypernuclear physics" in the journal Nature Reviews Physics, which highlights previous results, open questions and new possibilities in the field of hypernuclear research. "Hypernuclei could shed light on what happens inside neutron stars. According to current predictions, hypernuclei should exist there abundantly. However, some of their properties have not yet been accurately

FAIR

The new accelerator facility FAIR is under construction at GSI. Learn more.

GSI is member of

HELMHOLTZ

Funded by

Bundesministerium für Bildung und Forschung

Hessisches Ministerium für Wissenschaft und Kunst

Rheinland-Pfalz

Coronavirus

Preventive measures at GSI and FAIR

Drone flight over the FAIR construction site

Wissenschaft für Alle – online

Wissenschaft für Alle

Wednesday, October 27, 2021 | 2 p.m.

Die Physik von Star Trek

Markus Roth,

Technische Universität Darmstadt

Information on dial-in and procedure at the web page of the lecture series (German only)

Online visits

www.gsi.de

In newspapers

Austrian national newspaper, Der Standard

DERSTANDARD › Wissenschaft

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Startseite › Wissenschaft › Technik

46 Postings

EXOTISCHE PARTIKEL

Teilchenphysiker auf der Jagd nach Hyperkernen

Hyperkerne, die in Neutronensternen in großer Zahl vorgekommen könnten, sollen mit dem WASA-Detektor erforscht werden

23. Oktober 2021, 10:12 46 Postings

Herkömmliche Atomkerne bestehen aus Protonen und Neutronen. Zerlegt man diese Atombausteine weiter, stellt man fest, dass sie sich aus insgesamt drei sogenannten Up- und Down-Quarks zusammensetzen. Neben drei weiteren Quark-Arten, den Charm-, Top- und Bottom-Quarks, existieren auch noch die Strange-Quarks. Diese seltsamen Partikel haben bei Kollisionen von Elementarteilchen eine vergleichsweise lange Lebensdauer.

Ersetzt man ein Up- oder Down-Quark eines Protonens oder Neutrons durch ein solches Strange-Quark, dann erhält man ein Hyperon. Atomkerne, in denen ein oder mehrere Hyperonen eingebaut sind, heißen Hyperkerne. Sie lassen sich mithilfe von Teilchenkollisionen an Beschleunigern erzeugen. Diese durchaus exotischen Hyperkerne will man nun mithilfe des WASA-Detektors, einem neuen Messgerät am GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, näher unter die Lupe nehmen.

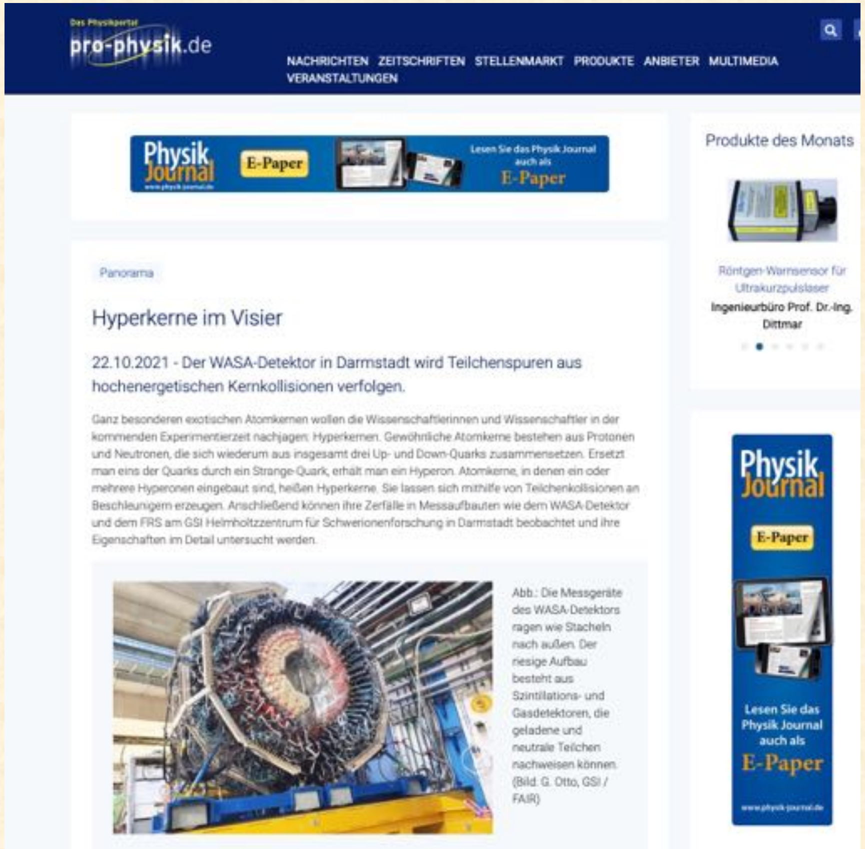
Die Messgeräte des WASA-Detektors ragen wie Stacheln nach außen. Der riesige WASA-Aufbau besteht aus Szintillations- und Gasdetektoren, die geladene und neutrale Teilchen nachweisen können.

Hyperkerne in Neutronensternen

"Die Hyperkerne könnten Licht auf die Vorgänge im Inneren von Neutronensternen werfen. Nach aktuellen Vorhersagen sollten Hyperkerne dort sehr zahlreich vorkommen", sagt Takehiko Saito, leitender Wissenschafter beim Forschungsprojekt NUSTAR. Allerdings sind einige ihrer Eigenschaften noch

https://www.derstandard.at/story/2000130648525/teilchenphysiker-uf-der-jagd-nachhyperkernen-nach

pro-physic in Germany



Das Physikportal pro-physik.de

NACHRICHTEN ZEITSCHRIFTEN STELLENMARKT PRODUKTE ANBIETER MULTIMEDIA VERANSTALTUNGEN

Panorama

Hyperkerne im Visier

22.10.2021 - Der WASA-Detektor in Darmstadt wird Teilchenspuren aus hochenergetischen Kernkollisionen verfolgen.

Ganz besonderen exotischen Atomkernen wollen die Wissenschaftlerinnen und Wissenschaftler in der kommenden Experimentierzeit nachjagen: Hyperkernen. Gewöhnliche Atomkerne bestehen aus Protonen und Neutronen, die sich wiederum aus insgesamt drei Up- und Down-Quarks zusammensetzen. Ersetzt man eins der Quarks durch ein Strange-Quark, erhält man ein Hyperon. Atomkerne, in denen ein oder mehrere Hyperonen eingebaut sind, heißen Hyperkerne. Sie lassen sich mithilfe von Teilchenkollisionen an Beschleunigern erzeugen. Anschließend können ihre Zerfälle in Messaufbauten wie dem WASA-Detektor und dem FRS am GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt beobachtet und ihre Eigenschaften im Detail untersucht werden.

Abb.: Die Messgeräte des WASA-Detektors ragen wie Stacheln nach außen. Der riesige Aufbau besteht aus Szintillations- und Gasdetektoren, die geladene und neutrale Teilchen nachweisen können. (Bild: G. Otto, GSI / FAIR)

https://www.pro-physik.de/nachrichten/hyperkerne-im-visier

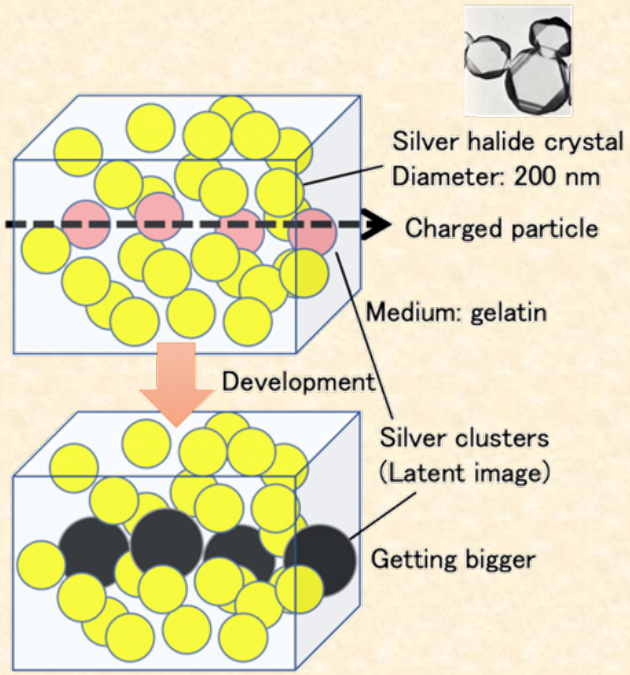
How about
the hypertriton binding energy?

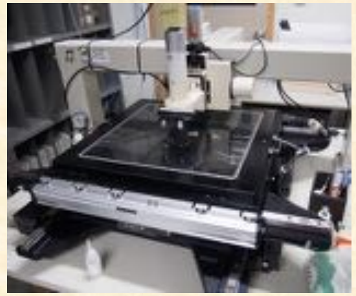
Nuclear Emulsion:

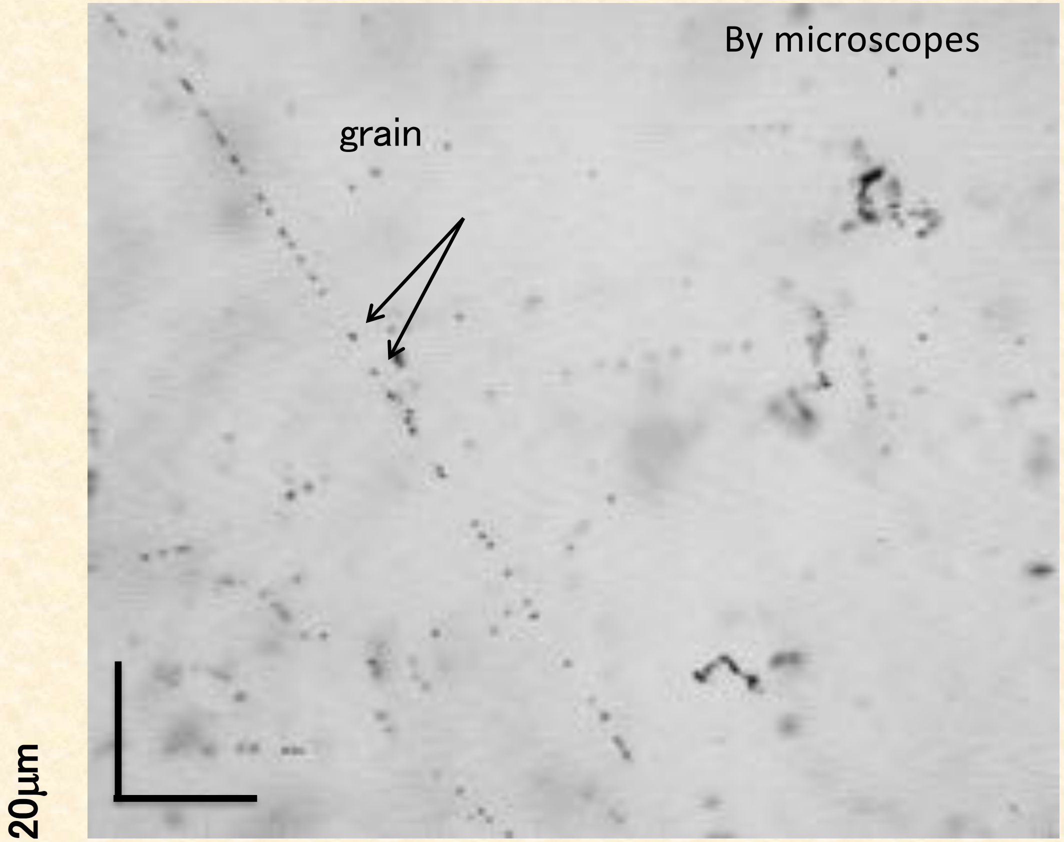
Charged particle tracker with

the best spatial resolution

(easy to be < 1 μm, 11 nm at best)

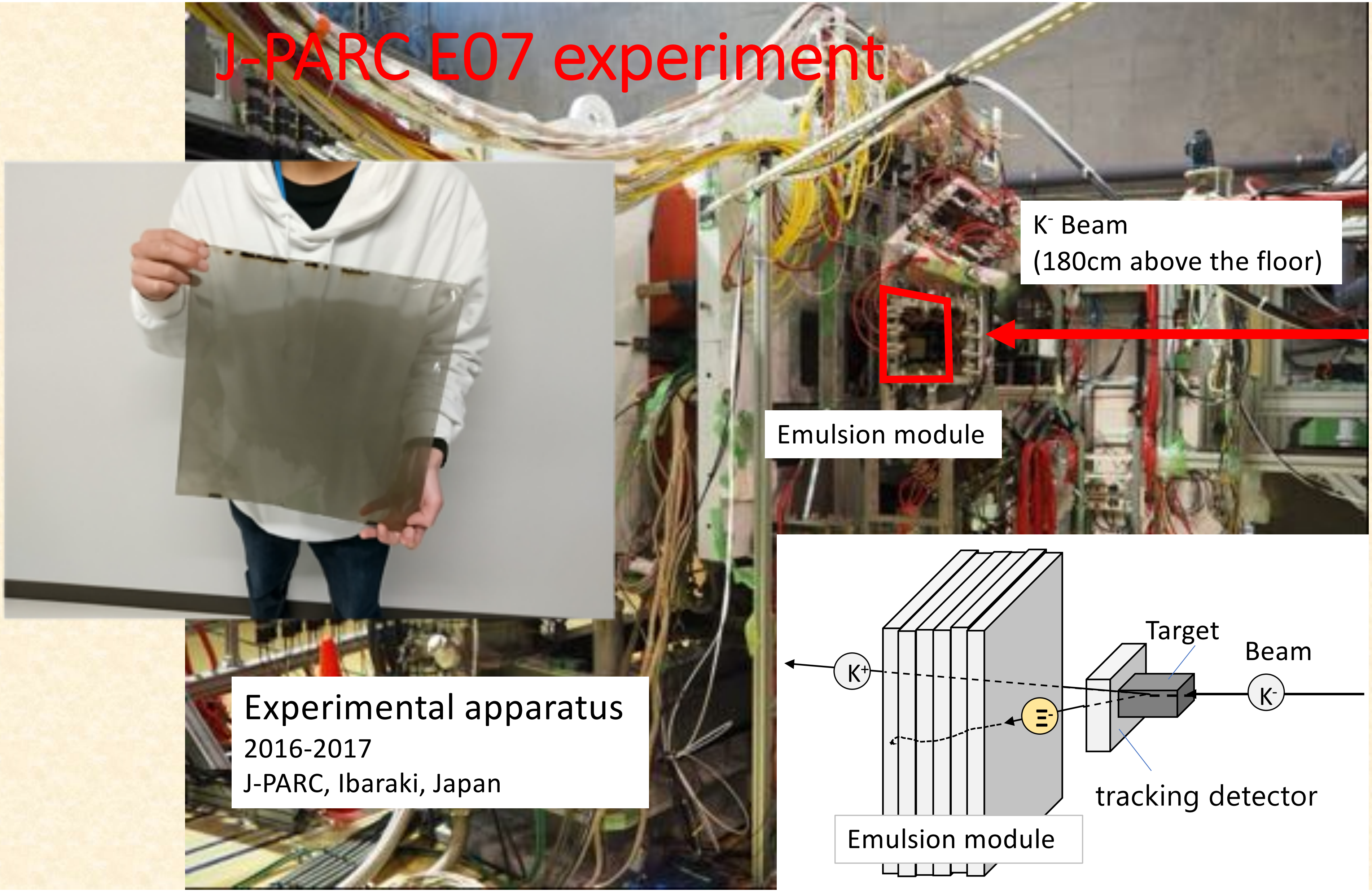




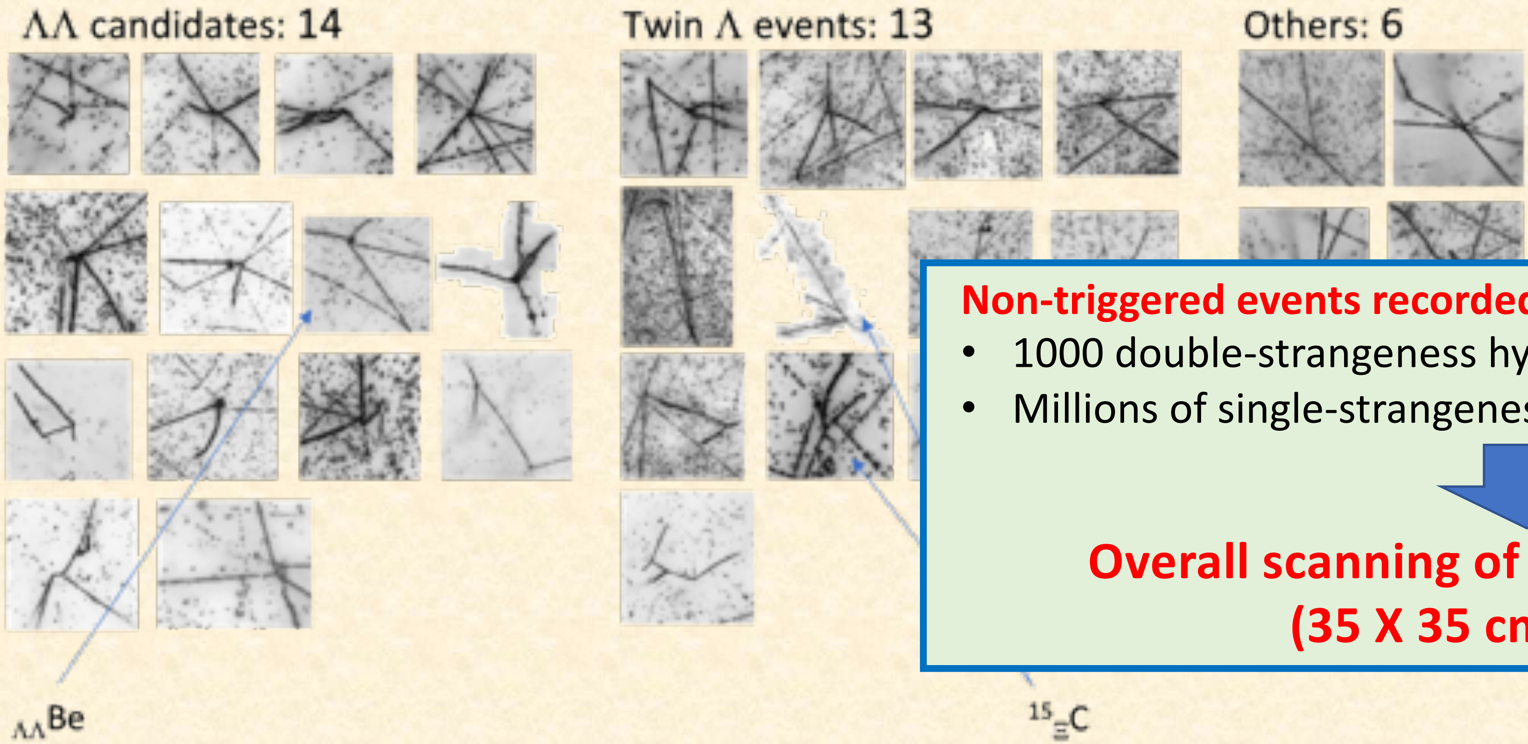


J-PARC accelerator facility

J-PARC E07 experiment



Results from J-PARC E07 (Hybrid method)



Non-triggered events recorded in 1000 emulsions sheets

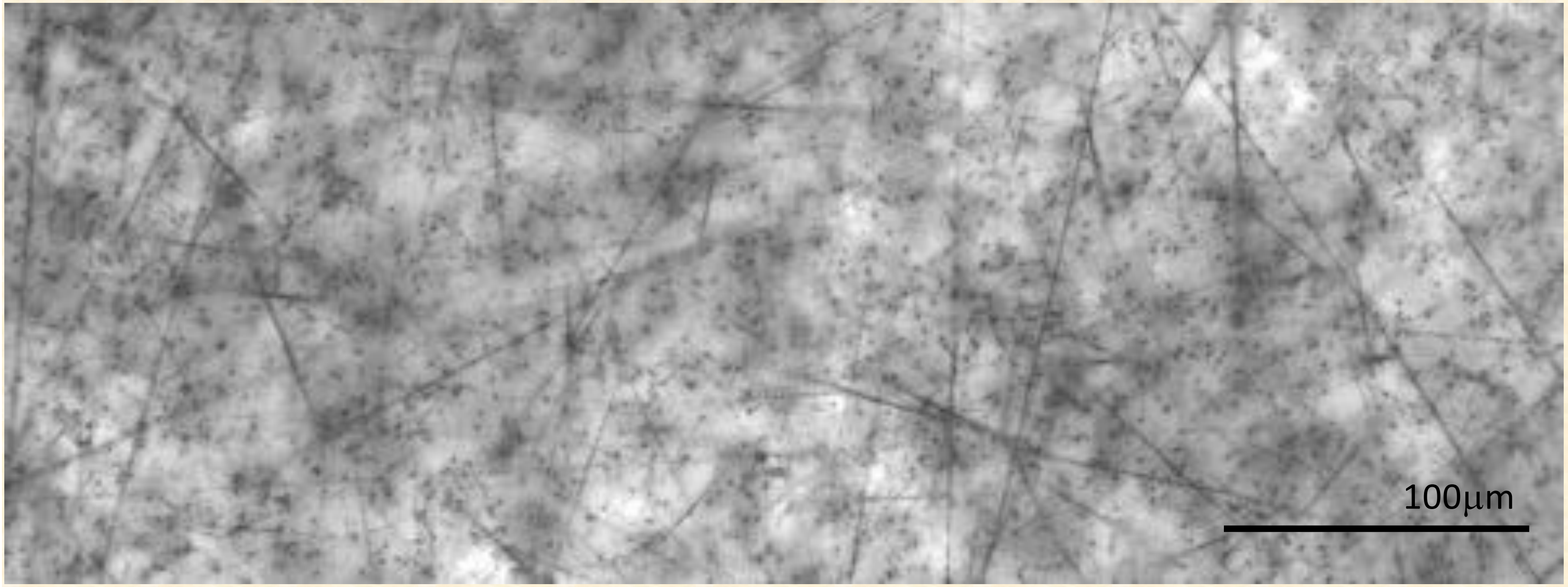
- 1000 double-strangeness hypernuclear events
- Millions of single-strangeness hypernuclear events

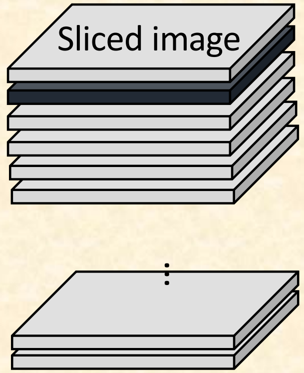
Overall scanning of all emulsion sheets
(35 X 35 cm^2 X 1000)

H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

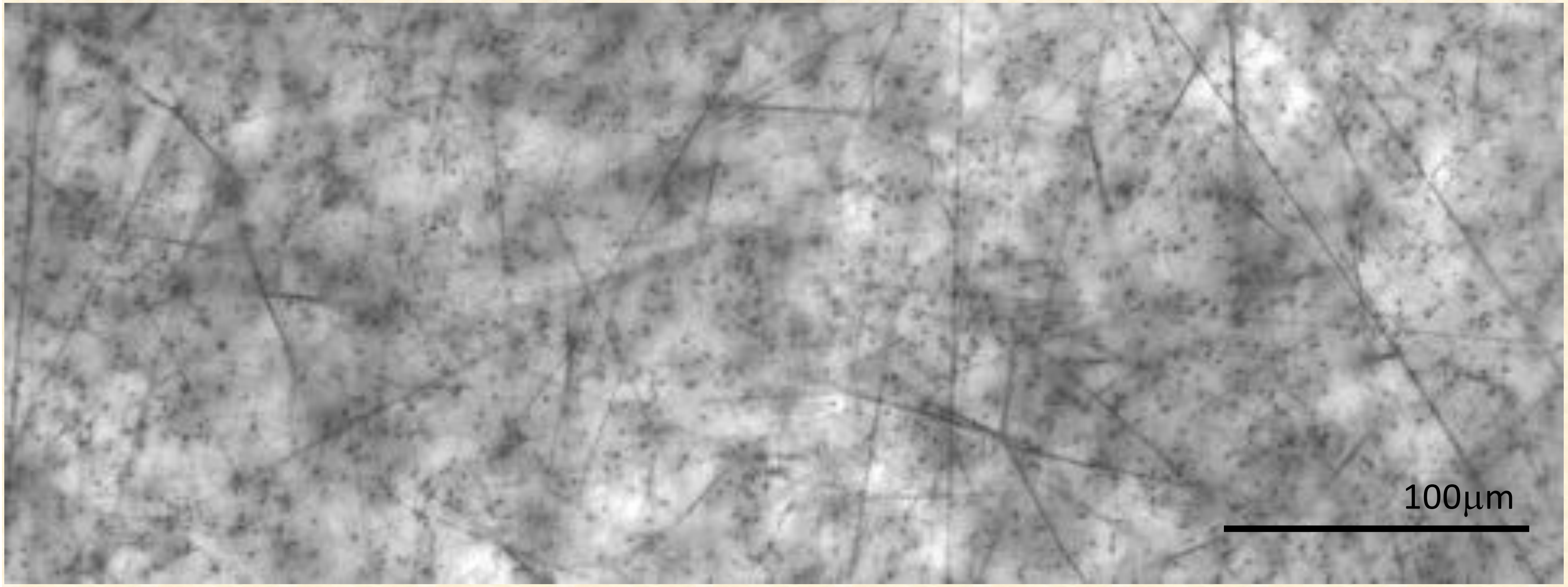
S. H. Hayakawa et al.,
Physical Review Letters, 126, 062501 (2021)

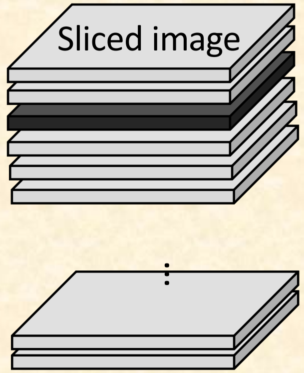
Overall scanning for E07 emulsions



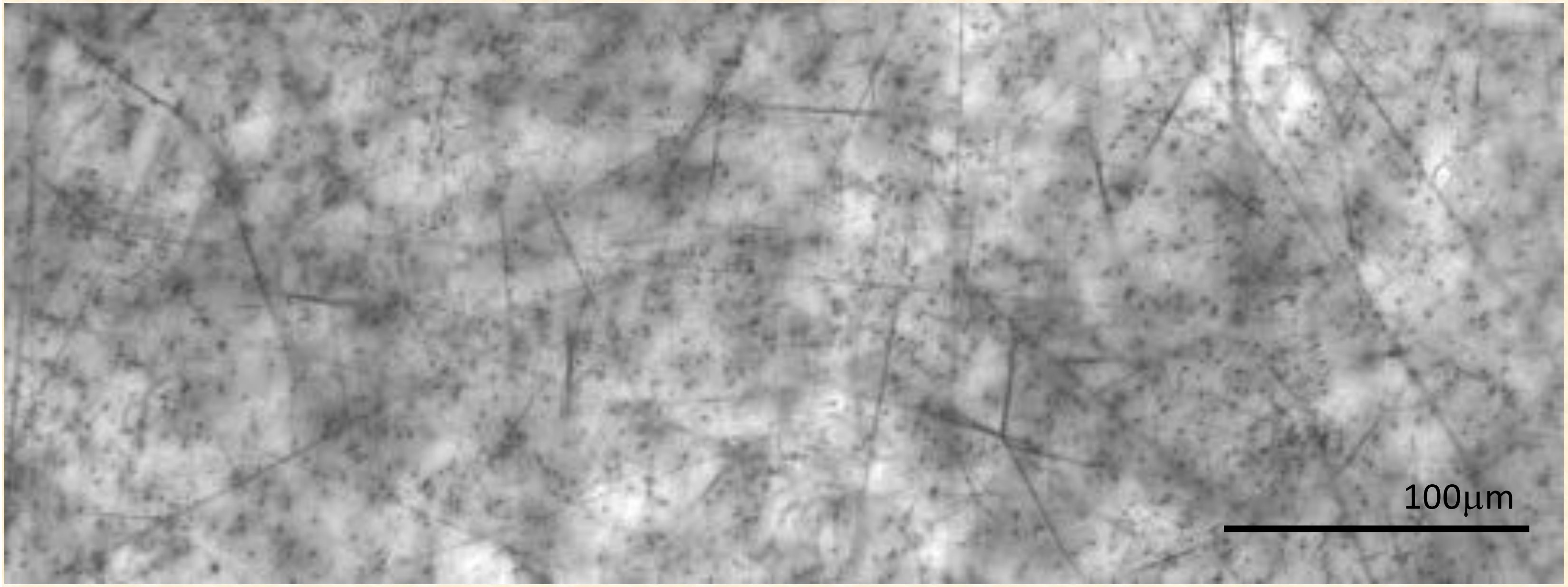


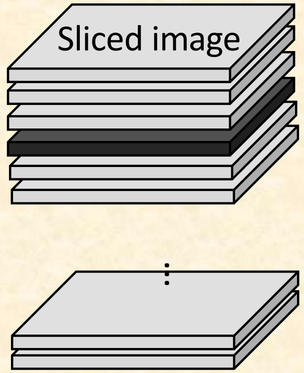
Overall scanning for E07 emulsions



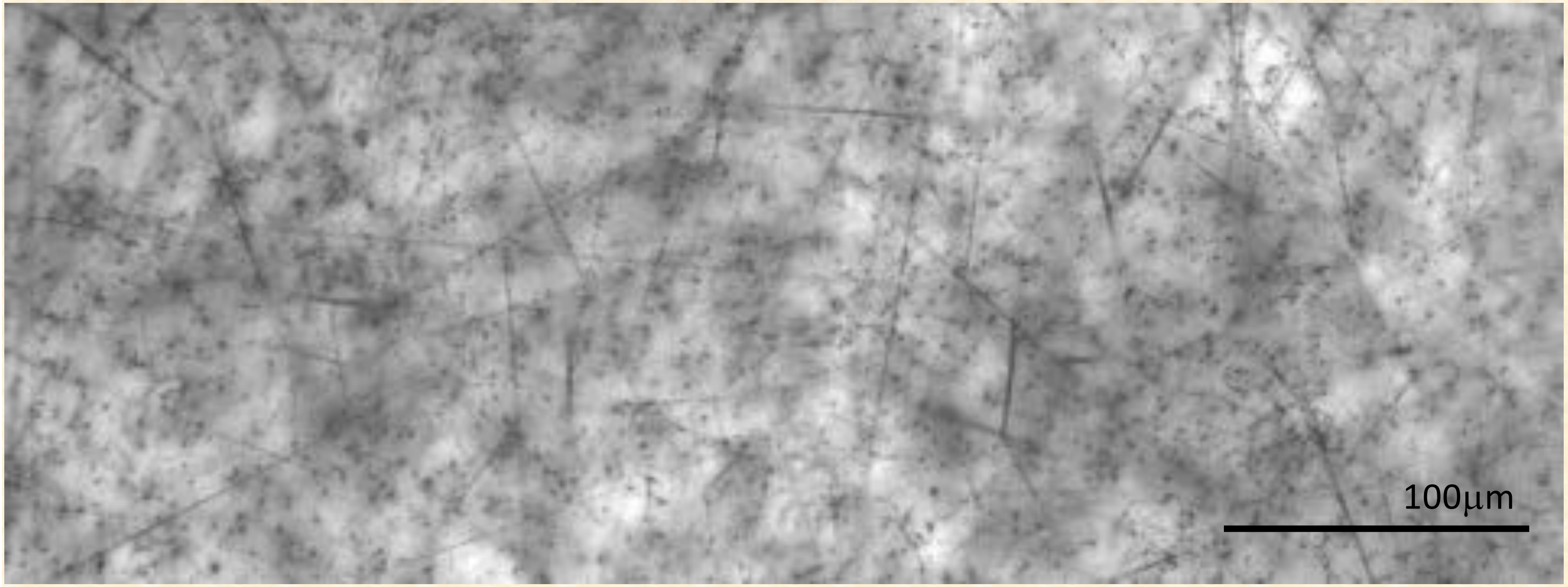


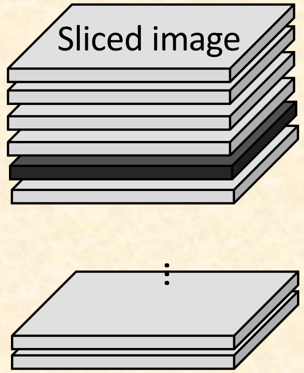
Overall scanning for E07 emulsions



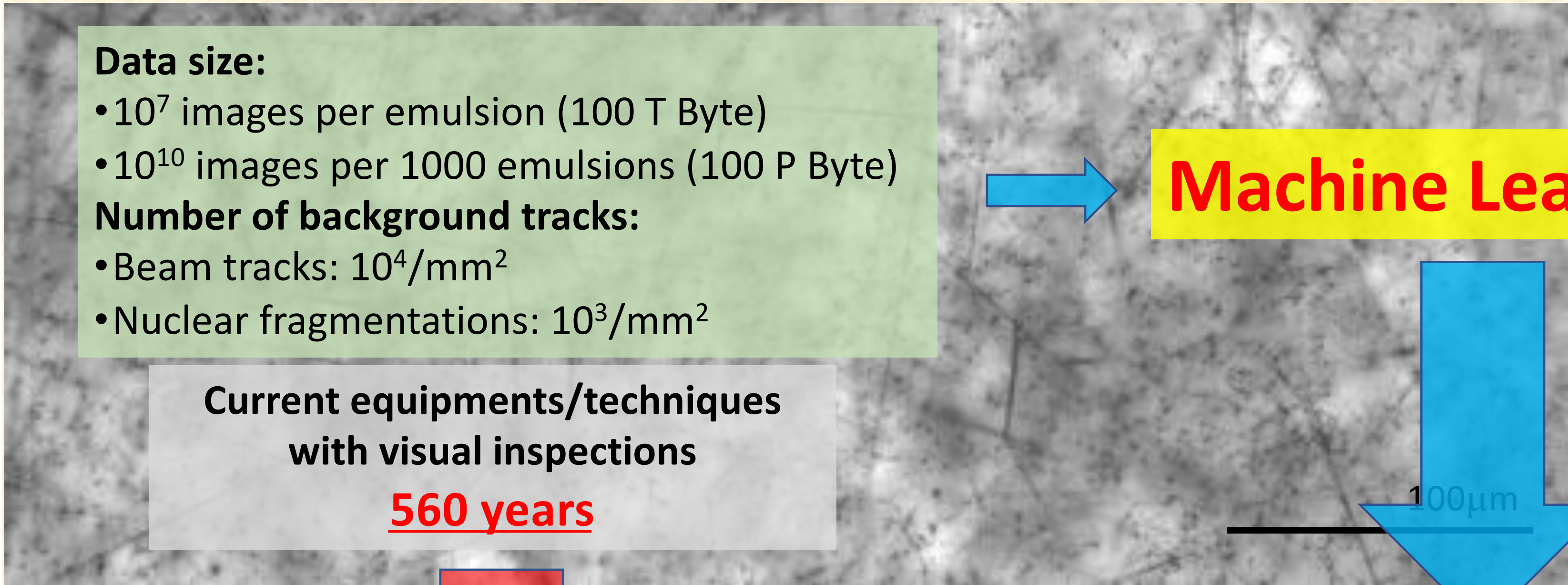


Overall scanning for E07 emulsions





Overall scanning for E07 emulsions



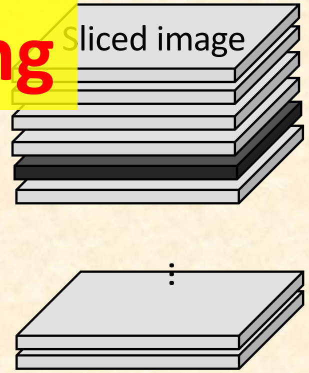
Data size:
- 10^7 images per emulsion (100 T Byte)
- 10^{10} images per 1000 emulsions (100 P Byte)

Number of background tracks:
- Beam tracks: $10^4/mm^2$
- Nuclear fragmentations: $10^3/mm^2$

Current equipments/techniques with visual inspections

560 years

Machine Learning



3 years

Millions of single-strangeness hypernuclei
1000 double strangeness hypernuclei (formerly only 5)

Challenges for Machine Learning Development

MOST IMPORTANT:

- **Quantity and quality of training data**

However,

No existing data for hypertriton with emulsions for training

Our approaches:

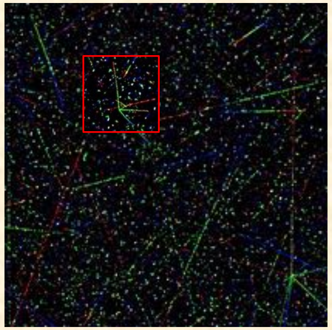
Producing training data with

- Monte Carlo simulations
- Image transfer techniques

Production of training data

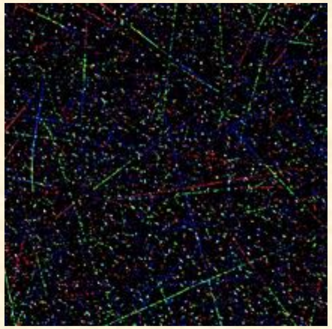
Monte Carlo simulations and GAN(Generative Adversarial Networks)

Binarized tracks from MC simulations
+ background from the real data

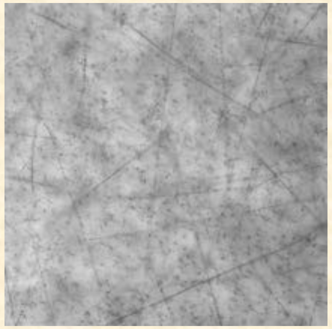


Imitated
emulsion image

GAN: pix2pix



Binarized (like for simulations)

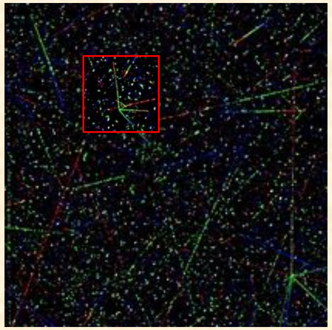


Real emulsion image

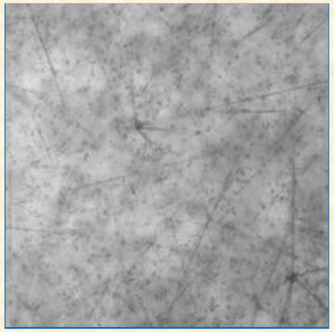
Production of training data

Monte Carlo simulations and GAN(Generative Adversarial Networks)

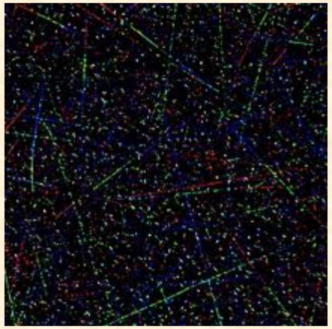
Binarized tracks from MC simulations
+ background from the real data



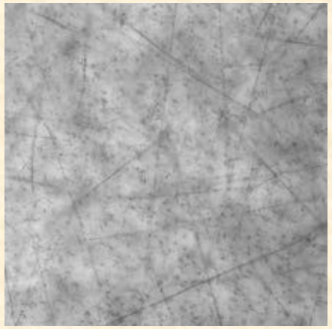
Produced training data



GAN: pix2pix



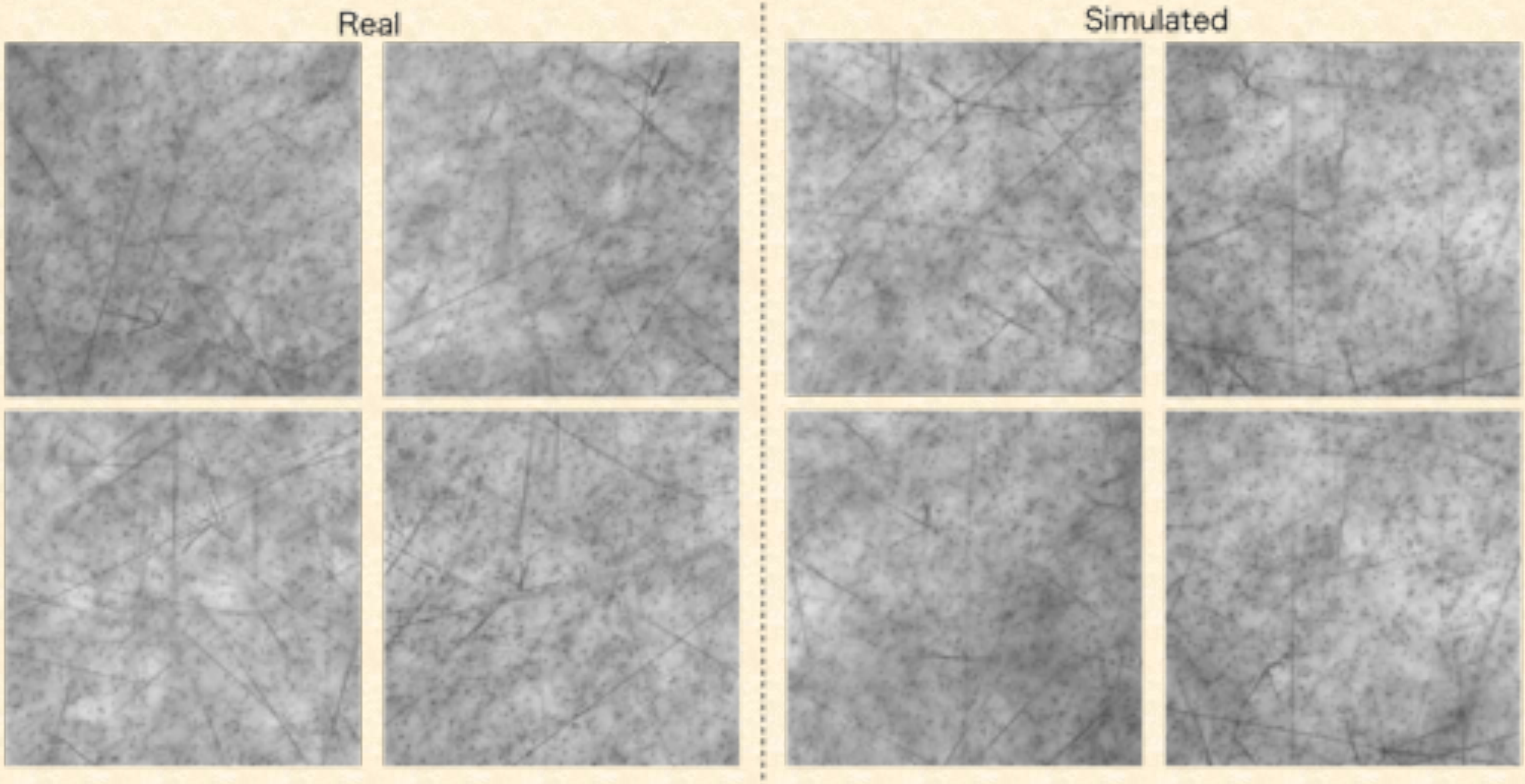
Binarized (like for simulations)



Real emulsion image

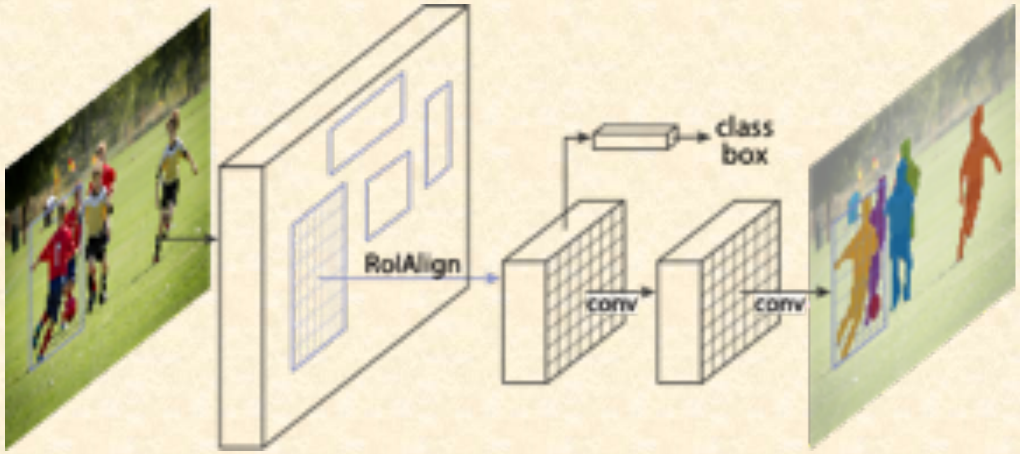
Production of training data

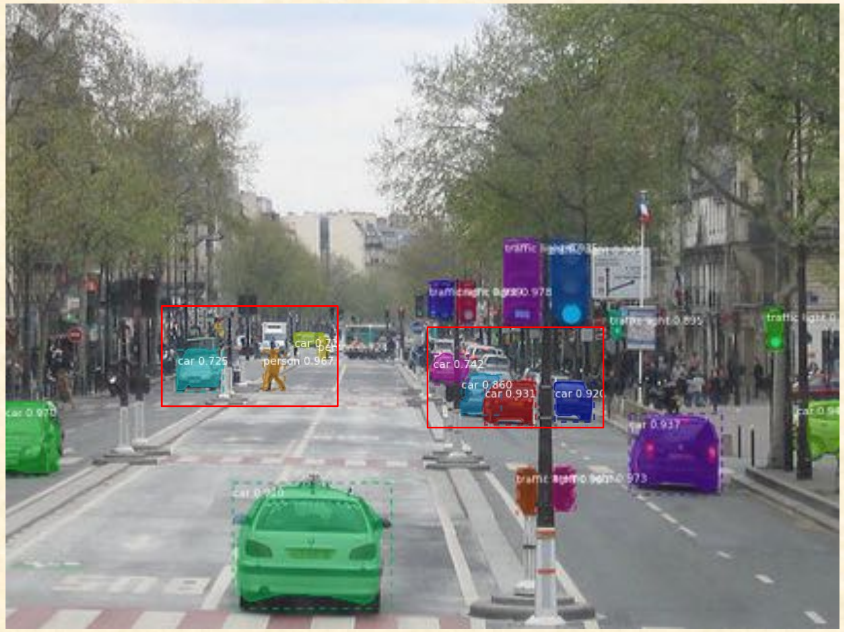
Monte Carlo simulations and GAN(Generative Adversarial Networks)



Detection of hypertriton events

With Mask R-CNN model



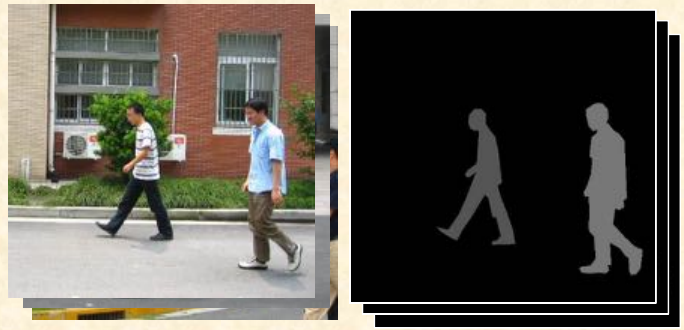


Detection of each object

At large object density

Detection of hypertriton events

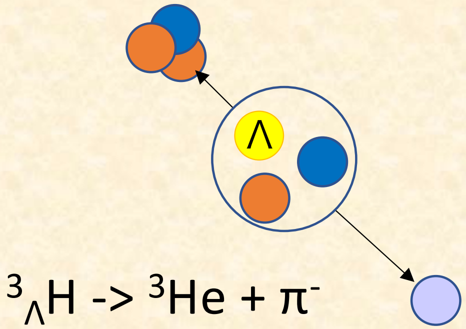
Mask R-CNN



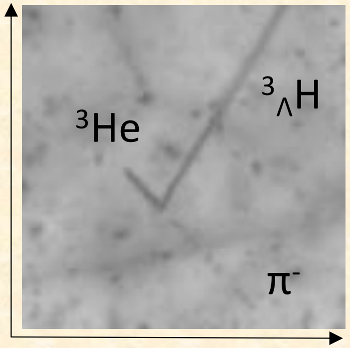
Annotation (creating masks) by humans

https://www.cis.upenn.edu/~jshi/ped_html/

Hypertriton decay at rest

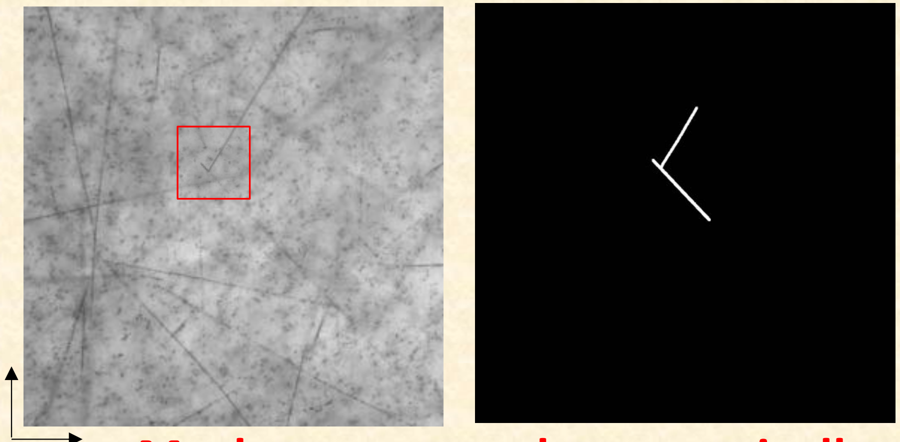


Simulations



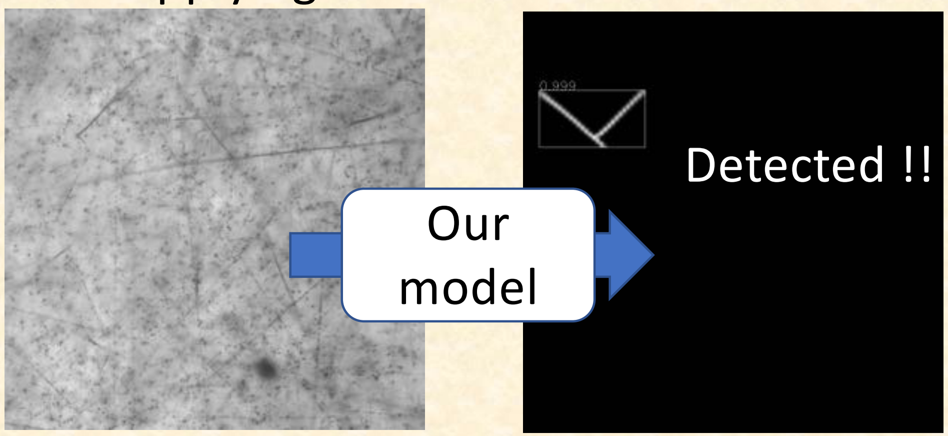
50 μm

Training and mask data



50 μm **<u>Masks are created automatically</u>**

Applying to real emulsion data



Discovery of the first hypertriton event in E07 emulsions

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nature > nature reviews physics > perspectives > article

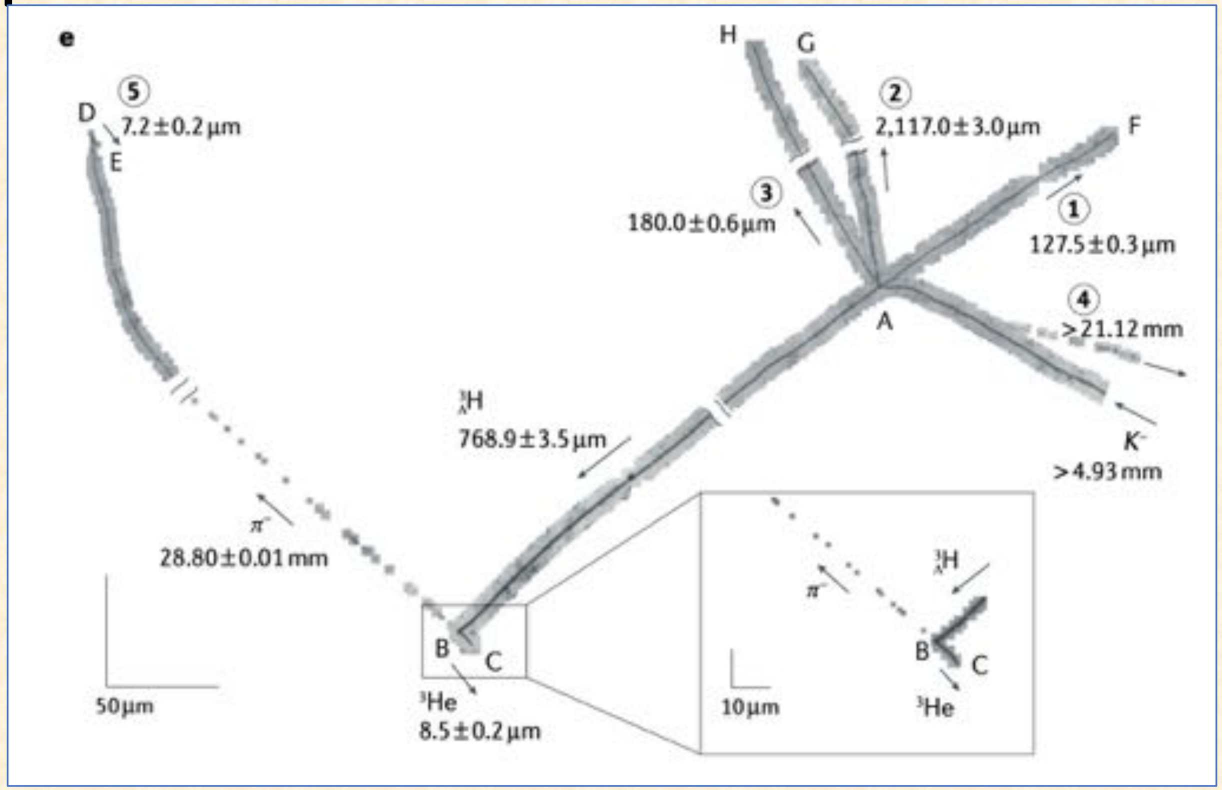
Perspective | Published: 14 September 2021

New directions in hypernuclear physics

Takehiko R. Saito ✉, Wenbou Dou, Vasyl Drozd, Hiroyuki Ekawa, Samuel Escrig, Yan He, Nasser Kalantar-Nayestanaki, Ayumi Kasagi, Myroslav Kavatsyuk, Enqiang Liu, Yue Ma, Shizu Minami, Abdul Muneem, Manami Nakagawa, Kazuma Nakazawa, Christophe Rappold, Nami Saito, Christoph Scheidenberger, Masato Taki, Yoshiki K. Tanaka, Junya Yoshida, Masahiro Yoshimoto, He Wang & Xiaohong Zhou

Nature Reviews Physics (2021) | Cite this article

DOI: https://doi.org/10.1038/s42254-021-00371-w
Cover of December 2021 issue



Guaranteeing the determination of the hypertriton binding energy VERY PRECISELY (±27 keV) SOON

Press release at RIKEN on September 14th

with Gifu University, Rikkyo University and Tohoku University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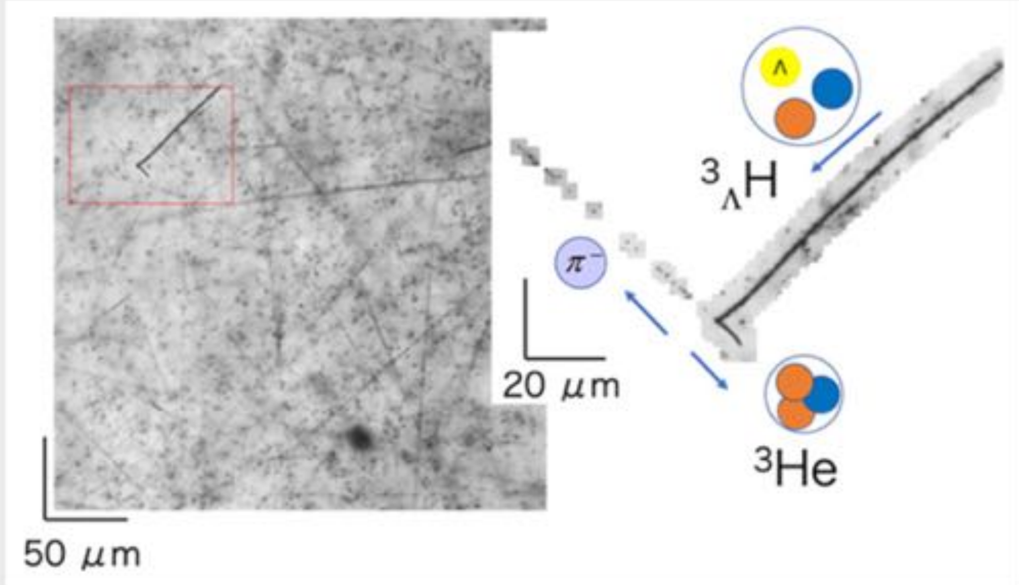
2021年9月14日
理化学研究所
岐阜大学
東北大学
立教大学

ハイパー核の束縛エネルギー精密測定へ

－ハイパートライトンパズルの解明に向けて－

理化学研究所（理研）開拓研究本部齋藤高エネルギー原子核研究室の齋藤武彦主任研究員、岐阜大学教育学部・工学研究科の仲澤和馬シニア教授、大学大学院理学研究科の吉田純也助教、立教大学大学院人工知能科学研究科の瀧雅人准教授らの国際共同研究グループは、大強度陽子加速器施設「PARC」[1]においてK中間子[2]ビームが照射された写真乾板データを、独自に開発した機械学習[3]モデルによって解析し、ハイパー核[4]の一種であ「ハイパートライトン[4]」の生成と崩壊の事象を可視的に検出することに成功しました。

本研究成果は、写真乾板からハイパートライトンを大量に効率良く検出できることを示しており、その束縛エネルギー[5]を世界最高精度で決定することで「ハイパートライトンパズル」と呼ばれる謎の解決への貢献が期待できます。



発見されたハイパートライトンの崩壊事象

https://www.riken.jp/press/2021/20210914_3/

Also in Japanese newspapers

岐阜新聞 Web

ホーム　岐阜のニュース　国内外　岐阜のスポーツ　FC岐阜　おでかけ・グル　エンタメ

トップページ ＞ 岐阜のニュース ＞ 科学

ハイパー核の飛跡、ＡＩで検出成功、宇宙誕生の解明に道筋　岐阜大の仲澤シニア教授ら

2021年09月15日 09:27

国立研究開発法人の理化学研究所（理研）は１４日までに、岐阜大の仲澤和馬シニア教授らが参加する国際共同研究グループが、物質を構成する原子の中心にある原子核の研究で、原子核の一種であるハイパー核のうち最も軽い「ハイパートライトン」が生成されてから崩壊するまでの飛跡を効率的に検出することに成功したと発表した。近年技術的な進化が著しい人工知能（ＡＩ）を活用することで、人の手では数百年かかる検出作業が数年に短縮するという。

実際に検出されたハイパートライトン（3ΛH）の崩壊までの飛跡（左）と仕組み。崩壊後にパイマイナス中間子（π−）とヘリウム３原子核（3He）が左右に放出されている。単位にある「μm」はマイクロメートルで、1μmは１０００分

研究グループは理研の研究員を中心に、仲澤シニア教授ら国内外の研究者１５人で組織。岐阜大大学院の笠置歩さんも理研の大学院生リサーチ・アソシエイトとして参加した。物質の構造や起源を探るための研究の一環で、宇宙誕生の解明につながるとしている。

１３日の記者説明会で解説した理研の齋藤武彦主任研究員によると、原子核を構成する陽子と中性子の間に働く引力を調べる中で、鍵となるのが特殊な原子核であるハイパー核だという。ただ、ハイパー核の理論の基準となるハイパートライトンの性質は未知のままで、原子核と粒子の間に働く引力などが正確に測定されていない課題があった。

研究グループは、２０１６～１７年に仲澤シニア教授が茨城県東海村の大強度陽子加速器施設「Ｊ－ＰＡＲＣ」で行った実験で得られ、ハイパートライトンの飛跡が記録されていると思われる１３００枚の写真乾板に注目。これまでは顕微鏡を使って人の目で丹念に探す必要があったが、ＡＩで自動検出する手法に挑戦した。

ＡＩが検出の参考にする飛跡の観測写真はないものの、飛跡情報をシミュレーションし、モデルとなる模擬画像を画像変換技術を用いて作成。それと同じものを写真乾板の膨大な記録から抜き出そうと、車の自動運転などにも使われる物体検出の技術を使い、ハイパートライトンが生成されてから崩壊するまでの飛跡の自動検出に成功した。今後も複数の飛跡を検出することで、未知だったハイパートライトンの性質を世界最高精度で明らかにできるという。

齋藤主任研究員は「物質の成り立ちの解明への大きな一歩になる」とし、仲澤シニア教授も「これまでの理論が根底から変わるかもしれない」と話している。研究結果をまとめた論文は１４日、英文の科学雑誌「Ｎａｔｕｒ

Gifu Shinbun, September 15th 2021

Akahata Shinbun, September 18th 2021

NOW WE KNOW

How to measure very precisely

- Binding energy
- Lifetime

NEXT steps:

- **Precise measurements for various key hypernuclei**
- **Hypernuclei at extreme isospins (very neutron-rich)**

Beyond WASA-FRS

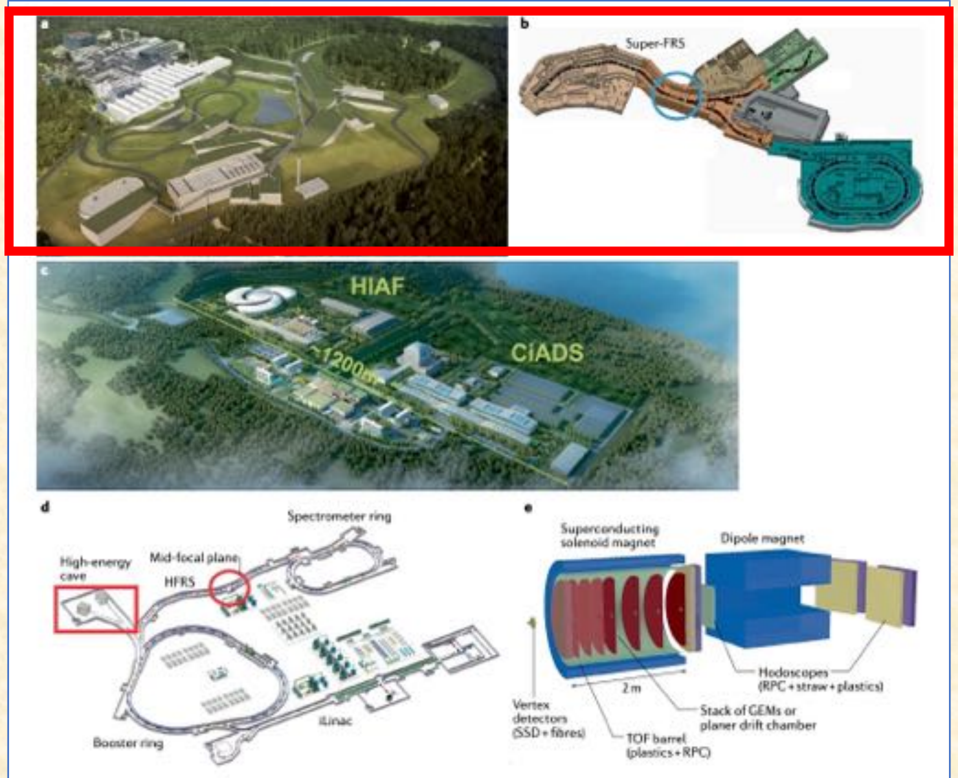


Fig. 3 | **Upcoming hypernuclear experiments. a** | A rendered bird's-eye view image of the Facility for Antiproton and Ion Research (FAIR) facility. **b** | A schematic layout of the NUSTAR facility. The Super-FRS is shown with its pre-separator and main separator in light brown and orange, respectively. A dedicated experimental setup for hypernuclear experiments will be installed in the mid-focal plane, indicated by the blue circle. **c** | A rendered bird's-eye view image of the High Intensity Heavy-ion Accelerator Facility (HIAF), together with the China initiative Accelerator Driven System (CiADS). **d** | Layout of the HIAF accelerator complex. **e** | The proposed detector setup in the high-energy cave. A part of the setup with the superconducting solenoid magnet will also be used in the mid-focal plane (indicated by the red circle in panel **d**) of the high-energy fragment separator (HFRS). GEMs, gas electron multipliers; RPC, resistive plate chamber; SSD, Si-strip detector; TOF, time-of-flight. Panel **b** is adapted with permission from REF.[76].

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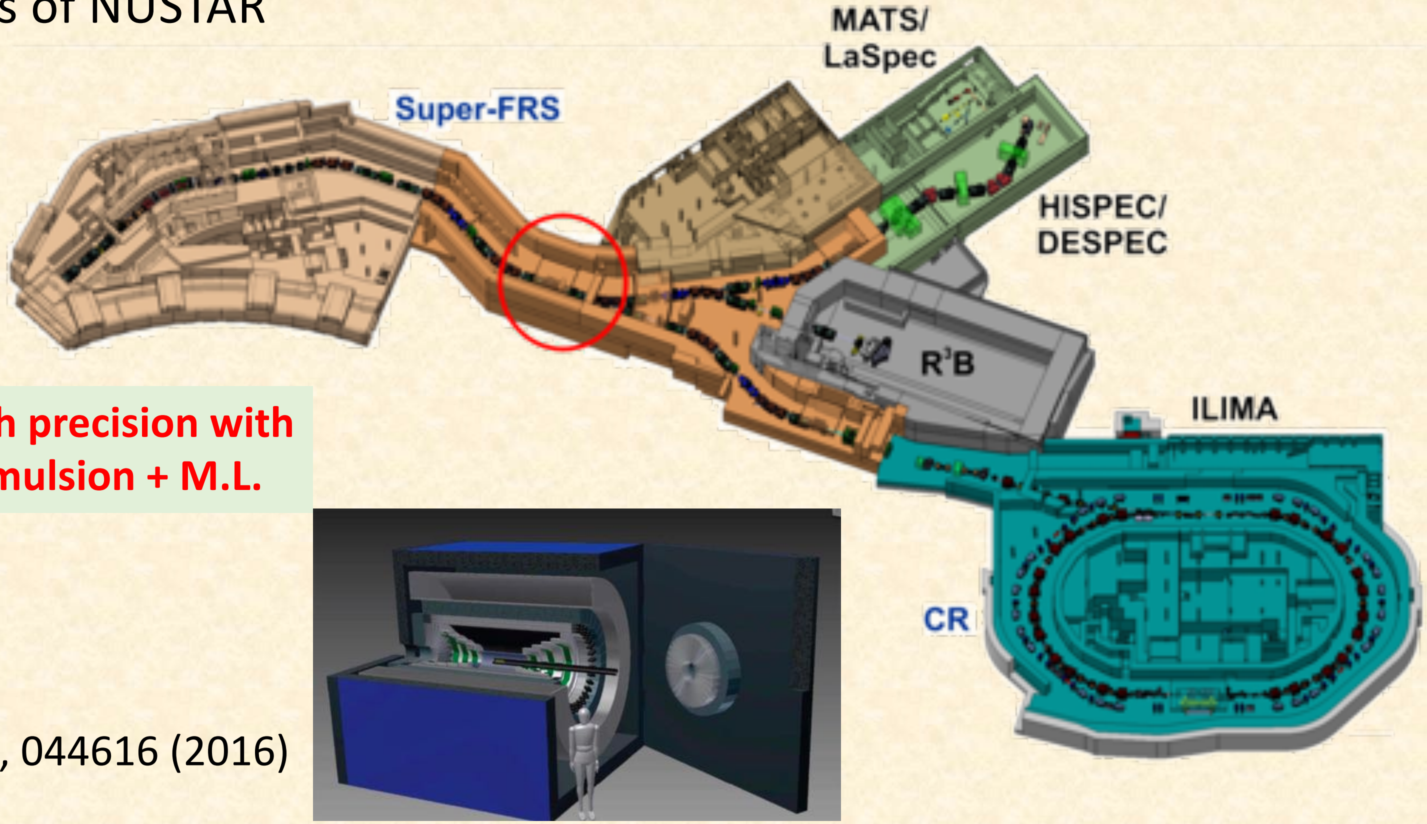
Hypernuclear experiments with Super-FRS

One of Day-1 experiments of NUSTAR



Single-strangeness hypernuclei
Up to A~20
Also with multibody-decay channels

- Hypernuclear lifetime
  very precisely
- Hypernuclear binding energy
  reasonably precise
- Hypernuclear resonance

High precision with Emulsion + M.L.

- Proton rich hypernuclei
  with proton-rich RI-beams
  C. Rappold et al., Phys. Rev. C 94, 044616 (2016)

- **Extremely neutron-rich hypernuclei**
  with charge exchange reactions
  MISSING MASS method

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THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

Novel method for producing very-neutron-rich hypernuclei via charge-exchange reactions with heavy ion projectiles

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Communicated by Alexandre Obertelli

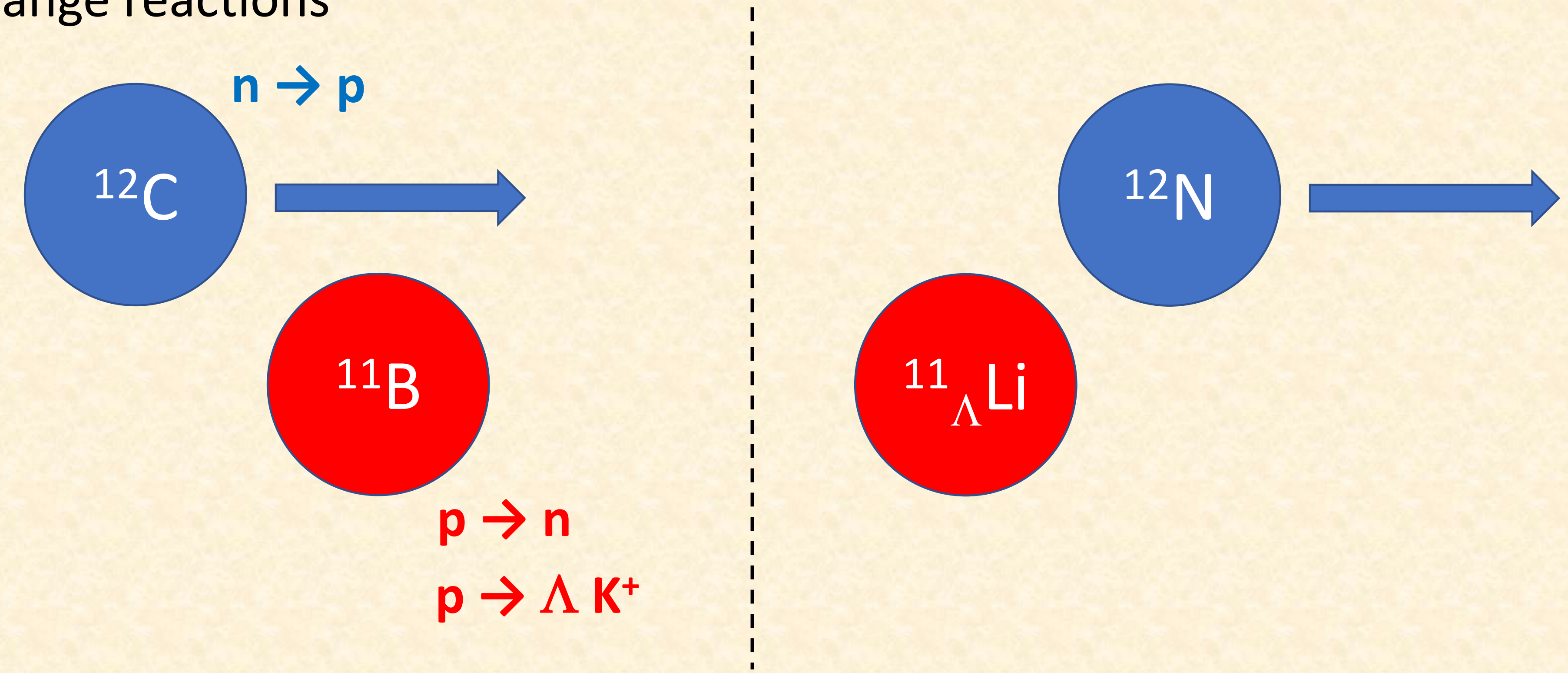
Abstract We propose a novel method for producing very-neutron-rich hypernuclei and corresponding resonance states by employing charge-exchange reactions via pp(^{12}C, ^{12}N K^+)nΛ with single-charge-exchange and ppp(^{9}Be, ^{9}C K^+)nnΛ with double-charge-exchange, both of which produce ΛK^+ in a target nucleus. The feasibility of producing very-neutron-rich hypernuclei using the proposed method was analysed by applying an ultra-relativistic quantum molecular dynamics model to a ^{6}Li + ^{12}C reaction at 2 A GeV. The yields of very-neutron-rich hypernuclei, signal-to-background ratios, and background contributions were investigated. The proposed method is a powerful tool for studying very-neutron-rich hypernuclei and resonance states with a hyperon for experiments employing the Super-FRS facility at FAIR and HFRS facility at HIAF.

the nature of fragmentation reactions of heavy ion beams, the isospin values of the produced hypernuclei were widely distributed. Therefore, neutron-rich and proton-rich hypernuclei could be studied.

One of the problems revealed by the results of the HypHI Phase 0 experiment is the possible existence of an unprecedented bound state of a Λ-hyperon with two neutrons, denoted as Λnn ($^3_\Lambda$n) [3]. Neutral nuclear states with neutrons and Λ-hyperons are of particular interest because the natures of these states should have an impact on our understanding of the deep cores of neutron stars. However, theoretical calculations have shown negative results for the existence of Λnn bound states [4–7]. Although there is disagreement between the results of the HypHI Phase 0 experiment and theoretical calculations, whether or not the Λnn state can exist has recently become a hot topic in experimental and theoretical

Novel method to produce exotic hypernuclei

Production of neutral and very-neutron-rich hypernuclei with charge exchange reactions



European Physical Journal A 57 (2021) 159.

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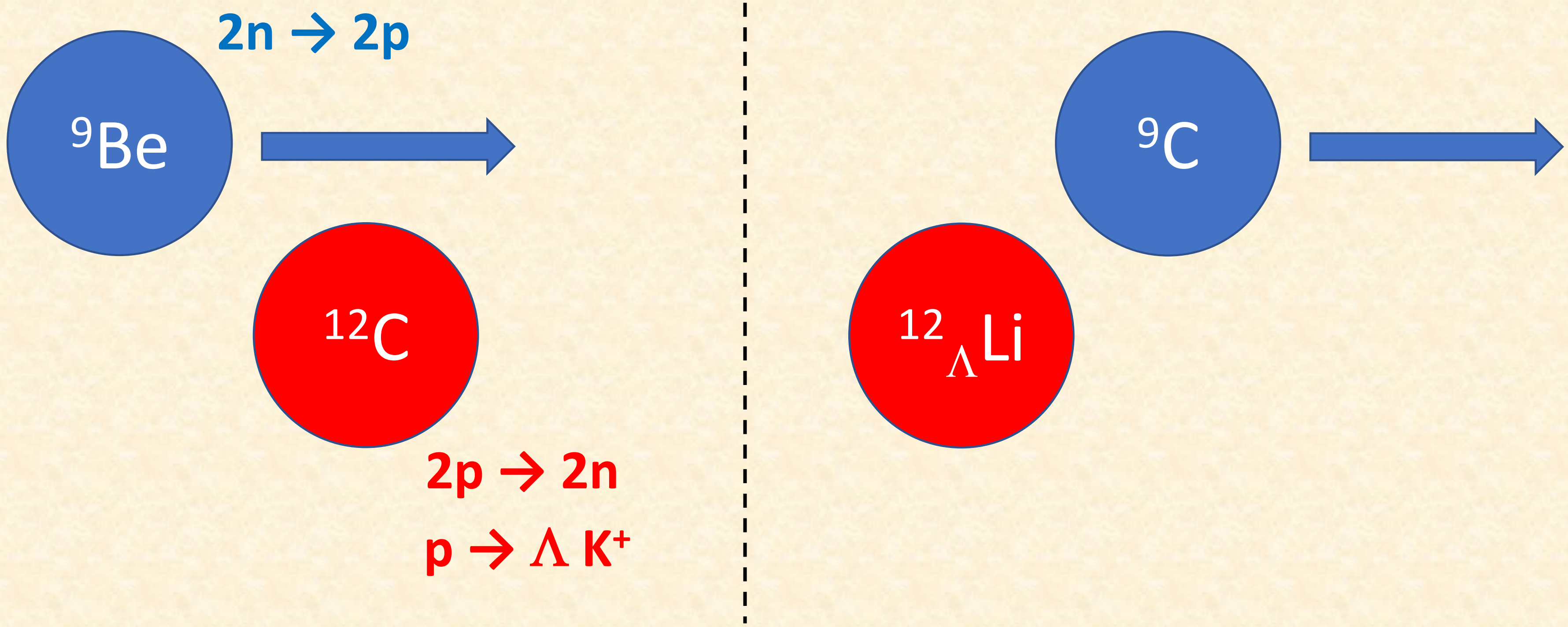

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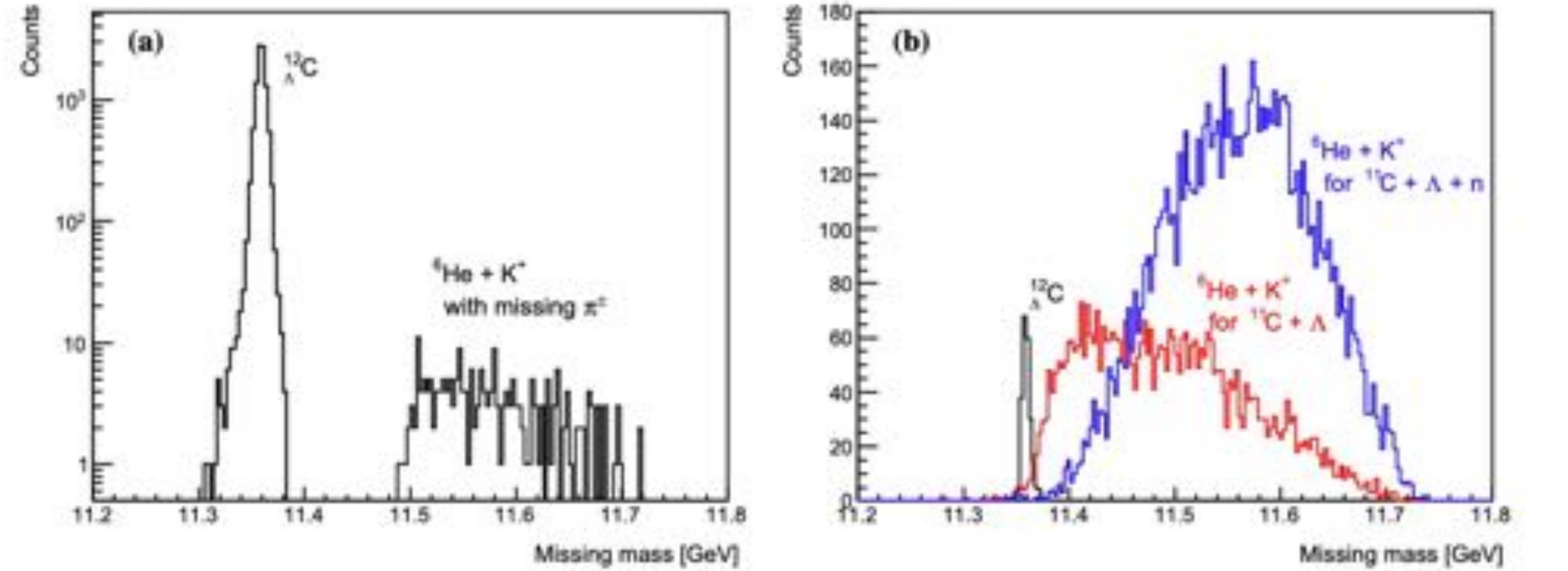

Fig. 5 Left panel **a** missing mass distributions reconstructed by measurements of ^{6}He and K^{+} for the perfect case, $^{6}Li + ^{12}C$ at 2 A GeV $\rightarrow$ $^{6}He + K^{+} + ^{12}_{\Lambda}C$, and an incomplete case with missing π^{+}, $^{6}Li + ^{12}C$ at 2 A GeV $\rightarrow$ $^{6}He + K^{+} + ^{12}_{\Lambda}B + \pi^{+}$. Right panel **b** Missing mass distributions based on observing ^{6}He and K^{+} for the case of $^{6}Li + ^{12}C$ at 2 A GeV $\rightarrow$ $^{6}He + K^{+} + ^{11}C + \Lambda$ (red colour) and $^{6}Li + ^{12}C$ at 2 A GeV $\rightarrow$ $^{6}He + K^{+} + ^{10}C + n + \Lambda$ (blue colour) with the $^{12}_{\Lambda}C$ peak. The width of the $^{12}_{\Lambda}C$ peak is approximately 4.5 MeV in σ

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Novel method to produce exotic hypernuclei

Production of neutral and very-neutron-rich hypernuclei with charge exchange reactions

Single charge exchange
pp (^{12}C, ^{12}N) np
with $K^+\Lambda$ production from proton
pp (^{12}C, ^{12}N K+) nΛ

Double charge exchange
ppp (^{9}Be, ^{9}C) nnp
with $K^+\Lambda$ production from proton
ppp (^{9}Be, ^{9}C K+) nnΛ

Table 1 Summary of hypernuclei/resonances and proposed charge-exchange reactions for $Z = 0 \sim 8$.

Target	Single-charge exchange (^{12}C, ^{12}N K^+)	Double-charge exchange (^{9}Be, ^{9}C K^+)	Produced hypernuclei or resonance	Former observation
^{3}He	✓		$^{3}_{\Lambda}$n (Λnn)	[3]
^{4}He	✓		$^{4}_{\Lambda}$n	
^{6}Li		✓	$^{6}_{\Lambda}$n	
^{7}Li		✓	$^{7}_{\Lambda}$n	
^{6}Li	✓		$^{6}_{\Lambda}$H	[12]
^{7}Li	✓		$^{7}_{\Lambda}$H	
^{9}Be		✓	$^{9}_{\Lambda}$H	
^{9}Be	✓		$^{9}_{\Lambda}$He	
^{10}B		✓	$^{10}_{\Lambda}$He	
^{10}B	✓		$^{10}_{\Lambda}$Li	[14]
^{11}B	✓		$^{11}_{\Lambda}$Li	
^{12}C		✓	$^{12}_{\Lambda}$Li	
^{12}C	✓		$^{12}_{\Lambda}$Be	
^{14}N		✓	$^{14}_{\Lambda}$Be	
^{14}N	✓		$^{14}_{\Lambda}$B	
^{16}O		✓	$^{16}_{\Lambda}$B	
^{16}O	✓		$^{16}_{\Lambda}$C	
^{19}F		✓	$^{19}_{\Lambda}$C	
^{19}F	✓		$^{19}_{\Lambda}$N	
^{20}Ne		✓	$^{20}_{\Lambda}$N	
^{20}Ne	✓		$^{20}_{\Lambda}$O	
^{23}Na		✓	$^{23}_{\Lambda}$O	

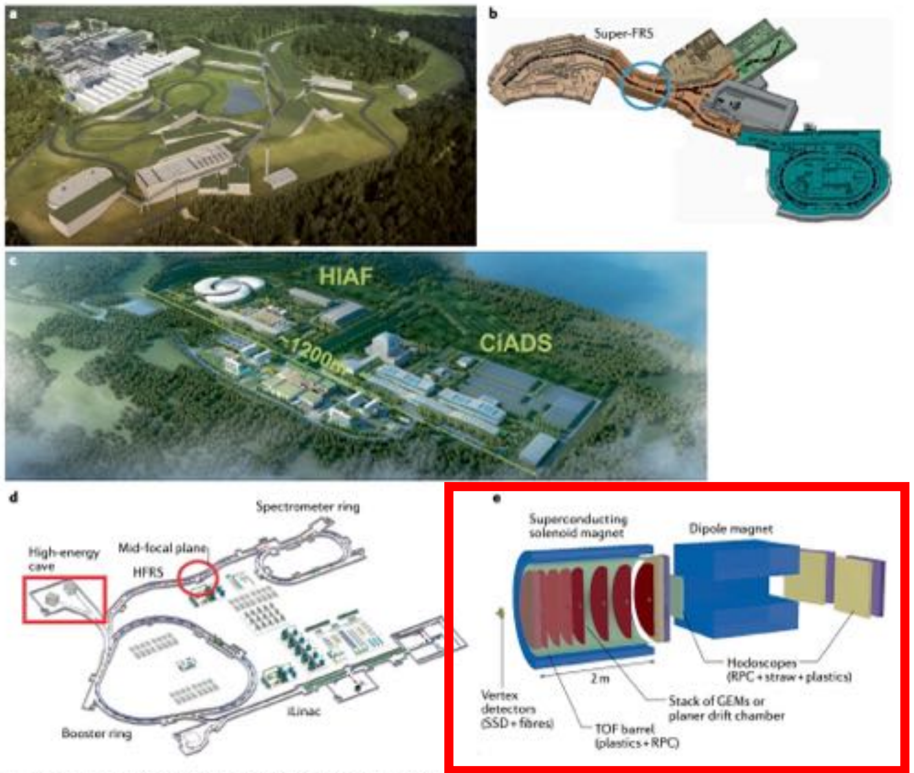
30 – 50 pb

Both bound and resonance states

Possibility on γ–ray spectroscopy

European Physical Journal A 57 (2021) 159.

Beyond WASA-FRS



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Setup like HypHI + WASA

High energy heavy ion beams:

- 10 A GeV at **FAIR**
- 4.25 A GeV at **HIAF in China**

Double-strangeness hypernuclei
Single strangeness hypernuclei

- Lifetime and binding energy precisely
- **Hypernuclear scattering**

Summary

FAIR Phase 0 with FRS:

The WASA-FRS experiment in February – March in 2022

- Lifetime of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ at the best precision
- Confirmation of existence of nnΛ bound state or not

FAIR with Super-FRS:

New superconducting magnet and detectors at Super-FRS

- Further measurements for hypernuclear lifetime and binding energy
- Proton-rich hypernuclei with proton-rich projectiles
- Extremely neutron rich hypernuclei with charge-exchange reactions with p -> ΛK^+

Together with very precise binding energy measurements with emulsion + M.L.