“Hypernuclear physics is in a strange position. It is neither fish nor fowl. High-energy physicists do not look to it for valuable advances in their understanding of the interactions of fundamental particles. Nuclear physicists also see the field as something apart. Its main relevance for the fundamentals is the information it can provide on the Λ-N and Λ-Λ interactions...”

Beyond the conventional nuclear chart: hyperons and antihyperons in nuclear systems

- introduction
- short reminder of basic properties
- international hypernuclear network
- nuclei with antihyperons
- conclusion
How it began

Marian Danysz
Jerzy Pniewski
1953

6
6
He

number of baryons
N+Z+Y

(number of) hyperons
Y

element = total charge (not number of protons)
Hypernuclear physics: a multicultural activity

P. Navratil, 0711.2702v1


Hypernuclei offer a bridge between traditional nuclear physics, hadron physics and astrophysics. It helps to explore fundamental questions like:

- How do nucleons and nuclei form out of quarks?
- Can nuclear structure be derived quantitatively from QCD?
- Properties of strange baryons in nuclei and structure of QCD vacuum?
- Can we constrain the interior of neutron stars?
Basic properties
Weak decay of $\Lambda$ hypernuclei

- Free $\Lambda$ decay
  - $p_N \approx 100\text{MeV/c}$
  - $\Lambda \to p\pi^- + 38\text{MeV} (64\%)$
  - $\Lambda \to n\pi^0 + 41\text{MeV} (36\%)$
  - $\tau_\Lambda = 263\text{ps}$

- Mesonic decay of hypernuclei
  - Suppressed by Pauli blocking

- Non-mesonic decay
  - $\Lambda\Lambda \to Y N$
  - $q \sim 400\text{MeV/c} \Rightarrow$ probes short distances of baryon-baryon weak interaction

- $\Delta I = 1/2$ rule
  - Dominant in all but the lightest hypernuclei

$\Delta I = 1/2$ rule
Birth, life and death of a hypernucleus

target nucleus

\[ p,n \rightarrow \Lambda \]

\[ \gamma \]

\[ \gamma \]

\[ \gamma \]

\[ \Lambda \rightarrow np \]

\[ \Lambda \rightarrow n\pi^0 \]

\[ \Lambda \]

\[ \Lambda \rightarrow \Lambda \Lambda \]

\[ \Lambda \rightarrow \Lambda \Lambda \rightarrow YN \]

\[ e^+ + e^- \rightarrow \Phi \rightarrow K^+ + K^- \]

\[ K_{\text{stopped}}^- + ^A Z \rightarrow ^A Z + \pi^- \]

FINUDA

\[ e^+ + e^- \rightarrow \Phi \rightarrow K^+ + K^- \]

\[ K_{\text{stopped}}^- + ^A Z \rightarrow ^A Z + \pi^- \]

FINUDA

strangeness production

\[ (\pi^+, K^+), (\pi^-, K^0) \]

BNL, KEK, (GSI)

strangeness exchange

\[ (K^-, \pi^+), (K^-, \pi^0) \]

BNL, KEK, JPARC

electroproduction

\[ (e,e'K^+), (\gamma, K^+) \]

Jlab, MAMI-C

Typical energy resolution

\[ K, \pi: \]

1-2 MeV

\[ K_{\text{stopped}}: \]

1 MeV

\[ e: \]

0.5 MeV

\[ \gamma-\text{transitions}: \]

5 keV

Electromagnetic decays

Mesonic decays

Nonmesonic weak decays

hadronic decay in emulsion
Single and double $\Lambda$ hypernuclei exist. The $\Lambda$ potential is about 2/3 of the nucleon potential. The spin-orbit potential is very weak.
Past and Presence of Hypernuclei

- Single and double $\Lambda$ hypernuclei exist
- The $\Lambda$ potential is about 2/3 of the nucleon potential
- The spin-orbit potential is very weak
Present limitations

- only single $\Lambda$-hypernuclei close to valley of stability
- only very few $\Lambda\Lambda$-hypernuclei events
- no information on antihyperons in nuclei
International Hypernuclear Network
International Hypernuclear Network

**JLab**
- electro-production
- single $\Lambda$-hypernuclei
- $\Lambda$-wavefunction

**KAOS @ MAMI**
- electro-production
- single $\Lambda$-hypernuclei
- $\Lambda$-wavefunction

**PANDA @ FAIR**
- anti-proton beam
- double $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy

**KEK † J-PARC**
- intense K- beam
- single and double $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy for single $\Lambda$

**HypHI @ GSI**
- heavy ion beams
- single $\Lambda$-hypernuclei
- weak decays
- at extreme isospins
- magnetic moments

**Dubna**
- heavy ion beam
- single $\Lambda$-hypernuclei
- weak decays

**FINUDA @ DAFNE**
- $e^+ e^-$ collider
- stopped-K- reaction
- single $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy
International Hypernuclear Network

Dubna
- heavy ion beam
- single $\Lambda$-hypernuclei
- weak decays

HypHI @ GSI
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- at extreme isospins
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KEK/J-PARC
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KEK/J-PARC
- intense K- beam
- single and double $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy for single $\Lambda$
High Resolution $\gamma$-Spectroscopy at KEK

$\Lambda$ Hypernuclear Chart (2005)

Several intense K- beam lines
γ-ray spectroscopy for single Λ
Complete study of light (A<30) hypernuclei
Study of medium and heavy hypernuclei
n-richer/p-richer mirror hypernuclei
Double strangeness

30GeV primary beam (phase 1)

Hyperball-J production target (T1)

SKS

Hyperball-J

Beam Dump

K1.8

K1.8BR

production target (T1)

T1 target

K0.8 C-type

K1.1 S-type

KL

KL
International Hypernuclear Network

**PANDA @ FAIR**
- anti-proton beam
- single L-hypernuclei
- gamma-ray spectroscopy

**Dubna**
- heavy ion beam
- single Λ-hypernuclei
- weak decays

**J-PARC**
- intense K⁻ beam
- single and double Λ-hypernuclei
- gamma-ray spectroscopy for single Λ

**HypHI @ GSI**
- heavy ion beams
- single Λ-hypernuclei
- at extreme isospins
- magnetic moments

**FINUDA @ DAFNE**
- e⁺e⁻ collider
- stopped-K⁻ reaction
- single L-hypernuclei
- gamma-ray spectroscopy

**KAOS @ MAMI**
- electro-production
- single L-hypernuclei
- L-wavefunction

It is presently **THE** hypernuclear factory in Europe.
Spectroscopy of single hypernuclei
weak decays
search for neutron rich hypernuclei

Future of FINUDA @ DAΦNE

- high resolution $\gamma$-spectroscopy
- high statistics weak decay
International Hypernuclear Network

**PANDA @ FAIR**
- anti-proton beam
- double $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy

**KAOS @ MAMI**
- electro-production
- single $\Lambda$-hypernuclei
- $\Lambda$-wavefunction

**JLab**
- electro-production
- single $\Lambda$-hypernuclei
- $\Lambda$-wavefunction

**FINUDA @ DAFNE**
- $e^+e^-$ collider
- stopped-$K$-
- single $\Lambda$-
- $\gamma$-ray spectroscopy

**KEK**
- Intense $K$- beam
- Single and double $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy for single $\Lambda$

**HypHI**
- Heavy ion beam
- Single $\Lambda$-hypernuclei
- At extreme isospins
- Magnetic moments

**Dubna**
- heavy ion beam
- single $\Lambda^-$ hypernuclei
- weak decays

**KAOS @ MAMI**
- electro-production
- single $\Lambda$-hypernuclei
- $\Lambda$-wavefunction

**JLab**
- electro-production
- single $\Lambda$-hypernuclei
- $\Lambda$-wavefunction

**PANDA @ FAIR**
- anti-proton beam
- double $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy
KAOS @ MAMI

- wave function of $\Lambda$
- large momentum transfer components
- particle unstable states
The KAOS Spectrometer

![Graph showing survival probability of K+ as a function of flight path (m)]

- Survival probability of K+ is plotted against the flight path (m).
- The graph includes lines for different flight paths marked as K, 1600, 800, 400, 200, 100, 50, and 0.
- The flight path ranges from 0 to 14 meters.

![Image of the KAOS Spectrometer apparatus]

- The apparatus consists of large blue, green, and red cylindrical structures.
- The setup is part of the GUTENBERG MAINZ project.
Double Spectrometer KAOS at 0°

- MAMI-C: 1.5GeV electrons

Patrick Achenbach (Mainz)
First \( p(e,e'K)\Lambda \) @ MAMI

- 5cm long liquid hydrogen target

Patrick Achenbach (Mainz)
Nov. 2008
International Hypernuclear Network

JLab
- electro-production
- single Λ-hypernuclei
- Λ-wavefunction

KAOS @ MAMI
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- single Λ-hypernuclei
- Λ-wavefunction

PANDA @ FAIR
- anti-proton beam
- double Λ-hypernuclei
- γ-ray spectroscopy

Dubna
- heavy ion beam
- single Λ-hypernuclei
- weak decays

HypHI @ GSI
- heavy ion beam
- single Λ-hypernuclei at extreme isospins
- magnetic moments

FINUDA @ DAFNE
- e+e- collider
- stopped-K-reaction
- single Λ-hypernuclei
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HypHI @ GSI
- heavy ion beam
- single Λ-hypernuclei at extreme isospins
- magnetic moments

FINUDA @ DAFNE
- e+e- collider
- stopped-K-reaction
- single Λ-hypernuclei
- γ-ray spectroscopy
neutron and proton rich single $\Lambda$ hypernuclei
weak decays, lifetimes
hypermatter at low density
magnetic moment of $\Lambda$ inside nucleus

Take Saito (GSI, Mainz)
Hypernuclear chart before HypHI

Known hypernuclei
HypHI Phase 0 experiment

phase 0 (2009) at GSI:
light hypernuclei

Known hypernuclei
Phase 0 experiment at GSI, in 2009

GSI accelerator facility

Cave C
Hypernuclear landscape with

**Phase 1** (2009-2012) at GSI:
Proton rich hypernuclei

**Phase 0** (2009) at GSI:
Light hypernuclei

Known hypernuclei
$10^4$ /week
$10^3$ /week
Hypernuclear landscape with

**Phase 1** (2009-2012) at GSI:
Proton rich hypernuclei

**Phase 2** (2012-) at R3B/FAIR:
Neutron rich hypernuclei

**Phase 0** (2009) at GSI:
Light hypernuclei

Known hypernuclei
$10^4$/week
$10^3$/week
Phase 2 with R3B @ FAIR

- Neutron-proton asymmetric nuclei – structure and reactions
- Nuclear astrophysics
- Asymmetric nuclear matter
- Hypernuclei (HypHI)
Hypernuclear landscape with HyperHI

Phase 0 (2009) at GSI:
Light hypernuclei

Phase 1 (2009-2012) at GSI:
Proton rich hypernuclei

Phase 2 (2012-) at R3B/FAIR:
Neutron rich hypernuclei

Phase 3 (201X-) at FAIR:
Hypernuclear separator

Known hypernuclei
$10^4$ /week
$10^3$ /week

With hypernuclear separator
Magnetic moments
Hypernuclei in Multifragmentation

\[ E^{hyp}_{sam} = Y \left( -10.68 + \frac{48.7}{A^{2/3}} \right) \]

\[ E^{hyp}_{LD} = \frac{Y}{A} \left( -10.68 + 21.27 A^{2/3} \right) \]

T=4 MeV

100-40 H_0=2

relative yield

liquid-drop

Samanta

A, fragment mass number
HypHI – Doorwy to MEMO’s

- metastable exotic multihypernuclear objects
  - 2(Ξ^-), 2(ΛΞ^-), 2(nΛΞ^-), 2(pΛΞ^-),…
International Hypernuclear Network

**JLab**
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- single Λ-hypernuclei
- Λ-wavefunction

**KAOS @ MAMI**
- electro-production
- single Λ-hypernuclei

**HypHI @ GSI**
- heavy ion beam
- single Λ-hypernuclei
- weak decays
- magnetic moments at extreme isospins

**PANDA @ FAIR**
- anti-proton beam
- double Λ-hypernuclei
- γ-ray spectroscopy

**Dubna**
- heavy ion beam
- single Λ-hypernuclei
- weak decays

**FINUDA @ DAFNE**
- e⁺e⁻ collider
- stopped-K-reaction
- single L-hypernuclei
- γ-ray spectroscopy
High resolution $\gamma$-spectroscopy of double $\Lambda\Lambda$ hypernuclei
weak decays
The first double Λ nucleus

1.3-1.5 GeV/c K^-+Emulsion; 31000 K^-

PHYSICAL REVIEW LETTERS

1 July 1963

OBSERVATION OF A DOUBLE HYPERFRAGMENT

M. Danysz, K. Garbowska, J. Pniewski, T. Pniewski, and J. Zakrzewski
Institute of Experimental Physics, University of Warsaw, Warsaw, Poland
and Institute for Nuclear Research, Warsaw, Poland

and

E. R. Fletcher
H. H. Wills Physics Laboratory, University of Bristol, Bristol, England

and

J. Lemonde, P. Renard, and J. Sacton
Université Libre de Bruxelles, Bruxelles, Belgium

and

W. T. Toner†
CERN, Geneva, Switzerland

and

D. O’Sullivan, T. P. Shah, and A. Thompson
Institute for Advanced Studies, Dublin, Ireland

and

P. Allen, Jr., M. Heenan, and A. Montwill
University College, Dublin, Ireland

and

J. E. Allen, M. J. Beniston, D. H. Davis, and D. A. Garbutt
University College, London, England

During a systematic scan for interactions of 1.3- and 1.5 GeV/c K^- ion beams, an event has been found which is interpreted as the production and subsequent decay of a double hyperfragment. The event is interpreted as a Λ^+ hyperon capture at K leading to the emission of a double hyperfragment. The event was carefully reanalyzed by P.H. Fowler, V.M. Mayes, and E.R. Fletcher, and Dalitz et al., Proc. R. Soc. Lond. A426, 1 (1989).
The first event (2)

FIG. 1. A photomicrograph and a schematic drawing of the production of a $\Xi^-$ hyperon in a 1.5-GeV/c $K^-$-meson interaction at A followed by capture at rest of the $\Xi^-$ hyperon at B with the emission of a double hyperfragment decaying in cascade at C and D.
Summary

Interpreting $\Delta B_{\Lambda\Lambda}$ as $\Lambda\Lambda$ bond energy one has to consider e.g.

- dynamical change of the core nucleus
- $\Lambda N$ spin-spin interaction for non-zero spin of core
- $\Lambda\Lambda$-$\Xi N$-$\Sigma\Sigma$ coupling
- excited states possible, but have not been clearly identified so far
Production of $\Lambda\Lambda$ Hypernuclei

- simultaneous implantation of two $\Lambda$'s impossible

- $\Xi^-$ conversion in $2\Lambda$: $\Xi^- + p \rightarrow \Lambda + \Lambda + 28\text{MeV}$
  \[ \Rightarrow \text{large probability that two $\Lambda$'s stick to same nucleus} \]

- two-step process
  \[ \Rightarrow \text{spectroscopic studies only via the decay products} \]

- PANDA: $\Xi^-$ production with $p + p \rightarrow \Xi + \Xi$ reaction in nuclei

---

**OBSERVATION OF PRODUCTION OF A $\Xi^- + \Xi^+$ PAIR**


Brookhaven National Laboratory, Upton, New York

and

C. Baltay, E. C. Fowler, J. Sandweiss,‡ J. R. Sanford, and H. D. Taft

Yale University, New Haven, Connecticut

(Received February 15, 1962)

The reaction $\bar{p} + p \rightarrow \Xi^- + \Xi^+$ has been observed in a 20-in. liquid hydrogen bubble chamber exposed to a separated antiproton beam of 3.3-Bev/c momentum produced in a tungsten target in the Brookhaven alternating gradient synchrotron. While expected to exist, the $\Xi^+$ has so far not been observed, partially because the cross section for $\Xi$ production is small in comparison with the production of other hyperons, and partially because beams of high enough energy have been available only recently. Figure 1 shows a photograph and sketch of the event. Both cascade hyperons decay in the visible region of the chamber, as does the antilambda from the $\Xi^+$ decay.

Table I gives essential information on the event. The figures given are from the first measurement.
Production of $\Lambda\Lambda$ Hypernuclei at PANDA

- $\bar{p}$ beam
- Sandwich target
  - Si-strip
  - Be, B, C absorbers
- Primary $^{12}$C target
- Active secondary target
- Kaons
- 3 GeV/c
- $+28$ MeV
- $\gamma$
PANDA Setup

- $\theta_{\text{lab}} < 45^\circ$: $\Xi^-$, K- trigger (PANDA)
- $\theta_{\text{lab}} = 45^\circ - 90^\circ$: $\Xi$-capture, hypernucleus formation
- $\theta_{\text{lab}} > 90^\circ$: $\gamma$-detection Euroball at backward angles
Spectroscopy of $\Lambda \Lambda$-hypernuclei

E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yamamoto
Phys. Rev. 66 (2002), 024007

- 4-body cluster model for light nuclei
- parameters adjusted to single hypernuclei and one double hypernucleus event (NAGARA)
many excited, particle stable states in double hypernuclei predicted

$\gamma$-spectroscopy of these states is mandatory to study them
Simulation within PANDA_ROOT

Example: secondary $^{12}$C target

A. Sachez, A. Botvina, J.P.

Alicia Sanchez (Mainz)
Simulation within PANDA_ROOT

- Example: secondary $^{12}_C$ target

Alicia Sanchez (Mainz)
Exploring the Potential of Antihyperons in Nuclei
Antihyperons in Nuclei

-2 -1 0 2

\[ \frac{2}{\rho} \]

\[ \rho / \rho_0 \]

\[ W(\text{MeV}) \]

\[ r(\text{fm}) \]

quark picture

NSC97a
NSC97f

NN
\Sigma N
\Sigma \Sigma
\Xi \Sigma
\Xi \Xi
**Elastic Antiproton-Nucleus Scattering**

**Elastic Scattering of Antiprotons from Complex Nuclei**

**Gerson Goldhaber† and Jack Sandweiss‡**

*Physics Department and Radiation Laboratory, University of California, Berkeley, California*

(Received May 5, 1958)

**Table III.** Comparison of experimental data for elastic antiproton-nucleus scattering of energy $T^p = 80$ to 200 Mev with Glassgold's calculations at $T^p = 140$ Mev. (Projected angle $\geq 2^\circ$.)

<table>
<thead>
<tr>
<th>Angular interval (degrees)</th>
<th>Experimental ($T^p = 80$ to 200 Mev)</th>
<th>Number of events</th>
<th>Calculated for potential $V = -15$ Mev</th>
<th>Calculated for potential $V = -528$ Mev</th>
</tr>
</thead>
<tbody>
<tr>
<td>2–6</td>
<td>54</td>
<td>56</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>6–12</td>
<td>20</td>
<td>17.1</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>12–24</td>
<td>5</td>
<td>4.3</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>24–180</td>
<td>1</td>
<td>1.4</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>2–180</td>
<td>80</td>
<td>78.8</td>
<td>114.5</td>
<td></td>
</tr>
</tbody>
</table>
Antiproton production in HI Collisions

- see e.g.
Antiproton production in HI Collisions

see e.g.

\[ p + ^{12}\text{C} \rightarrow \bar{p} + X \text{ at 4.0 GeV} \]

\[ \text{Nucleon} \approx -40\text{MeV} \]
\[ \text{Lambda} \approx -27\text{MeV} \]
\[ \text{Antinucleon} \sim -150\text{MeV} \]
\[ \text{Antilambda} \sim ? \]
Antihyperons stopped in Nuclei
Antihyperons stopped in Nuclei
Antihyperons stopped in Nuclei

before

after
Antihyperons stopped in Nuclei

- antibaryons stopped in nuclei
  \[
  \bar{p} + A \rightarrow \bar{B} A + X
  \]
  - suggested observables
    - “Super-transitions” from Fermi to Dirac sea
      (mono-energetic mesons)
    - Transitions between levels
      of each sea
    - Explosion of compressed nucleus
      after antibaryon annihilation
      A.B. Larionov et al., arXiv:0802.1845v2
    - formation multi-qqbar clusters

- Production mechanism
  - forward ("2"-body) kinematics (c.f. kaonic atoms)
How to measure a potential (difference)

\[ \tilde{p}_Y = \sqrt{p_Y^2 - 2U_Y m_Y} \]

If \( m_Y \approx m_Y \approx m \) and \( U_Y \approx U_Y \approx U \) ⇒

\[ \alpha = \frac{\tilde{p}_Y - \tilde{p}_Y}{\tilde{p}_Y + \tilde{p}_Y} = \frac{\sqrt{p_Y^2 - 2m_Y U_Y} - \sqrt{p_Y^2 - 2m_Y U_Y}}{\sqrt{p_Y^2 - 2m_Y U_Y} + \sqrt{p_Y^2 - 2m_Y U_Y}} \approx \frac{U_Y - U_Y}{4 \left( \frac{p_Y^2}{2m} - U \right)} \approx \frac{U_Y - U_Y}{4E_{kin}} \]
Can we measure the potential for $\bar{Y}$?

- Antiprotons are optimal for the production of mass without large momenta
- $p + \bar{p} \rightarrow Y + \bar{Y}$ close to threshold within a nucleus
- $\Lambda$ and $\bar{\Lambda}$ that leave the nucleus will have different asymptotic momenta depending on the respective potential

- Experimental complications
  - Fermi motion of struck proton
  - Non-isotropic production
  - Density distribution $U(\rho)$
  - Exclusiveness

$\Rightarrow$ need to look at average transverse momentum close to threshold of coincident $Y\bar{Y}$ pairs
For $\bar{p}^\uparrow + ^{12}\text{C}$ data at 1.45, 1.66 and 1.77 GeV/c been analyzed: Stephan Pomp, thesis (1999) priv. com

Only polarization data published so far.
Carbon target only

Stephan Pomp, Tord Johansson

\[ \alpha_T = \frac{p_T^\Lambda - p_T^{\bar{\Lambda}}}{p_T^\Lambda + p_T^{\bar{\Lambda}}} \]

\( a_T = 0 \) for elementary \( \bar{p} + p \rightarrow \Lambda + L \) reaction
- Carbon target only
- Stephan Pomp, Tord Johansson

\[ \alpha_T = \frac{p_T^\Lambda - p_T^{\bar{\Lambda}}}{p_T^\Lambda + p_T^{\bar{\Lambda}}} \]

- \( a_T = 0 \) for elementary \( \bar{p} + p \rightarrow \Lambda + L \) reaction
The good news...

- Calculations are probably not incompatible with available data

\[ S(\bar{\Lambda}) = -200 \text{MeV} \]
\[ V(\Lambda) + S(\bar{\Lambda}) = -400 \text{MeV} \]
\[ -200 \text{MeV} \]
\[ 0 \text{MeV} \]

PS185 preliminary
(not to be quoted)

- carbon
Other hadron-antihadron pairs

\[
\begin{align*}
1.66 \text{ GeV/c} & \quad \bar{p}^{12}\text{C} \rightarrow \Lambda+\bar{\Lambda} \\
2.9 \text{ GeV/c} & \quad \bar{p}^{12}\text{C} \rightarrow \Xi+\bar{\Xi} \\
6.7 \text{ GeV/c} & \quad \bar{p}^{12}\text{C} \rightarrow D^++D^- 
\end{align*}
\]

Required running time for \( da/a = 10\% \):

- \( \Lambda\bar{\Lambda} \): few minutes
- \( \Xi\bar{\Xi} \): several h
- \( D\bar{D} \): several months

at PANDA
Conclusions

Worldwide, several new activities will help to overcome present limitations of this field:

- MAMI, JLAB, structure function
- J-PARC, heavy single hypernuclei
- FINUDA, weak decay
- HypHI, extreme isospin
- FAIR, double hypernuclei, antihyperons