The HypHI project at GSI

Hypernuclear spectroscopy with heavy ion beams

Take R. Saito, for the HypHI collaboration

GSI-Darmstadt
Helmholtz Center for Heavy Ion Research
and
Johannes Gutenberg-Universität Mainz
How much can we extend this landscape?

- Around the \( \beta \)-stability line
  - \((\pi^+, K^+), (K^-, \pi^-), (e, e'K^+)\)
  - BNL, KEK, J-PARC, CEBAF, FINUDA, MAMI C

- Neutron rich hypernuclei
  - \((K^-, \pi^+)\)
  - J-PARC, FINUDA

- Toward hypernuclei at nucleon drip-lines: Hypernuclei at extreme isospins
  - Heavy ion collision
  - JINR, HypHI

The HypHI project, T.R. Saito, HYP2006 Mainz
**Heavy Ion Beams:**
**Powerful Tools for Hypernuclear Spectroscopy**

Relativistic hypernuclei: projectile fragment $\rightarrow$ hypernuclei

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The HypHI project, T.R. Saito, HYP2006 Mainz
How much can we extend this landscape?

Around the $\beta$-stability line
- $(\pi^+, K^+), (K^-, \pi^-), (e, e'K^+)$
- BNL, KEK, J-PARC, CEBAF, FINUDA, MAMI C

Neutron rich hypernuclei
- $(K^-, \pi^+)$
- J-PARC, FINUDA

Toward hypernuclei at nucleon drip-lines: Hypernuclei at extreme isospins
- Heavy ion collision
- JINR, HypHI

Λ-hypernuclear chart

The HypHI project, T.R. Saito, HYP2006 Mainz
Hypernuclear magnetic moments

- **With meson and electron beam induced hypernuclear production**
  - Very small recoil momentum of produced hypernuclei
  - Almost impossible to perform direct measurements of hypernuclear magnetic moments
  - B(M1) measurements with $\gamma$-ray spectroscopy
    - Hyperball-J at J-PARC
    - Contributions from nuclear collective motion have to be subtracted

- **With heavy ion collisions**
  - Hypernuclei at projectile rapidity → relativistic hypernuclei
  - Hypernuclei can be separated by a magnetic spectrometer
  - Precession of hypernuclear spin alignment in magnetic field
    - Perturbed $\pi^-$ asymmetry → magnetic moments
  - Can be performed only at FAIR in near future
The HypHI project

- Hypernuclear spectroscopy with heavy ion beams at GSI/FAIR
- LOI: submitted to the GSI PAC in March 2005
- Approved by Helmholtz Association as Helmholtz-University Young Investigators group at GSI with Mainz University
- A proposal of the Phase 0 experiment
  - Submitted to the GSI PAC
  - To be discussed on October 23rd

- Giessen University, Germany
- GSI (DVEE, KP2, KP3), Germany
- JINR, Dubna, Russia
- Johannes Gutenberg University Mainz, Germany
- KEK, Japan
- Moscow State University, Russia
- Nara Women’s University, Japan
- Niels Bohr Institute, Denmark
- Osaka Electro-Communication University, Japan
- Osaka University, Japan
- Peking University, China
- RIKEN, Japan
- Soltan Institute for Nuclear Studies, Poland
- Tokyo University, Japan
- Tokyo University of Science, Japan
- Tohoku University, Japan
- TRIUMF, Canada

Still expanding ......
Spokesperson : Take R. Saito, GSI
Hypernuclei with Heavy Ion Beams: The HypHI project

- Heavy ion induced reaction at relativistic energies (heavy-ion collision)
  - NN → ΛKN: Energy threshold ~ 1.6 GeV
  - Heavy ion beams with E > 1.6 GeV/u needed
  - Stable heavy ion beam at GSI
  - Stable heavy ion beam at FAIR
  - RI-beam from FRS and super-FRS

- Large Lorentz factor γ (>3)
  - Effective lifetime: Longer by the Lorentz factor
    - 200 ps → 600 ps with γ=3
    - 200 ps → 4 ns with γ=20

- Only a few light hypernuclei so far identified with heavy ion beams at Dubna (³ΛH and ⁴ΛH, ~ 0.2 μb, with ⁴He and ⁷Li beams)
### Heavy Ion Beams: Powerful Tools for Hypernuclear Spectroscopy

- **E > 1.7 A GeV**
- **I > 10^5/s**

#### Chart:

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**FRS Super-FRS**

The HypHI project, T.R. Saito, HYP2006 Mainz
Hypernuclei with Heavy Ion Beams: The HypHI project

- Heavy ion induced reaction at relativistic energies (heavy-ion collision)
  - \( \text{NN} \rightarrow \Lambda KN \): Energy threshold \( \sim 1.6 \text{ GeV} \)
  - Heavy ion beams with \( E > 1.6 \text{ GeV/u} \) needed
  - Stable heavy ion beam at GSI
  - Stable heavy ion beam at FAIR
  - RI-beam from FRS and super-FRS

- Large Lorentz factor \( \gamma (>3) \)
  - Effective lifetime: Longer by the Lorentz factor
    - \( 200 \text{ ps} \rightarrow 600 \text{ ps with } \gamma=3 \)
    - \( 200 \text{ ps} \rightarrow 4 \text{ ns with } \gamma=20 \)

- Only a few light hypernuclei so far identified with heavy ion beams at Dubna (\( ^3\Lambda H \) and \( ^4\Lambda H \), \( \sim 0.2 \mu b \), with \( ^4\text{He} \) and \( ^7\text{Li} \) beams)
Produced hypernucleus at the similar velocity of projectiles

- Large Lorents factor $\gamma > 3$
- 200ps -> 600ps ($\gamma=3$), hypernuclear decay in flight

Example: $^{12}\text{C} + ^{12}\text{C} \rightarrow A_{\Lambda}Z + K^{+,0} + X$

Mesonic weak decay
- $\Lambda \rightarrow \pi^- + p$

Non-mesonic weak-decay
- $\Lambda p \rightarrow np$
Goals of the HypHI project

**Hypernuclear magnetic moments**
- Quark bulding blockes
  - Quark Pauli blocking effect
- $\Lambda/\Sigma$ coupling as functions of isospins
- Kaon currents in the nuclear matter

**Hypernuclei at extreme isospins**
- Cold neutron matter
- $\Lambda/\Sigma$ coupling
Accelerator facility at GSI
The goal of the Phase 0 experiments

To confirm Dubna’s hypernuclear production at 2 A GeV with $^6$Li primary beams: Mesonic decay $\Lambda \rightarrow \pi^- + p$

$^3\Lambda H \rightarrow \pi^- + ^3\text{He}$
$^4\Lambda H \rightarrow \pi^- + ^4\text{He}$
$^5\Lambda \text{He} \rightarrow \pi^- + ^4\text{He} + p$
ALADiN magnet
TOF detectors

- **TOF-start (new development)**
  - Polycrystalline diamond detector
  - High rate: $10^8 \text{/s}$
  - Excellent time resolution: < 15 ps

- **ALADiN TOF wall (existing)**
  - Plastic scintillator bars
  - For negative charged particles (mainly $\pi^-$)
  - Horizontal(x)-vertical(y) tracking

- **TOF+ (new development)**
  - Plastic scintillator bars
  - For positive charged particles
  - $xy$ tracking

- **GSI**
Scintillating fiber arrays

- TR0
  - x and y planes
  - Energy and time readout

- TR1 and TR2
  - x, y and d planes
  - Time readout
  - Used for tracking triggers

Osaka Electro-communication University, Osaka Univ., Mainz Univ., GSI
Trigger design

- **Tracking trigger (K+ and K0 channel)**
  - Two types of vertices
    - One vertex in the target
      - Meson production
      - Fragmentation
    - Vertex out of the target
      - Hypernuclear decay
      - Free-Λ decay
  - FPGA/DSP based trigger module

- Efficiency to 4ΛH events: ~ 14%
  → HypHI poster, S. Minami et al

- GSI, Mainz Univ.
\( \pi^- \) trigger (hypernuclear decay)

- \( \pi^- \) from the target
  - Low momentum
  - Hitting to the side yoke of the ALADiN magnet

- \( \pi^- \) from hypernuclei and free-\( \Lambda \) at projectile rapidity region
  - Lorentz boosted at \( \gamma \approx 3 \)
  - Larger momentum
  - Observed by the ALADiN TOF

**Efficiency**
- 28 % for \( ^4 \Lambda H \) events

\( \rightarrow \) HypHI poster, S. Minami et al
Z=2 trigger by TOF+

Z=2 particles from the hypernuclear decay

- $^3\Lambda H \rightarrow ^3He + \pi^-$
- $^4\Lambda H \rightarrow ^4He + \pi^-$
- $^5\Lambda He \rightarrow ^4He + p + \pi^-$

By TOF+

Efficiency

- 95% for $^4\Lambda H$ events

→ HypHI poster, S. Minami et al
### Estimates

<table>
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<th>Expected cross section [μb]</th>
<th>Reconstructed events /week</th>
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<tr>
<td>$^3\Lambda H$</td>
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<tr>
<td>$^4\Lambda H$</td>
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<tr>
<td>$^5\Lambda He$</td>
<td>0.5</td>
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- **Beam:** $^6\text{Li}$, $10^7$ /s, 2 A GeV
- **Target:** $^{12}\text{C}$, 8 g/cm$^2$

- **Trigger efficiency with tracking + $\pi^-$ + Z=2:** 7 %
- **Trigger rate:** ~ 340 Hz

- **Additional detectors considered**
  - $K^+$ detector: Osaka Univ.
  - Drift chambers: GSI, KEK

- **Proposal:** submitted to the GSI PAC
- **Experiment:** beginning of 2008

- **What to be measured:**
  - Cross section
  - Lifetime
  - Polarization
  - Forward correlation between $\Lambda$ and other charged particles
HypHI Project at GSI/FAIR

- HypHI project started 2004
- LOI and progress report to the GSI PAC, Design study 2005
- Design study, preparation for the phase 0 experiment 2006
- Phase 0: experiment with $^3\Lambda H$, $^4\Lambda H$ and $^5\Lambda He$ 2007
- Design study for the setup for hypenuclear non-mesonic weak decay measurements 2008
- Phase 1: Experiments for proton-rich hypernuclei 2009
- Phase 2: Experiment for neutron-rich hypernuclei at R3B/NuSTAR/FAIR ~2011
- Phase 3: Hypernuclear separator
  - Hypernuclear magnetic moments
  - Hypernuclear drip-lines

The HypHI project, T.R. Saito, HYP2006 Mainz
### HypHI Project at GSI/FAIR

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<tr>
<th>Event</th>
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<tr>
<td>HypHI project started</td>
<td>2004</td>
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<tr>
<td>LOI and progress report to the GSI PAC, Design study</td>
<td>2005</td>
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<tr>
<td>Design study, preparation for the phase 0 experiment</td>
<td>2006</td>
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<tr>
<td>Phase 0: experiment with $^3\Lambda$H, $^4\Lambda$H and $^5\Lambda$He</td>
<td>2007</td>
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<td>Phase 1: Experiments for proton-rich hypernuclei</td>
<td>2009</td>
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<tr>
<td>Phase 2: Experiment for neutron-rich hypernuclei at R3B/NuSTAR/FAIR</td>
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<td>Phase 3: Hypernuclear separator</td>
<td>~2011</td>
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  - Hypernuclear magnetic moments
  - Hypernuclear drip-lines

The HypHI project, T.R. Saito, HYP2006 Mainz
The HypHI project started in 2004.

- LOI and progress report to the GSI PAC, Design study in 2005.
- Design study, preparation for the phase 0 experiment in 2006.
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- Phase 1: Experiments for proton-rich hypernuclei in 2009.
- Phase 2: Experiment for neutron-rich hypernuclei at R3B/NuSTAR/FAIR in ~2011.
- Phase 3: Hypernuclear separator with Hypernuclear magnetic moments and Hypernuclear drip-lines.

The HypHI project, T.R. Saito, HYP2006 Mainz.
The HypHI project started in 2004. LOI and progress report to the GSI PAC, Design study were conducted in 2005. Design study, preparation for the phase 0 experiment was done in 2006. Phase 0: experiment with $^3\Lambda$H, $^4\Lambda$H and $^5\Lambda$He took place in 2007. Design study for the setup for hypenuclear non-mesonic weak decay measurements occurred in 2008. Phase 1: Experiments for proton-rich hypernuclei were conducted in 2009. Phase 2: Experiment for neutron-rich hypernuclei at R3B/NuSTAR/FAIR is planned for ~2011. Phase 3: Hypernuclear separator includes hypernuclear magnetic moments and hypernuclear drip-lines.
HypHI Project at GSI/FAIR

- HypHI project started: 2004
- LOI and progress report to the GSI PAC, Design study: 2005
- Design study, preparation for the phase 0 experiment: 2006
- Phase 0: experiment with $^3\Lambda\text{H}$, $^4\Lambda\text{H}$ and $^5\Lambda\text{He}$: 2007
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- Hypernuclear magnetic moments
- Hypernuclear drip-lines

The HypHI project, T.R. Saito, HYP2006 Mainz
International Hypernuclear Network

PANDA at FAIR
- 2012~
- Anti-proton beam
- Double $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy

MAMI C
- 2007~
- Electro-production
- Single $\Lambda$-hypernuclei
- $\Lambda$-wavefunction

FINUDA at DAΦNE
- $e^+e^-$ collider
- Stopped-$K^-$ reaction
- Single $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy (2012~)

HypHI at GSI/FAIR
- Heavy ion beams
- Single $\Lambda$-hypernuclei
- Single $\Lambda$-hypernuclei at extreme isospins
- Magnetic moments

SPHERE at JINR
- Heavy ion beams
- Single $\Lambda$-hypernuclei

JLab
- 2006~
- Electro-production
- Single $\Lambda$-hypernuclei
- $\Lambda$-wavefunction

J-PARC
- 2009~
- Intense $K^-$ beam
- Single and double $\Lambda$-hypernuclei
- $\gamma$-ray spectroscopy for single $\Lambda$

The HypHI project, T.R. Saito, HYP2006 Mainz
Backup slides
Trigger design

- Tracking trigger (K\(^+\) and K\(0\) channel)
  - Two types of vertices
    - One vertex in the target
      - Meson production
      - Fragmentation
    - Vertex out of the target
      - Hypernuclear decay
      - Free-\(\Lambda\) decay
  - FPGA/DSP based trigger module

- Efficiency to \(4_\Lambda\)H events: \(\sim 14\%\)
Tracking trigger

Made with scintillating fiber trackers
- Secondary vertex behind the target
- Hypernuclear/Λ decay

PMT

Discriminator card with GSI chip-3

LVDS

VME Logic module with FPGA and DSP

VME Logic module with FPGA and DSP

VME Logic module with FPGA and DSP

Tracking trigger

New development at GSI

500 MHz

7 to VME bus
Phase 0 of HypHI

The goal of the Phase 0 experiments

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$^3\Lambda H \to \pi^- + ^3\text{He}$

$^4\Lambda H \to \pi^- + ^4\text{He}$

$^5\Lambda \text{He} \to \pi^- + ^4\text{He} + p$
Improved setup for phase 0

Positive charged particles: p, d, t, $^3$He, $^4$He, $^6$Li

Negative charged particles: $\pi^-$
Expanding field

FINUDA at Frascati

- De Mori

J-PARC

- Noumi, Tamura, Fukuda, Nakazawa, Hiyama,

PANDA at FAIR/GSI

- Motoba, Gariaaldi, Tedeschi, Tang, Tang, Hahimoto, Song

Kaos at MAMI C

The HypHI project, T.R. Saito, HYP2006 Mainz
Difficulties on these experiments

- Direct measurements on hypernuclear magnetic moments
  - Quark building blocks (Quark Pauli effect and so on)
  - $\Lambda/\Sigma$ coupling
  - Kaon currents in nuclei
- Hypernuclei away from the $\beta$-stability line (at extreme isospins), especially for heavy hypernuclei
  - Isospin dependence on the hyperon wavefunction
  - $\Lambda N$ interactions
  - Very neutron rich hypernuclei (cold neutron matter)
  - Very proton rich hypernuclei

Heavy ion induced hypernuclear spectroscopy
Why hypernuclei

Baryon-baryon interaction

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>n (udd)</th>
<th>p (uud)</th>
<th>Λ (uds)</th>
<th>Σ (uds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>N.R.</td>
<td>N.R.</td>
<td>S.H.</td>
<td>S.H.</td>
</tr>
<tr>
<td>p</td>
<td>N.R.</td>
<td>S.H.</td>
<td>S.H.</td>
<td>S.H.</td>
</tr>
</tbody>
</table>

N.R. : Nuclear reaction
S.H. : Single-s Hypernuclei
D.H. : Double-s Hypernuclei

Baryons in the core of neutron stars

τ ~ 10^{-10} s

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Essential to study baryon-baryon interaction under SU(3)$_f$
- 40/64 vertices can be studied with hypernuclei
S=-1 sector

Only 37 $\Lambda$-hypernuclei identified

$\Lambda$ Hypernuclear Chart (2004)

Spectroscopic studies by

$(K,\pi)$  $(\pi^+,K^+)$  $(K_{\text{stop}},\pi^+)$  $(e,e'\pi^+)$  $(K_{\text{stop}},\pi^0)$  $(\pi,K^+)$

\[\gamma\text{ spectroscopy} \quad \text{emulsion data}\]
New VME logic module

- Purely VME based
- 256 channels I/O
  - LVDS
- Fast logic calculations with a large FPGA at 500 MHz
- Slow complicated calculations by DSP
- Data transfer to the VME bus

Modules will also be used by the MAMI C KaoS experiments
FAIR: a future facility of GSI

China is an associated member of FAIR!!
Hypernuclear separator (Phase 3)

- Hypernuclear production at 20 A GeV at the FAIR facility
- Hypernuclei separated by a superconducting magnet

- Hypernuclear magnetic moments
- Hypernuclei toward the nucleon drip-lines
Hypernuclear separator (Phase 3)

- Hypernuclear production at 20 A GeV at the FAIR facility
- Hypernuclei separated by a superconducting magnet

Hypernuclear production at 20 A GeV. Carbon or diamond target, 12g/cm².
Hypernuclear separator (Phase 3)

- Hypernuclear production at 20 A GeV at the FAIR facility
- Hypernuclei separated by a superconducting magnet

4m long superconducting magnet.
Separation of hypernuclei with the collimator.

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Hypernuclear separator (Phase 3)

- Separation by the 4m 5T magnet

\[ ^6\text{Li} + ^{12}\text{C} \text{ at } 20 \text{ A GeV} \]

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Hypernuclear separator (Phase 3)

- Hypernuclear production at 20 A GeV at the FAIR facility
- Hypernuclei separated by a superconducting magnet

Removing light hadrons from the hypernuclear decay before the sweeping magnet.

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Hypernuclear separator (Phase 3)

- Hypernuclear production at 20 A GeV at the FAIR facility
- Hypernuclei separated by a superconducting magnet

Hypernuclear events reconstruction tagged by mesonic and non-mesonic weak decay
Hypernuclear separator (Phase 3)

- Hypernuclear production at 20 \( \text{A GeV} \) at the FAIR facility
- Hypernuclei separated by a superconducting magnet

Precession of the spin distribution of hypernuclei.
Precession angle:
- 225 degrees with free-\( \Lambda \) magnetic moment
- 205 degrees with 8.8% reduction due to the kaon exchanging current
Hypernuclear separator (Phase 3)

- Hypernuclear production at 20 A GeV at the FAIR facility
- Hypernuclei separated by a superconducting magnet

Asymmetric pionic hypernuclear decay
Almost 4 \( \pi \) sr solid angle

Precession of the spin distribution of hypernuclei.
Precession angle:
- 225 degrees with free-\( \Lambda \) magnetic moment
- 205 degrees with 8.8% reduction due to the kaon exchanging current

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## Rate estimate with the hypernuclear separator (Phase 3)

- Beam intensity: $10^{10}$/s at 20 A GeV
- Target: $^{12}$C, 12 g/cm$^2$
- Reconstruction efficiency in the decay region: 10%

<table>
<thead>
<tr>
<th>Project order</th>
<th>Hypernucleus</th>
<th>Reaction</th>
<th>Expected cross section [nb]</th>
<th>Expected rate [/week]</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1</td>
<td>$^5_\Lambda$He</td>
<td>$^6$Li$^{+12}$C</td>
<td>$\sim$100</td>
<td>$\sim 2 \times 10^5$</td>
<td>Magnetic moment</td>
</tr>
<tr>
<td># 2</td>
<td>$^7_\Lambda$He</td>
<td>$^9$Be$^{+12}$C</td>
<td>$\sim$10</td>
<td>$\sim 2 \times 10^4$</td>
<td>Magnetic moment</td>
</tr>
<tr>
<td># 3</td>
<td>$^6_\Lambda$Be</td>
<td>$^9$Be$^{+12}$C</td>
<td>$\sim$10</td>
<td>$\sim 2 \times 10^4$</td>
<td>Production, magnetic moment</td>
</tr>
<tr>
<td># 4</td>
<td>$^5_\Lambda$Be</td>
<td>$^9$Be$^{+12}$C</td>
<td>$\sim$1</td>
<td>$\sim 2 \times 10^3$</td>
<td>Production, magnetic moment</td>
</tr>
<tr>
<td># 5</td>
<td>$^5_\Lambda$H</td>
<td>$^9$Be$^{+12}$C</td>
<td>$\sim$10.0</td>
<td>$\sim 2 \times 10^4$</td>
<td>Production</td>
</tr>
<tr>
<td># 6</td>
<td>$^6_\Lambda$H</td>
<td>$^9$Be$^{+12}$C</td>
<td>$\sim$10.0</td>
<td>$\sim 2 \times 10^4$</td>
<td>Production</td>
</tr>
<tr>
<td># 7</td>
<td>$^9_\Lambda$He</td>
<td>$^{18}$O$^{+12}$C</td>
<td>$\sim$0.1</td>
<td>$\sim 2 \times 10^2$</td>
<td>Production</td>
</tr>
<tr>
<td># 8</td>
<td>$^{10}_\Lambda$He</td>
<td>$^{18}$O$^{+12}$C</td>
<td>$\sim$0.01</td>
<td>$\sim 2 \times 10^1$</td>
<td>Production</td>
</tr>
<tr>
<td># 9</td>
<td>$^{12}_\Lambda$Li</td>
<td>$^{18}$O$^{+12}$C</td>
<td>$\sim$0.01</td>
<td>$\sim 2 \times 10^1$</td>
<td>Production</td>
</tr>
<tr>
<td># 10</td>
<td>$^{13}_\Lambda$Li</td>
<td>$^{18}$O$^{+12}$C</td>
<td>$\sim$0.001</td>
<td>$\sim 2 \times 10^9$</td>
<td>Production</td>
</tr>
<tr>
<td># 11</td>
<td>$^8_\Lambda$C</td>
<td>$^{18}$O$^{+12}$C</td>
<td>$\sim$0.1</td>
<td>$\sim 2 \times 10^2$</td>
<td>Production</td>
</tr>
<tr>
<td># 12</td>
<td>$^7_\Lambda$C</td>
<td>$^{18}$O$^{+12}$C</td>
<td>$\sim$0.01</td>
<td>$\sim 2 \times 10^1$</td>
<td>Production</td>
</tr>
</tbody>
</table>