FUTURE UPDATES AND HYPERNUCLEI PRODUCTION AT THE PUMA EXPERIMENTAL SETUP

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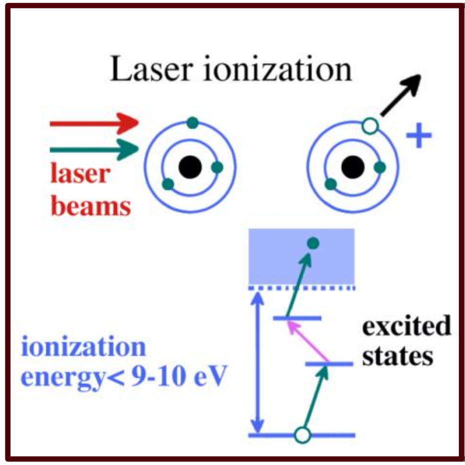
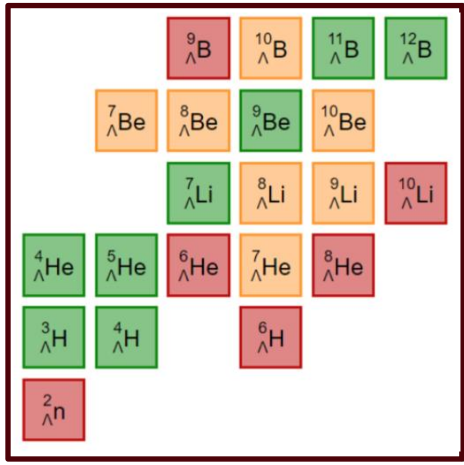
for the PUMA Collaboration
09.04.2024

INTRODUCTION



Upgrade 1

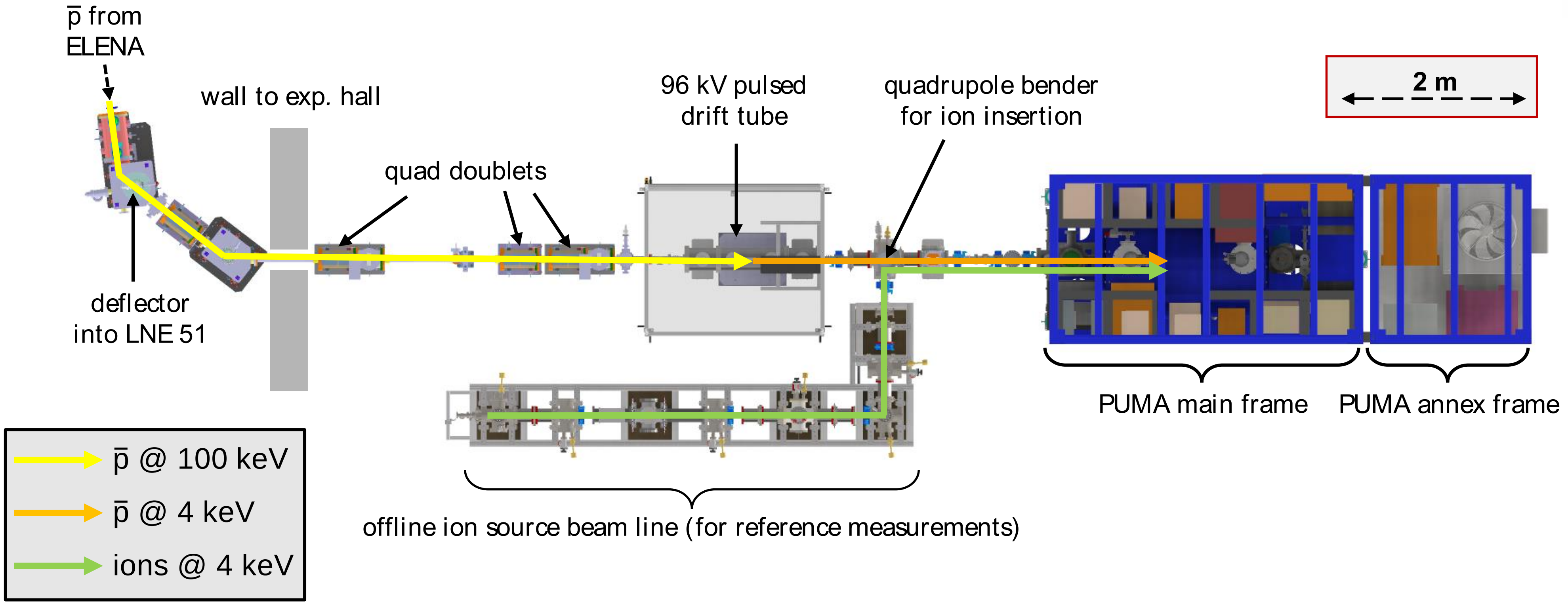
- Upgrade ion source setup with laser ablation source
- Enable ionization and *investigation of metal ions*



Upgrade 2

- Modify trap infrastructure with new detection system
- Use antiprotonic atoms to *produce new hypernuclei*

INTRODUCTION



$\bar{p}$ from ELENA

wall to exp. hall

quad doublets

96 kV pulsed drift tube

quadrupole bender for ion insertion

2 m

deflector into LNE 51

PUMA main frame

PUMA annex frame

offline ion source beam line (for reference measurements)

$\bar{p}$ @ 100 keV

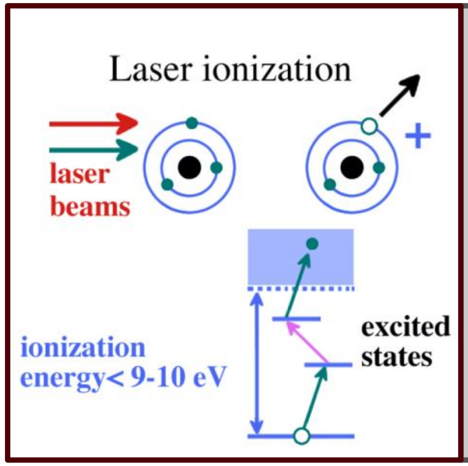
$\bar{p}$ @ 4 keV

ions @ 4 keV

experimental campaign 2024 / 2025

- Characterization of detection system: $p,\ d$
- Study final state interactions with nucleon number: $^{4}He,\ ^{16}O,\ ^{20}Ne,\ ^{40}Ar,\ ^{132}Xe$
- Investigate isospin dependence along isotopic chains: $^{78-86}Kr,\ ^{124-136}Xe$

UPGRADE 1



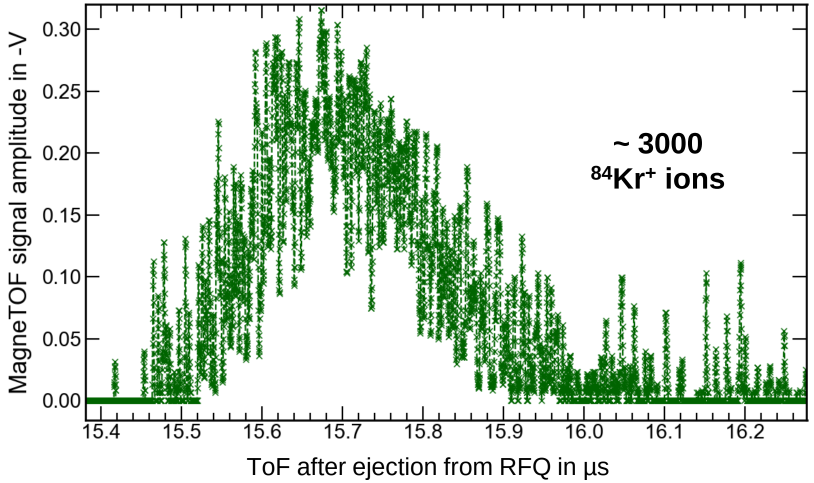
Upgrade 1

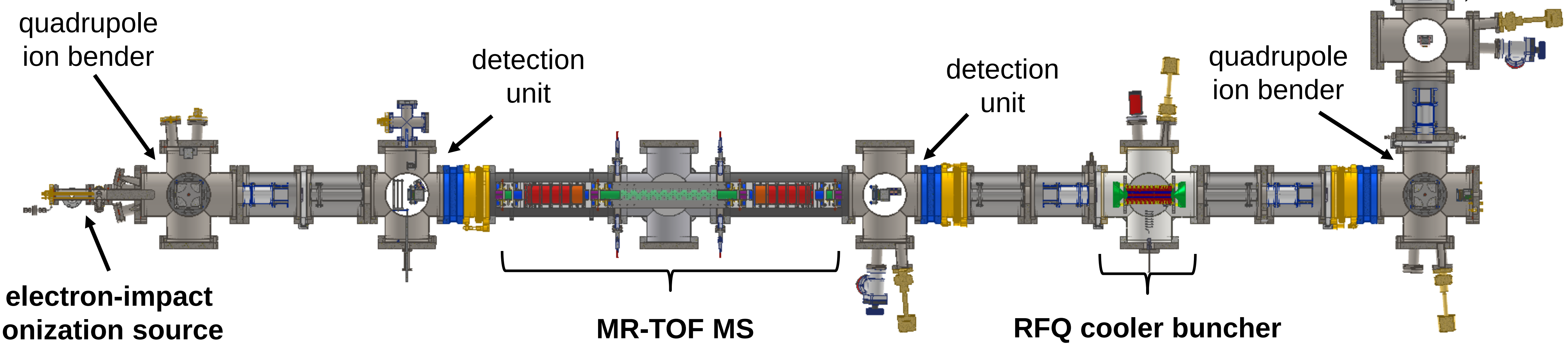
- Upgrade ion source setup with laser ablation source
- Enable ionization and *investigation of metal ions*

LASER ABLATION SOURCE – INTRODUCTION

PUMA ion source setup

- Produces isotopically pure ion bunches
- Provides up to 10^4 ions / bunch
- Current setup lacks versatility
  - → *Metal ions <u>cannot</u> be produced*





detection unit

quadrupole ion bender

detection unit

detection unit

quadrupole ion bender

electron-impact ionization source

MR-TOF MS

RFQ cooler buncher

LASER ABLATION SOURCE – MOTIVATION

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\cdot\delta^2 + \cdots$$

- Equation of state (EoS) of infinite nuclear matter:

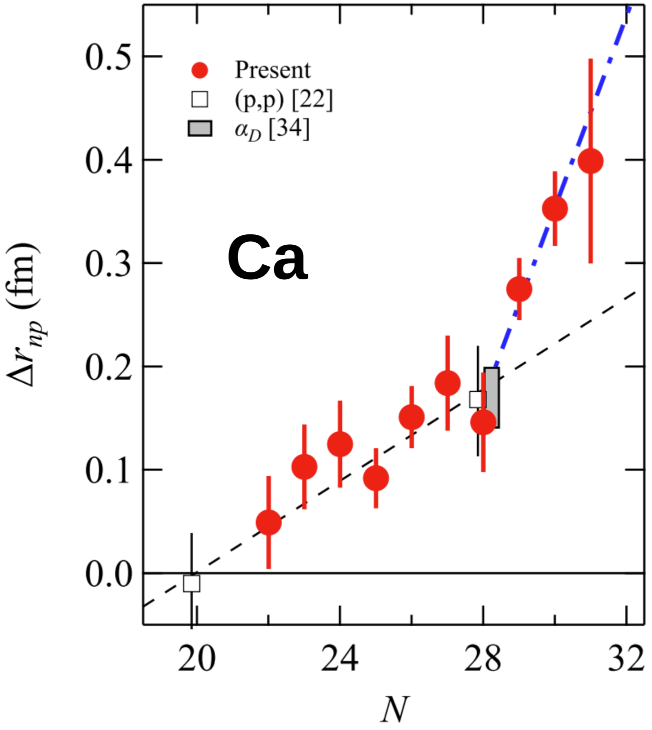
  with $S(\rho) = S(\rho_0) + \boldsymbol{L}\cdot\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \ \ldots$

  and $\rho = \rho_n + \rho_p\,,\quad \delta = \rho_n - \rho_p$

- Neutron skin thickness correlated with slope parameter ***L*** of EoS
- Medium-mass closed shell nuclei with neutron excess ideal to study neutron skins

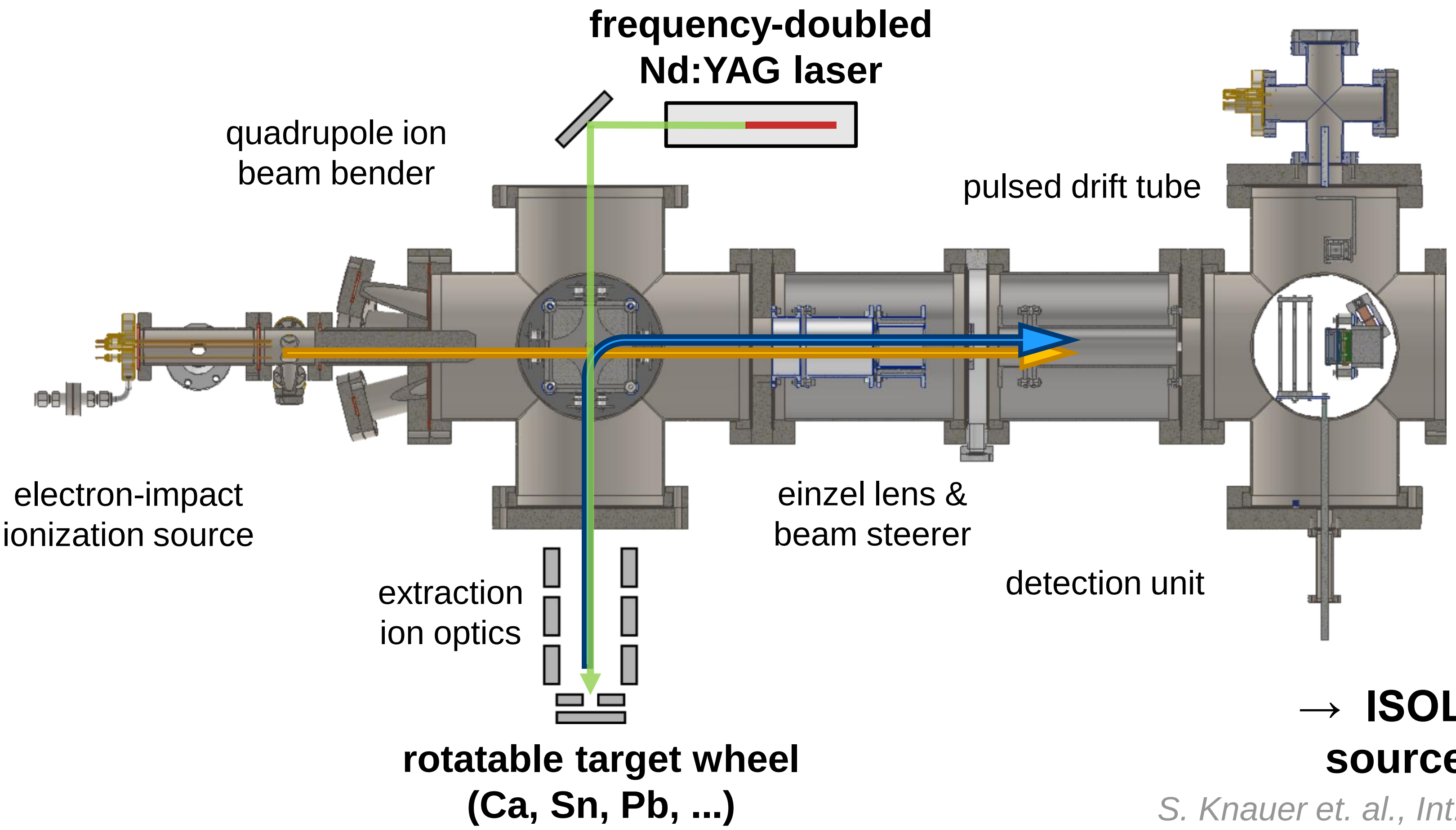
  → ***^{48}Ca, ^{208}Pb***
- Study proton-closed shell isotopic chains

  → ***$^{40\text{-}48}$Ca, $^{112\text{-}124}$Sn***



M. Tanaka et. al., *PRL* **124**, 102501 (2020)

LASER ABLATION SOURCE



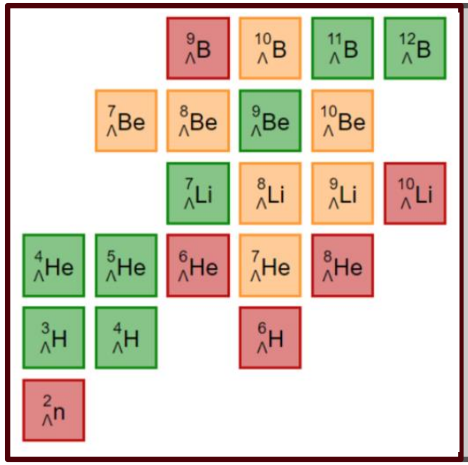
laser properties

- 532 nm wavelength
- 10 Hz repetition rate
- 330 mJ per pulse
- 1 mm² spot size

→ **ISOLTRAP's laser-ablation source serves as reference**

S. Knauer et. al., Int. J. Mass Spectrom. ***446****, 116189 (2019)*

UPGRADE 2



		🟥 ${}^{9}_{\Lambda}\mathrm{B}$	🟧 ${}^{10}_{\Lambda}\mathrm{B}$	🟩 ${}^{11}_{\Lambda}\mathrm{B}$	🟩 ${}^{12}_{\Lambda}\mathrm{B}$
	🟧 ${}^{7}_{\Lambda}\mathrm{Be}$	🟧 ${}^{8}_{\Lambda}\mathrm{Be}$	🟩 ${}^{9}_{\Lambda}\mathrm{Be}$	🟧 ${}^{10}_{\Lambda}\mathrm{Be}$	
		🟩 ${}^{7}_{\Lambda}\mathrm{Li}$	🟧 ${}^{8}_{\Lambda}\mathrm{Li}$	🟧 ${}^{9}_{\Lambda}\mathrm{Li}$	🟥 ${}^{10}_{\Lambda}\mathrm{Li}$
🟩 ${}^{4}_{\Lambda}\mathrm{He}$	🟩 ${}^{5}_{\Lambda}\mathrm{He}$	🟥 ${}^{6}_{\Lambda}\mathrm{He}$	🟧 ${}^{7}_{\Lambda}\mathrm{He}$	🟥 ${}^{8}_{\Lambda}\mathrm{He}$	
🟩 ${}^{3}_{\Lambda}\mathrm{H}$	🟩 ${}^{4}_{\Lambda}\mathrm{H}$		🟥 ${}^{6}_{\Lambda}\mathrm{H}$		
🟥 ${}^{2}_{\Lambda}\mathrm{n}$					

Upgrade 2

- Modify trap infrastructure with new detection system
- Use antiprotonic atoms to *produce new hypernuclei*

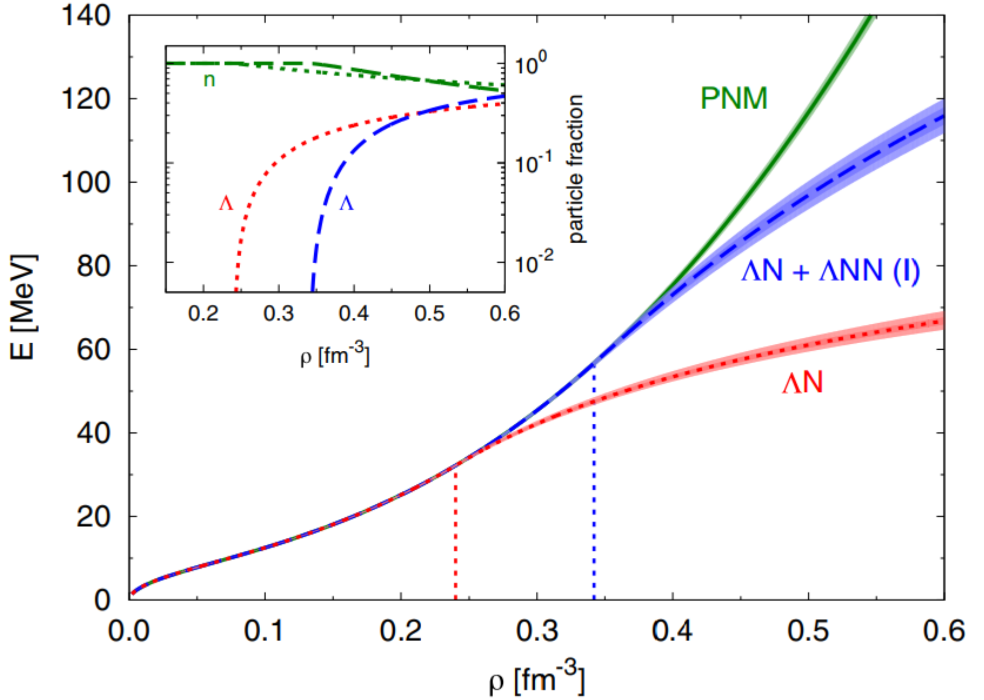
HYPERNUCLEI – MOTIVATION

- Strangeness in modern nuclear physics largely unexplored
  - → *~ 500,000 bound Λ hypernuclei (Λ<70, Z<120) predicted*

    E. Khan et al., Phys. Rev. C 92, 044313 (2015)

    but only ~ 40 observed so far
- How does strangeness content evolve with baryonic density?
  - → *Investigate influence on the nuclear EoS?*
- Increase experimental activities involving hypernuclei

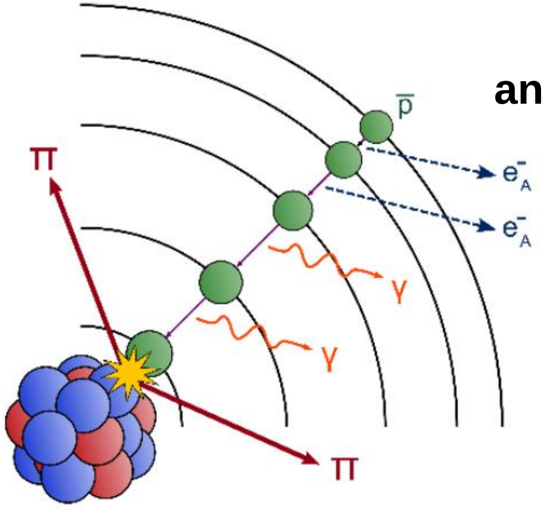
- Antiprotonic atoms as a tool for hypernuclei production
  - → *Use PUMA infrastructure*
  - → *Redesign trap and detection system*



D. Lonardoni et al., *Phys. Rev. Lett.* **114**, 092301 (2015)

HYPERNUCLEI – PRODUCTION MECHANISM

- Antiprotonic atom formed with target nucleus
- Meson emission after annihilation (dominated by pions)
- Kaons emitted in ~ 5% of all annihilations
- Strangeness production allows formation of Λ particles



antiprotonic atom

Courtesy A. Schmidt

two routes for hyperon generation

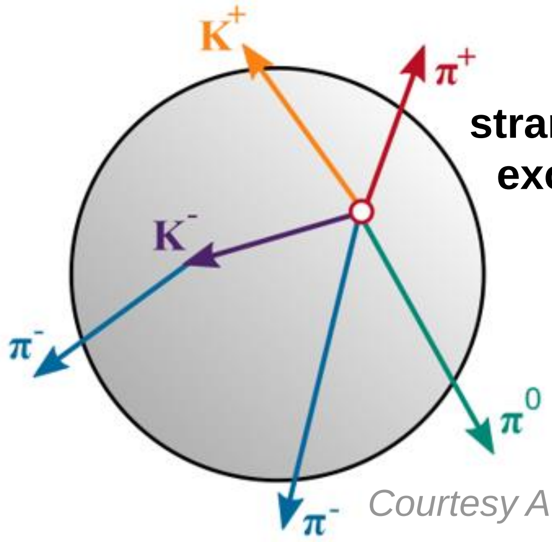
- Final state interactions of K^- or K^0 with nucleons

  $K^- n \to \Lambda \pi^-, K^- p \to \Lambda \pi^0$

  → *Strangeness exchange*
- Final state interactions of pions with nucleons

  $\pi n \to \Lambda K \pi, \pi p \to \Lambda K \pi$

  → *Strangeness pair production*

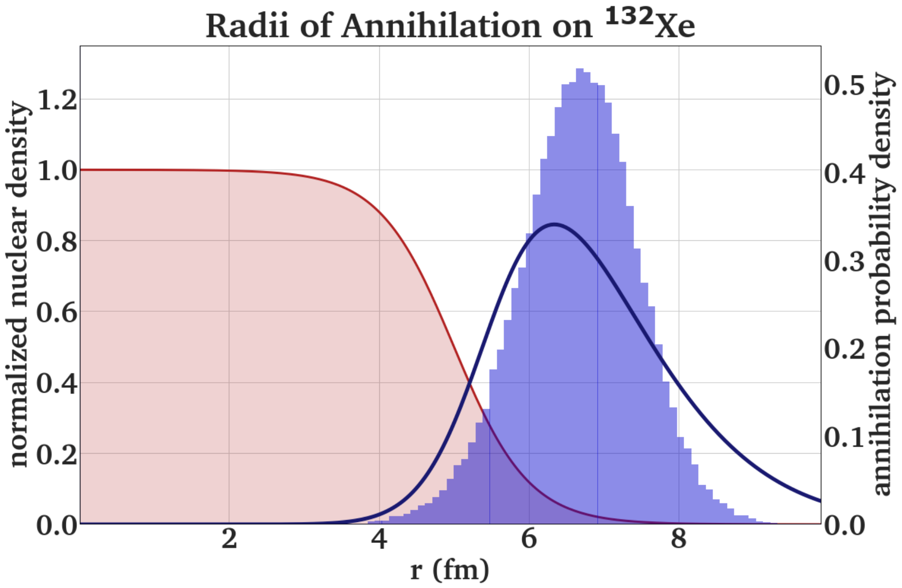


strangeness exchange

Courtesy A. Schmidt

HYPERNUCLEI – SIMULATIONS

- **1. STEP**: Simulation with GiBUU (Gießen Boltzmann-Uehling-Uhlenbeck) code
  - → Antiprotons (E_{kin} = 10 eV) collide with nucleus at rest
  - → Annihilation profile obtained from data on antiprotonic atoms
  - → Propagation of annihilation products & interaction with residual nucleus → Λ production
  - → Definition of excited hypernuclei based on phase space coalescence: $\rho_B > 0.01\ \rho_0$



A. Schmidt et al., Eur. *Phys. J. A* **60**, 55 (2024)

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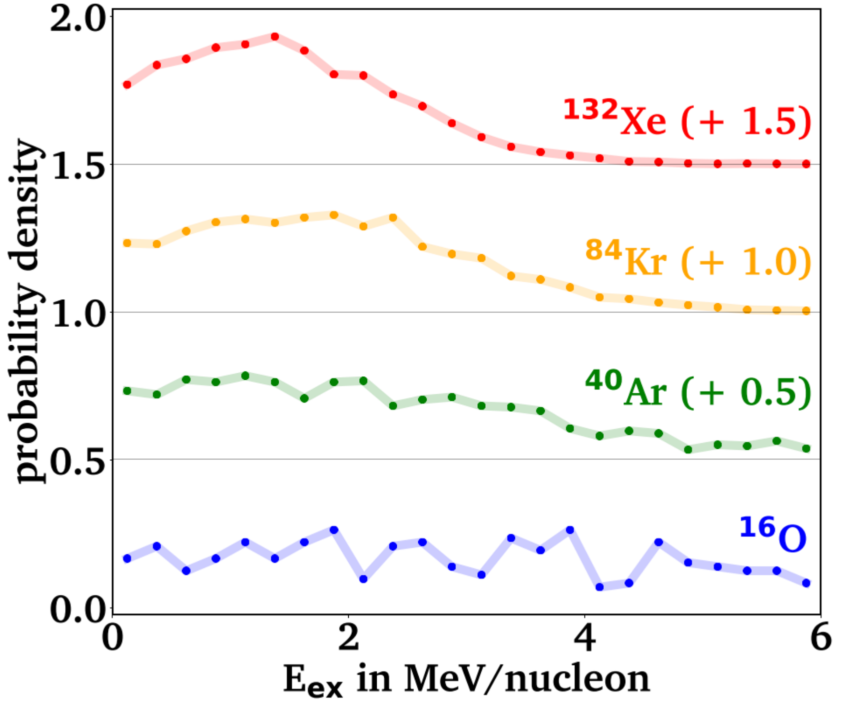


A. Schmidt et al., Eur. *Phys. J. A* **60**, 55 (2024)

- **2. STEP**: Deexcitation of hypernuclei simulated in ABLA++
  - → Typical excitation energies: 0 – 6 MeV / nucleon
  - → Deexcitation via fisson or evaporation of n, p, light particles
  - → Derivation of yields of different hypernuclei

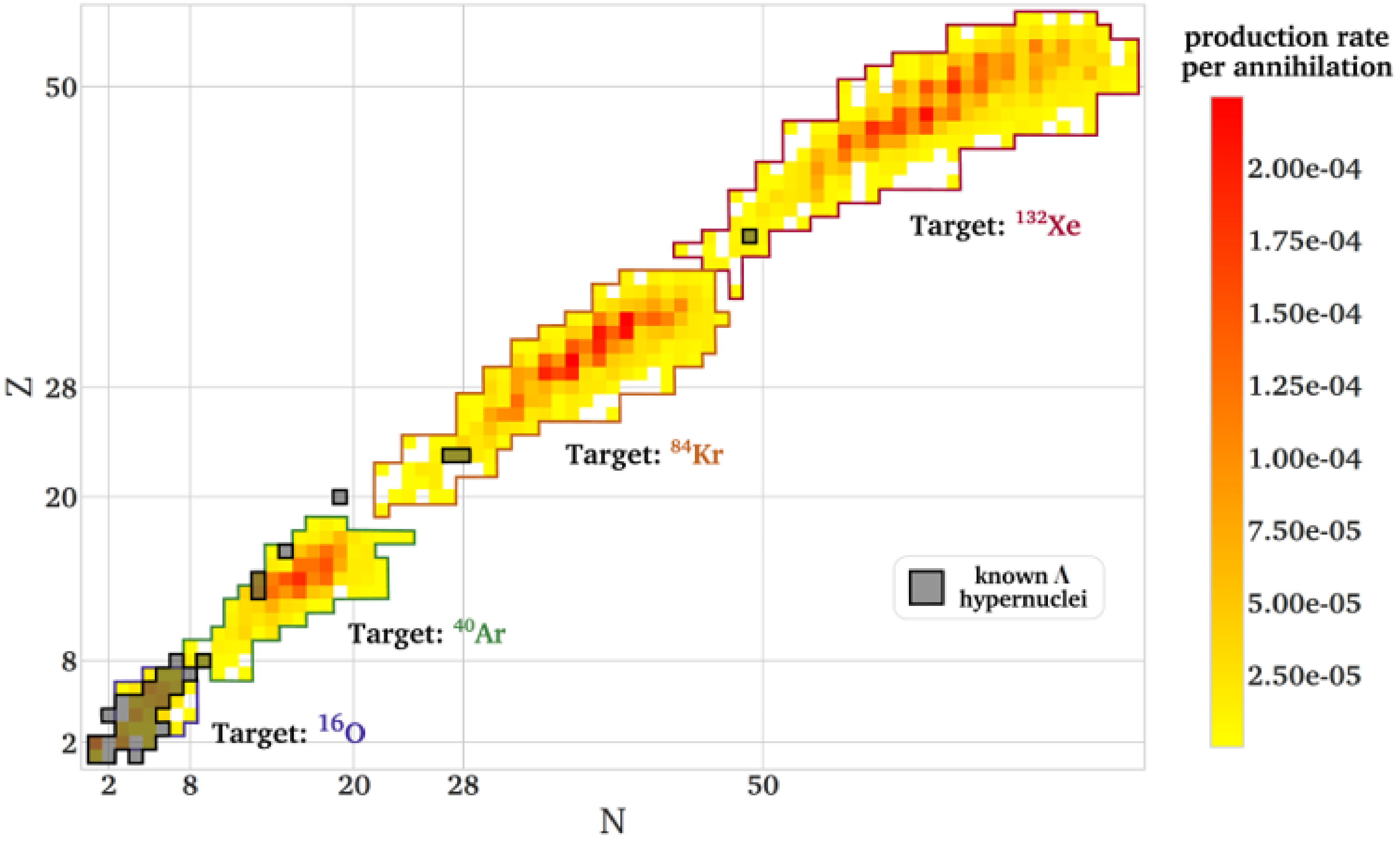
HYPERNUCLEI – PRODUCTION RATES

production rate per annihilation

^{16}O		^{40}Ar	
nucleus	p in 10^{-5}	nucleus	p in 10^{-5}
${}^{10}_{\Lambda}\mathrm{B}$	9 ± 2	${}^{29}_{\Lambda}\mathrm{Al}$	19 ± 3
${}^{7}_{\Lambda}\mathrm{Li}$	8 ± 2	${}^{32}_{\Lambda}\mathrm{Si}$	15 ± 3
${}^{10}_{\Lambda}\mathrm{Be}$	7 ± 2	${}^{28}_{\Lambda}\mathrm{Al}$	15 ± 3
${}^{11}_{\Lambda}\mathrm{B}$	6 ± 2	${}^{31}_{\Lambda}\mathrm{Al}$	13 ± 2
${}^{9}_{\Lambda}\mathrm{Be}$	5 ± 2	${}^{28}_{\Lambda}\mathrm{Mg}$	13 ± 2

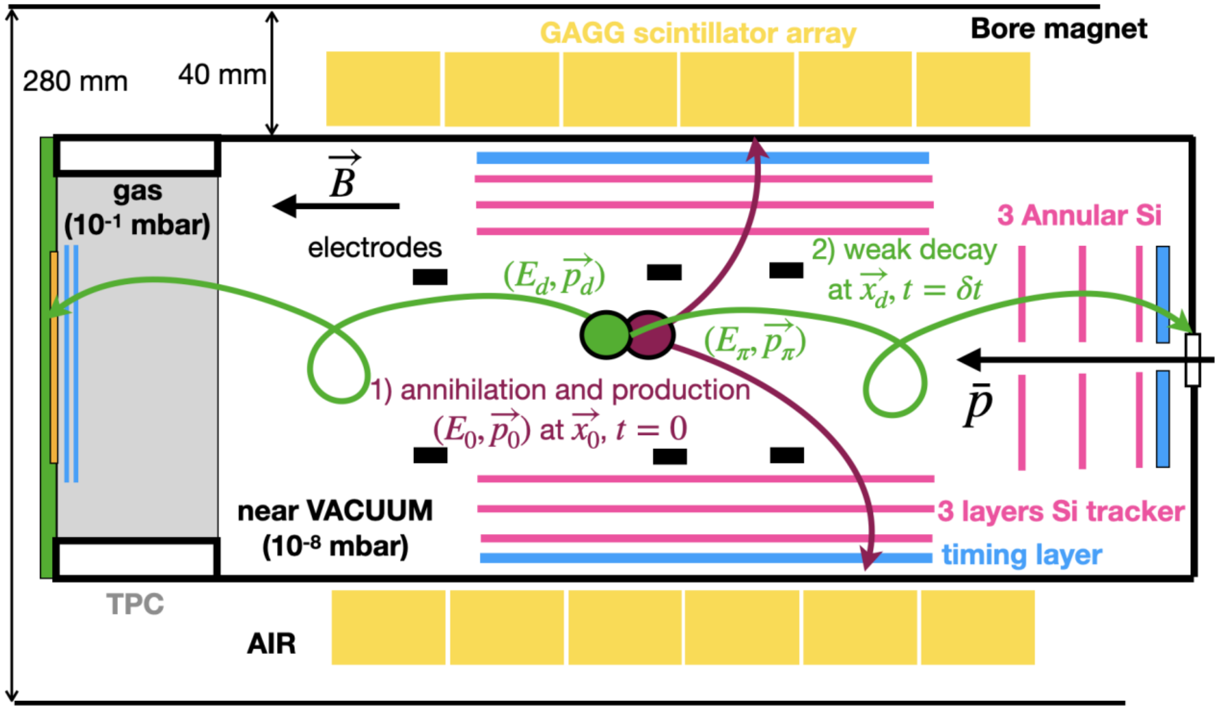
^{84}Kr		^{132}Xe	
nucleus	p in 10^{-5}	nucleus	p in 10^{-5}
${}^{65}_{\Lambda}\mathrm{Cu}$	28 ± 3	${}^{109}_{\Lambda}\mathrm{Ag}$	21 ± 3
${}^{72}_{\Lambda}\mathrm{Ge}$	24 ± 3	${}^{113}_{\Lambda}\mathrm{In}$	19 ± 3
${}^{71}_{\Lambda}\mathrm{Ga}$	21 ± 3	${}^{104}_{\Lambda}\mathrm{Pd}$	18 ± 3
${}^{69}_{\Lambda}\mathrm{Ga}$	20 ± 3	${}^{106}_{\Lambda}\mathrm{Pd}$	16 ± 3
${}^{62}_{\Lambda}\mathrm{Ni}$	19 ± 3	${}^{107}_{\Lambda}\mathrm{Ag}$	16 ± 3

A. Schmidt et al., Eur. *Phys. J. A* **60**, 55 (2024)



A. Schmidt et al., Eur. *Phys. J. A* **60**, 55 (2024)

HYPERNUCLEI – EXPERIMENTAL SETUP



Courtesy A. Obertelli

- Antiprotons decelerated to 50-80 keV with PDT and focused onto separation window (~ 10 mm)
- Antiprotons trapped in Penning trap to form antiprotonic atoms with target gas atoms
- Tune annihilation rate with target gas pressure
  - → *Approx. 10^{-8} mbar*
- Hypernuclei production tagged by time difference between annihilation and weak decay (~ 200 ps)

Residual nucleus identification → *TPC*
Weak decay pion identification → *silicon trackers*
Hypernuclei identification → *invariant mass method*

determine invariant mass of hypernucleus

$$M_Y^2 = m_\pi^2 + M^2 + 2\sqrt{m_\pi^2 + p_\pi^2 c^2}\sqrt{M^2 + p_r^2 c^2} - 2\vec{p_\pi} \cdot 2\vec{p_r}$$

HYPERNUCLEI – EFFICIENCY ESTIMATION

- Antiprotons per bunch: $N_{\bar{\mathrm{p}}} = 3 \cdot 10^6$ (every two minutes)
- Number of bunches: $N_{\mathrm{spill}} = 7800$ (15 days beam time)
- Trapping efficiency: $x_{\mathrm{cap}} = 30\,\%$ (conservative assumption)
- Y production rate: $f({}_{\Lambda}Y) = 0.01\,\%$ (based on simulations)
- Annihilation detection efficiency: $\epsilon_{\mathrm{a}} = 78\,\%$ (based on simulations)
- Mesonic decay branching ratio: $BR = 5\,\%$ (unfavorable case)
- Recoil fragment reaching TPC: $\epsilon_{\mathrm{f}} = 50\,\%$ (geometrical acceptance)
- Weak-decay-event timing selection: $\epsilon_{\omega} = 50\,\%$ (conservative assumption)
- Recoil fragment entering TPC: $\epsilon_{\mathrm{TPC}} = 60\,\%$ (conservative assumption)
- Tracking & identification efficiency: $\epsilon_{\mathrm{track}} = 60\,\%$ (conservative assumption)

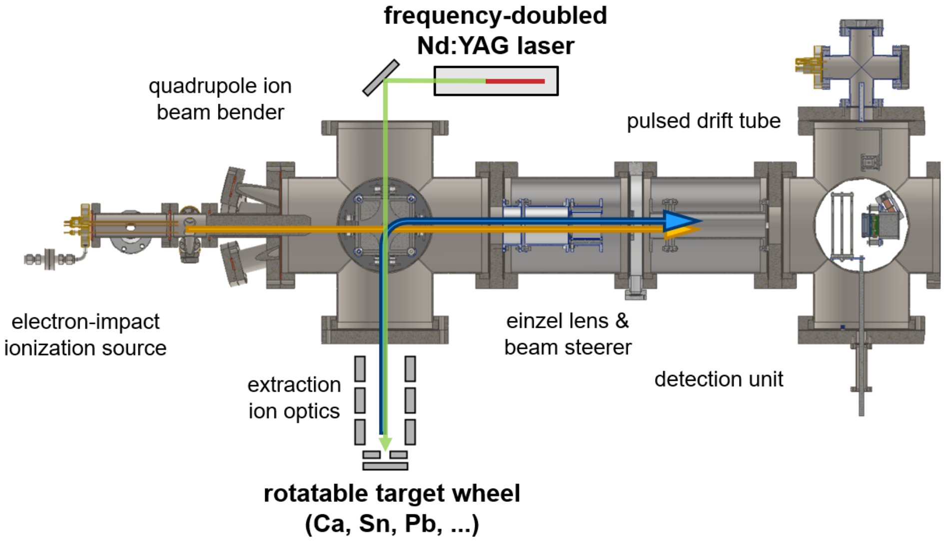
$N({}_{\Lambda}Y) = N_{\bar{\mathrm{p}}} \cdot N_{\mathrm{spill}} \cdot x_{\mathrm{cap}} \cdot f({}_{\Lambda}Y) \cdot \epsilon_{\mathrm{a}} \cdot BR \cdot \epsilon_{\mathrm{f}} \cdot \epsilon_{\omega} \cdot \epsilon_{\mathrm{TPC}} \cdot \epsilon_{\mathrm{track}} =$ **1500 identified hypernuclei**

SUMMARY

- Two upgrades for PUMA experiment planned

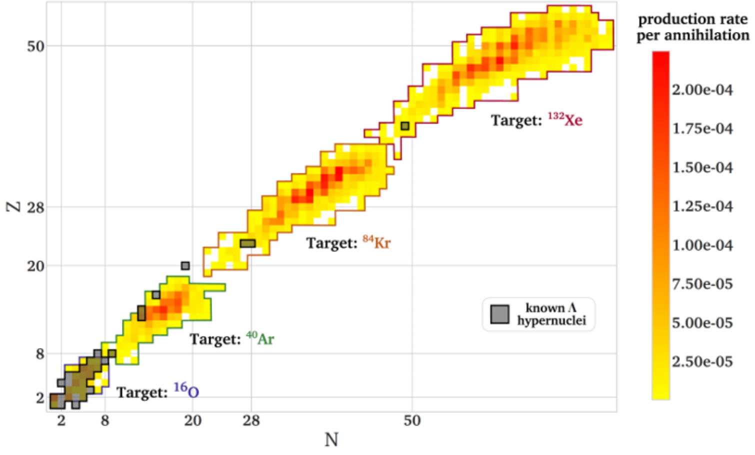
Upgrade 1

- Develop laser ablation ion source
  → Allow production of metal ions
- Study medium-mass closed shell nuclei
- *Commissioning planned for CERN’s Long Shutdown 3*



Upgrade 2

- Develop new detection system and modify Penning trap
  → Produce and detect new hypernuclei
- Simulations suggest accessibility of broad hyperisotope range
- *Experimental activity planned in post-PUMA future (2027-2028?)*

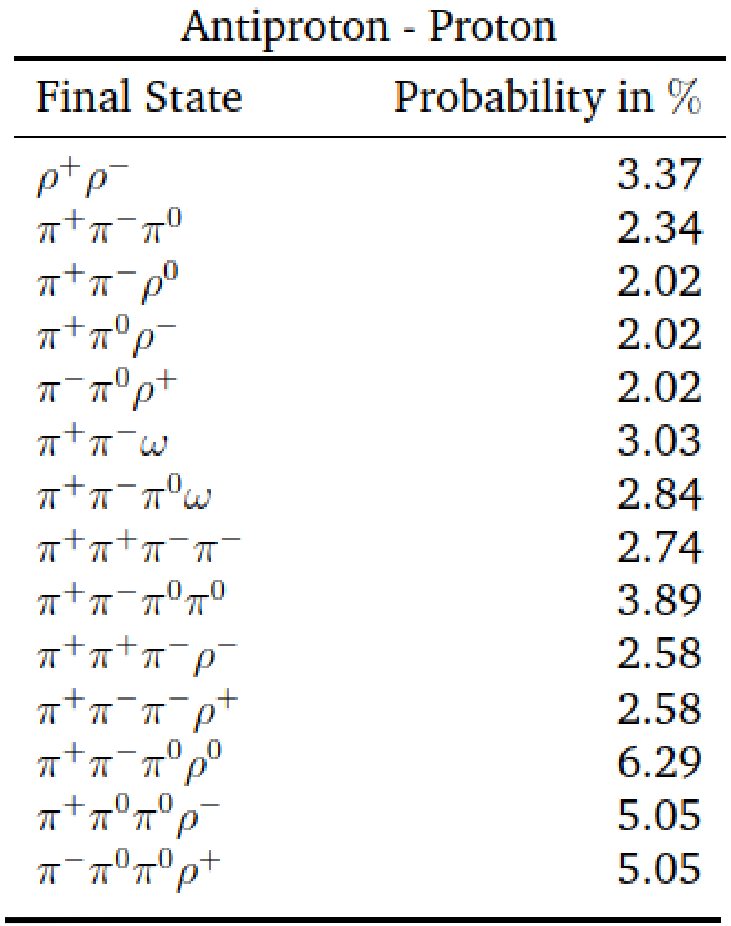


THE PUMA COLLABORATION

T. Aumann, N. Azaryan, W. Bartmann, A. Bouvard, O. Boine-Frankenheim, A. Broche, F. Butin, D. Calvet, J. Carbonell, P. Chiggiato, H. De Gersem, R. De Oliveira, T. Dobers, F. Ehm, J. Ferreira Somoza, J. Fischer, M. Fraser, E. Friedrich, M. Gomez-Ramos, J.-L. Grenard, G. Hupin, K. Johnston, C. Klink, M. Kowalska, Y. Kubota, P. Indelicato, R. Lazauskas, S. Malbrunot-Ettenauer, N. Marsic, W. Müller, S. Naimi, N. Nakatsuka, R. Necca, D. Neidherr, A. Obertelli, Y. Ono, S. Pasinelli, N. Paul, E. C. Pollacco, L. Riik, D. Rossi, H. Scheit, M. Schlaich, R. Seki, A. Schmidt, L. Schweikhard, S. Sels, E. Siesling, T. Uesaka, M. Wada, F. Wienholtz, S. Wycech, C. Xanthopoulou, S. Zacarias

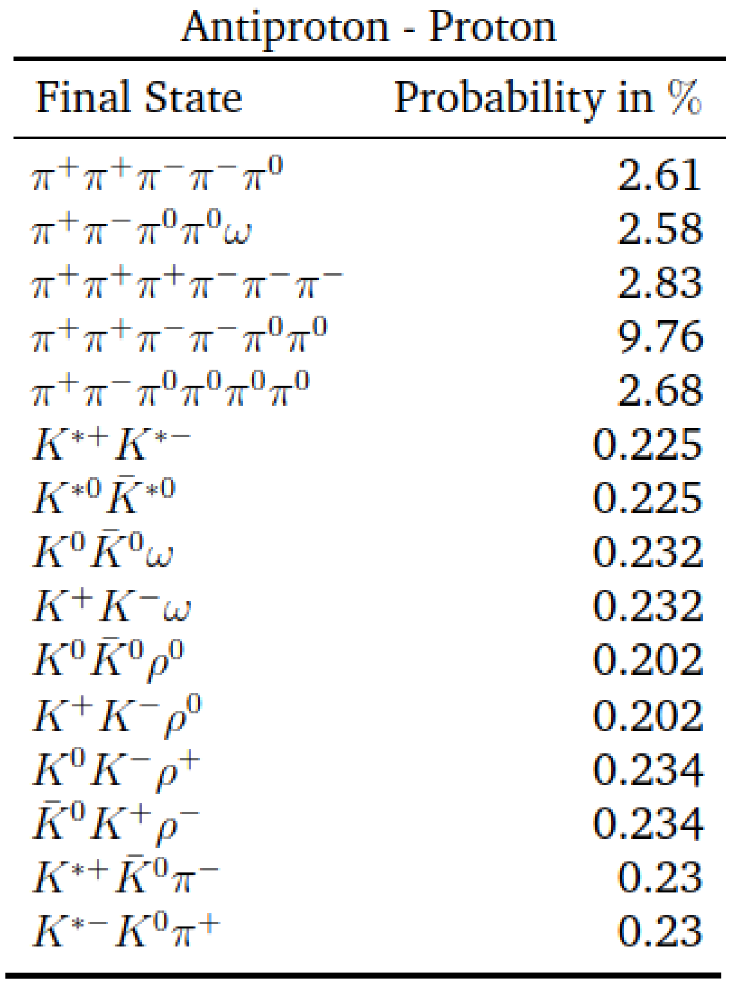
THANK YOU!

APPENDIX – BRANCHING RATIOS



Antiproton - Proton

Final State	Probability in %
$\rho^+\rho^-$	3.37
$\pi^+\pi^-\pi^0$	2.34
$\pi^+\pi^-\rho^0$	2.02
$\pi^+\pi^0\rho^-$	2.02
$\pi^-\pi^0\rho^+$	2.02
$\pi^+\pi^-\omega$	3.03
$\pi^+\pi^-\pi^0\omega$	2.84
$\pi^+\pi^+\pi^-\pi^-$	2.74
$\pi^+\pi^-\pi^0\pi^0$	3.89
$\pi^+\pi^+\pi^-\rho^-$	2.58
$\pi^+\pi^-\pi^-\rho^+$	2.58
$\pi^+\pi^-\pi^0\rho^0$	6.29
$\pi^+\pi^0\pi^0\rho^-$	5.05
$\pi^-\pi^0\pi^0\rho^+$	5.05



Antiproton - Proton

Final State	Probability in %
$\pi^+\pi^+\pi^-\pi^-\pi^0$	2.61
$\pi^+\pi^-\pi^0\pi^0\omega$	2.58
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$	2.83
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	9.76
$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	2.68
$K^{*+}K^{*-}$	0.225
$K^{*0}\bar{K}^{*0}$	0.225
$K^0\bar{K}^0\omega$	0.232
$K^+K^-\omega$	0.232
$K^0\bar{K}^0\rho^0$	0.202
$K^+K^-\rho^0$	0.202
$K^0K^-\rho^+$	0.234
$\bar{K}^0K^+\rho^-$	0.234
$K^{*+}\bar{K}^0\pi^-$	0.23
$K^{*-}K^0\pi^+$	0.23

A. Schmidt et al., Eur. *Phys. J. A* **60**, 55 (2024)

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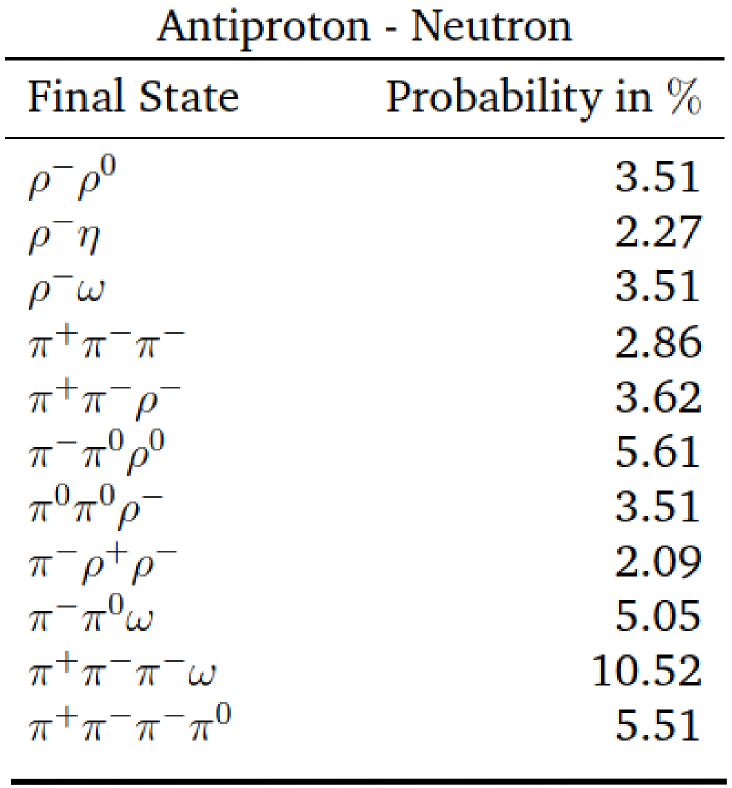
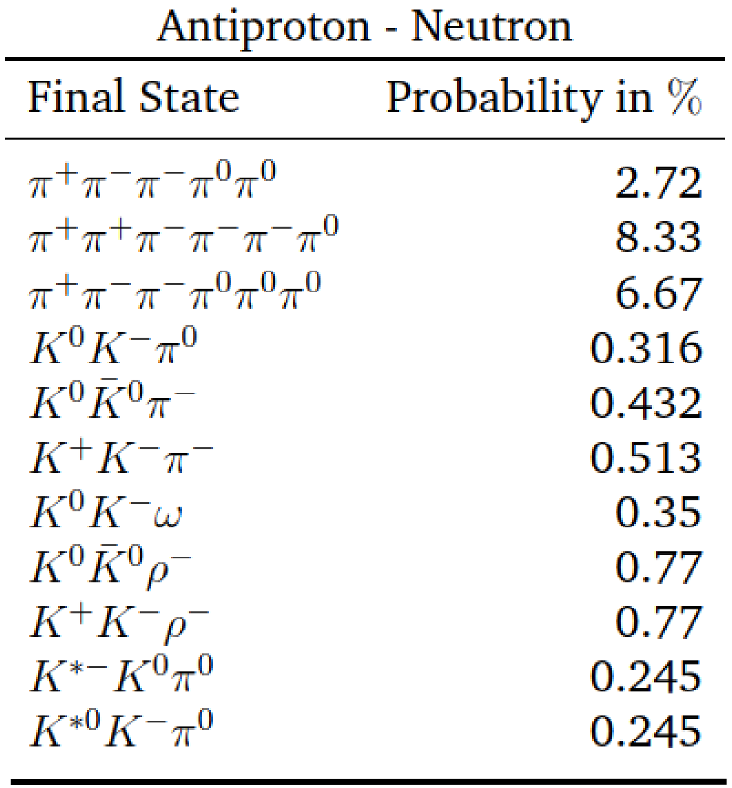


Antiproton - Neutron

Final State	Probability in %
$\rho^-\rho^0$	3.51
$\rho^-\eta$	2.27
$\rho^-\omega$	3.51
$\pi^+\pi^-\pi^-$	2.86
$\pi^+\pi^-\rho^-$	3.62
$\pi^-\pi^0\rho^0$	5.61
$\pi^0\pi^0\rho^-$	3.51
$\pi^-\rho^+\rho^-$	2.09
$\pi^-\pi^0\omega$	5.05
$\pi^+\pi^-\pi^-\omega$	10.52
$\pi^+\pi^-\pi^-\pi^0$	5.51



Antiproton - Neutron

Final State	Probability in %
$\pi^+\pi^-\pi^-\pi^0\pi^0$	2.72
$\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$	8.33
$\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0$	6.67
$K^0K^-\pi^0$	0.316
$K^0\bar{K}^0\pi^-$	0.432
$K^+K^-\pi^-$	0.513
$K^0K^-\omega$	0.35
$K^0\bar{K}^0\rho^-$	0.77
$K^+K^-\rho^-$	0.77
$K^{*-}K^0\pi^0$	0.245
$K^{*0}K^-\pi^0$	0.245

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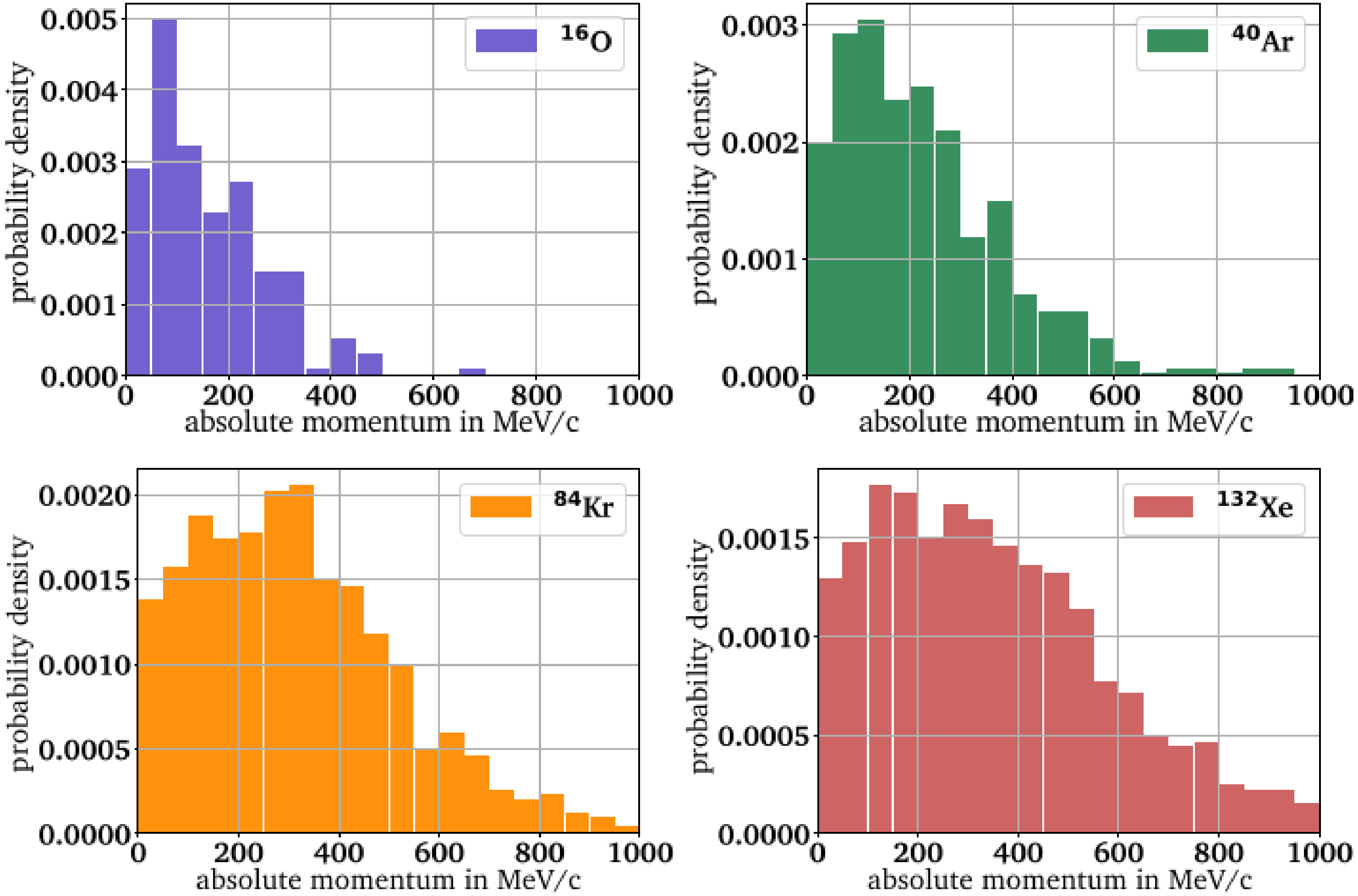
APPENDIX – MOMENTUM DISTRIBUTIONS



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