Exotic Nuclei & Antiprotons @ CERN ISOLDE & ELENA

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Neutron-rich nuclear systems

proton-neutron asymmetry

multi-neutron systems

neutron skins & halos

Z proton number

N neutron number

208\(^{\text{Pb}}\)

shell evolution

hypernuclei

multi-neutron systems

neutron skins & halos
Neutron skins

\[ \Delta r_{np} = \langle r_n \rangle - \langle r_p \rangle \approx \langle r_m \rangle - \langle r_c \rangle \]

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- neutron skins have been extensively studied
- structure phenomenon difficult to characterise and to measure accurately
- studies also motivated by the Nuclear Equation of State (EOS)


\[ \frac{E}{A}(\rho_n, \rho_p) = \frac{E_0}{A}(\rho) + \mathcal{S}(\rho) \left( \frac{\rho_n - \rho_p}{\rho} \right)^2 \]

Charge and matter/neutron radii, ex. of $^{208}$Pb

Charge radii:
- Charge density distributions extracted from (e,e') measurements for stable nuclei
- Not accessible for short-lived nuclei, except at SCRIT at RIKEN (starting)
- Relative charge radii from fine structure studies (ex. ISOLDE)

Matter radii:
- Most precise: proton scattering, coherent $\pi^0$ photoproduction, parity-violating expts (JLab)

A. Meucci et al., PRC 90, 027301 (2014)
Discovery of halos

Experiment @ Berkeley, USA
➢ I. Tanihata, experiment at LBL (1984)
➢ $^{12}$C, $^{16}$O primary beams at 800 A MeV
➢ interaction cross section for Be, Li isotopes

Interpretation @ ISOLDE
➢ Halo nuclei have a diffuse neutron wave function extending « out » of the nucleus through tunnelling
➢ $^9$Li-2n two body system, zero-binding energy for 2n system

\[
\psi(r) \propto e^{-r/\rho} \quad \text{with} \quad \rho = \hbar/\sqrt{2\mu B}
\]
\(\mu\) reduced mass,
B two-neutron binding energy
Neutron halos

S-wave dominate: $^{11}\text{Be}$, $^{15}\text{C}$, $^{19}\text{C}$, $^{6}\text{He}$, $^{8}\text{He}$, $^{31}\text{Ne}$, $^{37}\text{Mg}$

$^{11}\text{Li}$: mix of s wave and p wave

$^{14}\text{Be}$: mix of s wave and d wave

Necessary conditions for halos:
- Small separation energy (<1MeV)
- Low orbital angular momenta ($l=0$ or 1)
P-wave halos in Ne and Mg isotopes

- $^{31}$Ne, $^{37}$Mg are claimed to be *p-wave deformed* neutron halos

**Case of $^{37}$Mg:** RIBF, 6 pps

- Pb and C targets @ 240 MeV/nucleon
  - Combined Coulomb & nuclear breakup reactions
  - 1-neutron removal channel
- Large $\sigma(E1)=0.5$ barn found: hint of a halo
- $S_n$ and $C^2S(gs-gs)$ are (model-dependently) extracted from cross sections
- Data consistent with $s$ or $p$ waves
- Shell model excludes the $s$ wave option
- $^{37}$Mg is considered to be a *p-wave halo* with $S_n = 0.22(10)$ MeV
Do proton halos exist?

- $^{17,18}$Ne proposed as proton halos from charge radii
  W. Geithner et al., PRL 101 (2008)

- In agreement with Molecular Dynamic model (FMD) which predict a proton halo in $^{17}$Ne

- No “direct” evidence yet
Neutron skins in medium-mass nuclei

\[ N_{\text{halo}} = \int_{r_0}^{+\infty} \rho(r) r^2 \, dr \]

Beyond the radius \( r_0 \): core density is one order of magnitude smaller than the halo one.

EDF with \textbf{Sly4 Skyrme} force

Correlations in the low-density surface region

- Correlations at low density / deformation may modify the picture of neutron skins / halos
- Example:
  - Generalized relativistic density functional
  - Alpha clustering at low density, increasing with N,Z asymmetry (neutron skin)

Antiproton annihilation: a probe for the nuclear density tail

What would be an ideal probe?

- isospin sensitivity: selectivity of protons and neutrons
- sensitivity to the tail of the nuclear density, where the skin/halo are
- usable for short-lived and low-rate production nuclei

... low-energy antiprotons as a probe fulfill these requirements
[was proposed in the past at CERN and GSI/FAIR (FLAIR project)]
Antiproton annihilation: a probe for the nuclear density tail

1. Captured antiproton
2. Decay X-rays
3. Auger electrons
4. Surface annihilation & pion emission
5. Cascade & residue production, decay

Antiproton annihilation: a probe for the nuclear density tail

High cross section \( (\approx 100 \text{ Mbars}) \) at low relative energy \( (\approx 100 \text{ eV}) \)


Antiproton annihilation: a probe for the nuclear density tail

Ex. $^{172}$Y @ CERN, R. Schmidt et al., PRC 58, 3195 (1998)

\[ \Gamma \] reaction probability
\[ \Phi_{nl} \] antiproton radial wave function
\[ V(r) \] antiproton-nucleus potential
\[ a \] effective N-antiproton scattering length
\[ \rho(r) \] nuclear density convoluted with pbar-N range (0.75-1 fm if finite range)

ex. \( a = -1.53 - 2.5 \text{ fm} \) (Batty, NPA 1997)

\[ \Gamma_{nl} = \int \text{Im} \, V(r) |\Psi_{nl}(r)|^2 \, r^2 \, dr \]

with \( V(r) = \frac{2\pi}{\mu} \, a \rho(r) \)
Antiproton annihilation: a probe for the nuclear density tail

- **Features:**
  - **High cross section** (Mbarns) at low energy (100 eV)
  - **Net electric charge conservation**
    - -1: neutron annihilation
    - 0: proton annihilation
  - Sensitive to **neutron-proton density ratio at surface**

- **Surface annihilation & pion emission**
- **Decay X-rays**
- **Auger electrons**
- **Cascade & residue production, decay**

\[ \frac{N_n}{N_p} \] theory \[ \frac{\rho_n}{\rho_p} \]

Extracted from data

Sensitivity to final state interactions

- Pions may re-interact with residual nucleus
  Stable nuclei: probability 20-50%

- Solution: analyse charged pion multiplicity (M) AND sum charge (Sigma_c)

- Treatment of final state interactions:
  \( \lambda^+ : \pi^0 + p \rightarrow \pi^+ + n \)
  \( \lambda^- : \pi^0 + n \rightarrow \pi^- + p \)
  \( \omega^+ : \pi^- + p \rightarrow \pi^0 + n \)
  \( \omega^- : \pi^+ + n \rightarrow \pi^0 + p \)

- Analysis of M-Sigma matrices should lead to \( N(p\bar{n})/N(p\bar{p}) \) with good accuracy and precision (<5% for \( 10^5 \) annihilations)

- New and systematic analysis based on simulated Monte-Carlo annihilations in progress (A. Corsi et al.)
PUMA: Pbar Unstable Matter Annihilation

- Transport antiprotons from ELENA (CERN) to ISOLDE
- Device to be build (funded from 01/2018, for 5 years)
- First experiment at ISOLDE foreseen in 2022
- Pioneer experiment with antiprotons as a probe for short-lived nuclei

Storage of antiprotons at CERN/AD/ELENA at the GBAR experiment

PUMA trap for antiprotons

Transport the antiprotons...

... to ISOLDE at CERN for unstable ion annihilation.
The GBAR experiment at CERN / ELENA

How does antimatter fall in the gravitational field?

Classical free fall: \( z = z^0 + \nu^0 z t + \frac{1}{2} g t^2 \)

- Produce ion \( \bar{H}^+ \)
- Sympathetic cooling 20 \( \mu \)K
- Photodetachment of \( e^+ \)
- Time of flight

Error dominated by temperature of \( \bar{H}^+ \)

Spokesperson: P. Pérez (CEA/IRFU)
The GBAR experiment

GBAR requires limitations on the fringe field gradient at the free fall region (force from magnetic moment in gradient of B field)

\[ dB/B < 0.02 \text{ G} / \text{ m} \] (0.1% precision fro gbar)
PUMA: a magnetic bottle for antiprotons

Technical challenges:
- Store a large number of antiproton (<10^8) for a long time
- Transport low-energy ions inside the ultra high vacuum

about 900 mm
“Day one” physics cases

Production rates at ISOLDE

- Example of yield estimate:
  - At relative energy of about 100 eV, the capture cross section is $10^{-16}$ cm$^2$ (100 Mbars)
  - $10^7$ cm$^{-2}$ antiproton « target », 6-cm long
  - trapping time of 10 ms: ions go through antiprotons $10^4$ times each
  - 1000 pps production rate of radioactive Ion (10 ions / bunch of 10 ms)
  - this least to an annihilation rate of 1 / minute ($10^2$ / day)
Main assumption: about $10^7$ charges / cm$^3$ is feasible with limited space charge effect

Collision trap (C trap): $10^7$ antiprotons
- $L=100$ mm: (i) size of magnet, (2) detection
- Volume of antiprotons: a cylinder with $R=2$ mm, $L=100$ mm: $1.2$ cm$^3$ (ISOLDE low-E beams)
- Trap radius could be taken as $R=10$ mm for manipulation before radius reduction

Storage zone (S trap): $10^9$ antiprotons
- Trap radius of $R=50$ mm (for a cloud of $R= 40$ mm) and a length $L=150$ mm
- Cloud volume is: $750$ cm$^3$
Tracking and solenoid dimensions

- TPC dimensions set to optimise tracking
- Inner radius set by C-trap radius: 56 mm
- Ext. radius: optimized for pion charge ID
- Simulations give 110 mm
- 80% efficiency (detection + ID)

- Supraconducting solenoid to be built
- Bore radius: 130mm, length: 700 mm
- 4T, active shielding
- 0.1% homogeneity in trapping region
- about 1% in tracking region
- Initial design G. Aubert (CEA), now TU Darmstadt

Along symmetry axis
1 meter from solenoid
5 mT (50 gauss)
Status of the development & timelines

- **Magnet**: design at TU Darmstadt, Prof. De Gersem
  4T, active shielding, homogeneity: 0.1% in trap regions, <3% in tracking region
  Bore radius: 130 mm, effective length: 700 mm
  Call for tender to be sent around April 2018

- **Tracking**: TPC and scintillator barrels, design at CERN (R. Olivera), collaboration with CEA
  About 4000 pads (3*1 mm²), to be fine tune with extended simulations
  Electronics: not decided yet. Several options considered
  System can be ready for tests mid-2019

- **Trap**: TU Darmstadt, MPI Heidelberg, RIKEN (T. Uesaka, S. Naimi, S. Ulmer), Isolde
  Call open for a 2-year postdoc + extension, one PhD student from next year

- **Trap cryostat**: see next slides. Starting discussions with TU Munchen, RIKEN (S. Ulmer)

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**4-5 people team at TU Darmstadt** (to be built): 1 staff, 10 years of postdoc, 3 PhD over the next 5 years.
Trapping challenges

- **Transporting** charges in a Penning trap
  In 1993, trapped electrons from West to East coast in the US

- Trapping a **large amount** of antiprotons
  In 2006, few $10^6$ antiprotons trapped by the ASACUSA collaboration

- Trapping antiprotons for a **long time**
  Today, BASE experiment: about 10 antiprotons stored without loss for >1.5 year

- Efficient extraction of a **subpart of stored antiprotons**

- High efficiency **transfer of charges** from a trap to another with smaller diameter

**Main challenge of PUMA:** all the above in one
10\(^{-17}\) mbar ultra high vacuum

- Lifetime of antiprotons determined by the vacuum

\[
P_H(\text{mbar}) = 6 \times 10^{-16} \frac{T(\text{K})}{\tau(\text{jours})}
\]

- **ONE solution:** cryogenic (4 K) sealed vacuum

- « routinely » done at CERN for antiproton physics: P<10\(^{-17}\) mbar
  
  *Ex. G. Gabrielse, BASE experiment*

- **PUMA:** thin sealing window needed for ion insertion
  
  - Material candidate: Si3N4. Well known properties, highly used membranes.
  - Membranes commercially available from 8 nm
  - Dimensions from 100 \(\mu\text{m}\) to few mm (depends on thickness)

*Example:*

- 1 mm\(^2\)
- 50 nm thick
- 200 mm Si substrat
Si₃N₄ thin windows

- Silicon nitrite spread in industry
- Preferred material for TEM windows
- Stands pressure difference of 1 bar
- 4 mm² for 10 nm remains a challenge

Ex. OCTALAB, Singapore, created in 2008

Film Thicknesses Available on 200 micron thick frames

- Pure Silicon
- Silicon Oxide
- Silicon Nitride

Single Window
- (1) 0.1 mm window
- (1) 0.5 mm window
- (1) 1.0 mm window

Single Square - 1mm² Window 200 μm Frame

- 2.95 mm
- 1.0 mm
- 1.28 mm
- 0.71 mm

1.0 x 1.0 mm

- high vacuum implies special soldering technique of the substrat to a surface
- expertise at TU Munchen: J. Wieser, A. Ulrich
- window from e⁻ gun to gas volume

J. Wieser et al., EPJD 48, 383 (2008)
12 keV e⁻ beam through a 250 nm membrane
Other potential physics opportunities with PUMA

- Repulsive hard-core + tensor of the nuclear interaction induces **high-momentum correlations**
- Stable nuclei: **20% of nucleons** are concerned with **90% of neutron-proton pairs**

![Diagram](image)

NOT in the current physics program:
PUMA can measure any **high-momentum charged partner after nucleon annihilation** (efficiency=10%, to be improved by **additional detection inside the trap**; F. Flavigny, IPN Orsay, application ongoing (2018))

- short range correlations at **the very surface of nuclei**
- high-momentum pair **proportion in proton-neutron asymmetric matter**

Subedi *et al.*, Science **320** (2008)
Other potential physics opportunities with PUMA

- nucleon stripping from (super) heavy elements at rest, gamma spectroscopy (S3, GANIL)
  low production yields compensated by long life time

- precision measurement experiments in low-background environment

- low-energy antiproton capture process

- in medium meson production (phi-meson study proposed by RCNP, Japan)
Summary

- **PUMA**: new program at CERN / ELENA and ISOLDE (official start on 02.01.2018)
- antiprotons as a new probe for the nuclear density tail of short-lived nuclei
- halos and thick neutron skins searched in medium mass short-lived nuclei
- transport trapped antiprotons from ELENA to ISOLDE
- trap and cryostat to be designed and built (not started)
- first physics experiments expected in 2022