Antiprotonic atoms - a tool for the investigation of the nuclear periphery

for PS209 collaboration

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Outline

- Antiprotonic atoms – strong interaction effects
- Information on the nuclear surface from annihilation products ($f_{\text{halo}}$)
- Neutron density distribution from antiprotonic X rays
- Systematics of $\Delta r_{\text{np}}$: comparison with theory & other experiments
- Summary & future plans
Antiprotonic atoms

- creation: $\bar{p}$ capture on the “high” orbit ($n_\bar{p} \approx 43 \times n_e$)
- cascade: emission of Auger electrons and X rays
Strong interaction effects

levels broadening and shift

measured in experiment: \( \Gamma_{up}, \Gamma_{low}, \epsilon \)
Annihilation products

\[ Z_t N_t \]

Outline
- Antiprotonic atoms
- Strong interaction effects
- Annihilation products
- \( f_{\text{halo}} \)
- Neutron density from \( \Delta r_{\text{np}} \)
- \( f_{\text{halo}} \) vs \( \Delta r_{\text{np}} \)
- Antiprotonic X-rays ...
- Experiment
- Harvest of PS209
- Determination of \( \rho_n \)
- Neutron density – results
- \( \Delta r_{\text{np}} \) – Pb
- \( c_p = c_n \) ?
- \( \Delta r_{\text{np}} \) systematics
- Comparison with theory
- Comparison with other experiments
- Summary & conclusions
- Future
- PS209 Collaboration
Annihilation products

measured in experiment:

yield of \( \left\{ \begin{array}{l} Y_{N_t-1} \sim \rho_n(r_{\text{annihil.}}) \\ Y_{Z_t-1} \sim \rho_p(r_{\text{annihil.}}) \end{array} \right\} \)

\[ f_{\text{halo}} = \frac{Y_{N_t-1}}{Y_{Z_t-1}} \cdot \frac{Z}{N} \cdot \frac{\text{Im} a_{p\bar{p}}}{\text{Im} a_{n\bar{p}}} \]

\[ f_{\text{halo}} \sim \frac{\rho_n}{\rho_p} \]

at \( r \approx (r_{1/2} + 2.5) \) fm
Observations:

- strong correlation between \( f_{\text{halo}} \) and neutron energy separation
- in nuclei with \( B_n < 9 \text{ MeV} \) periphery reach in neutrons
Neutron density from $\Delta r_{np}$

$$\rho(r) = \rho_0 \left(1 + \exp\left(\frac{r - c}{a}\right)\right)^{-1}$$

$$\langle r^2 \rangle = \frac{3}{5} c^2 + \frac{7}{5} \pi^2 a^2 \Rightarrow \langle r^2 \rangle(c, a)$$

let's consider two extreme cases:

- $\Delta r_{np}$ results from the half-density radii difference
  $$a_n = a_p, \quad c_n \neq c_p, \quad \text{“neutron skin”}$$
- $\Delta r_{np}$ results from the surface diffuseness difference
  $$a_n \neq a_p, \quad c_n = c_p, \quad \text{“neutron halo”}$$

$\rho_p$ known from experiments with $e$ or $\mu$

$\rho_n$ calculated from $\Delta r_{np}$ (under the above assumptions)

What is difference between these cases?
Neutron density from $\Delta r_{np}$

- $\Delta r_{np}$ results from the half-density radii difference ($a_n = a_p$, $c_n \neq c_p$, “neutron skin”)
- $\Delta r_{np}$ results from the surface diffuseness difference ($a_n \neq a_p$, $c_n = c_p$, “neutron halo”)

\[ \rho_p \]
\[ \rho_n \times Z/N \]

\[ \langle r^2 \rangle^{1/2} \]

\[ a_n = a_p \]

"neutron skin"

\[ c_n = c_p \]

"neutron halo"
\[ f_{\text{halo}} \textbf{vs } \Delta r_{\text{np}} \]

\[ Z/N \frac{\rho_n}{\rho_p} \]

- \(48\text{Ca}\)
  - \(\Delta r = 0.16 \text{ fm}\)
- \(124\text{Sn}\)
  - \(\Delta r = 0.23 \text{ fm}\)
- \(208\text{Pb}\)
  - \(\Delta r = 0.17 \text{ fm}\)

\[ c_n = c_p \]
\[ a_n = a_p \]

\[ \sim \sim \Delta r_{\text{np}} \text{ caused by } a_n \neq a_p \text{ rather than by } c_n \neq c_p \]
Antiprotonic X-rays ...

... another tool for the investigation of the nuclear periphery: strong interaction level widths and shifts depend on the antiproton-nucleus potential:

\[
\frac{\Gamma}{2} \sim \int \text{Im} \ V(r) \ |\Psi_{nl}(r)|^2 \ r^2 \ dr \\
\frac{\epsilon}{2} \sim \int \text{Re} \ V(r) \ |\Psi_{nl}(r)|^2 \ r^2 \ dr
\]

\[
V_{\text{opt}} = -\frac{2\pi}{\mu} \left( \bar{a}_n \rho_n(r) + \bar{a}_p \rho_p(r) \right)
\]

\[
\bar{a}_p = \bar{a}_n = 2.5 + i \ 3.4 \ \text{fm}
\]

measured in experiment: \( \Gamma_{\text{up}}, \Gamma_{\text{low}}, \epsilon \)
Harvest of the PS209 measurements

before PS209 measurements
Harvest of the PS209 measurements

- Shift (eV)
- Width (eV)

Z

0 10 20 30 40 50 60 70 80 90 100

R:\\text{Assumption}\n\frac{f_{\text{halo}}}{\Delta r_{\text{np}}}

Neutron density from
\Delta r_{\text{np}}

\frac{f_{\text{halo}}}{\Delta r_{\text{np}}}

Antiprotonic X-rays ...

Experiment

Harvest of PS209

Determination of \( \rho_n \)

Neutron density – results

\Delta r_{\text{np}} – \text{Pb}

c_p=c_n?

\Delta r_{\text{np}} \text{ systematics}

Comparison with theory

Comparison with other experiments

Summary & conclusions

Future

PS209 Collaboration

Physics with Ultra Slow Antiprotonic Beams, TOKYO, March’05

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Determination of $\rho_n$ from antiprotonic X rays

known:
- $\rho_p$ (from electromagnet. interacting probes: e, $\mu$)
- $V_{\text{opt}}(\rho_p, \rho_n)$

assumed:
- 2-parameter-Fermi density distribution
- $c_n = c_p$ (to be discussed)

fitted: $a_n(V_{\text{opt}}, \Gamma_{\text{low}}, \Gamma_{\text{up}}, (\epsilon))$

$$\rho_n(c_n, a_n)$$
Neutron density – results

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**Physics with Ultra Slow Antiprotonic Beams, TOKYO, March'05**

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\[ \Delta r_{np} \text{ from X-ray data – } ^{208}\text{Pb example} \]

\[ \rho_p(c_p,a_p), \rho_n(c_n,a_n) \implies \Delta r_{np} \]
\[ \Delta r_{np} \text{ from X-ray data – } ^{208}\text{Pb example} \]

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\[ \Delta r_{np} - ^{208}\text{Pb} \]

\[ c_p = c_n \]?

\[ \Delta r_{np} \text{ systematics} \]

\[ \text{Comparison with theory} \]

\[ \text{Comparison with other experiments} \]

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\[ \text{PS209 Collaboration} \]
$c_p = c_n$?

![Graph showing $\Delta r_{np}$ vs $\Delta c$ for $^{208}$Pb]
\( \Delta r_{np} \) systematics from X-ray data

\[ \rho_p(c_p,a_p), \rho_n(c_n,a_n) \implies \Delta r_{np} \]
Comparison with theory

experimental data

\[ \delta = (N-Z)/A \]

\[ \Delta r_{np} \]

\[ f_{\text{halo}} \text{ vs } \Delta r_{np} \]

\[ \Delta r_{np} - \text{Pb} \]

\[ c_{\text{p}} = c_{\text{n}}? \]

\[ \Delta r_{np} \text{ systematics} \]

\[ \text{Comparison with theory} \]

\[ \text{Comparison with other experiments} \]

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Comparison with theory

HF and HFB calculations

\( \frac{d}{\delta} = (N-Z)/A \)

- HFB [SMO95] (SkP)
- HF [BRO00] (SkX)
- HF [HOF98] (SLy4)

fit to HFB (SkP) data

PS209 (antiprotons)
Comparison with theory


![Graph showing comparison with theory](image-url)

- **Droplet model - standard**
  \[ \Delta r = -0.019 + 0.718 \times \delta \]

- **PS209 fit**
  \[ \Delta r = -0.034 + 0.89 \times \delta \]
Comparison with other experiments

PS209 data

Comparison with theory

Comparison with other experiments

Summary & conclusions

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Comparison with other experiments

other experiments (hadron scattering data)

\[ \Delta r_{np} \text{ vs } \delta = \frac{(N-Z)}{A} \]

- Hadron scattering:
  - even nuclei
  - odd nuclei

- Fit to the data (even)
- PS209 (antiprotons)
Summary & conclusions

Two experimental methods using antiprotonic atoms were applied to investigate nuclear periphery:
- **radiochemical method**: \( \rho_n / \rho_p \approx r \approx c_p + 2.5 \) fm
- **antiprotonic X rays**: \((\rho_p + \rho_n) \approx r \approx c_p + 1.5\) fm

Reach set of precise data collected: material for theory (e.g. optical potential)

Experimental data were interpreted using 2pF density distribution

Neutron density distribution deduced for 26 isotopes

\( \Delta r_{np} \) systematics deduced from the data

excellent agreement of \( \Delta r_{np} \) from antiprotonic X rays and hadron scattering for \(^{208}\)Pb

good agreement of \( \Delta r_{np}(\delta) \) established from antiprotonic data and theoretical models

fair agreement with the data from other experiments (hadron scattering)

What next? \( \rightsquigarrow \) Future...
Future

What else is worth doing?

- measurements for deformed even-A nuclei (LS effect?)
- measurements for odd-A nuclei (e.g. Sn isotopes) – ??
- detailed study of Ca (double-magic isotopes $^{40}$Ca and $^{48}$Ca and possible measurement 3 levels for each isotope)
- investigation the properties of deeply bound states via E2 resonance
- search for a quasi-bound $\bar{p}p$ state - ??

Possibilities of measurements: AD @ CERN,
FLAIR @ Darmstadt
PS209 Collaboration

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