Information on nuclear surface obtained from antiprotonic atoms

Agnieszka Trzcińska

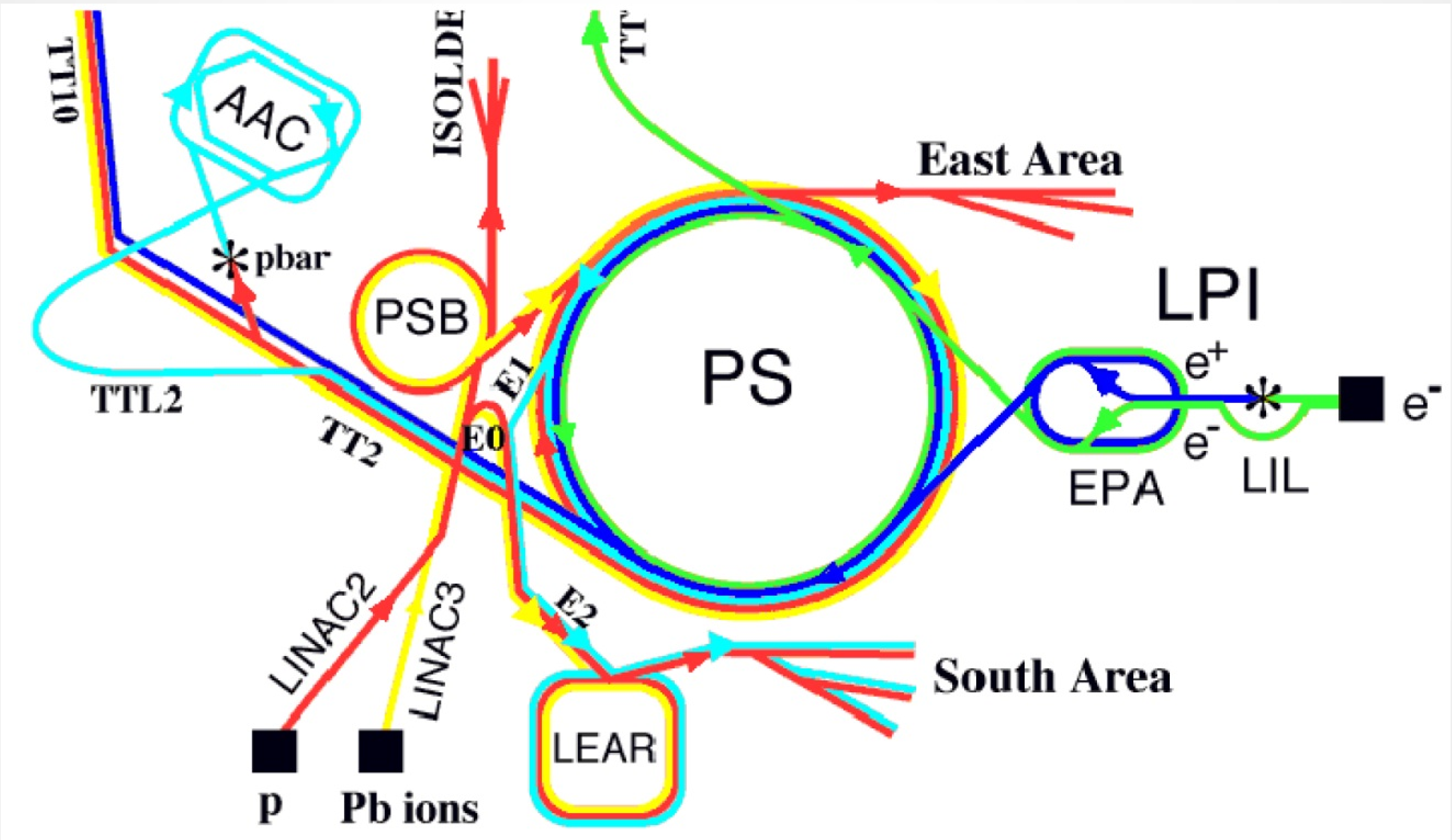
for PS209 Collaboration

in memory of Jerzy Jastrzębski 1934 - 2018

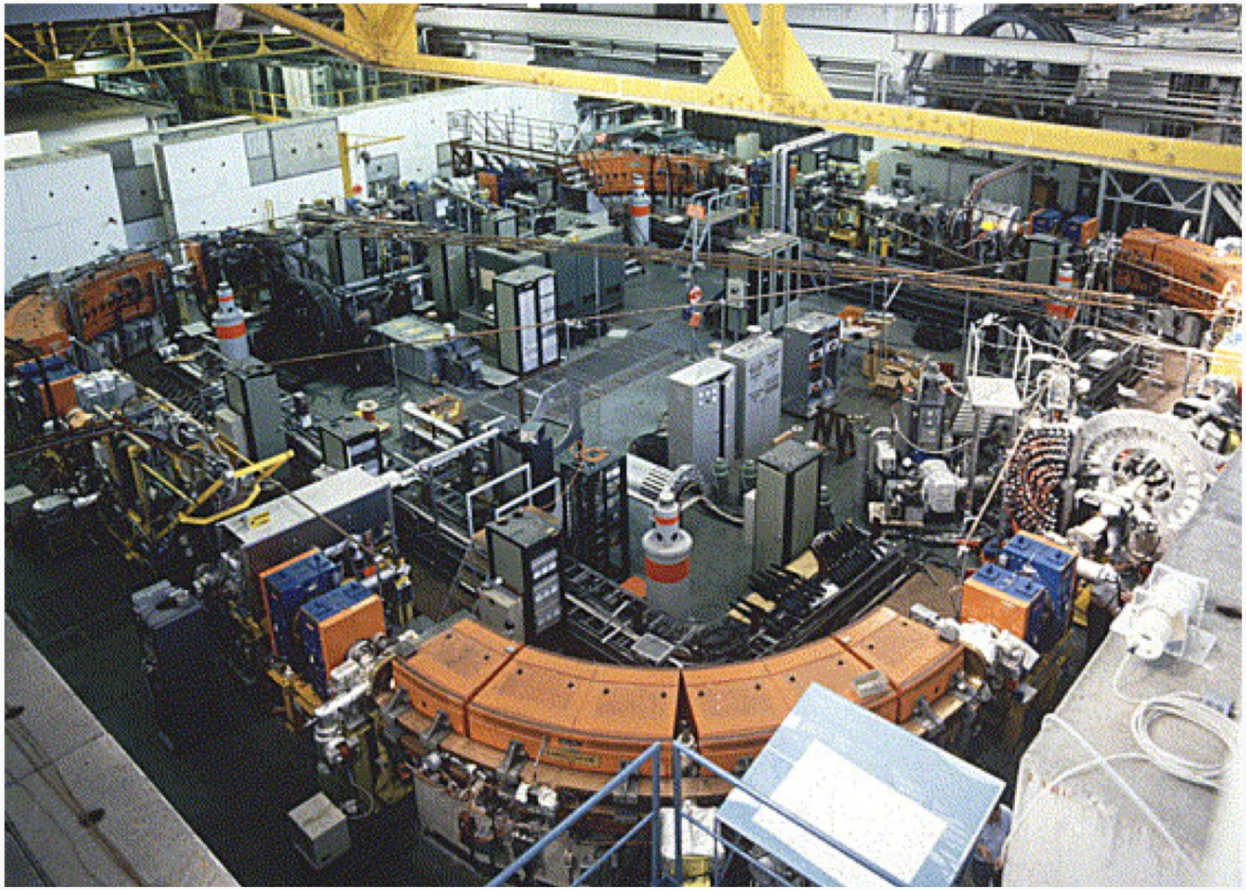
Low Energy Antitproton Ring (LEAR) @ CERN

- K. Kilian and collaborators proposed in 1976 cooling and deceleration of antiprotons as a way to obtain p beam of big intensity and high purity for low energy physics
- it triggered the proposal to add to the constructed SPS pp Collider a small facility with antiproton energy range from 5 to 1200 MeV
- In 1980 LEAR project was launched
- In June 1983 first beam for users

Low Energy Antitproton Ring (LEAR) @ CERN

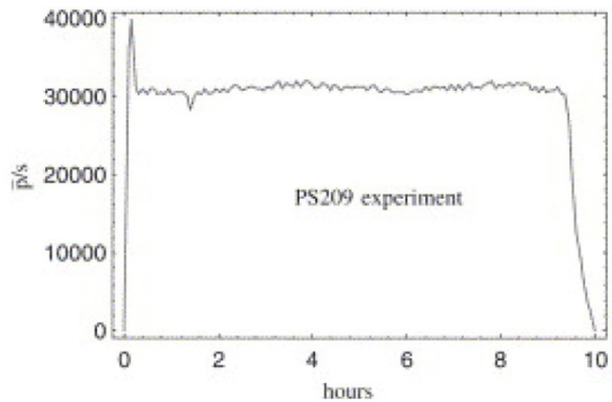


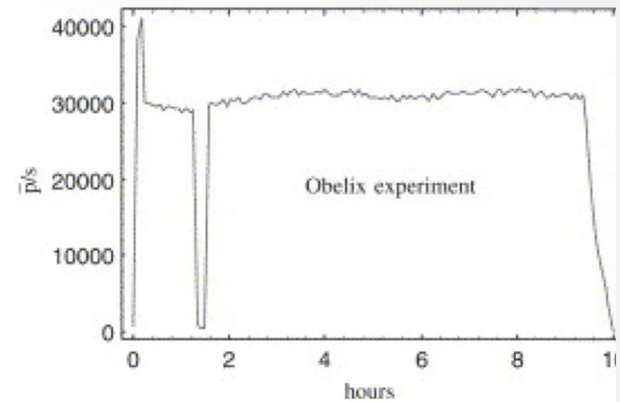
Low Energy Antitproton Ring (LEAR) @ CERN



Experiments

- 2 x 3 week runs in 1995 and 1996 @ LEAR (CERN) – as a parasitic exp.
- $\bar{p}$ beam:
  - 300 MeV/*c* and 400 MeV/*c* (1995)
  - 106 MeV/*c* (1996)





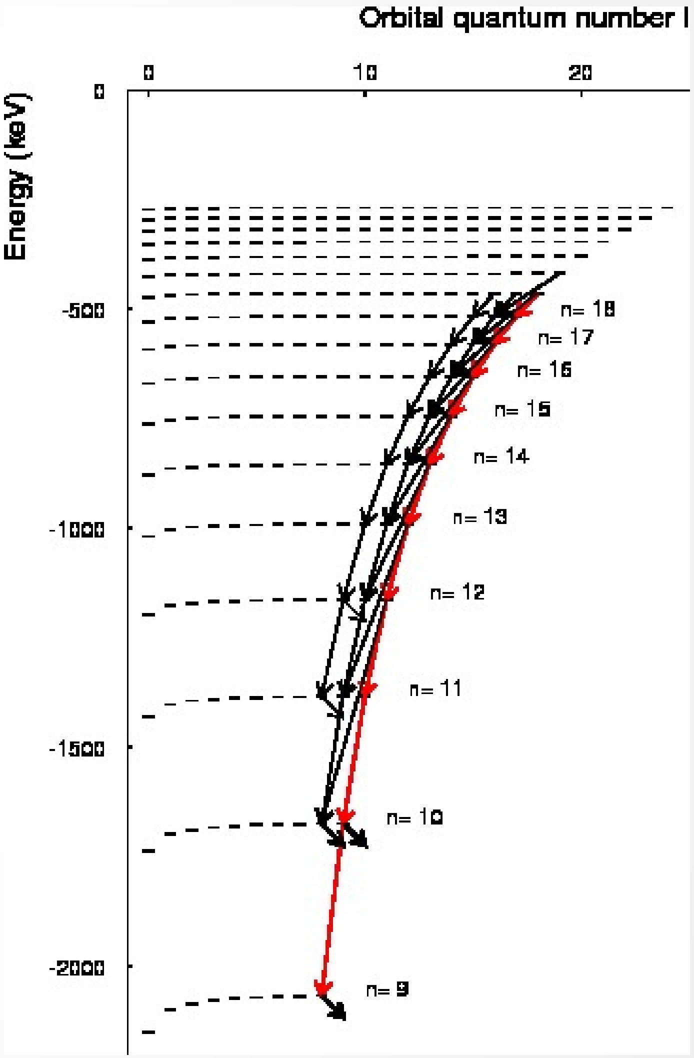
- Targets:
  - isotopically enriched materials
  - thickness: ~ 200 - 300 mg/cm^2 (1995) and ~ 50 - 100 mg/cm^2 (1996)
- 55 isotopes studied (from ^{16}O to ^{238}U)

Antiprotonic atoms

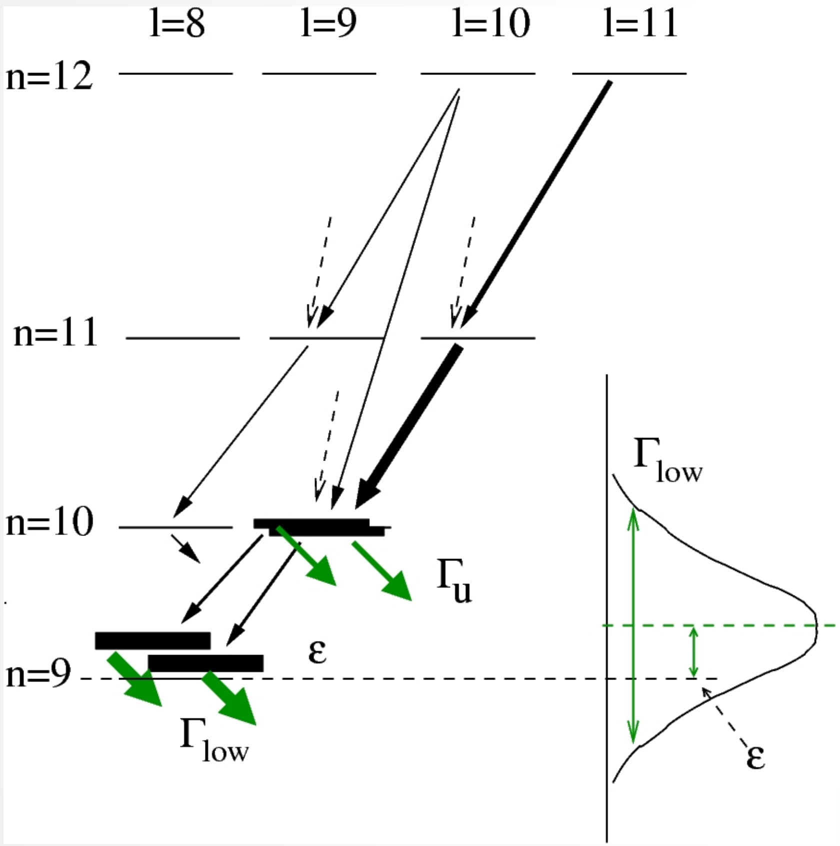
- creation:
  - $\bar{p}$ capture onto a “high” orbit

$$n_{\bar{p}} = \sqrt{(m_{\bar{p}}/m_e)} \times n_e \approx 43 \times n_e$$

- deexcitation (10^{-15} - 10^{-14} s):
  - emission of Auger electrons
  - X-rays emission (energy: γ-ray region)
  - annihilation



Antiprotonic atoms – strong interaction effects



strong interaction

↓

widens and **shifts p** levels

in the experiment we measure:

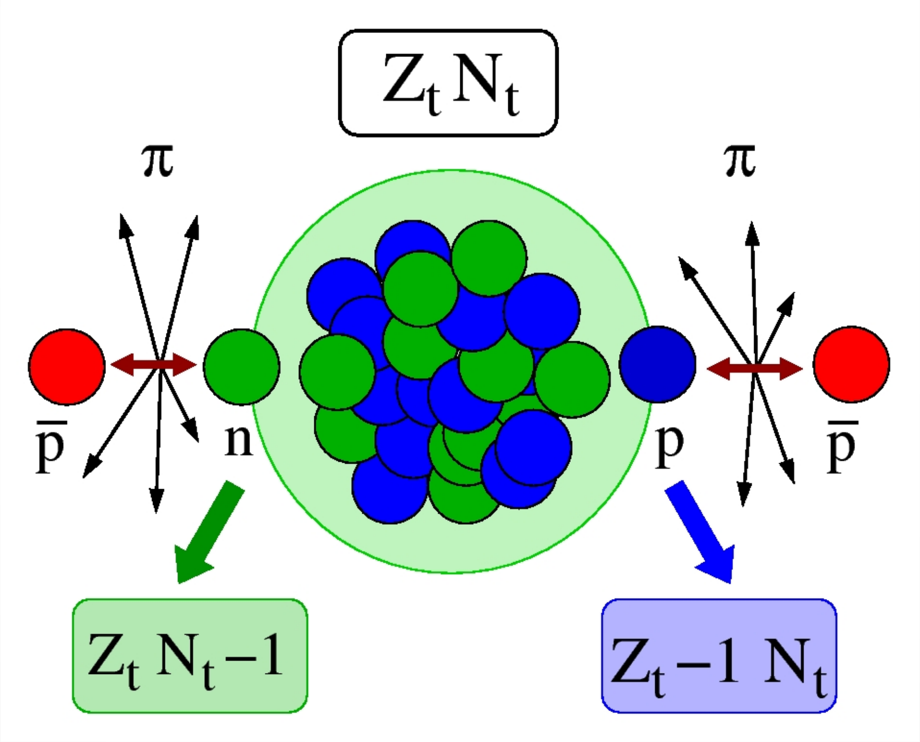
Γ_{low} - directly from the line shape

ε - determining the line energy

Γ_{up} - indirectly from the intensity balance

Antiprotonic atoms – anninihaltion

$\bar{p}$ ends its life in the atom **annihilating** with a peripheral nucleon (**p** or **n**)



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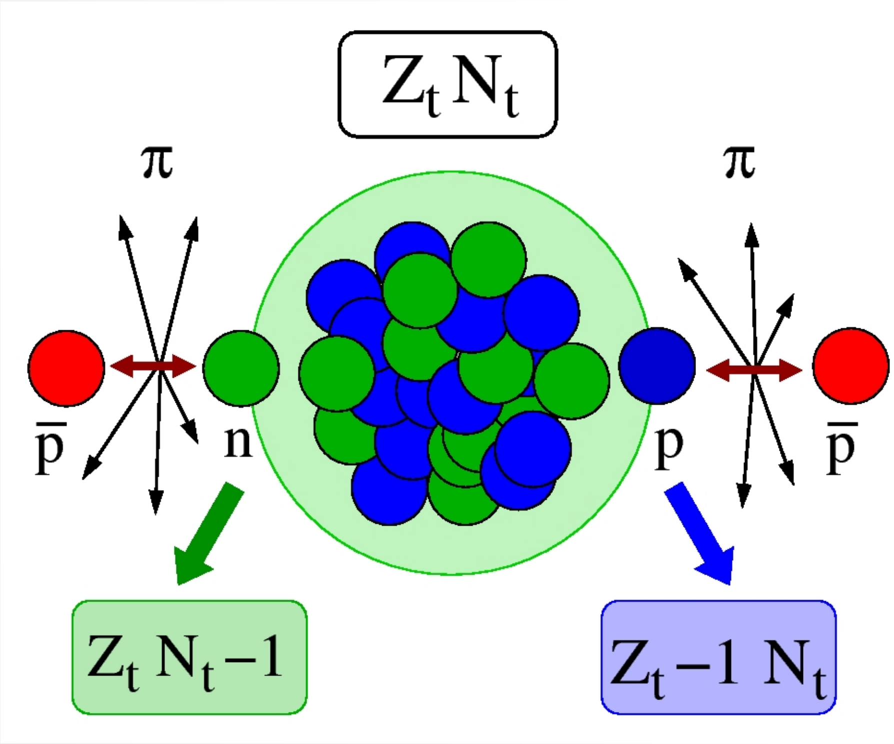


we measure:

$$N(N_t-1) \sim \rho_n(r_{annih})$$

$$N(Z_t-1) \sim \rho_p(r_{annih})$$

$$f_{halo} = \frac{N(N_t-1)}{N(Z_t-1)} \cdot \frac{\Im a_p}{\Im a_n} \cdot \frac{Z_t}{N_t}$$

$$f_{halo} \sim \frac{\rho_n}{\rho_p}(r_{1/2} + 1.5\,\text{fm})$$

“Radiochemical” method

experiment:

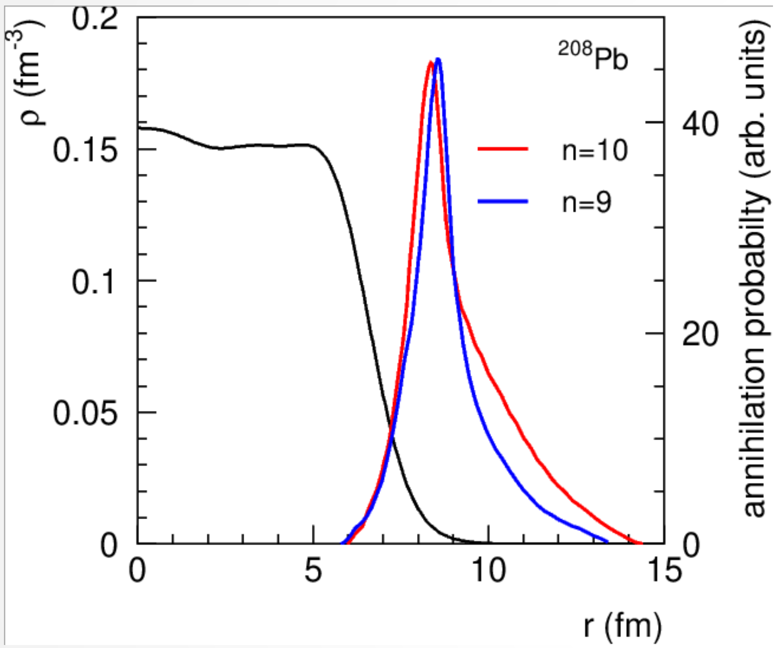
- irradiation: target with Al monitor foils
- measurement: off-line gamma spectroscopy (low-background)

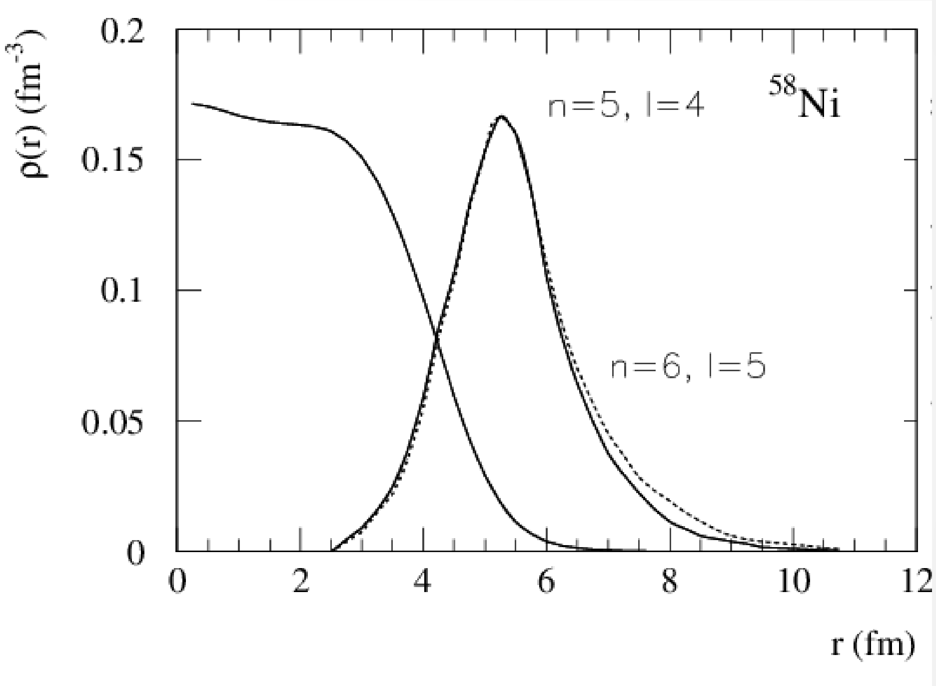
→ activity of of the products

- Al monitor foils → activity of ^{24}Na → pbar current

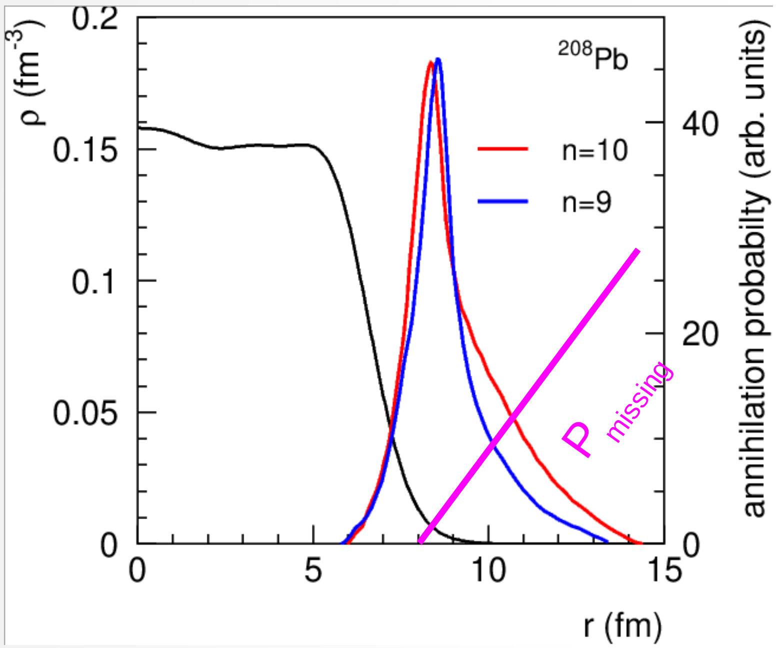
- irradiated target → $N(A_t - 1)$ → $N(N_t - 1) \sim \rho_n(r_{annih})$; $N(Z_t - 1) \sim \rho_p(r_{annih})$

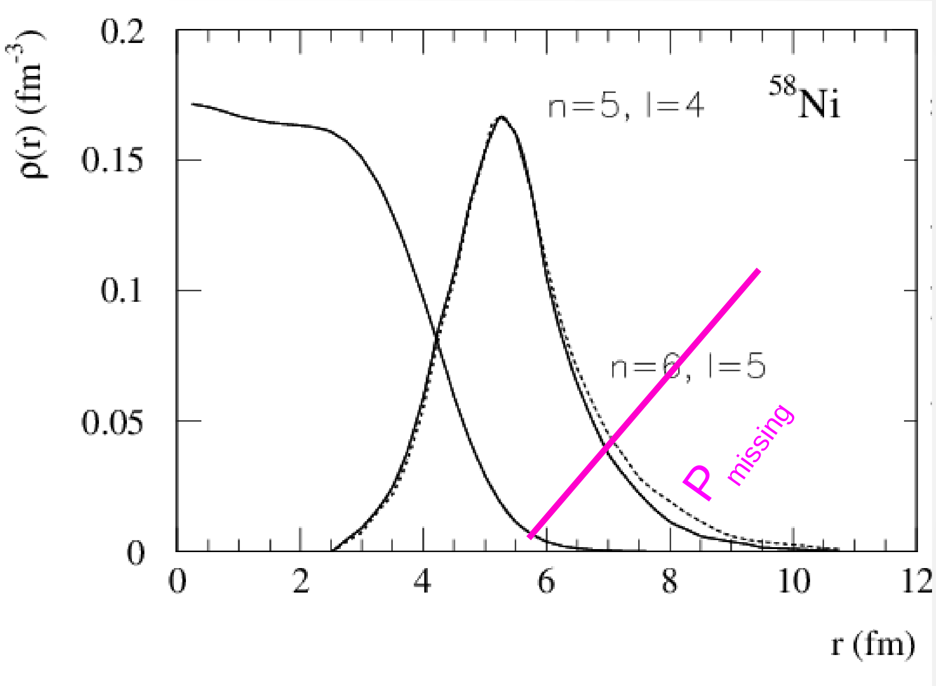
Antiprotonic atoms – anninihaltion





Antiprotonic atoms – anninihaltion





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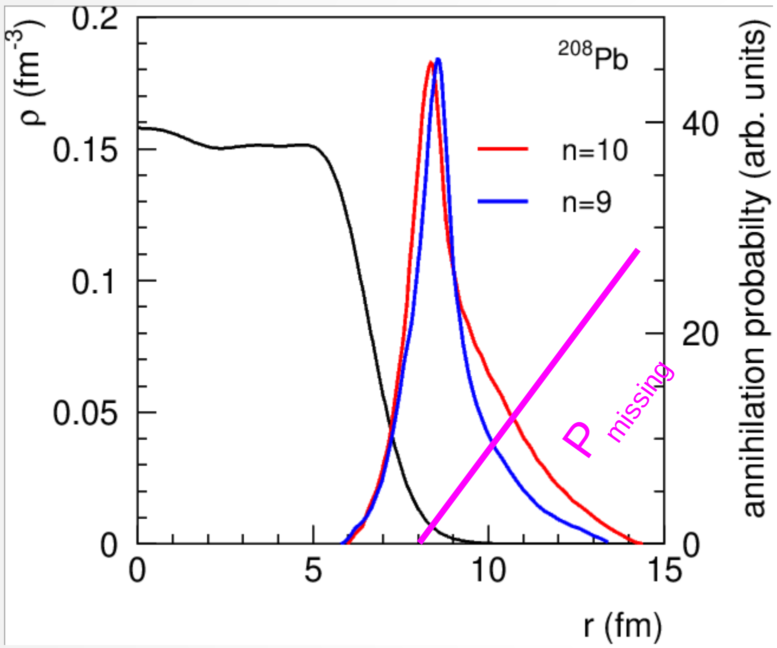
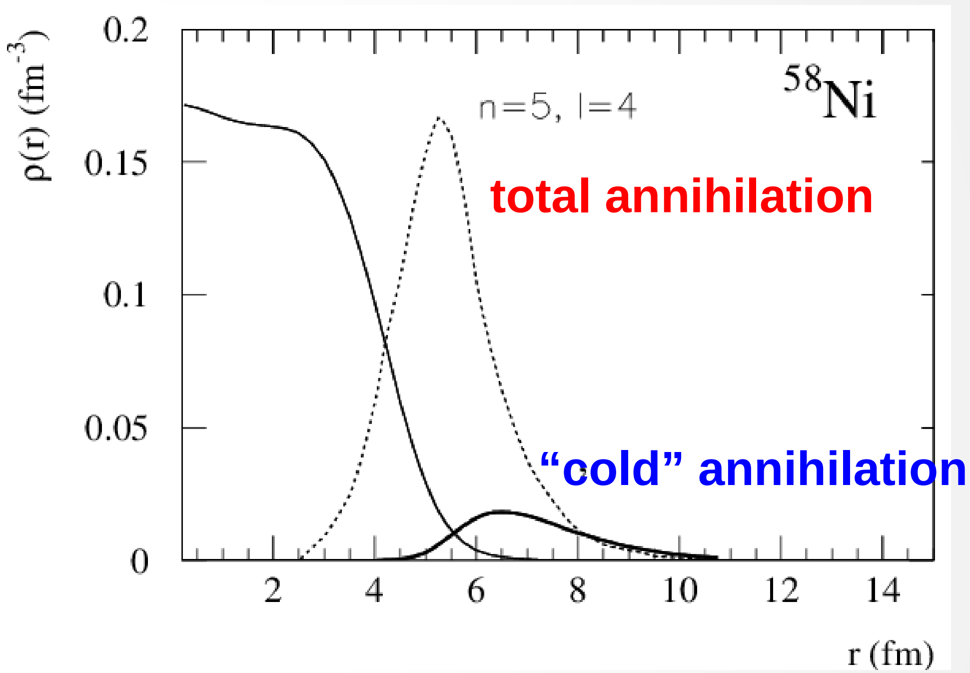
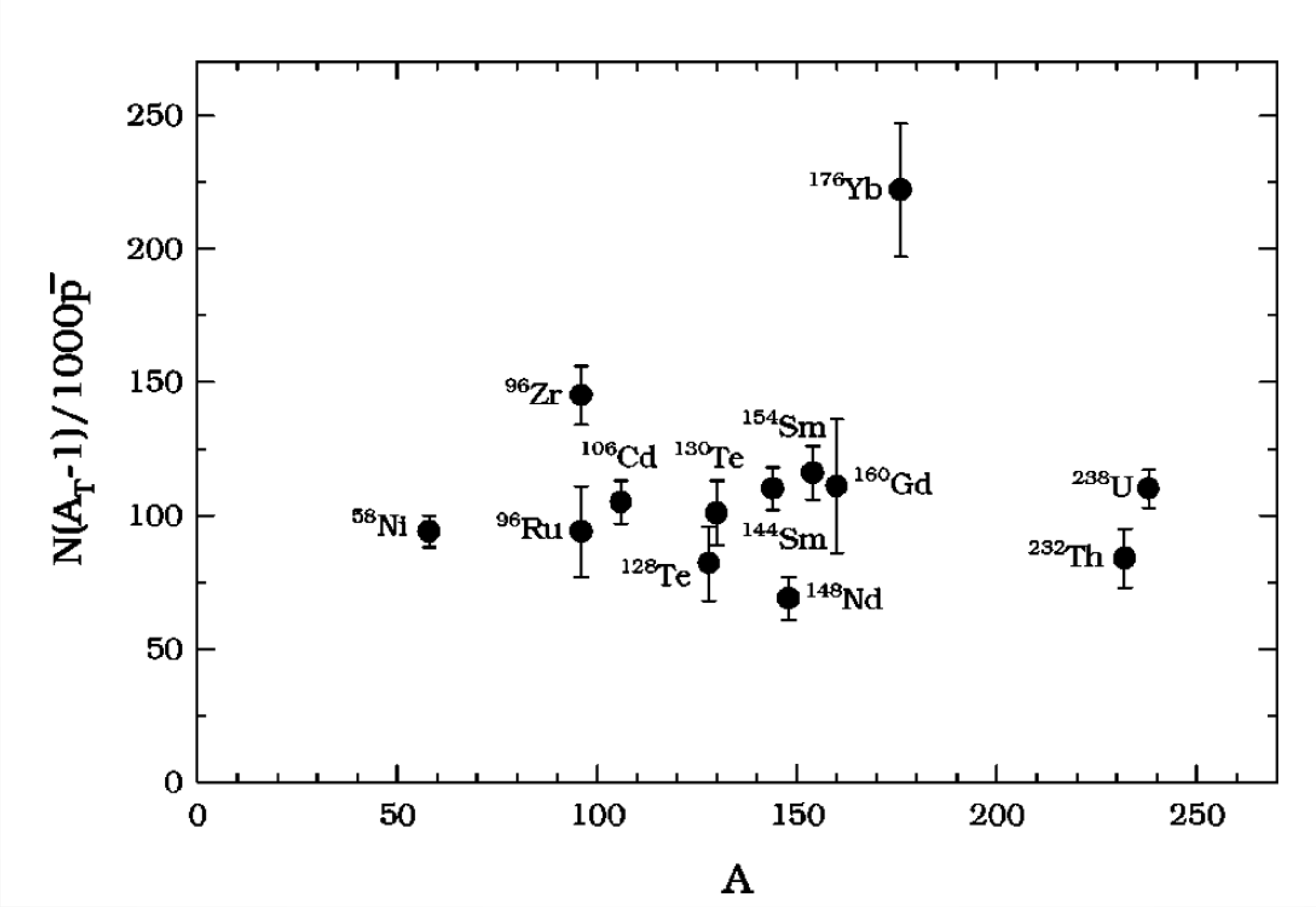




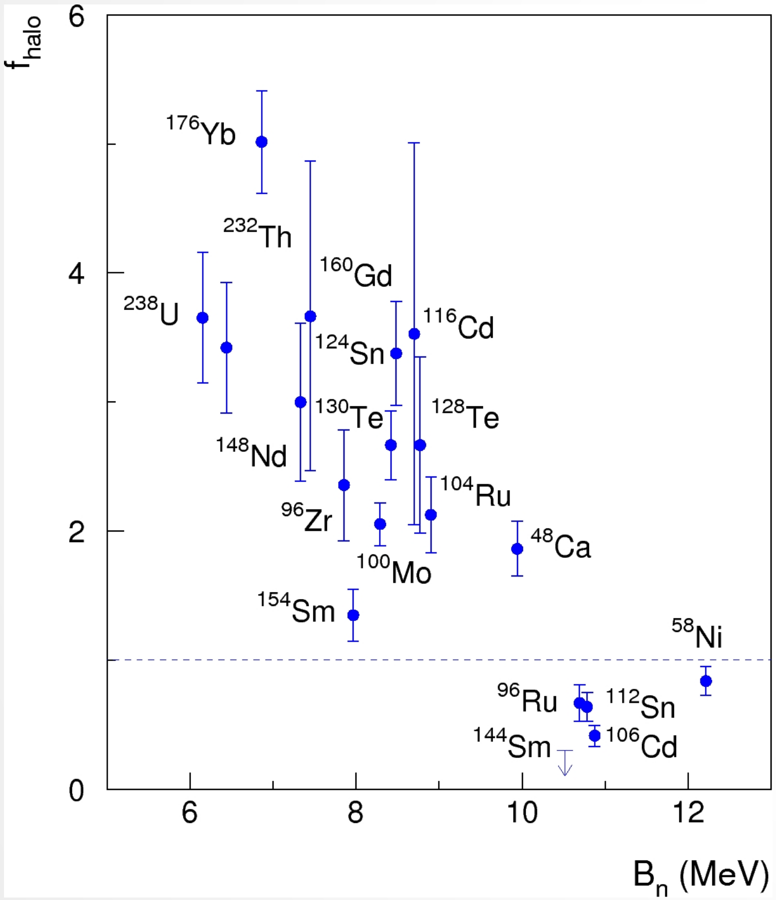
X-rays ~ $r_{1/2}$ + 1.5 fm

A_T-1 ~ $r_{1/2}$ + 2.5 fm

Antiprotonic atoms – A_T-1 production



halo factor



P. Lubiński et al., Phys. Rev. Lett. **73**(1994)3199

P. Lubiński et al., Phys. Rev. C **57**(1998)2962

R. Schmidt et al., Phys. Rev. C **60**(1999)054309

Observations:

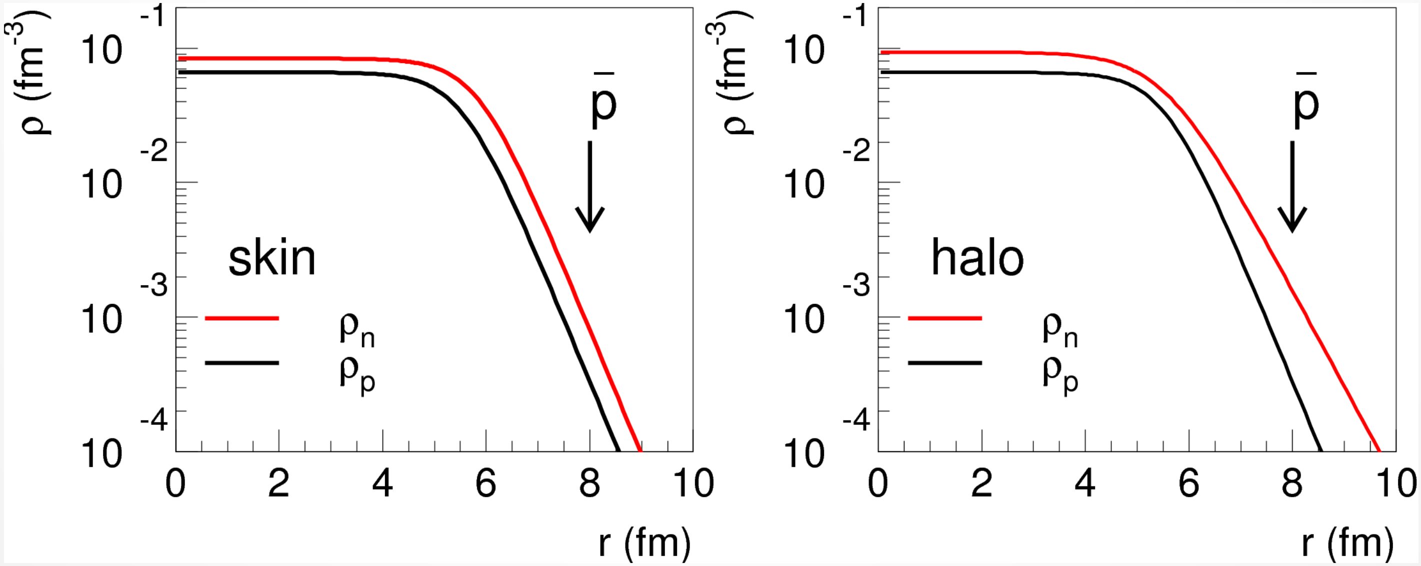
- strong correlation between f_{halo} and neutron separation energy B_n
- in nuclei with B_n < 9 MeV **nuclear periphery is reach in neutrons!**
- f_{halo} < 1 for nuclei with B_n > 10 MeV proton halo?? or NN bound state (S.Wycech)

halo factor → form of peripheral density distribution?

let's assume ρ in the form of 2pF: $\rho(r) = \rho_0 \cdot \left(1 + \exp\left(\frac{r-c}{a}\right)\right)^{-1}$

and consider 2 extreme situations:

- $a_n = a_p$, $c_n \neq c_p$ → Δr_{np} ("neutron skin")
- $a_n \neq a_p$, $c_n = c_p$ → Δr_{np} ("neutron halo")



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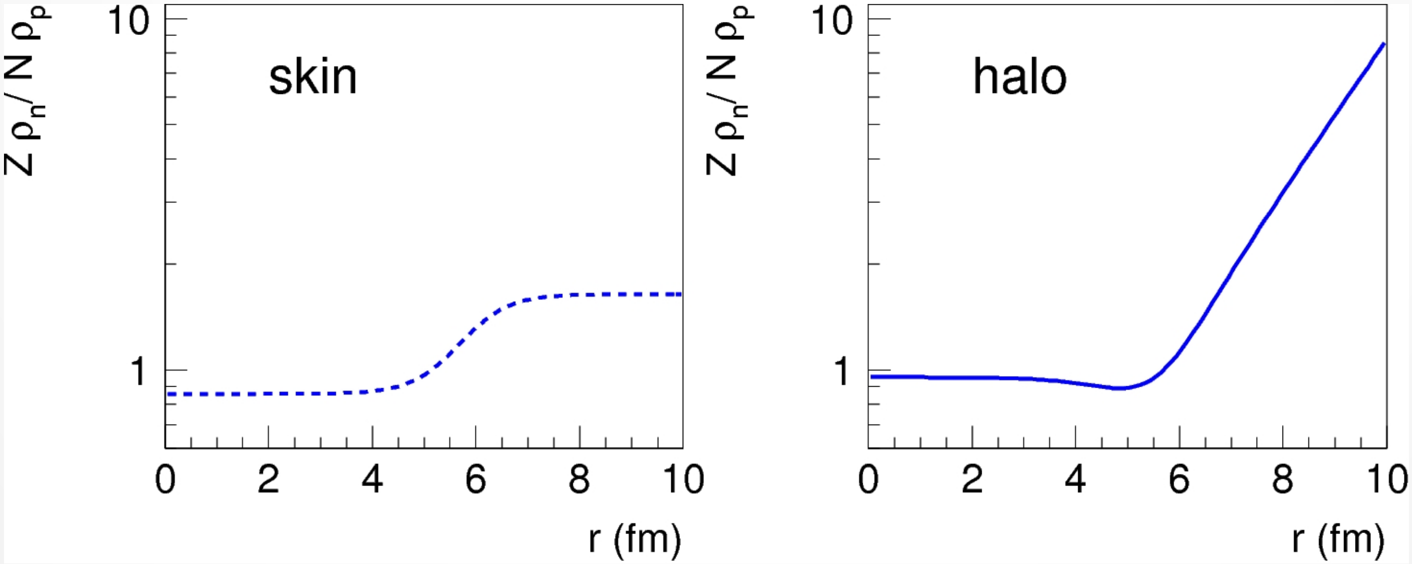

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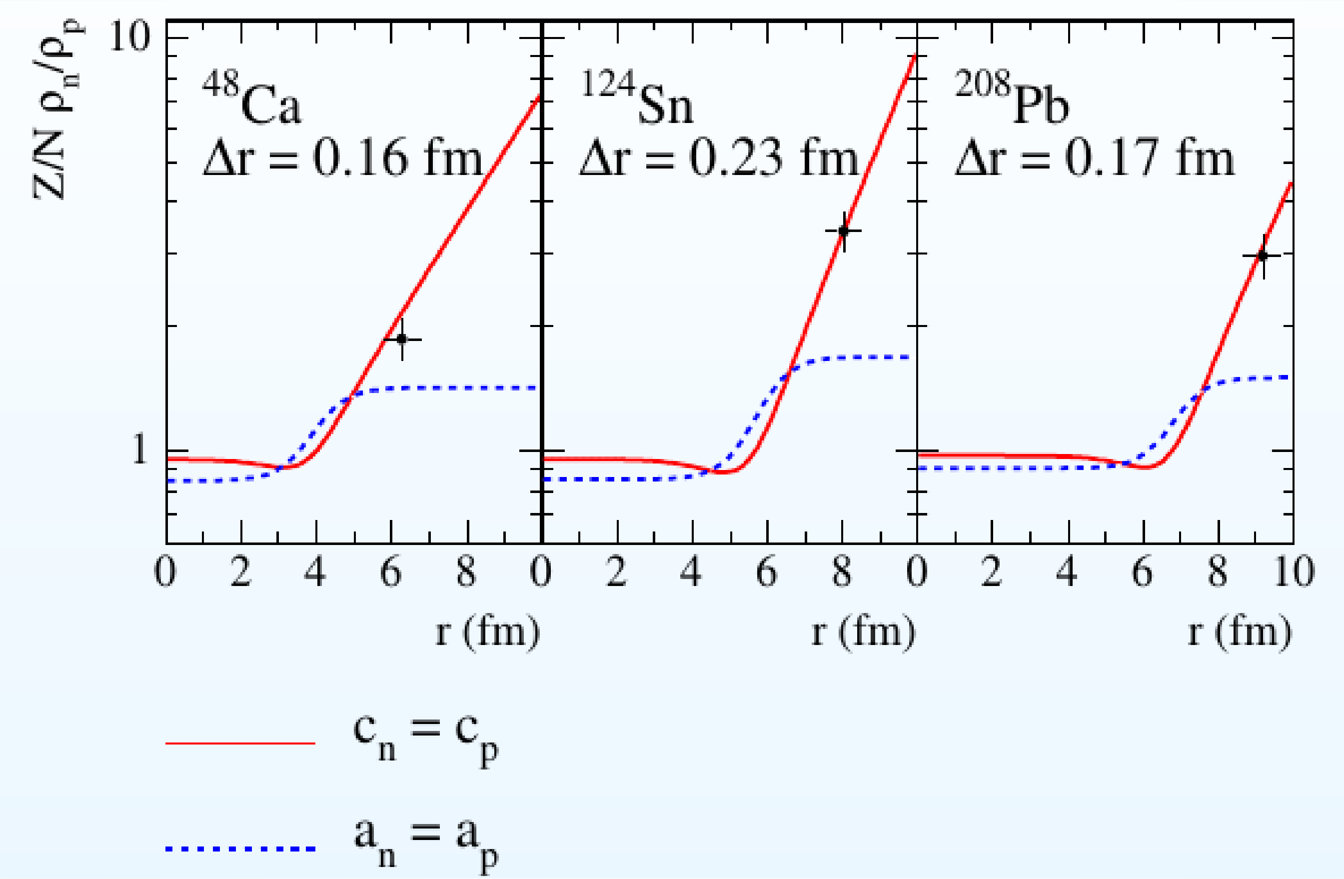


Δr_{np} is caused rather by $a_n \neq a_p$ than by $c_n \neq c_p$

antiprotonic atom X rays as nuclear surface probe

antiproton atom X rays → good tool for investigation of the nuclear periphery:

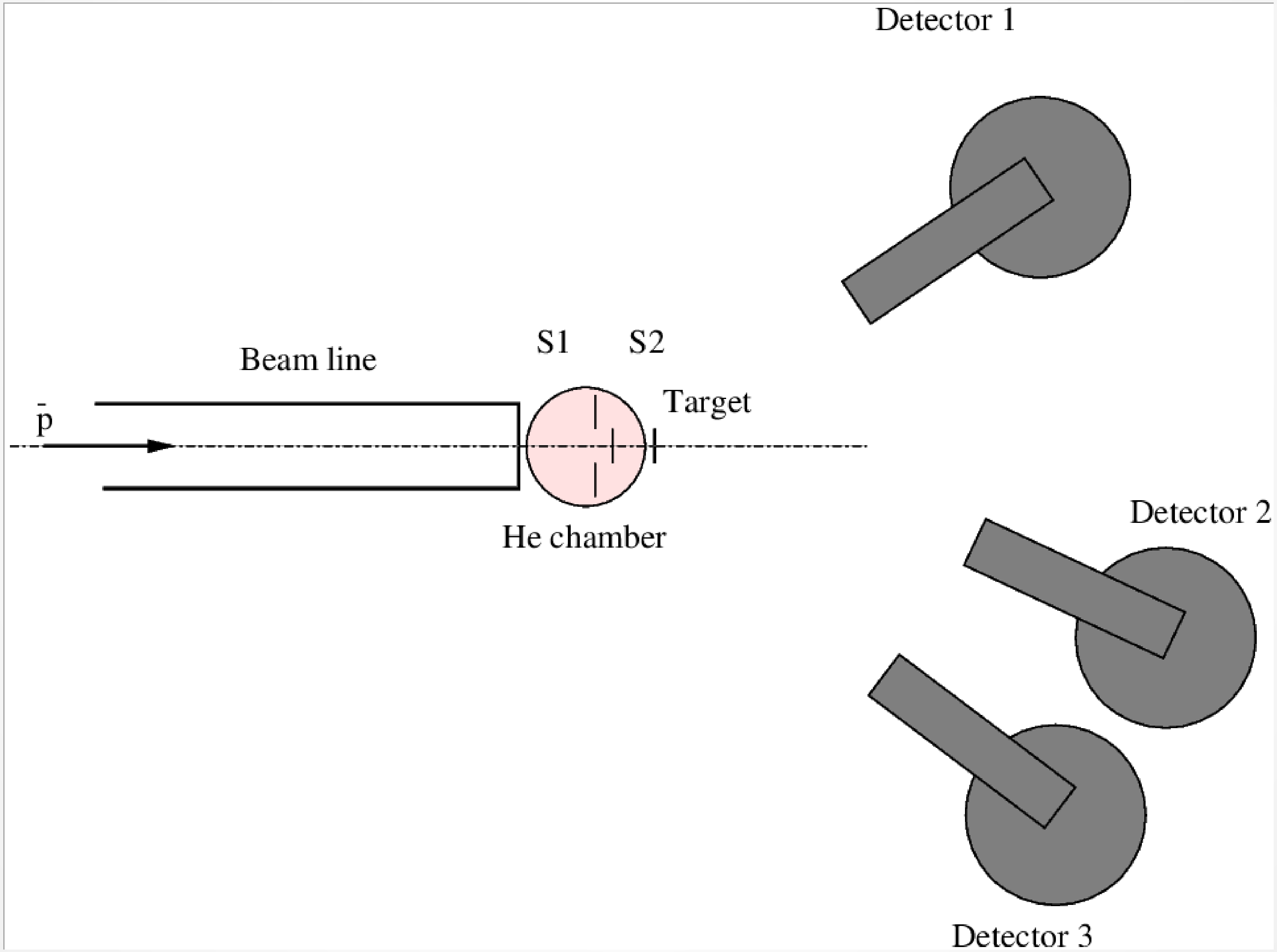
strong interaction **level width** and **shift** depend on the $\boldsymbol{\rho_p}$ and $\boldsymbol{\rho_n}$

via antiproton-nucleus potential:

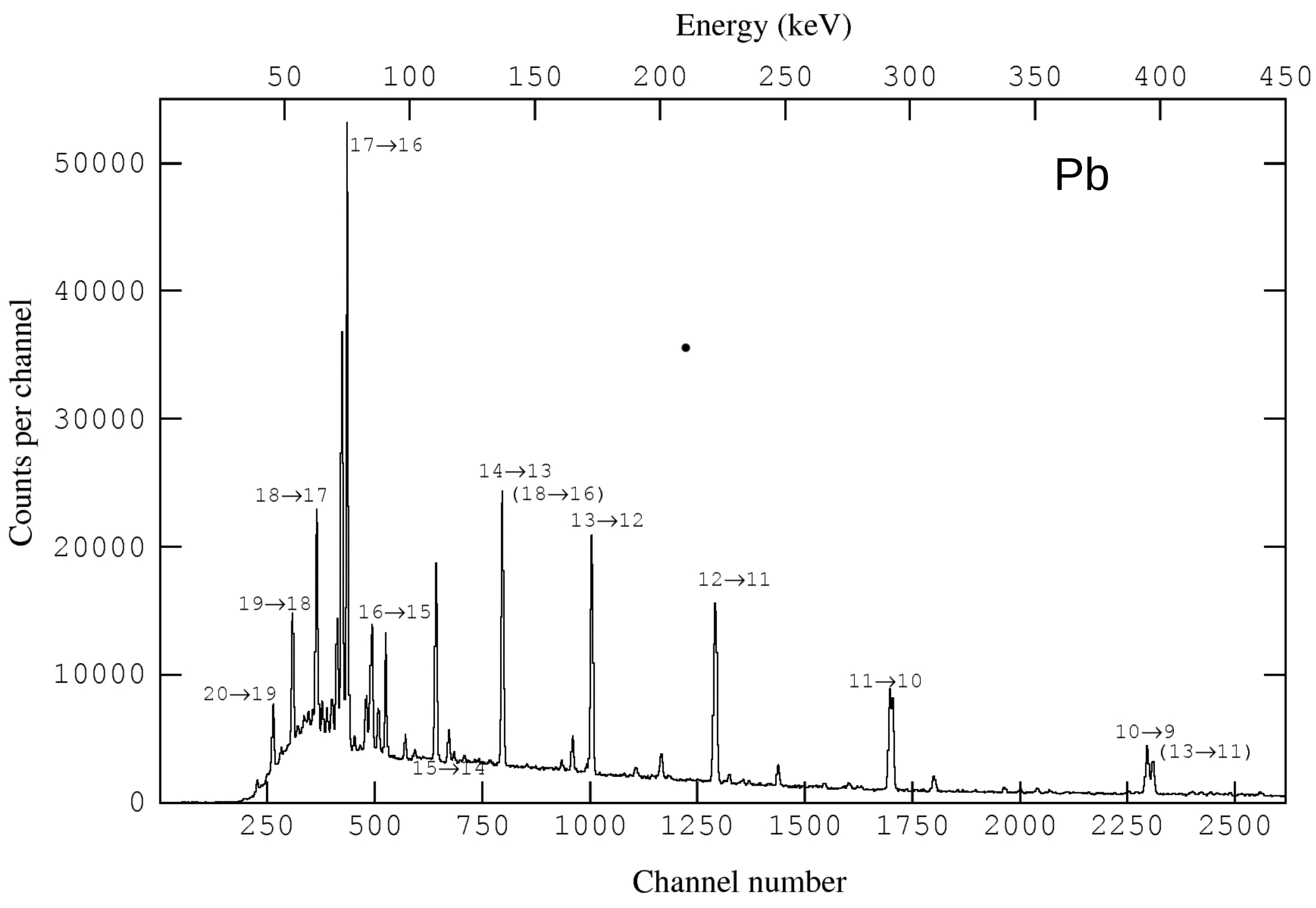
$$\epsilon/2 \sim \int \left(\Psi(r)^2 \right) \Re\left[V^{opt}(r,\rho) \right] d\bar{r}$$

$$\Gamma/2 = -\int \left(\Psi(r)^2 \right) \Im\left[V^{opt}(r,\rho) \right] d\bar{r}$$

Experimental set-up



Antiprotonic atoms X rays



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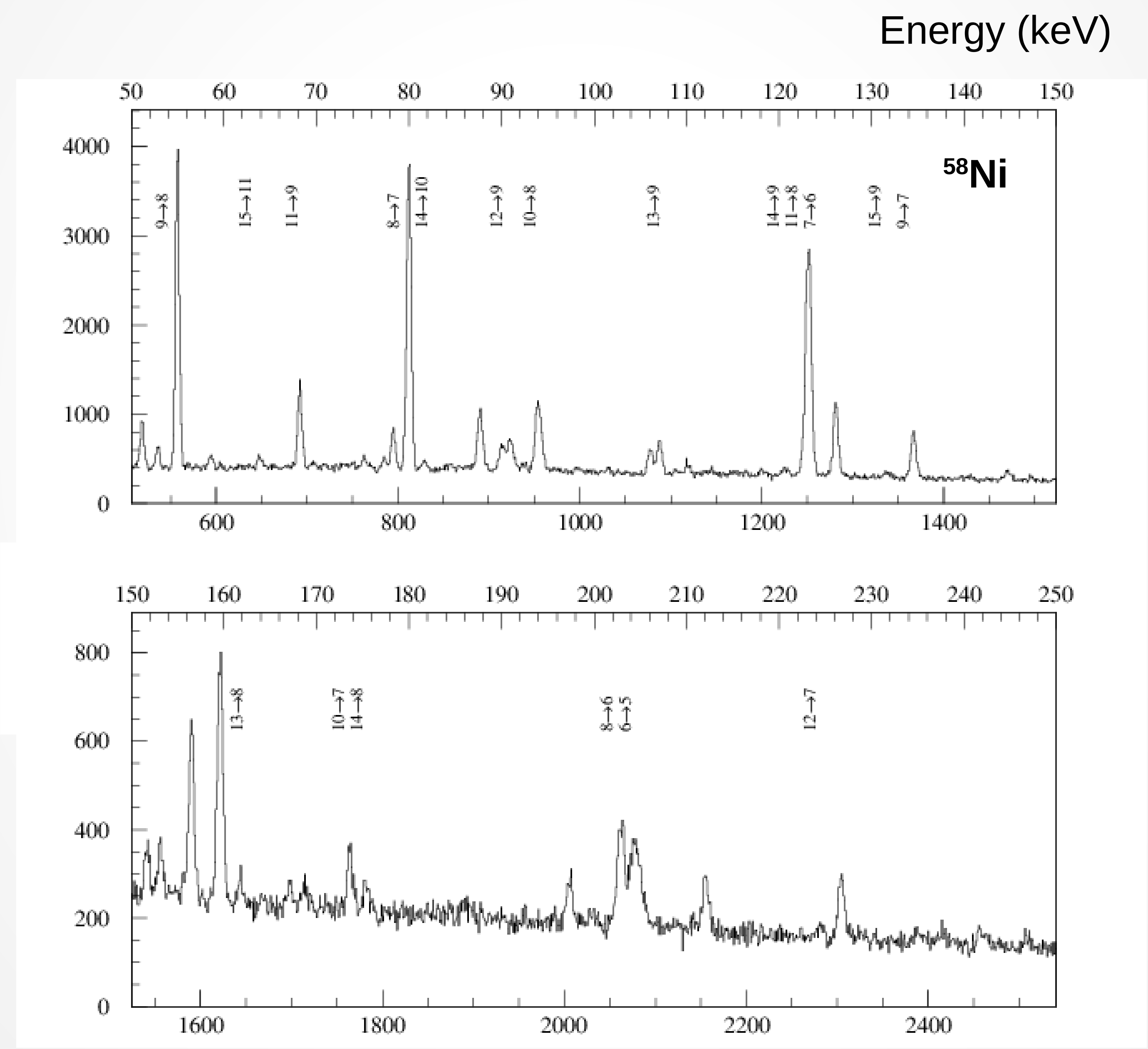
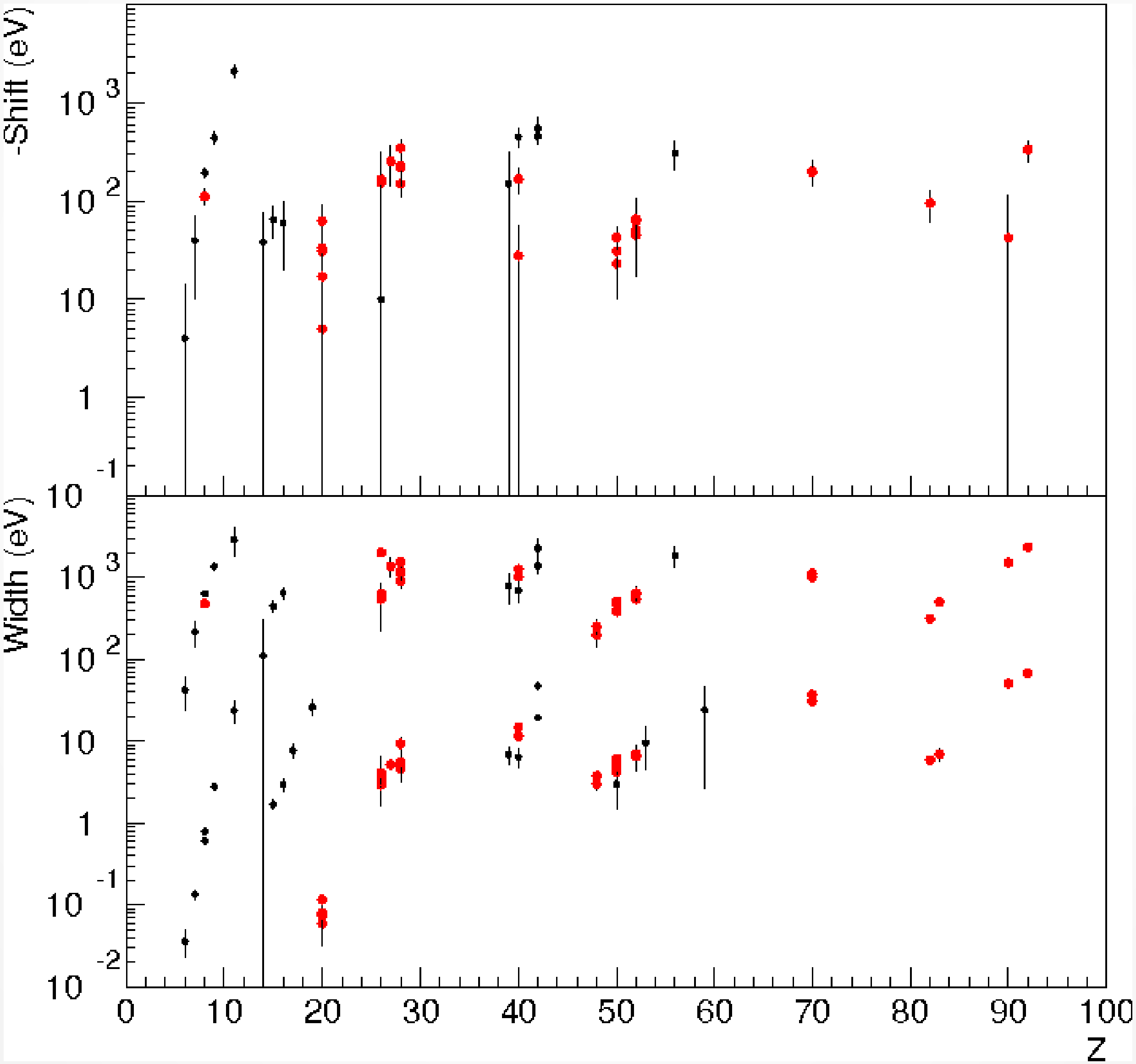
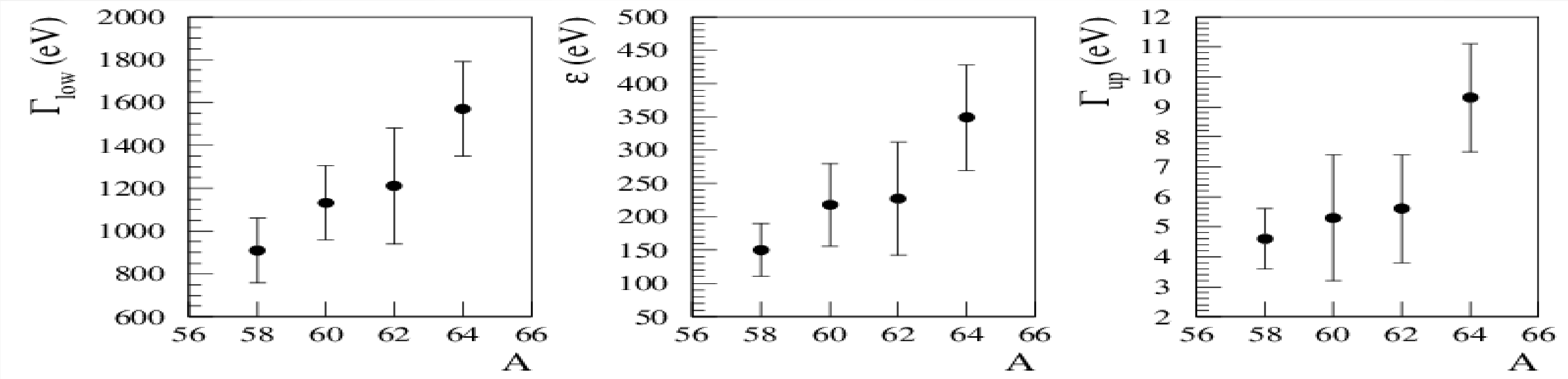


harvest of PS209 experiment

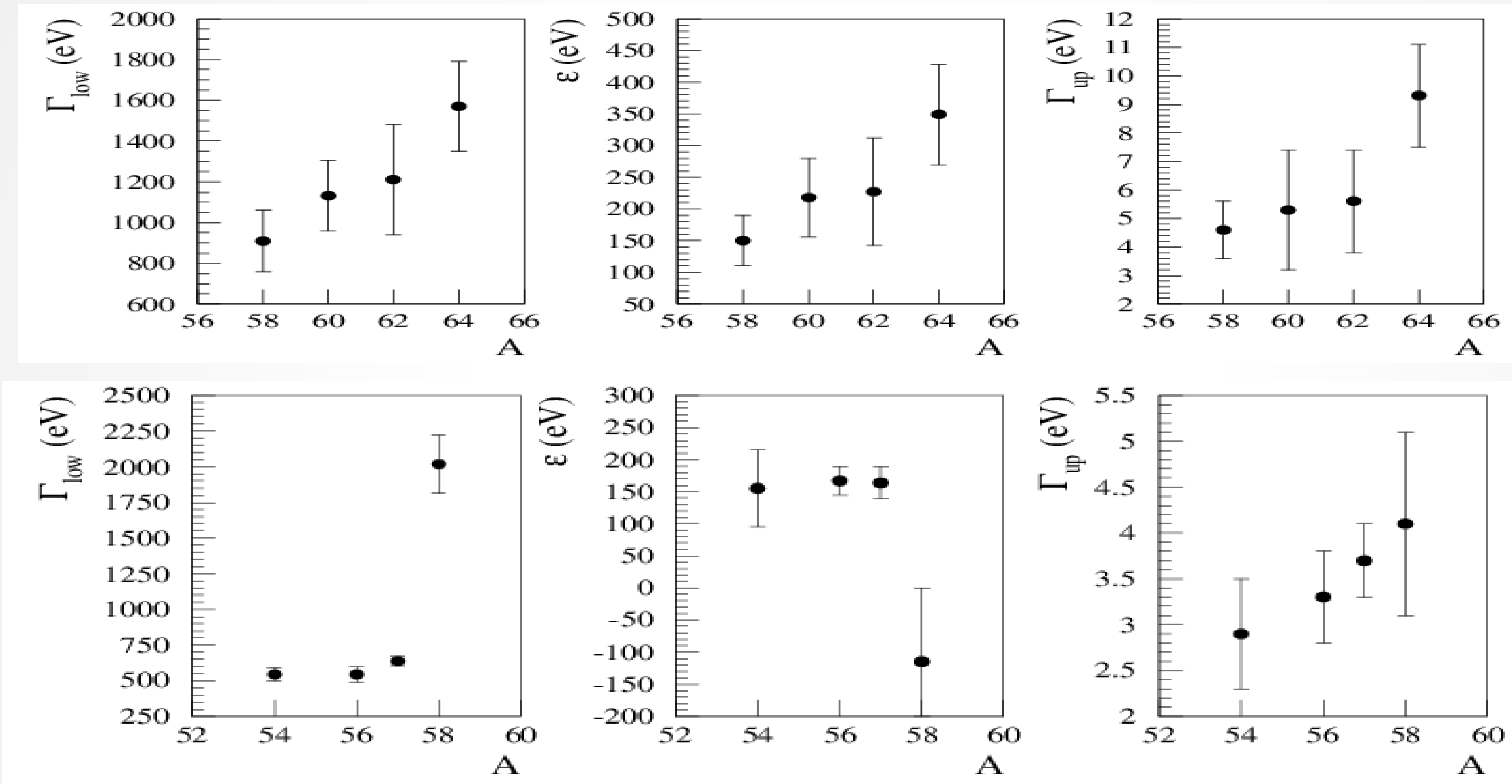


Isotopic effects



Ni

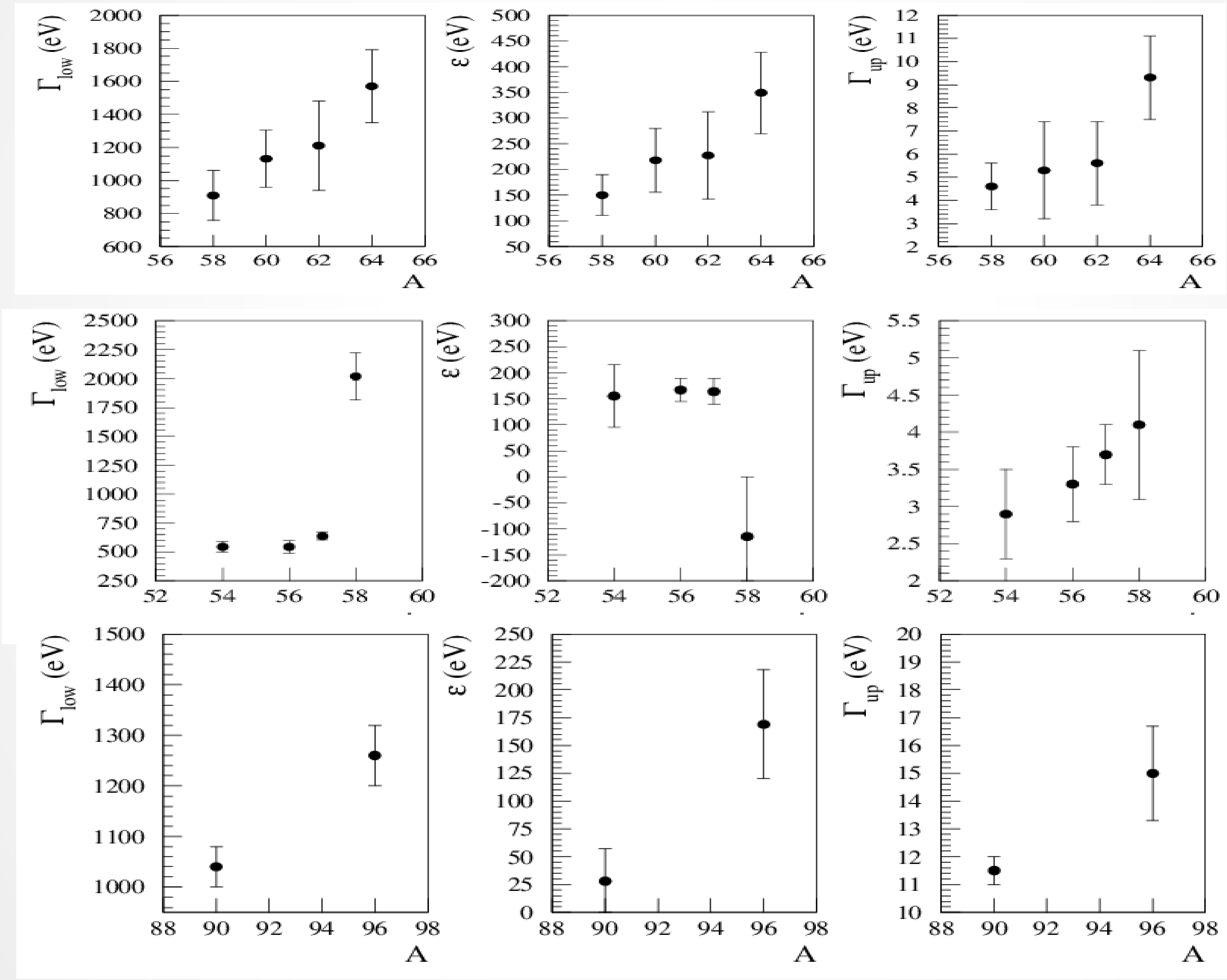
Isotopic effects



Ni

Fe

Isotopic effects

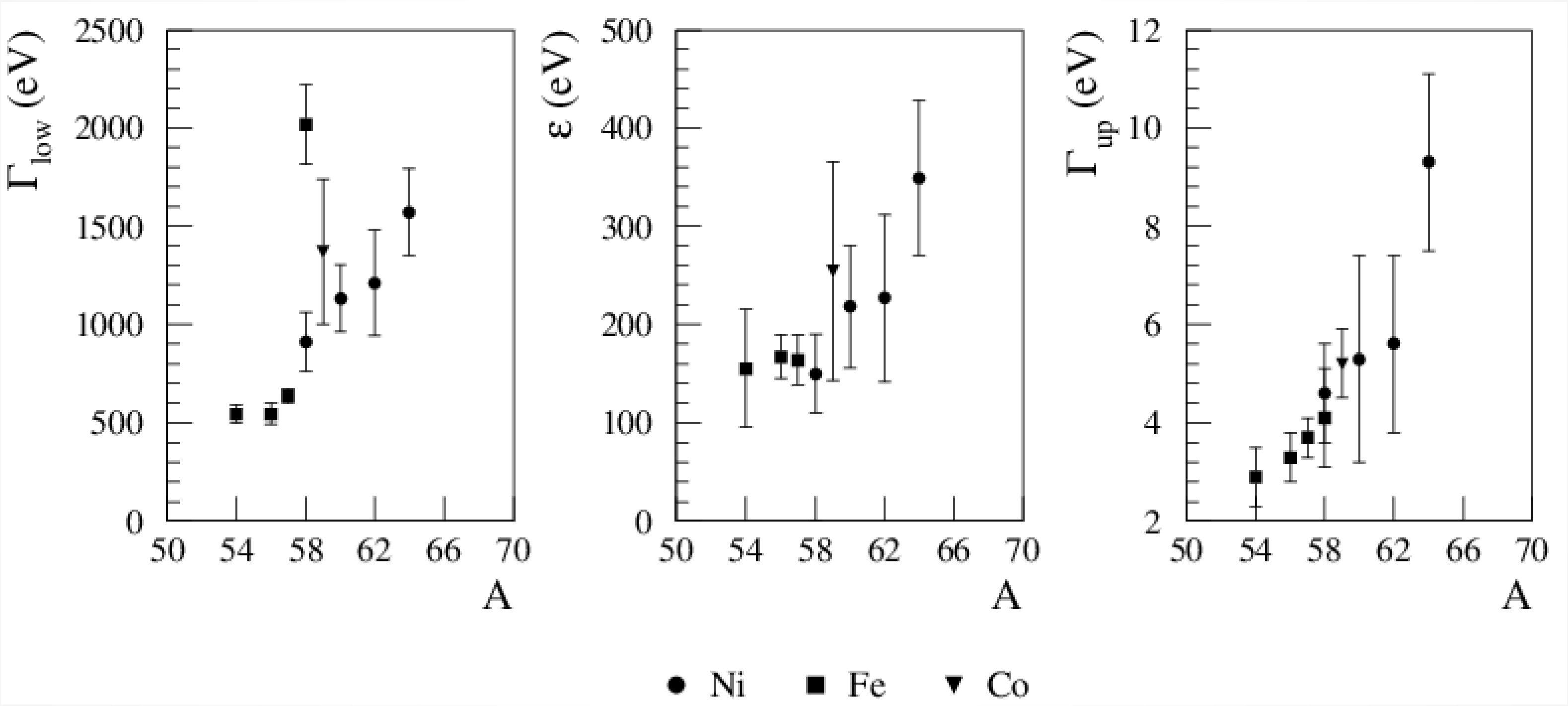


Ni

Fe

Zr

Isotopic effects



antiprotonic atom X rays as nuclear surface probe

- known:
  - ρ_p (from electromagnet. interacting probes: e, μ) - *well known?*
  - V_{opt} (ρ_p, ρ_n)
- assumed:
  - 2-parameter-Fermi density distribution
  - $c_n = c_p$ (information from comparison of f_{halo} and Δr_{np})
- fit: $a_n(V_{opt}, \Gamma_{low}, \Gamma_{up})$

⇨ ρ_n (c_n, a_n)

ρ_n for 26 isotopes deduced (from ^{40}Ca up to ^{238}U)

antiprotonic atom X rays as nuclear surface probe

zero range N$\bar{N}$ interaction

$$V_{opt} = \frac{-2\pi}{\mu}(\bar{a}_n \rho_n(r) + \bar{a}_p \rho(r)) \quad \text{where} \quad \bar{a}_n = \bar{a}_p = 2.5 + 3.4 \cdot i$$

C.J. Batty Nucl. Phys. **A592** (1995) 487

finite range N$\bar{N}$ interaction

$$V_{opt} = \frac{-2\pi}{\mu}\left(1 + \frac{\mu}{M}\frac{A-1}{A}\right)[b_0(\rho_n(r) + \rho_p(r)) + b_1(\rho_n(r) - \rho_p(r))]$$

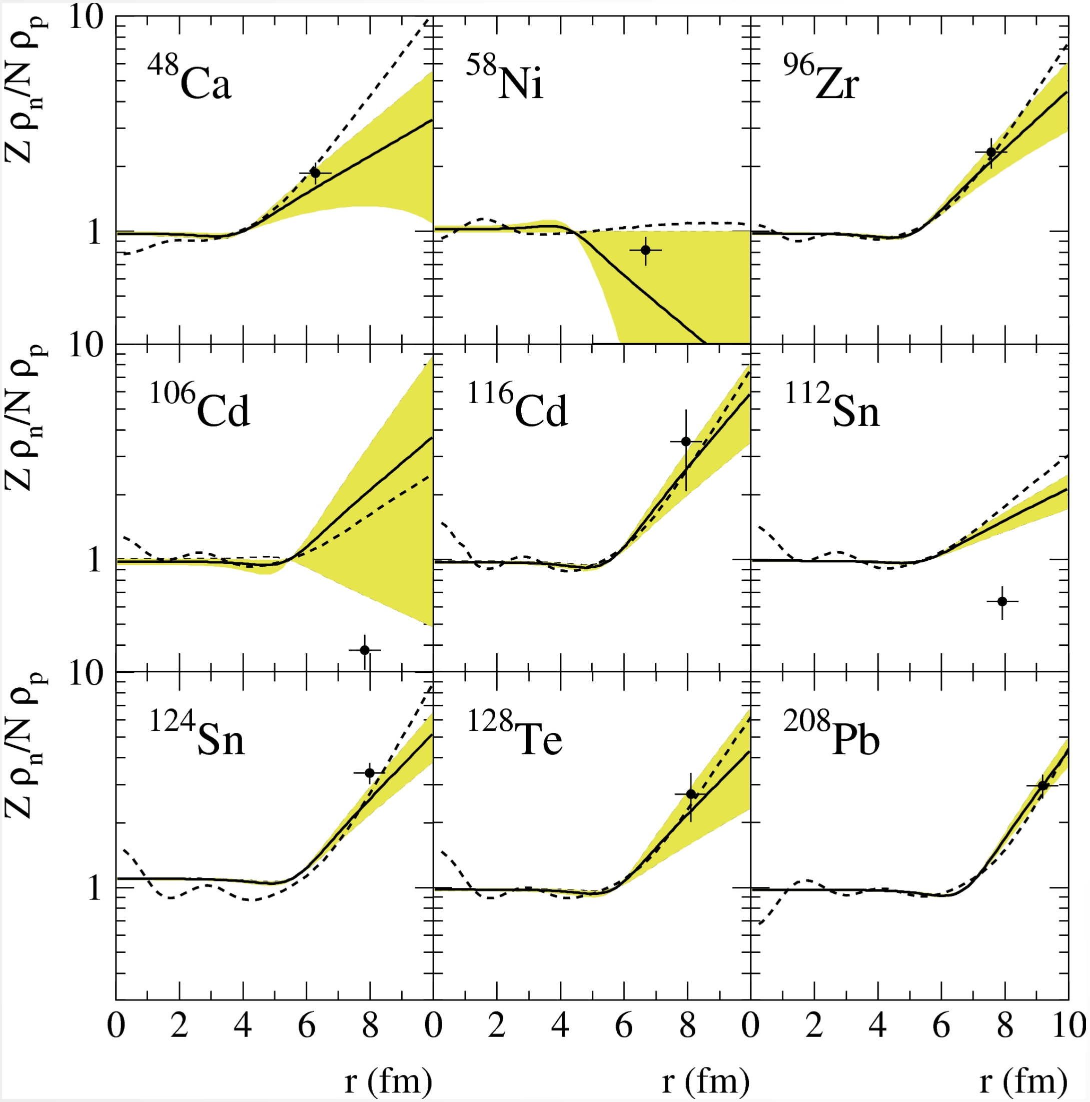
E. Friedman Nucl. Phys. **A761** (2005) 283

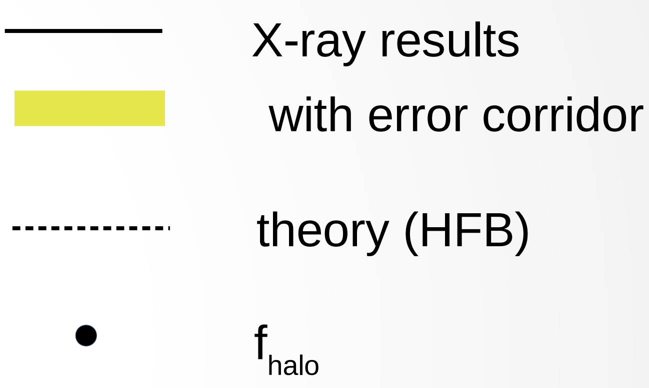
$$V^{opt} = \Sigma_{p,n}[V_S(r) + \nabla V_P(r)\nabla] = V_S + \hat{V}_P$$

$$V_{S,P}(r) = \frac{2\pi}{\mu_{\bar{N}N}} a_{S,P} \int d\mathbf{u}\, g_{S,P}(\mathbf{u})\rho(\mathbf{r} - \mathbf{u})$$

S. Wycech Phys. Rev. C **76** (2007) 034316

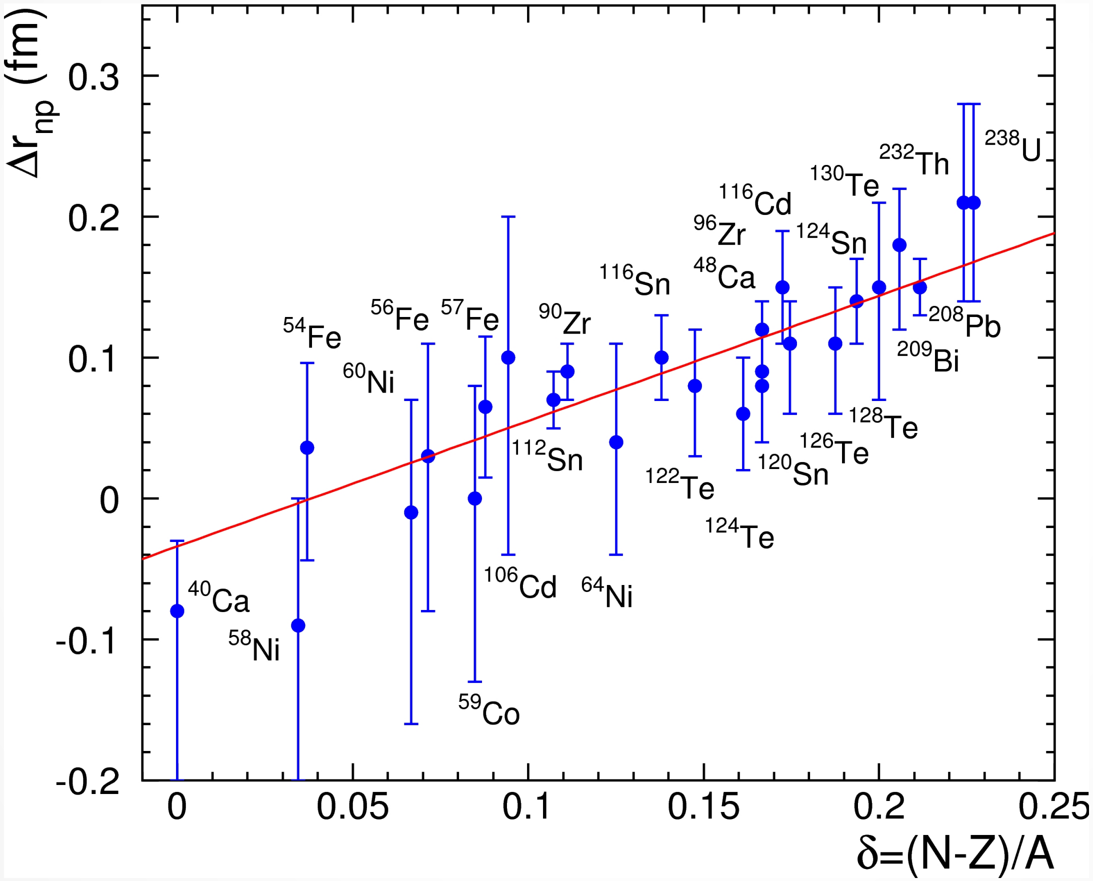
antiprotonic atom X rays as nuclear surface probe





Δr_{np}

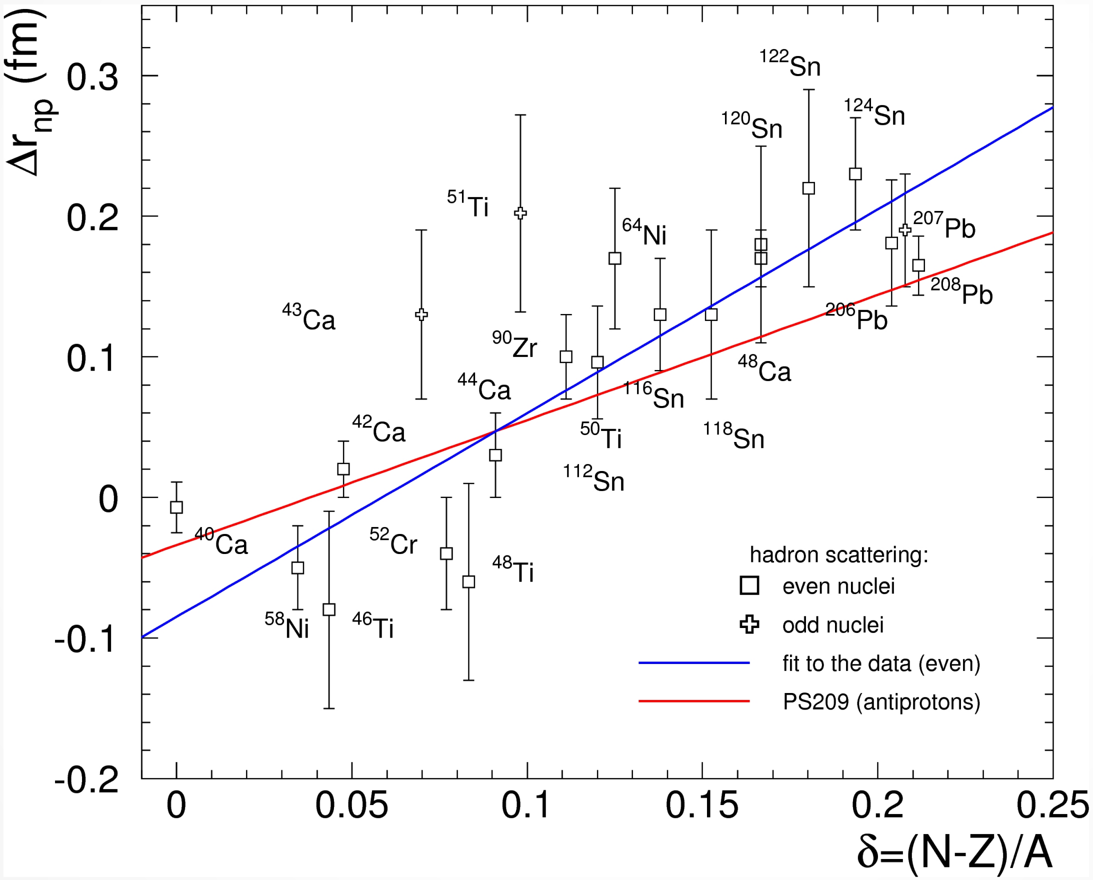
$\rho_p (c_n, a_n), \rho_n (c_n, a_n) \rightarrow \Delta r_{np}$



$$\Delta r_{np} = (-0.03 \pm 0.02) + (0.90 \pm 0.15) \cdot \delta$$

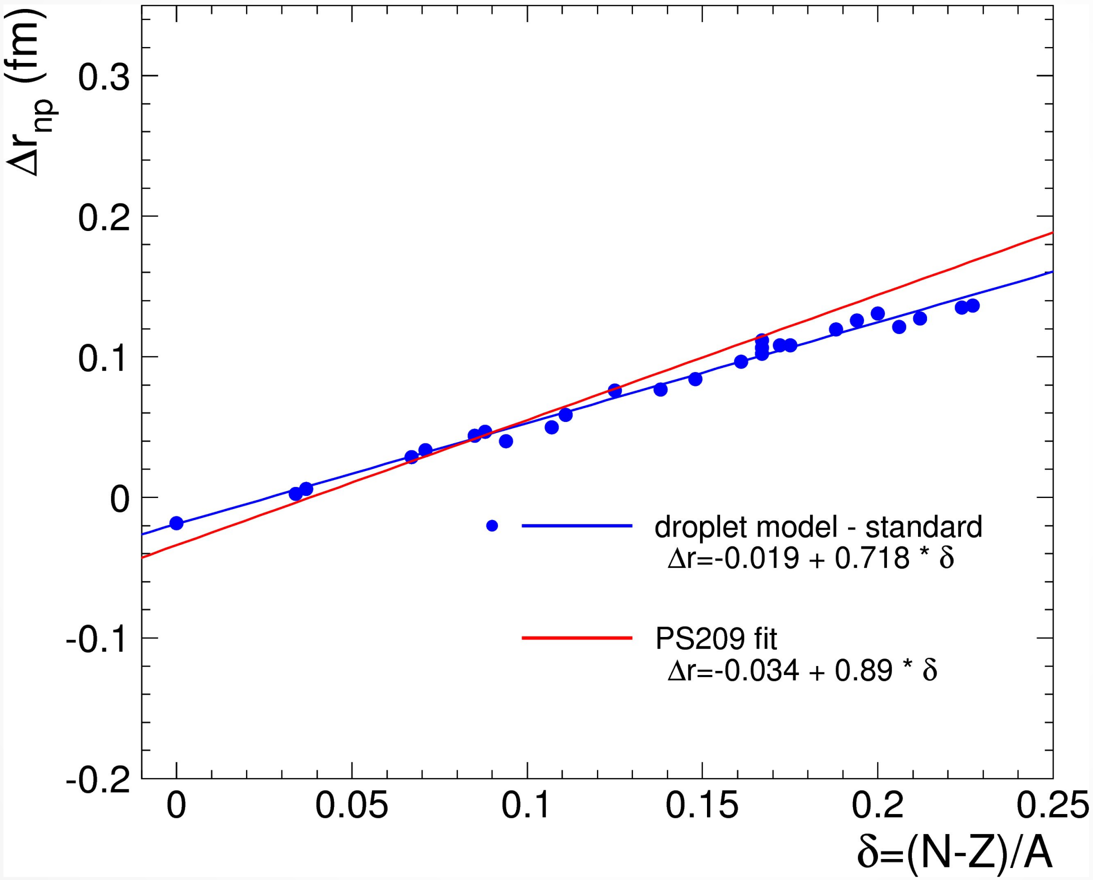
Δr_{np} – comparison with other experiments

$\rho_p (c_n, a_n), \rho_n (c_n, a_n) \rightarrow \Delta r_{np}$



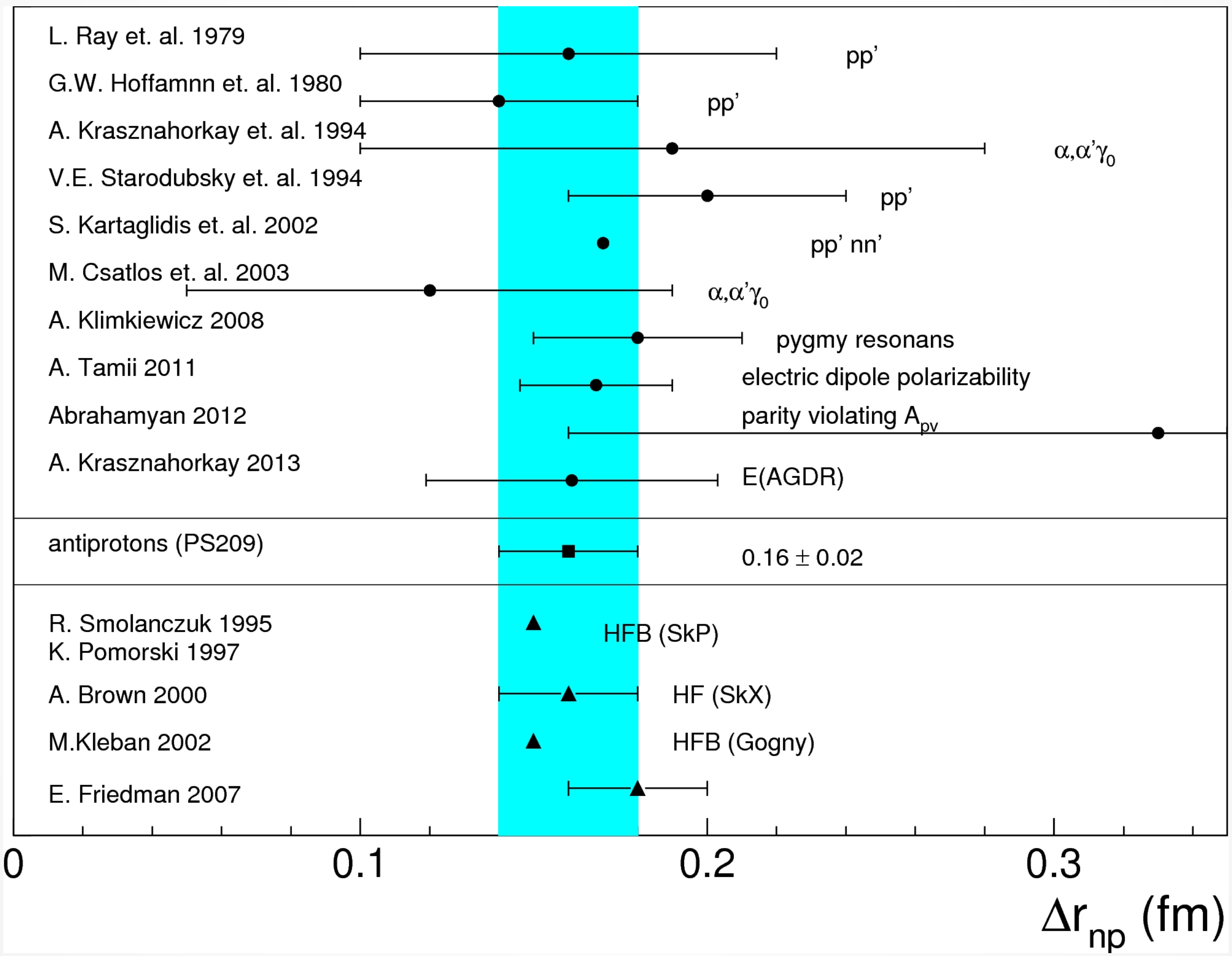
$$\Delta r_{np} = (-0.03 \pm 0.02) + (0.90 \pm 0.15) \cdot \delta$$

Δr_{np} – comparison with droplet model

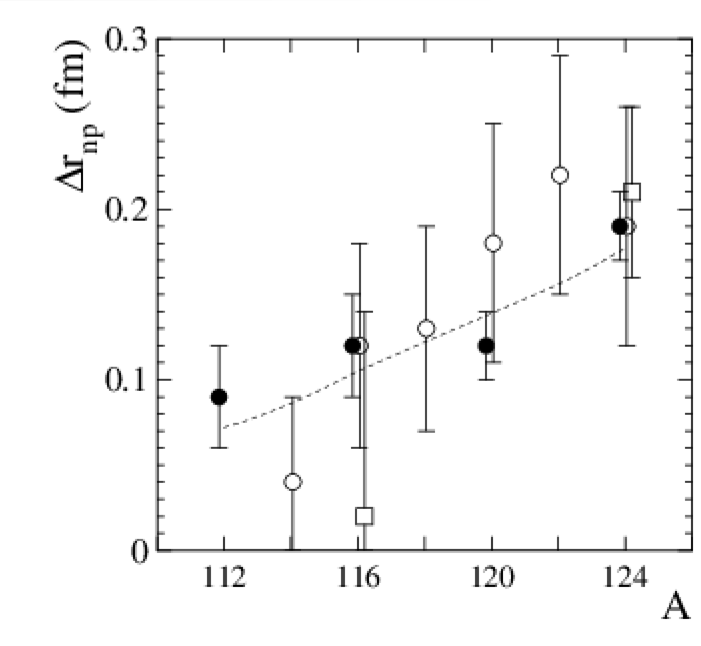


Droplet Model: D. Meyers, W. Swiatecki, Nucl. Phys. A336 (1980) 267

^{208}Pb Δr_{np} – comparison of the results



Sn Δr_{np} – comparison of the results



Sn

● antiprotonic atoms (PS209)

○ □ hardon probes

--------- HFB calculation

Summary

- Two experimental methods using antiprotonic atoms were applied to investigate nuclear periphery:
  - **radiochemical method** : ρ_n / ρ_p @ $r \approx c_{1/2} + 2.5$ fm
  - **antiprotonic X rays**: $(\rho_n + \rho_{p)}$ @ $\approx c_{1/2} + 1.5$ fm
- Reach set of **precise data** collected
  - base for nuclear periphery studies
  - ... and for optical potential construction
- Δr_{np} systematics deduced from the data
  - excellent agreement of Δr_{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)

Summary

- Open questions:
  - shifts - not reproduced with available potentials
  - poor agreement with pionic atom results
- Future ...
- Examples of interesting cases for continuation:
  - **Ca**: dobly-magic 40Ca and 48Ca isotopes (possible measurement of 3 levels for each isotope, study of the neutron halo evolution between N=20 and N=28
  - **odd-A isotopes** (eq. Sn) - study of unpaired nucleon effect, looking for LS effect
  - **deformed even-A nuclei**:
    - study of deeply-bound states via E2 resonacne
    - does deformation increases neutron-proton rms difference?
  - search for quasi-bound **pp** states - ??

PS209 Collaboration

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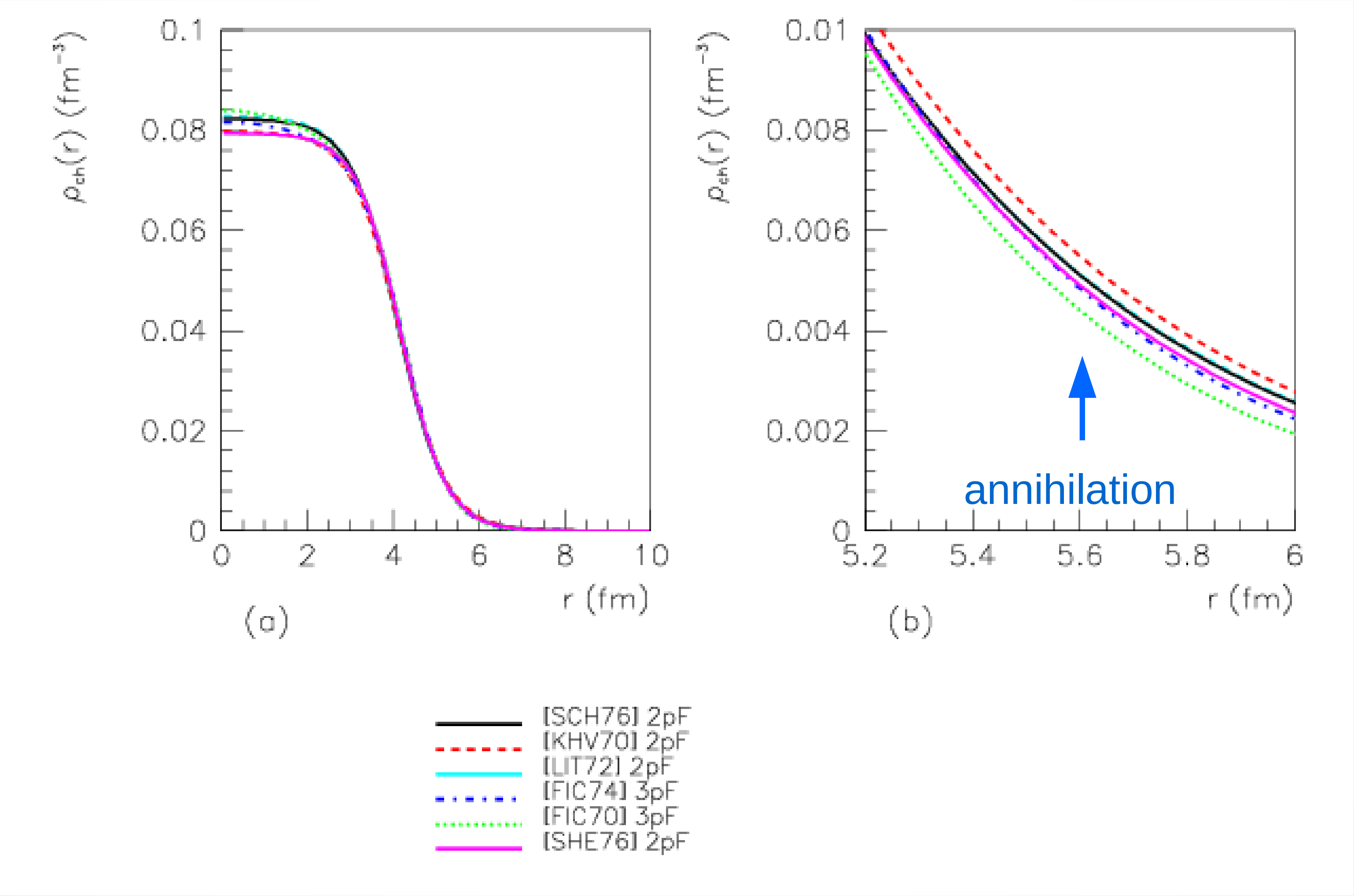
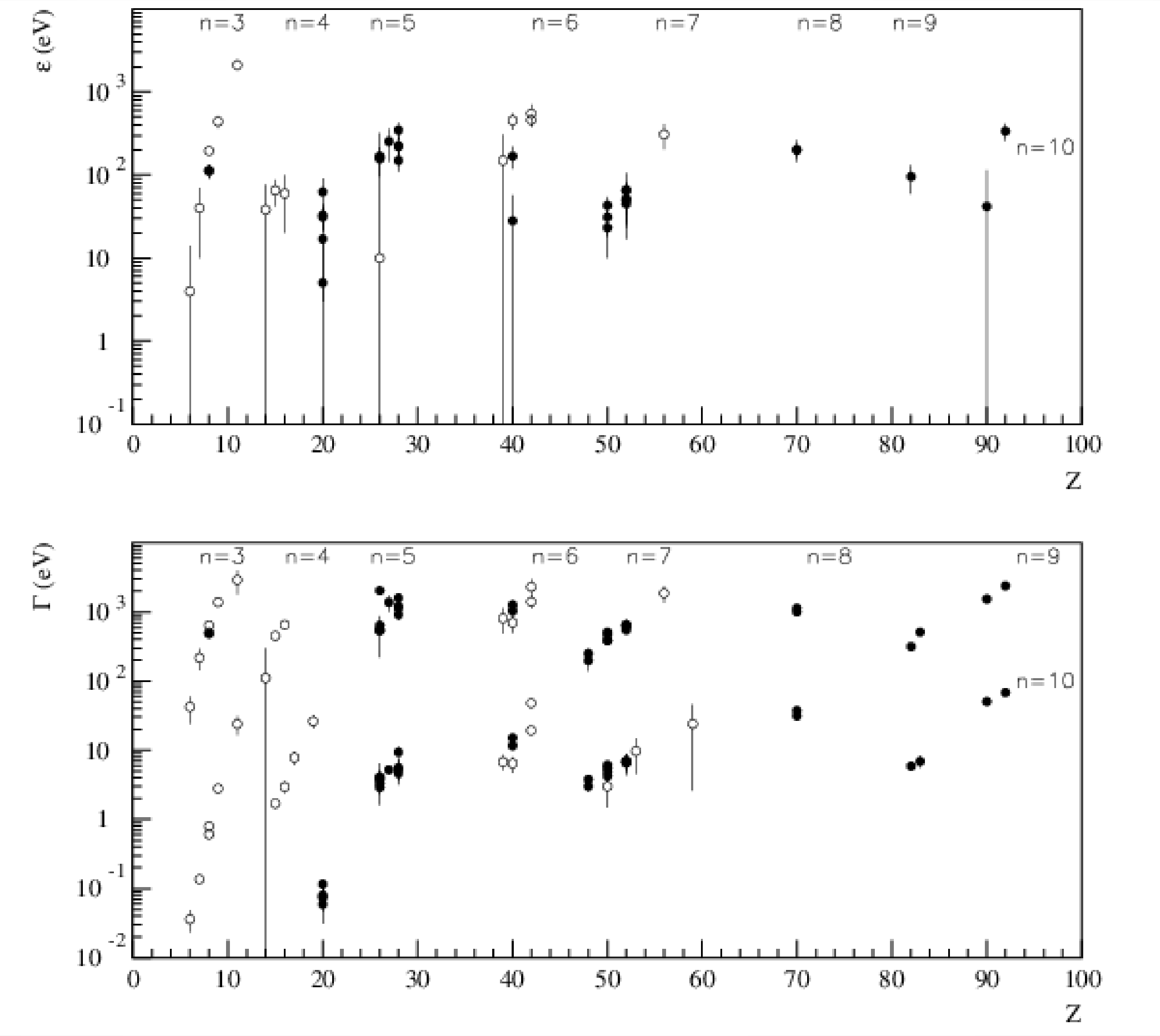
Thank you for the attention :)

Charge (proton) density distribution – realy well known??




ε (eV)
n=3
n=4
n=5
n=6
n=7
n=8
n=9
n=10
Z
Γ (eV)
n=3
n=4
n=5
n=6
n=7
n=8
n=9
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Z