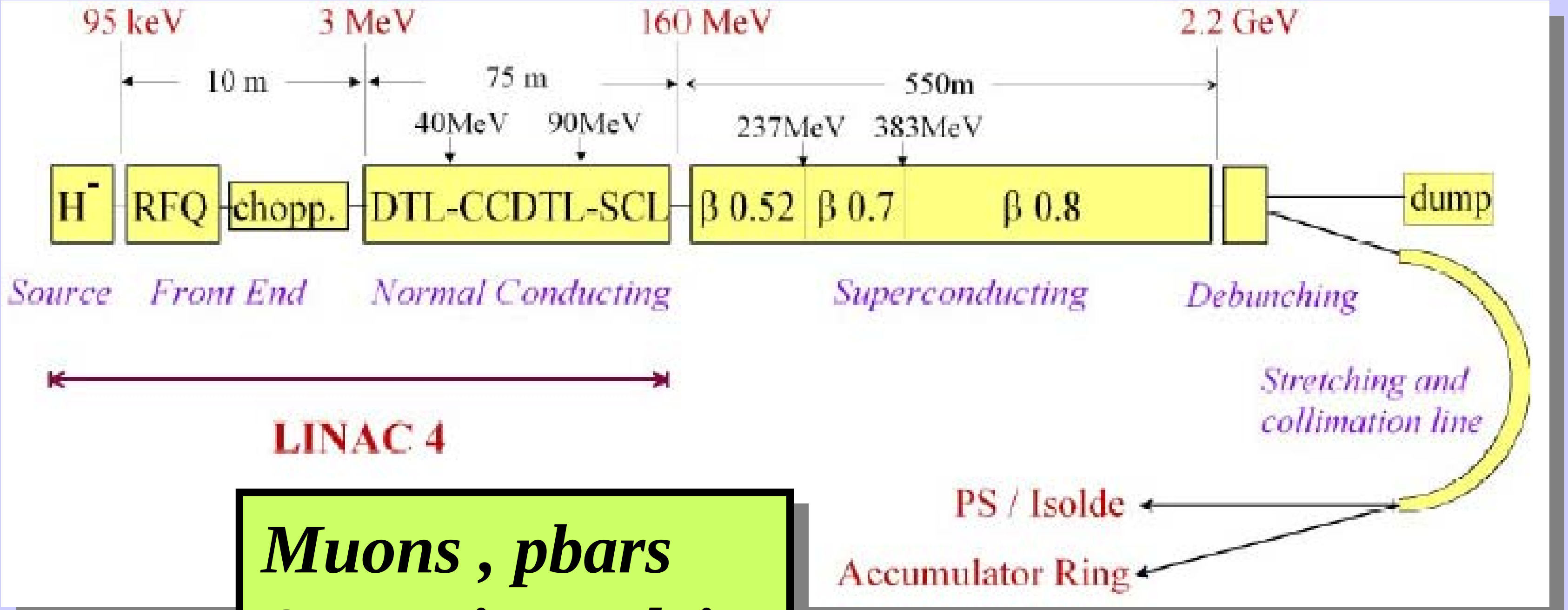
New approaches to the study of the nucleus

Juha Äystö



Muons , pbars
& Exotic nuclei

Thanks to H. Fynbo, K. Jungmann, P. Kienle, K.-H. Langanke,
M. Lindroos, T. Nilsson, K. Riisager,…

PHYSICS ISSUES ?

Explaining complex nuclei from basic constituents

Effective nuclear force – Origin of pairing interaction

Magic nuclei and shell structure far from stability

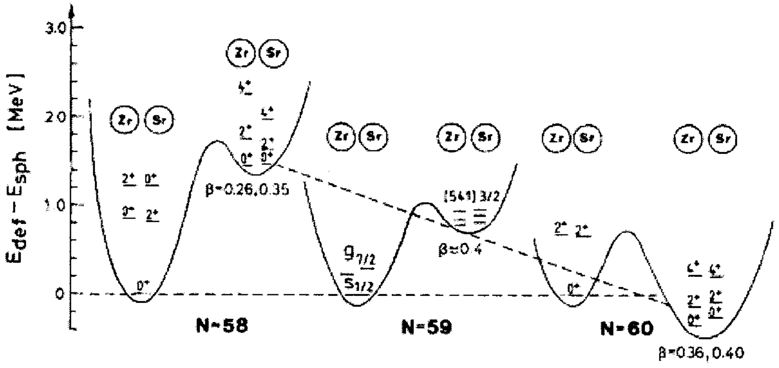
The size of the nucleus: halos and skins

Limits of nuclear existence and its implications

The end of Mendeleev's table: superheavy elements

Understanding the origin of elements
Testing the Standard Model
Applications in materials and life sciences

Example: neutron-rich Zr isotopes



"Ground state changes from spherical to deformed via coexistence"

Spectroscopic studies:

Beta decay experiments on ^{97}Zr, ^{99}Zr, ^{103}Zr

Prompt ff – γ ray coincidence experiments on

^{99}Zr: W. Urban et al., Eur. Phys. J. A16(2003)11

^{98,99}Zr: Nucl. Phys. A689(2001)605

^{100}Zr. C.Y. Wu et al., Phys. Lett. B541(2002)59

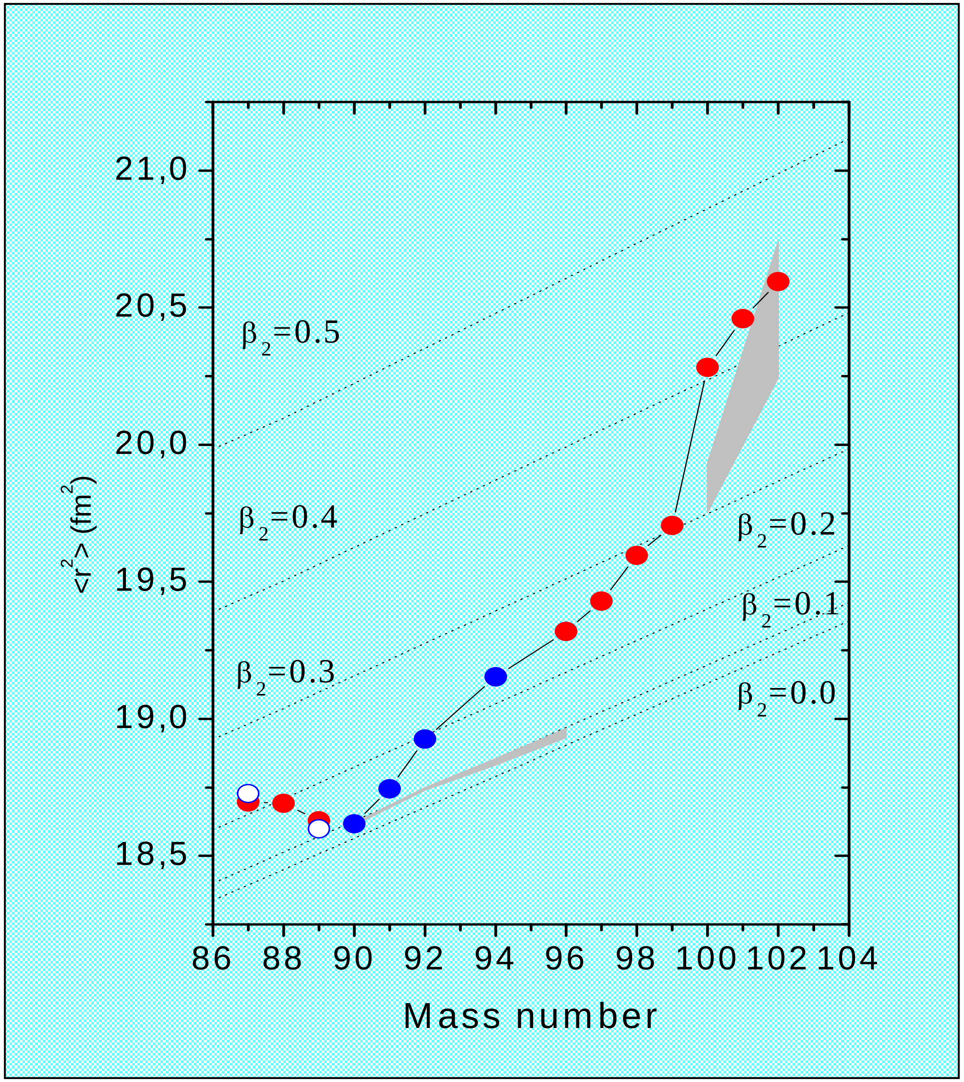
Collinear laser spectroscopy

$^{96\text{-}102}$Zr: P. Campbell et al., Phys. Rev. Lett. 89(2002)082501

Direct mass measurements with a Penning trap

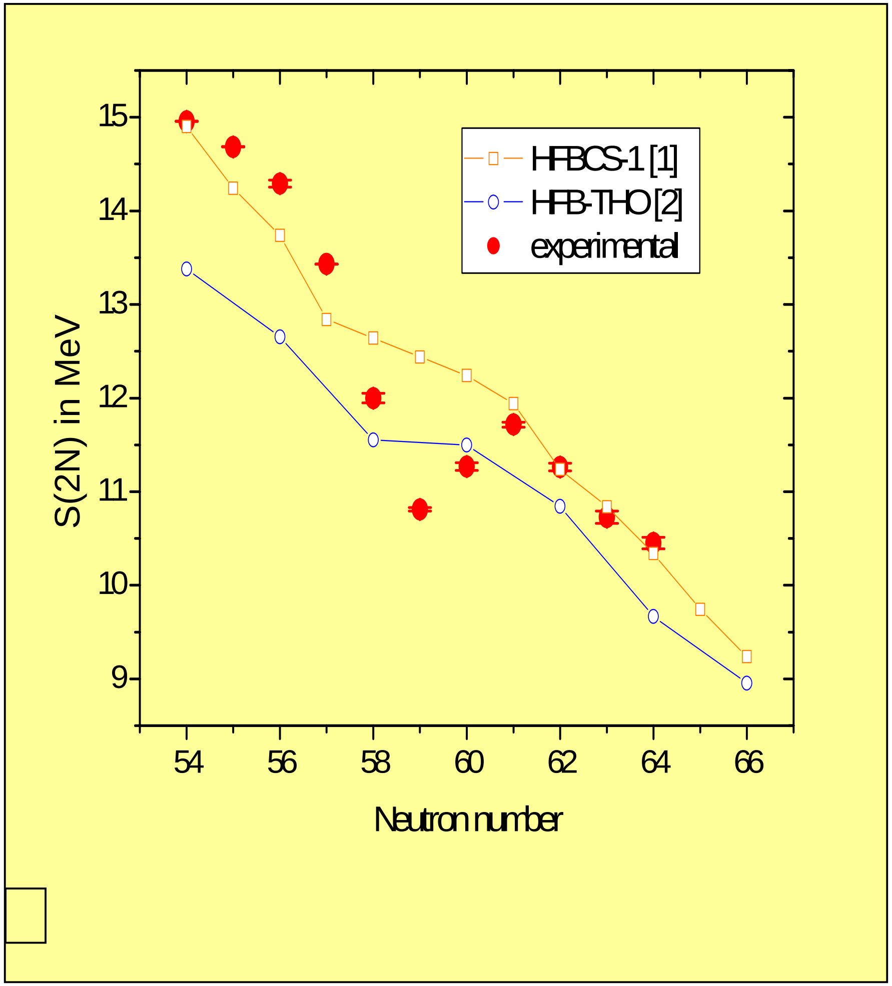
$^{96\text{-}104}$ Zr: S. Rinta-Antila et al., Phys. Rev. C, in press

Charge radii



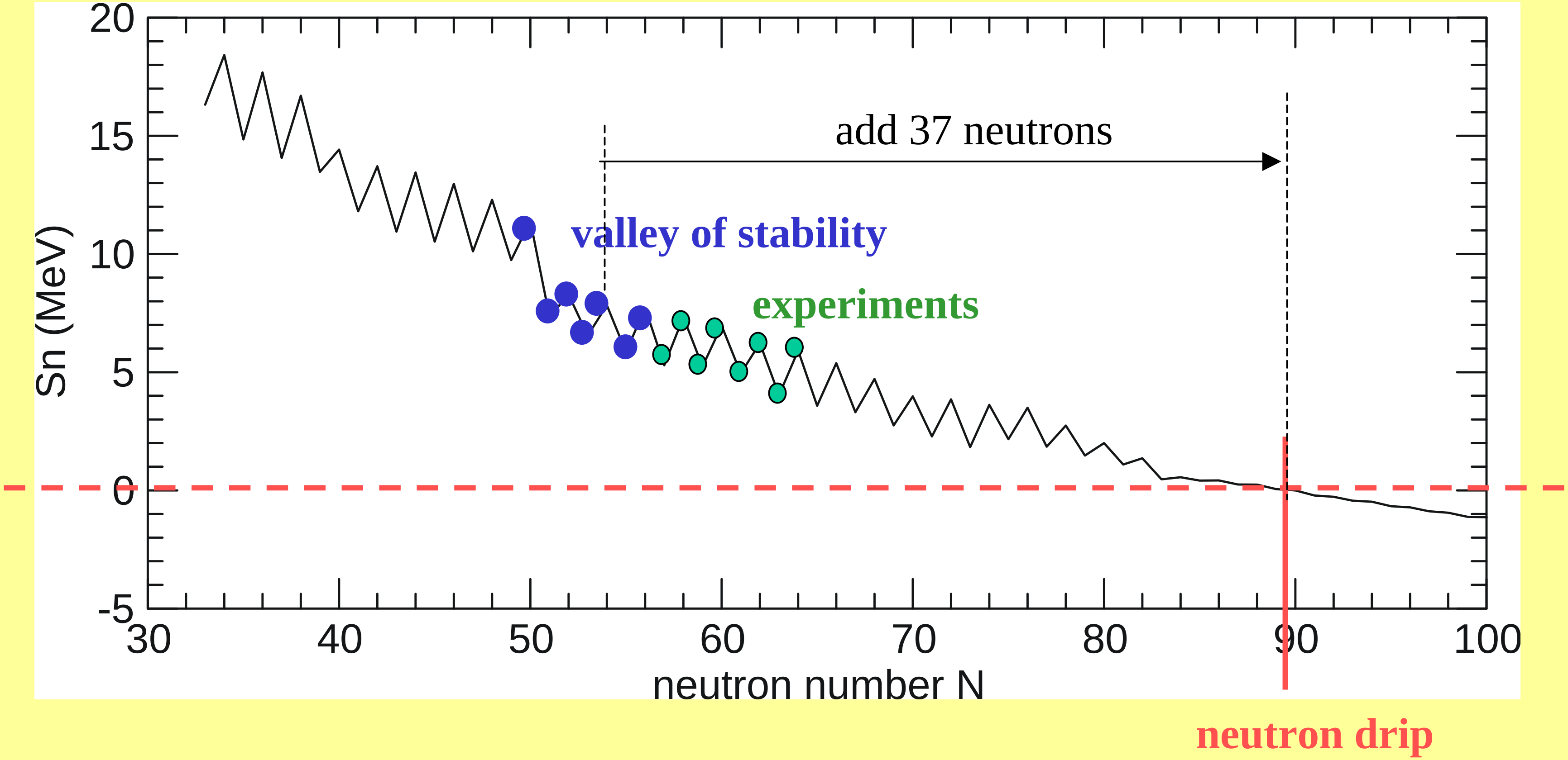
P. Campbell, et al.
Phys. Rev. Lett. 89(2002)082501

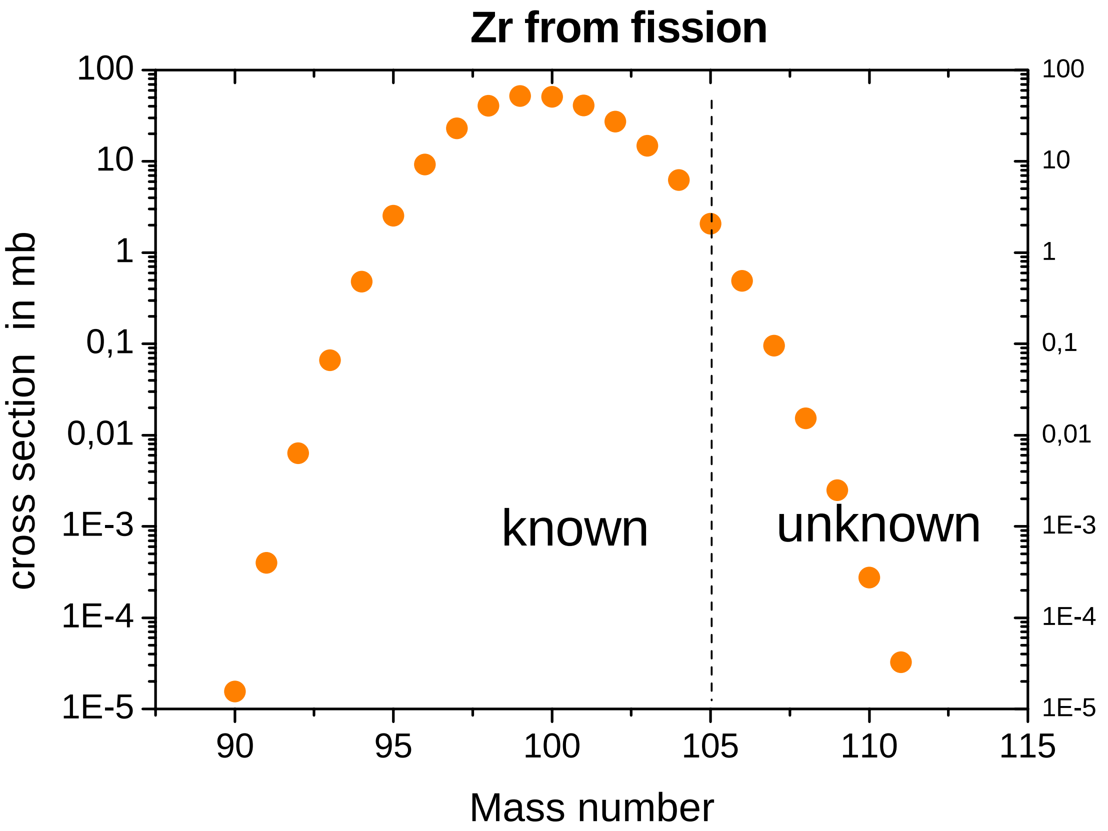
Two-neutron binding energies



S. Rinta-Antila et al., et al.
Phys. Rev. C, in press

Drip line???


20
15
10
5
0
-5
Sn (MeV)
30
40
50
60
70
80
90
100
neutron number N
add 37 neutrons
valley of stability
experiments
neutron drip



For most exotic species we need more sensitive methods:

ion by ion experiments

new probes: muons, antiprotons,...

Standard probes of nuclei

Mass, size and electromagnetic moments

Radioactive decays

Nuclear reactions

- elastic scattering
- Coulomb excitation
- Fusion
- Transfer

Electron scattering

Interaction cross sections < 1 mbarn !

Muons (μ^-) and radioactive atoms/ions

Formation of μ^- atoms ($\tau_{\text{free } \mu} \sim 2.2\ \mu s$)

Slowing down in matter (~ ns)

Atomic capture in high-l state (n~14)

Bohr radius ~ $n^2/(Zm)$
Binding energy ~ $(Z^2m)/n^2$

Cascade down to $n_\mu = 1$ = muonic 1s orbit (<< ns)

Auger electrons
muonic X-rays (keV → MeV)

Large cross section (~ $10^{-16}\ \text{cm}^2 \sim 10^8$ b !!!)

Muonic atom X-ray spectroscopy

nuclear rms charge radii (charge moments)

accuracy a few am

with e-scattering + optical isotope shift data

accuracy 1 am ($<10^{-3}$)

nuclear polarization effects

Physics to be extracted

Isotone shifts vs. isotope shifts

→ nuclear structure far from stability

Isobar charge distributions

→ charge breaking asymmetry in mirror states

Ground state parameters of Fr, Ra isotopes

→ P&T violation in atoms

C.Piller et al., Phys. Rev. C 42 (90)182

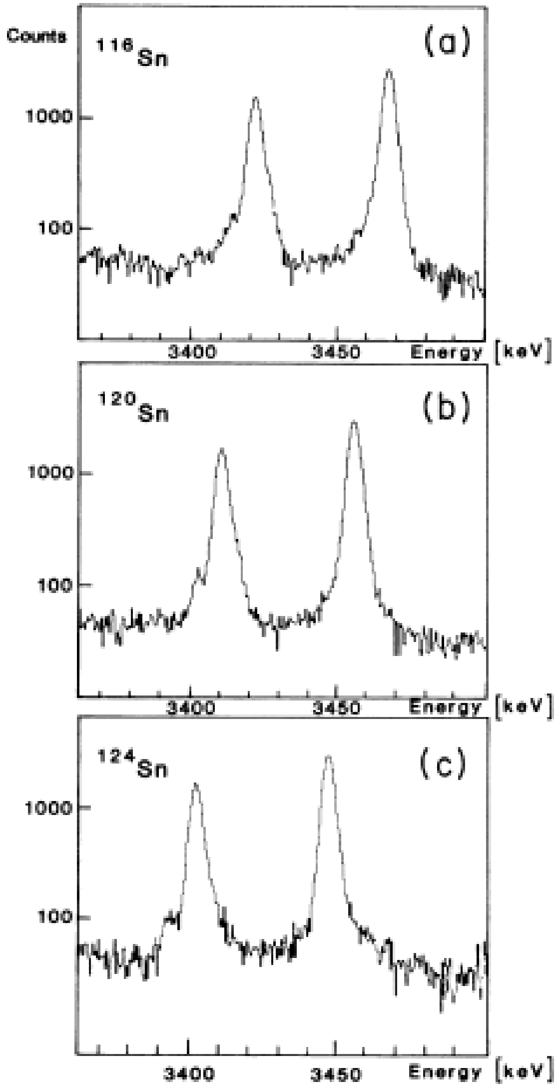
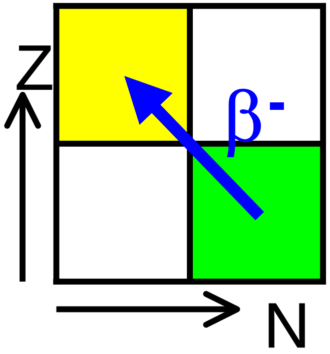
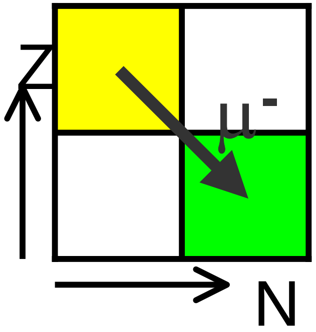


FIG. 2. Prompt muonic x-ray spectra showing the $2p_{1/2}$-1s and the $2p_{3/2}$-1s transitions in ^{116}Sn (a), ^{120}Sn (b), and ^{124}Sn (c).

Nuclear muon capture

- follows naturally muonic atom formation
- “inverse β⁻ decay” $${}^{A}_{Z}X + \mu^{-} \rightarrow {}^{A}_{Z-1}X + \nu_{\mu}$$





- capture rates can tell something about nuclear structure

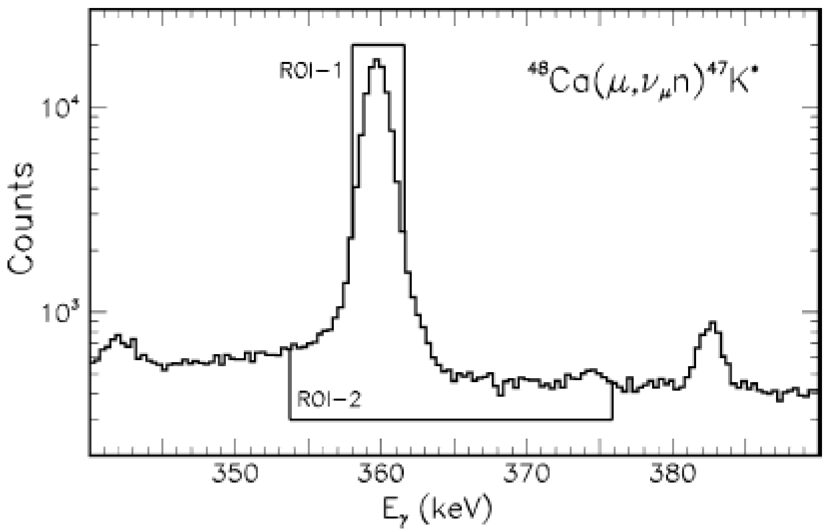
  E. Kolbe et al., Eur. Phys. J. A 11 (2001) 39
- produces exotic nuclei at high excitation energy

  → structure up to several 10 MeV
- several multipoles excited → medium spin states
- renormalization of g_A in nuclear medium

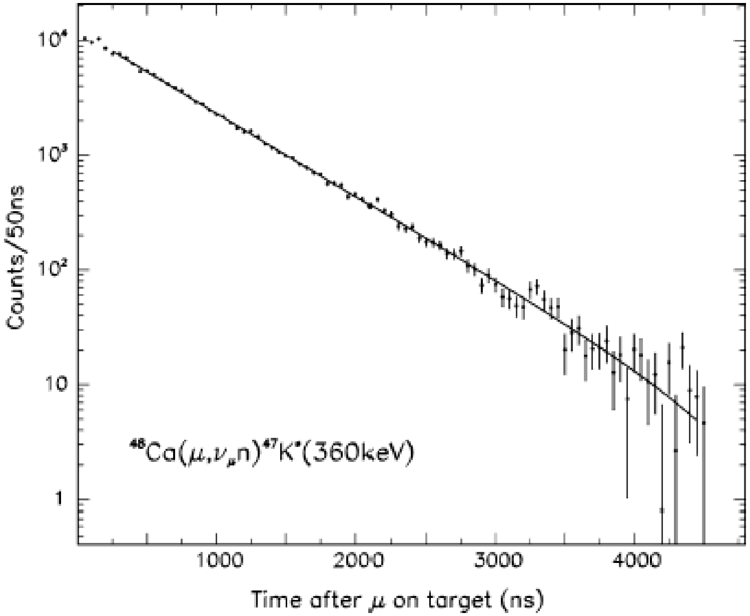
- Nuclear astrophysics, ν scattering (supernova), ν post-processing, …
- Neutrino physics

Probability of nuclear μ^- capture ?

H.O.U. Fynbo et al. / Nuclear Physics A 724 (2003) 493–501



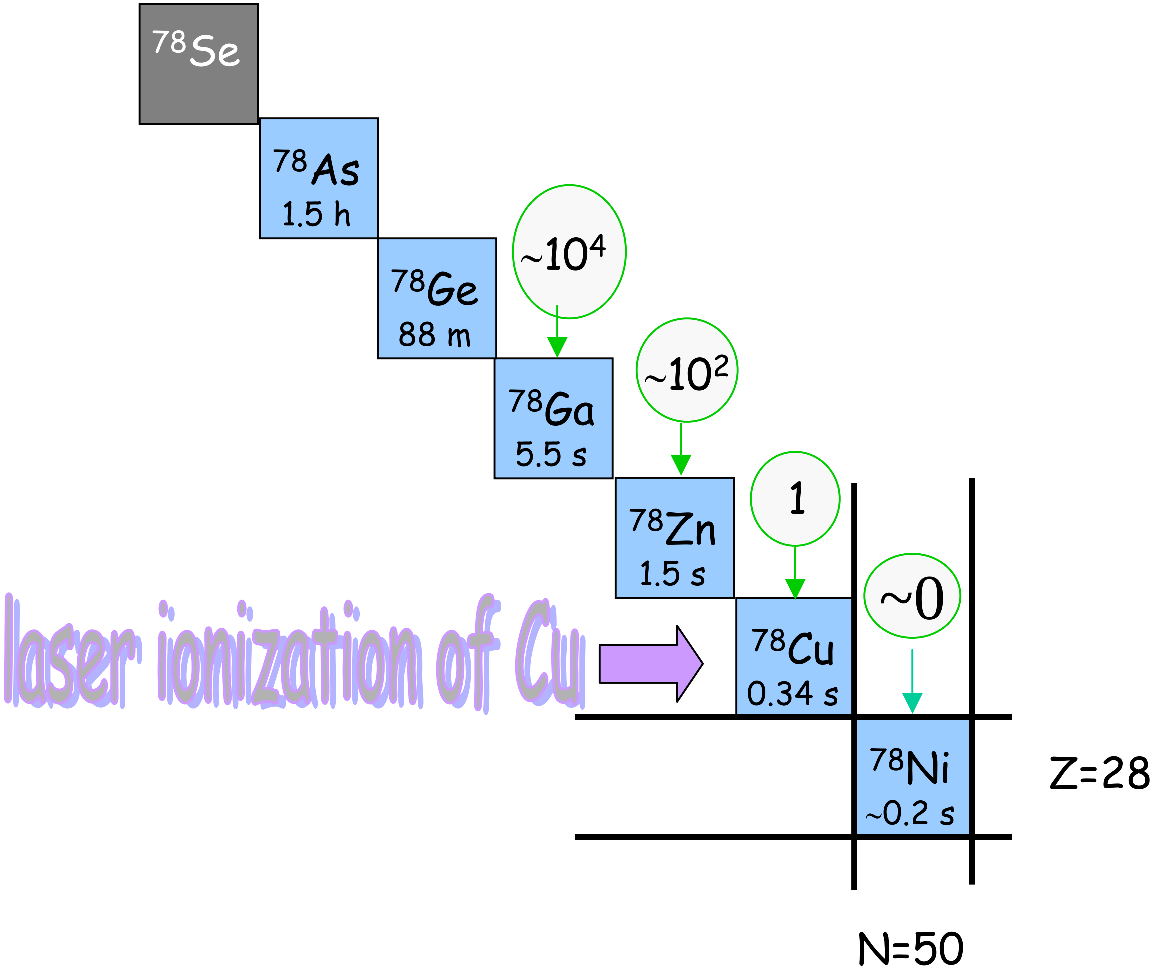
H.O.U. Fynbo et al. / Nuclear Physics A 724 (2003) 493–501



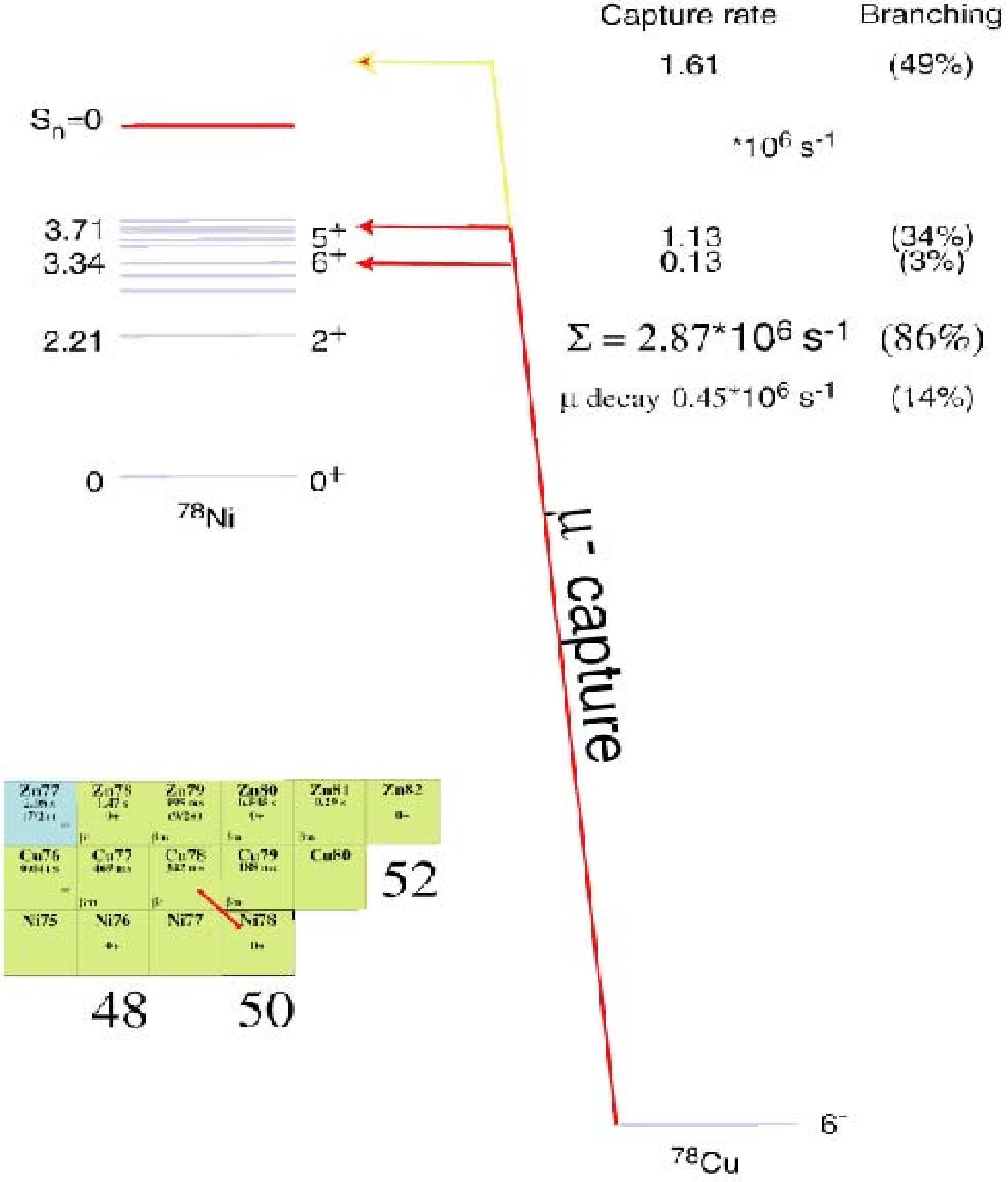
Capture lifetime (^{48}Ca) $\tau \sim 0.6\ \mu s$ → nuclear capture dominates over free muon decay $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

For Sn $\tau \sim 0.09\ \mu s$ and for Pb $\tau \sim 0.07\ \mu s$!

An example: $\mu^- + {}^{78}\mathrm{Cu} \rightarrow {}^{78}\mathrm{Ni}^* + \nu_\mu$



An example: $^{78}Cu+\mu^- \to {}^{78}Ni^*+\nu_\mu$ (K.-H. Langanke et al)



Capture rate	Branching
1.61	(49%)
1.13	(34%)
0.13	(3%)

$*10^6\ s^{-1}$

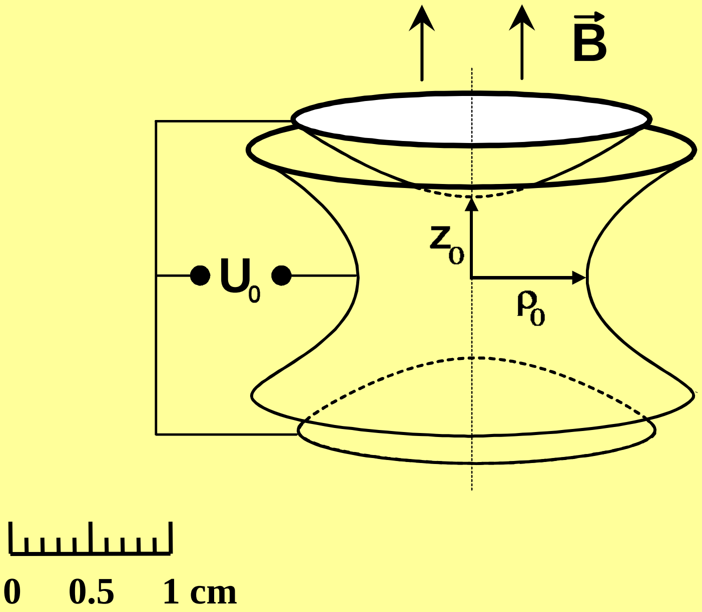
$\Sigma = 2.87*10^6\ s^{-1}$ (86%)

μ decay $0.45*10^6\ s^{-1}$ (14%)

STORAGE DEVICES

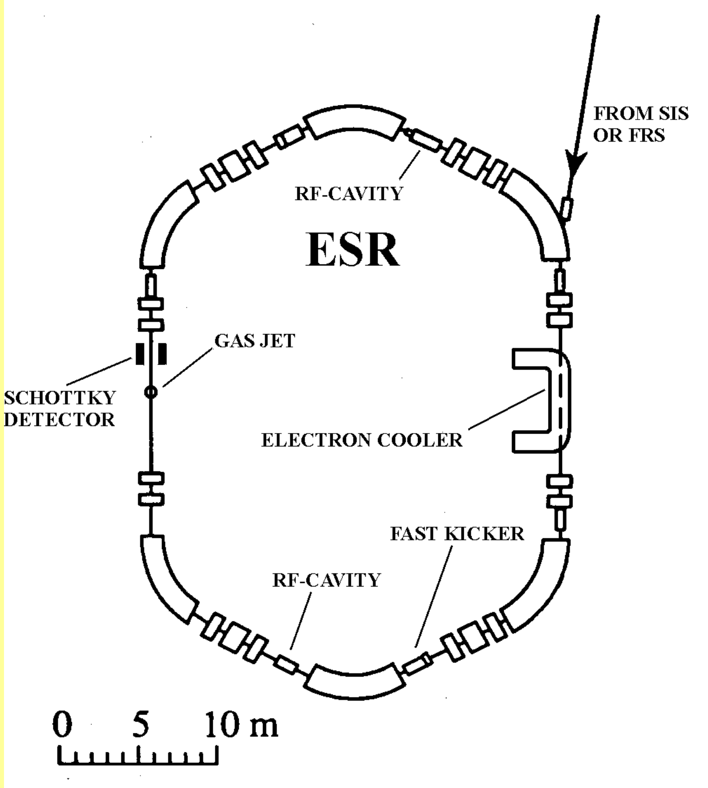
Low-Z Solid / Liquid catcher at K temperatures

Penning or Paul traps



particles: at nearly rest in space

Merging beams in Storage rings



at relativistic energies

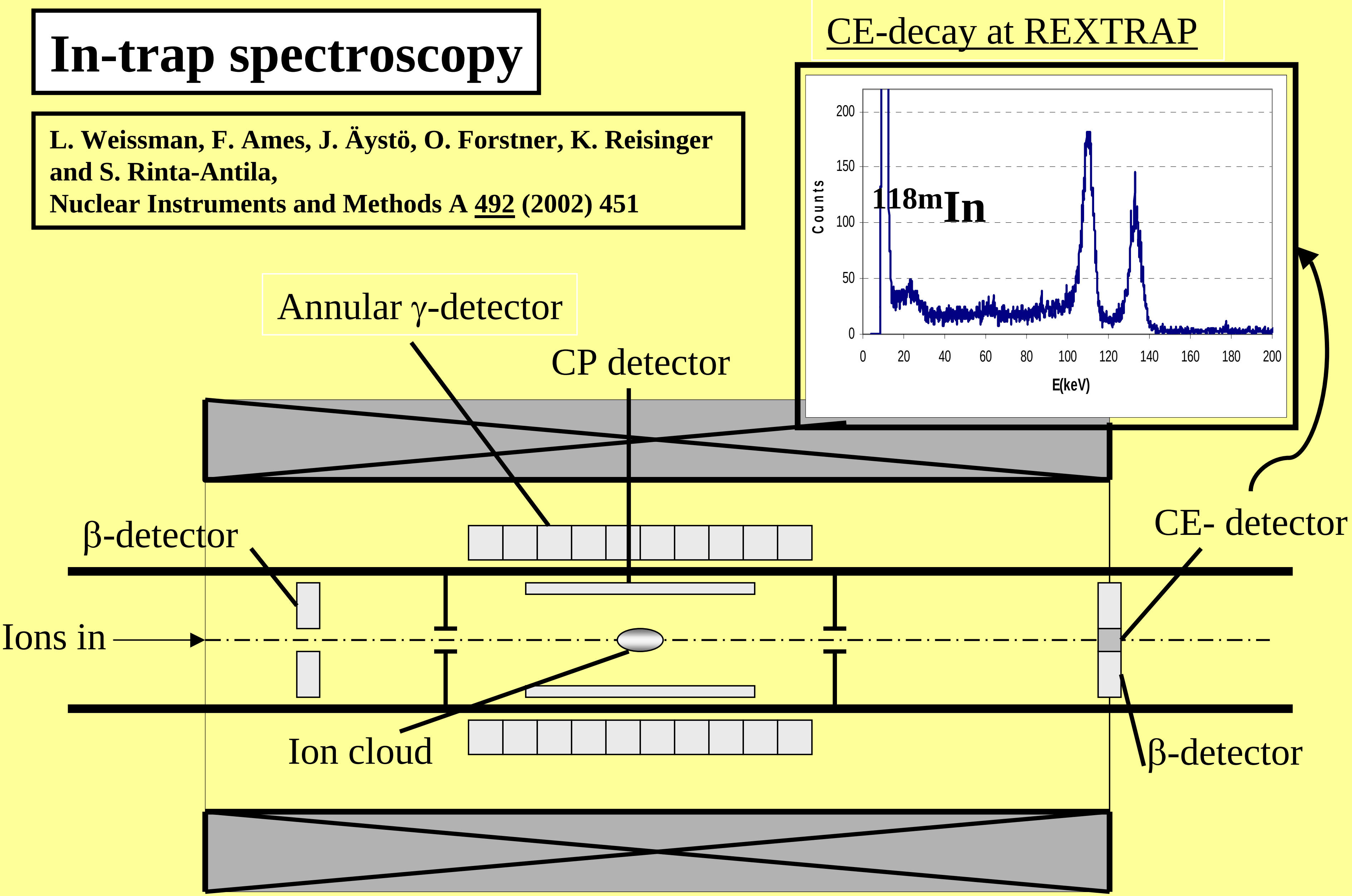
Estimates for muonic atom production rates:

based on 10^8 μ/s (low energy) on 10^8 atoms/cm^2

- nested ion & muon trap: rate 10 /s
- solid hydrogen: rate 1 /s (P. Strasser & K. Nagamine)
- superfluid helium: rate similar to solid H or better?
    - control of the movement of ions/muons by E fields
    - thin surface layer / high packing density
    - **(see poster of P. Dendooven)**

In-trap spectroscopy

L. Weissman, F. Ames, J. Äystö, O. Forstner, K. Reisinger and S. Rinta-Antila,
Nuclear Instruments and Methods A <u>492</u> (2002) 451



CE-decay at REXTRAP

Annular γ-detector

CP detector

β-detector

Ions in

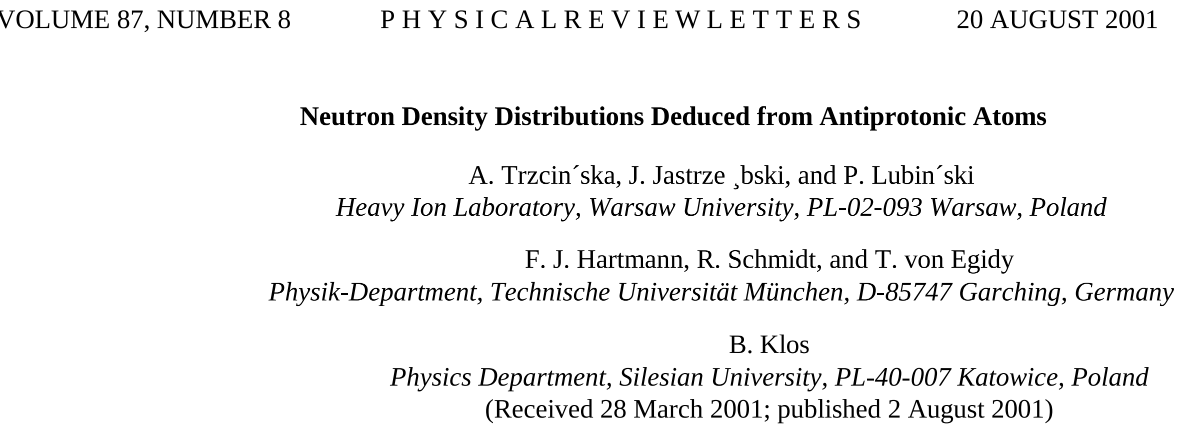
CE- detector

Ion cloud

β-detector

Antiprotonic radioactive atoms

Process	Observable	Deduced quantity	Physics
Capture in high orbit (atomic x-sections), cascade	Antiprotonic x-rays *O*(MeV)	Annihilation orbit, energy shifts	Matter distributions, neutron vs. protons on nuclear surface, …
Annihilation (n>7) on peripheral nucleon	De-excitation γ, particles, daughter activity	n vs. p annihilation	



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Neutron Density Distributions Deduced from Antiprotonic Atoms

A. Trzcińska, J. Jastrzębski, and P. Lubiński
Heavy Ion Laboratory, Warsaw University, PL-02-093 Warsaw, Poland

F. J. Hartmann, R. Schmidt, and T. von Egidy
Physik-Department, Technische Universität München, D-85747 Garching, Germany

B. Kłos
Physics Department, Silesian University, PL-40-007 Katowice, Poland

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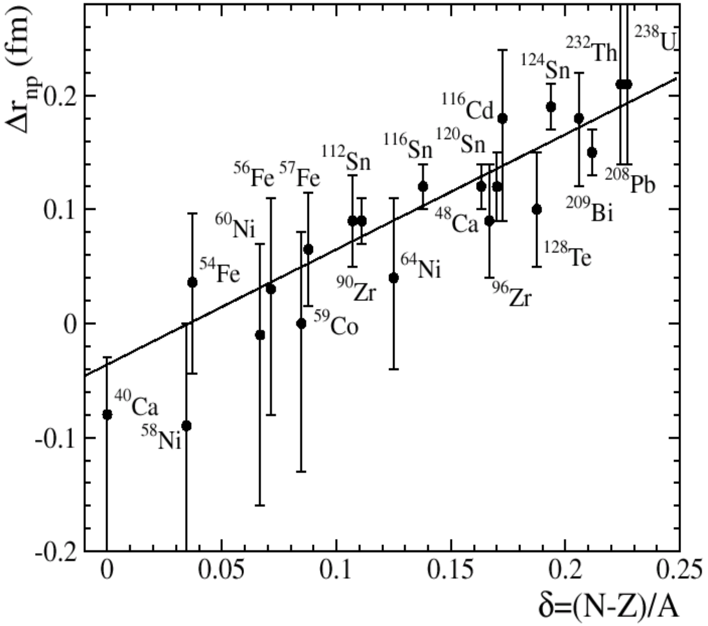

Collider Technique

(Paul Kienle, GSI Future workshop, Oct. 2003)

- Production of neutron rich nuclei: Fragmentation at medium energies or ISOL method + post acceleration
- Storing of products in a cooler ring
- Production of antiprotons with 20-30 GeV protons (site dependence?)
- Cooling and storing of antiprotons
- Transfer in collider rings

- Antiproton-Ion-Collider is proposed to measure
  - total/partial cross sections of antiproton absorption by RI nuclei

⇓

  - rms radii of n-p and their differences

Antiproton Absorption

- Yields of A-1 isobars with (N-1) or (Z-1)
- Absorption proportional to $\langle r^2 \rangle$ of neutrons or protons
- Exclusive recoil spectroscopy

Luminosity Unbunched beams

$$L = N_I \cdot f_I \cdot N_{\bar{p}} \cdot (l/C) \cdot (1/F) \cdot \gamma$$

N_I = number of ions

f_I = circulating frequency of the ions

$N_{\bar{p}}$ = number of antiprotons

(l/C) = ratio of intraction length to circumference factor

$(1/F)$ = inverse of interaction area

γ = Lorentz factor

EXAMPLE

For $N_I = 10^6$, $f_I = 2 \times 10^6\ \mathrm{s}^{-1}$, $N_{\bar{p}} = 10^9$, $(l/C) = 10^{-1}$, $(1/F) = 100\ \mathrm{cm}^{-2}$, $\gamma = 1.5$

$$L = 3 \cdot 10^{22}\ cm^{-2} s^{-1}$$

Reaction rate

$$R = L\sigma_R = 0.045\ s^{-1}\ \ for\ \ \sigma_R = 1.5 \cdot 10^{-24}\ cm^2$$

Conclusions

Muons and antiprotons offer an attractive method for high-sensitivity measurements on exotic nuclei

Charge and mass distributions obtained via
- atomic X-rays
- absorption experiments

Excited states probed via unique muon capture process

Request for muons and antiprotons
- thermal muon source of ~10^8 muons/s
- antiproton storage ring with ~10^9 p/s

Two RAMA workshops organized in 2001 @ CERN and Trento
Future: Working group should be set up in connection with SPL study