Recent NUSTAR Experiments with Relativistic Uranium Beams

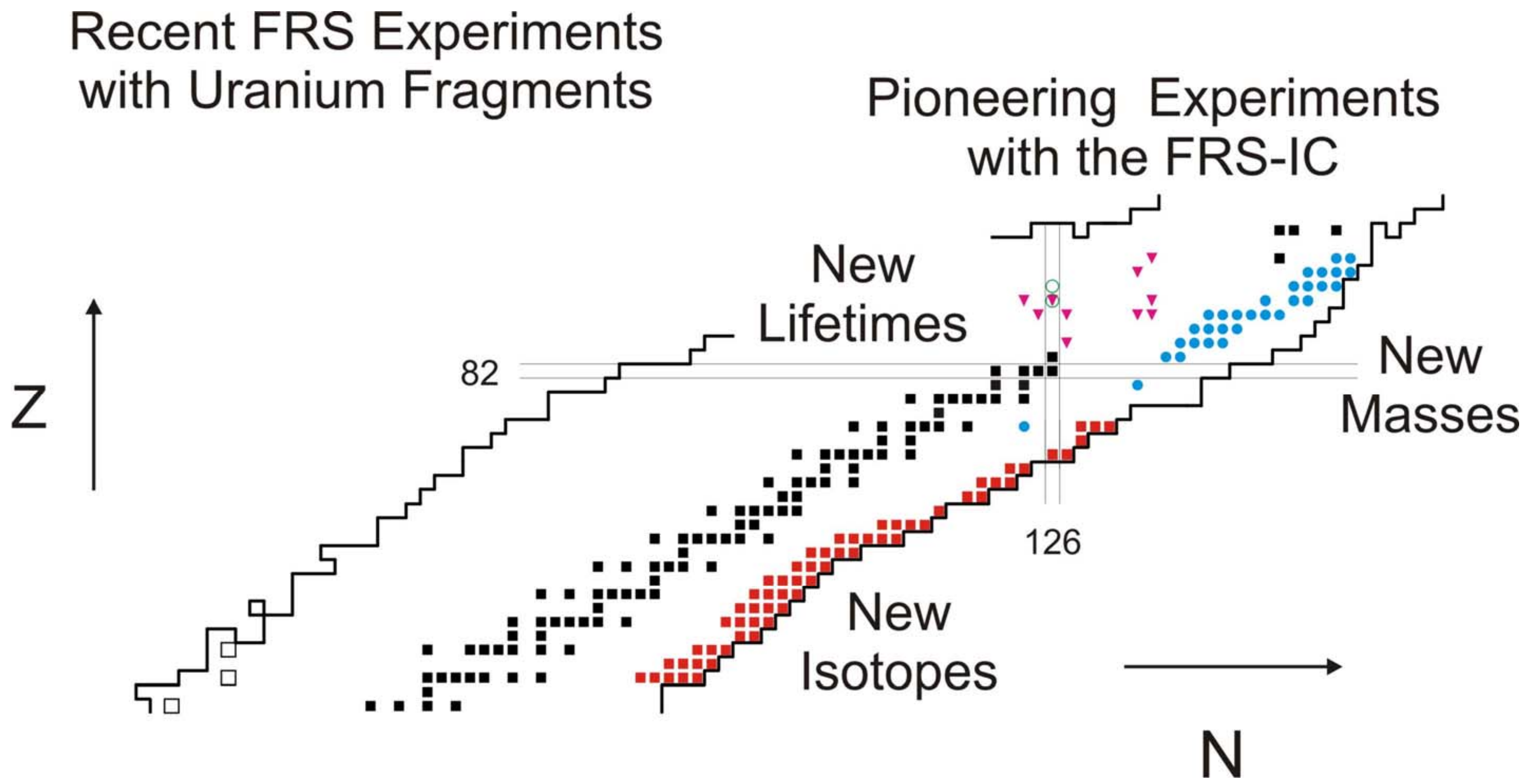
Hans Geissel

GSI and Justus Liebig University Giessen

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

- **Discovery of new n-rich Isotopes** Phys. Lett. B 717, 371 (2012)
- **New Accurate Mass Measurements** Nucl. Phys. A 882, 71, 2012
- **New Experimental Developments towards the Super-FRS**

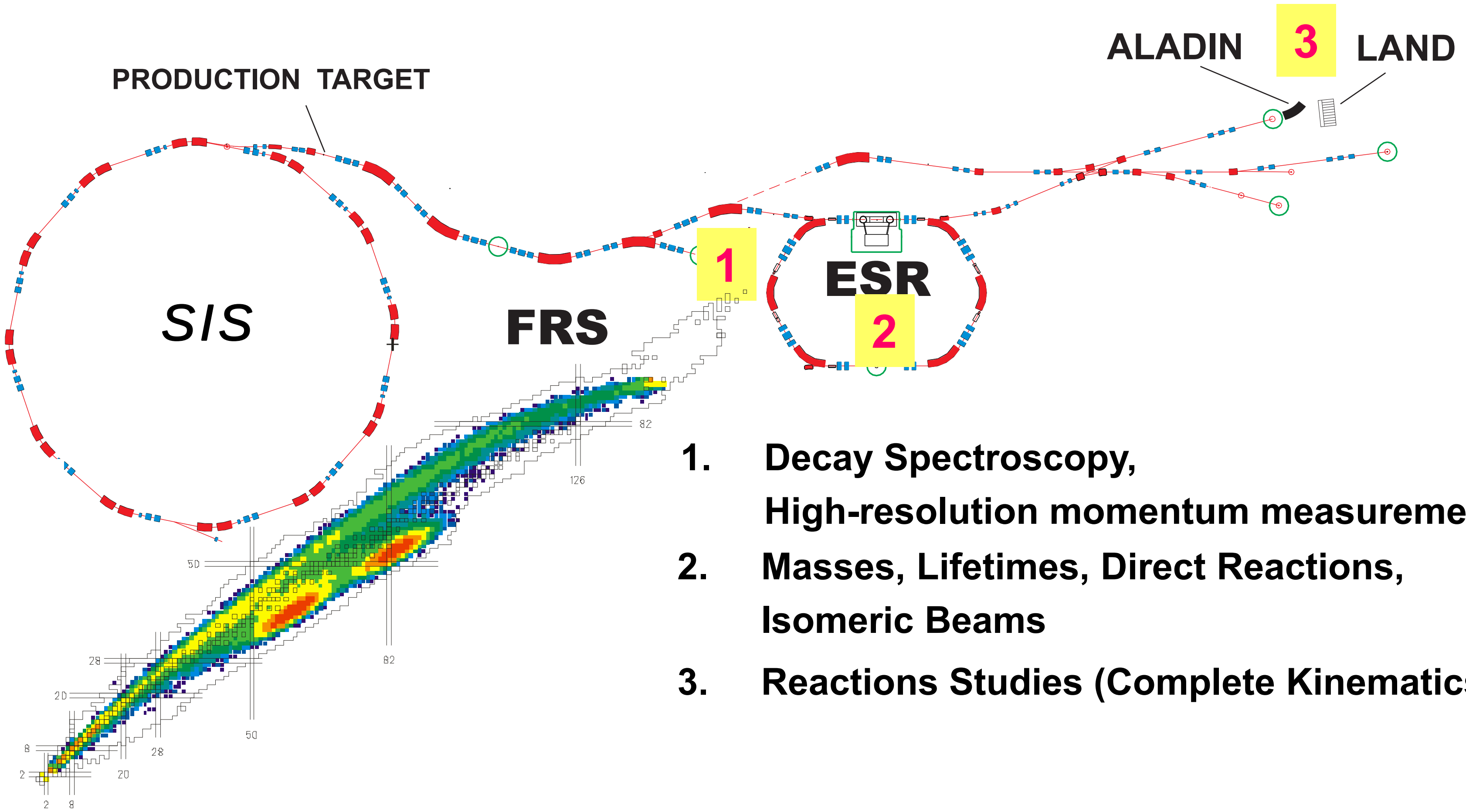
Overview



Recent FRS Experiments
with Uranium Fragments
Pioneering Experiments
with the FRS-IC
New
Lifetimes
82
New
Masses
Z
126
New
Isotopes
N

Secondary Nuclear Beam Facility

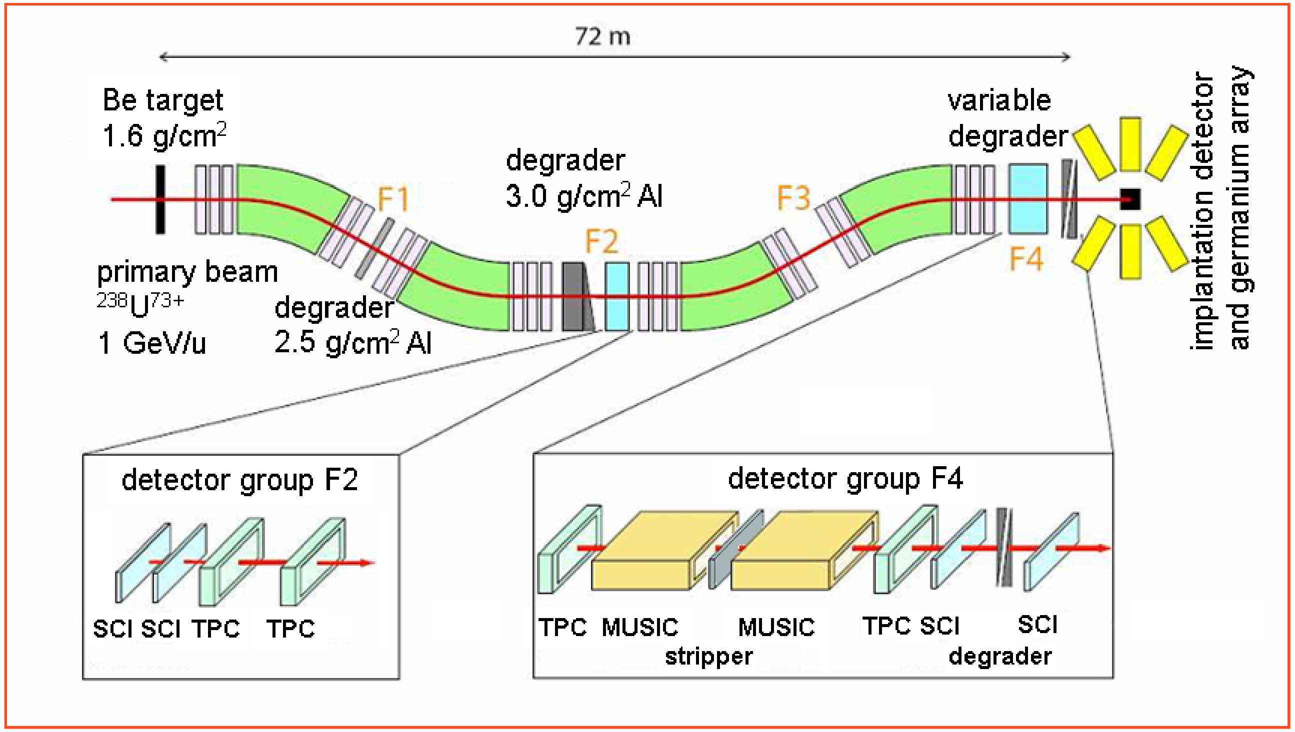
FRS: In-flight Separator & High-Resolution Spectrometer



1. Decay Spectroscopy,
   High-resolution momentum measurements
2. Masses, Lifetimes, Direct Reactions,
   Isomeric Beams
3. Reactions Studies (Complete Kinematics)

In-Flight Identification of Exotic Nuclei

FRS – Branch 1



$$TPC \rightarrow B\rho + \Delta E$$

$$TOF \rightarrow v$$

$$MUSIC \rightarrow \Delta E$$

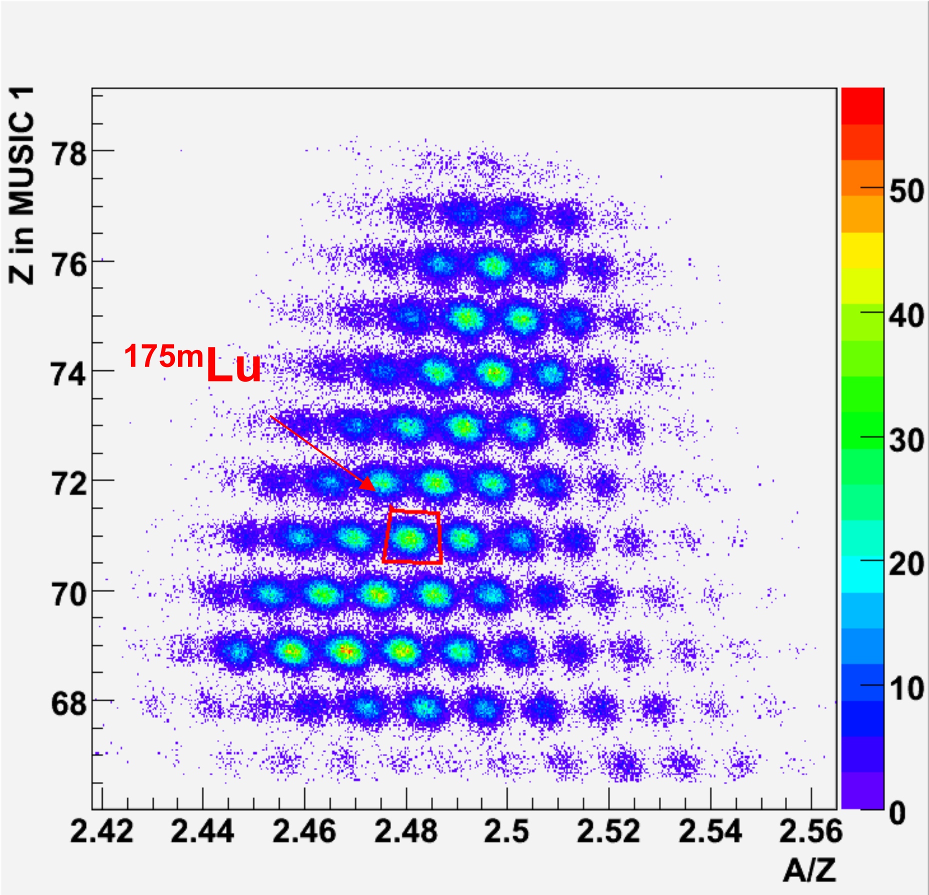
$$B\rho = \frac{mv\gamma}{q}$$

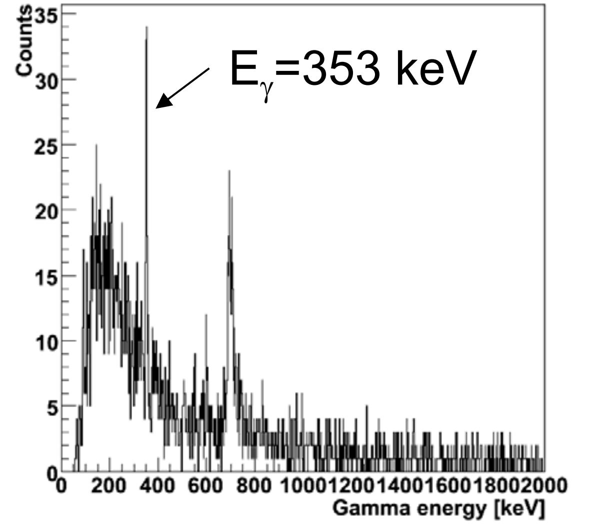
$$\Delta E \propto Z^2$$

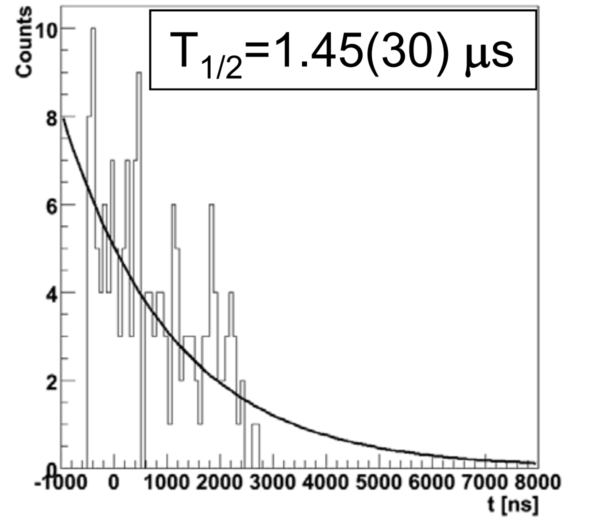
$$q = Z$$

Isomer Tagging Technique – ^{175}Lu

Verification of Particle Identification







^{175m}Lu: E_γ=353.3 keV ($5/2^- \rightarrow 7/2^+$), $T_{1/2}$=1.49(7) μs

P.E. Garrett et al. PRC69 (2004) 017302
K.H. Johansen et al, Nucl. Phys. A133 (1969) 213

Cross-Section Measurement

$$\sigma_f = \frac{N_f}{N_P \cdot N_T \cdot f_{corr}}$$

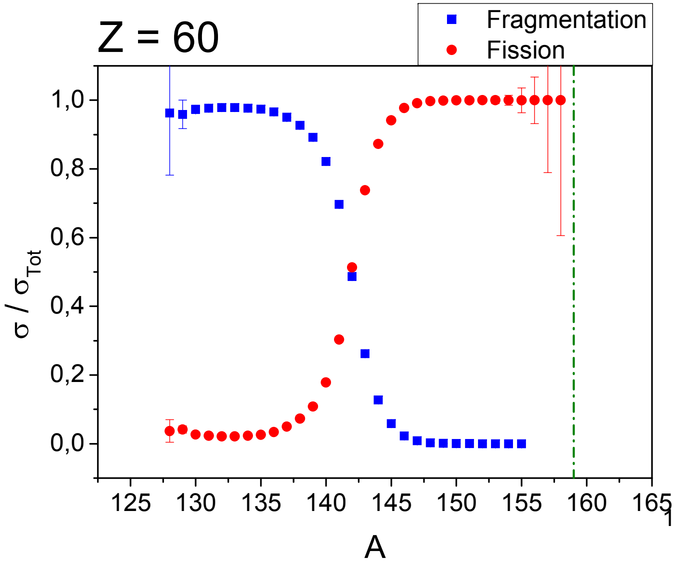
N_f : number of fragments reaching the final focaal plane

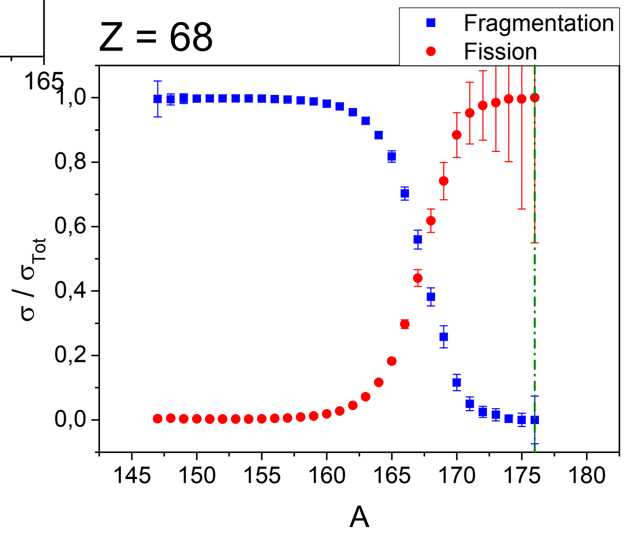
N_P : total number of primary beam particles

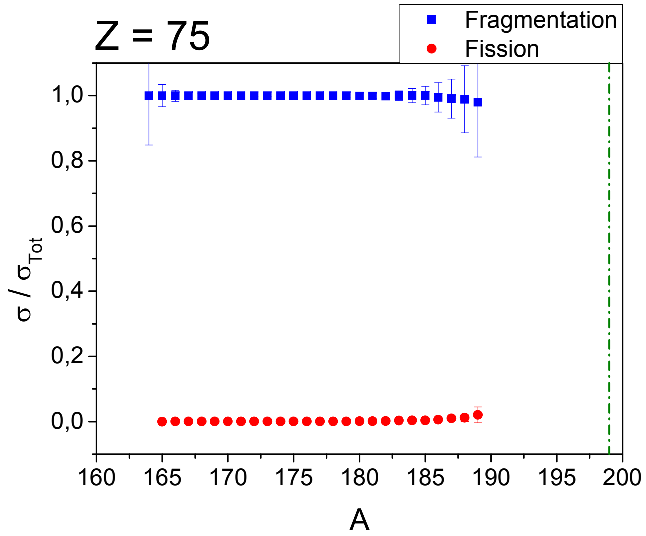
N_T : number of atoms in the target (cm^{-2})

f_{corr} accounts for:
- limited transmission of the FRS,
- losses due to secondary reactions in the matter,
- dead-time of the detectors and data acquisition.

Reaction Mechanism







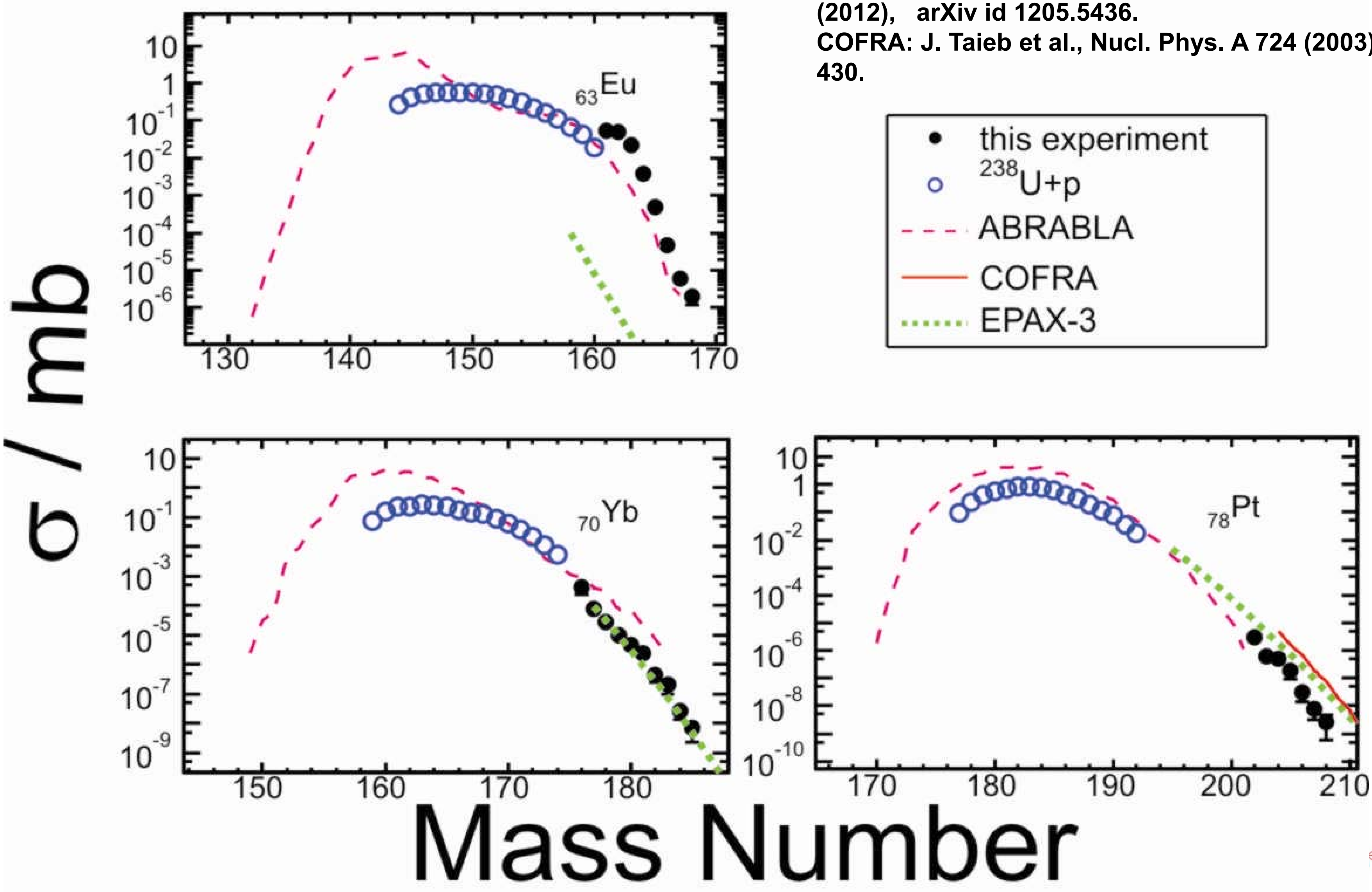
ABRABLA:

- **J.-J. Gaimard, K.-H. Schmidt Nucl. Phys. A 531 (1991) 709.**
- **A. Kelic et al., Proceedings of the Joint ICTP- IAEA, IAEA INDC(NDS)-530 (2008).**

New Neutron-Rich Isotopes

F. Farinon, J. Kucewicz

EPAX 3.0: K. Sümmerer to be published in Phys. Rev. C (2012), arXiv id 1205.5436.
COFRA: J. Taieb et al., Nucl. Phys. A 724 (2003) 413-430.



Discovery of 60 New Isotopes

Physics Letters B 717 (2012) 371–375

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Physics Letters B

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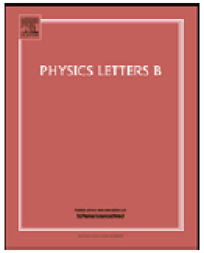


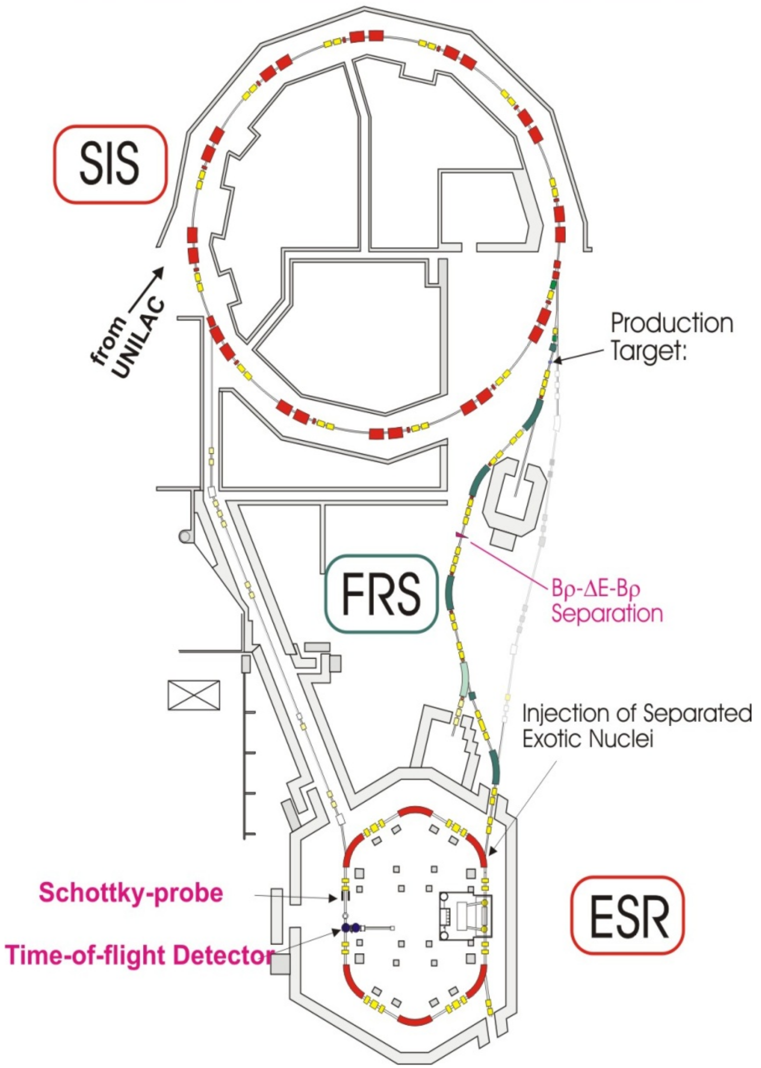
Discovery and cross-section measurement of neutron-rich isotopes in the element range from neodymium to platinum with the FRS

J. Kurcewicz [a,*], F. Farinon [a,b,1], H. Geissel [a,b], S. Pietri [a], C. Nociforo [a], A. Prochazka [a,b], H. Weick [a], J.S. Winfield [a], A. Estradé [a,c], P.R.P. Allegro [d], A. Bail [e], G. Bélier [e], J. Benlliure [f], G. Benzoni [g], M. Bunce [h], M. Bowry [h], R. Caballero-Folch [i], I. Dillmann [a,b], A. Evdokimov [a,b], J. Gerl [a], A. Gottardo [j], E. Gregor [a], R. Janik [k], A. Kelić-Heil [a], R. Knöbel [a], T. Kubo [l], Yu.A. Litvinov [a,m], E. Merchan [a,n], I. Mukha [a], F. Naqvi [a,o], M. Pfützner [a,p], M. Pomorski [p], Zs. Podolyák [h], P.H. Regan [h], B. Riese [a,b], M.V. Ricciardi [a], C. Scheidenberger [a,b], B. Sitar [k], P. Spiller [a], J. Stadlmann [a], P. Strmen [k], B. Sun [b,q], I. Szarka [k], J. Taïeb [e], S. Terashima [a,l], J.J. Valiente-Dobón [j], M. Winkler [a], Ph. Woods [r]

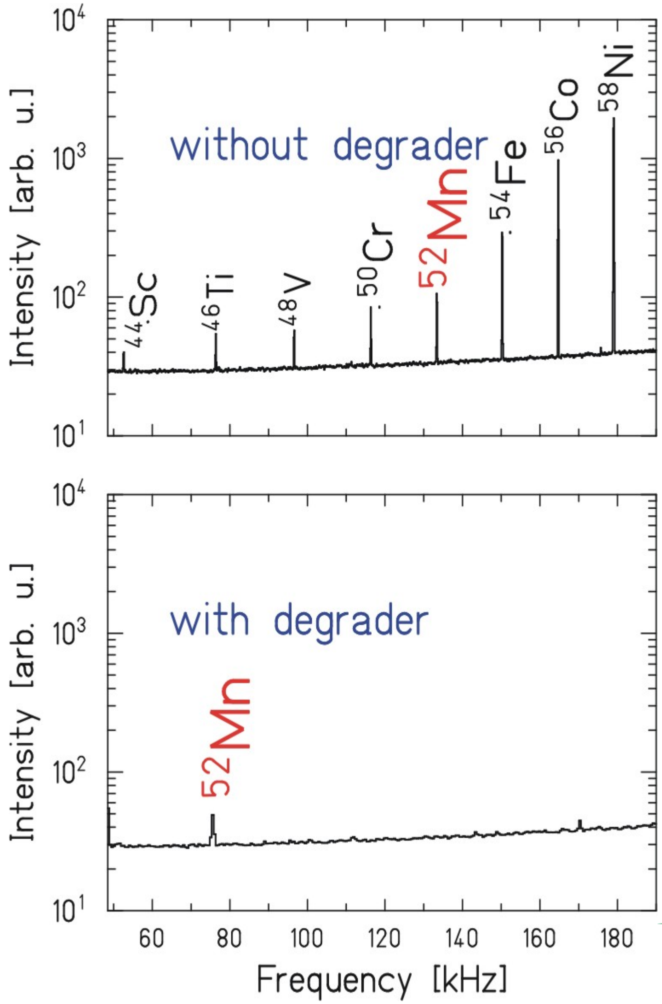
J. Kurcewicz, F. Farinon

FRS-ESR Experiments

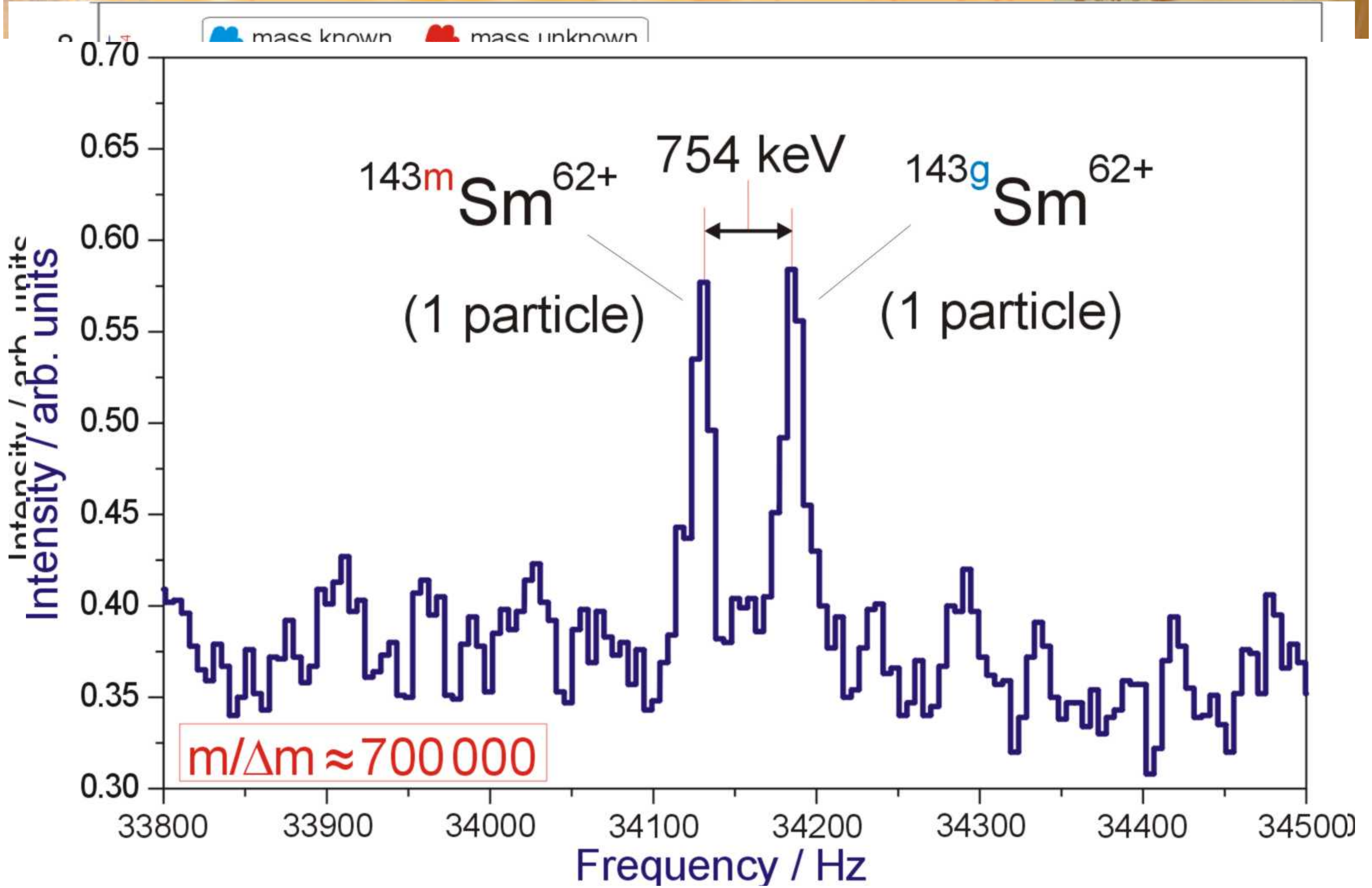
Precision Experiments with the combination of the FRS and the ESR



Monoisotopic Fragment Beams Stored in the ESR

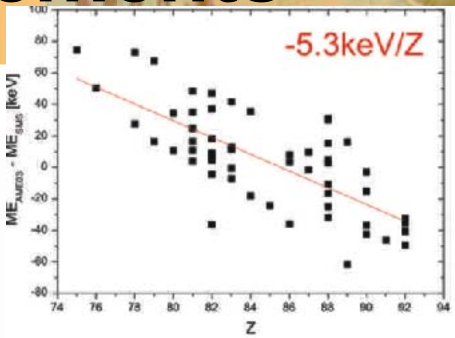


Schottky Frequency Spectra
Sensitivity to Single Ions



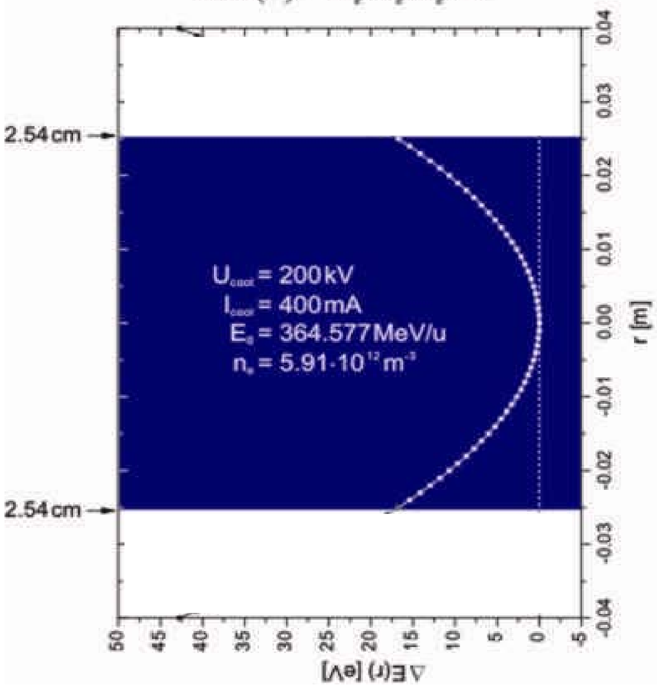
Velocity Profile of the Electron Beam Influence on the Mass Measurements

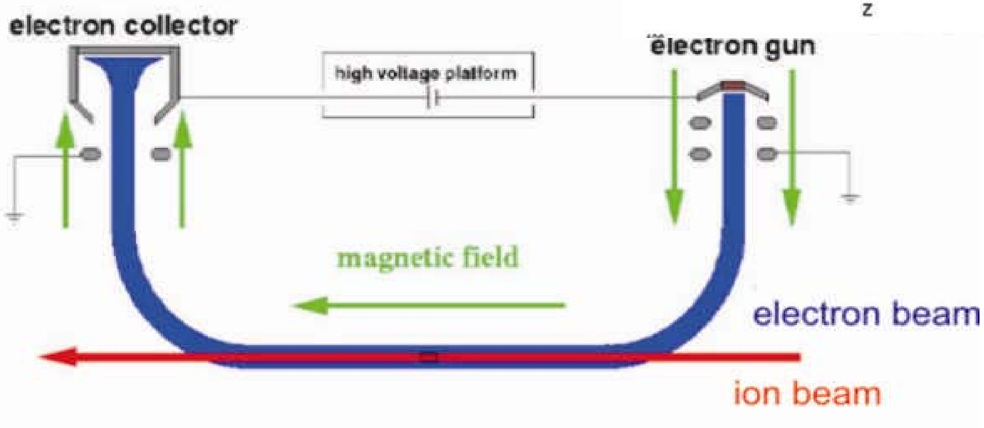
L. Chen et al., Nucl. Phys. A 882 (2012) 71.



$$\frac{f_i - f_j}{f_i} = -\alpha_p\left[\frac{(m/q)_i - (m/q)_j}{(m/q)_i}\right] + \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\left(\frac{v_i - v_j}{v_i}\right)$$

$$\Delta E(r) = n_e \pi r_e m_e c^2 r^2$$





$$R_{16} \approx 1cm/\%$$

$$r = R_{16} \cdot \frac{\Delta B\rho}{B\rho}$$

H. Poth, Phys. Rep. 196 (1990) 135.
M. Steck, Beam Cooling, Talk at the CERN Accelerator School Darmstadt, 28.09.2009-09.10.2009.
C. Brandau, Dissertation, Justus-Liebig-Universität Gießen, 2000.

$$\sum_i \frac{(M_i^b - M_{i,syst}^b)^2}{(\delta M_{i,syst}^b)^2 + (\sigma_i^{stat})^2 + (\sigma^{syst})^2} = N_n$$

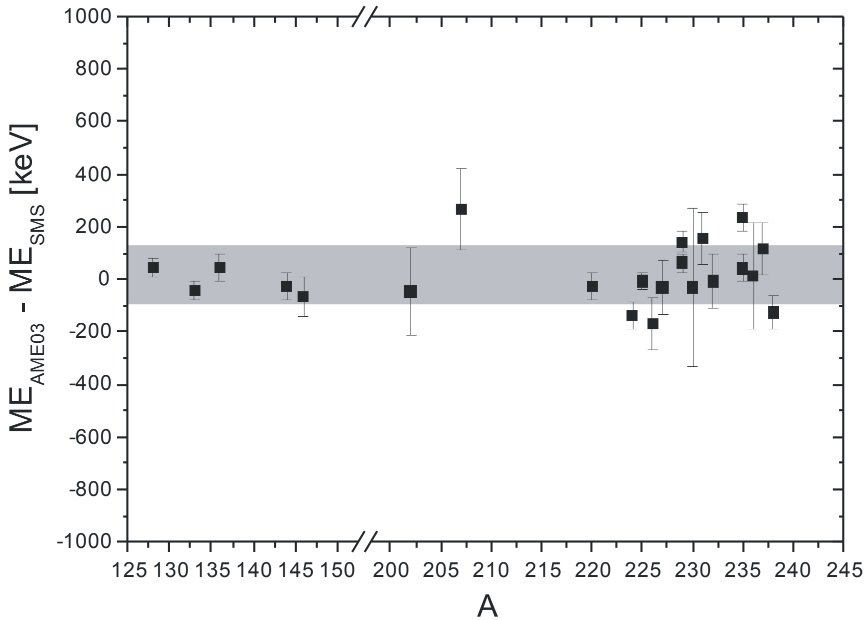
Systematic Error

$\sigma^{syst} \approx 10$ keV

Comparison with AME03

AME03: G. Audi, A. H. Wapstra, C. Thibault, Nucl. Phys. A 729 (2003) 337.

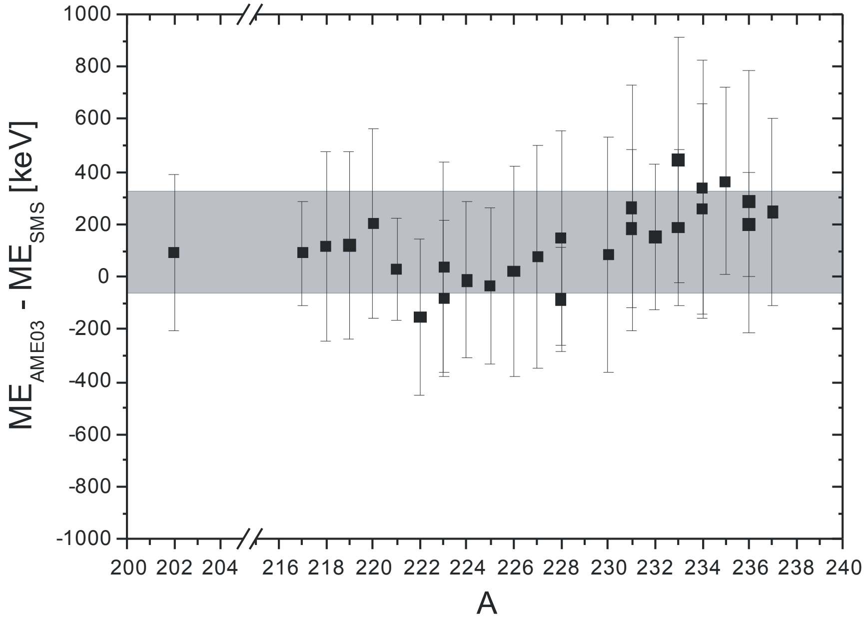
Comparison to
improved mass values



$$\overline{\Delta ME} = 19\ keV$$

$$\sigma_{rms} = 111\ keV$$

Comparison to
extrapolated mass values



$$\overline{\Delta ME} = 133\ keV$$

$$\sigma_{rms} = 195\ keV$$

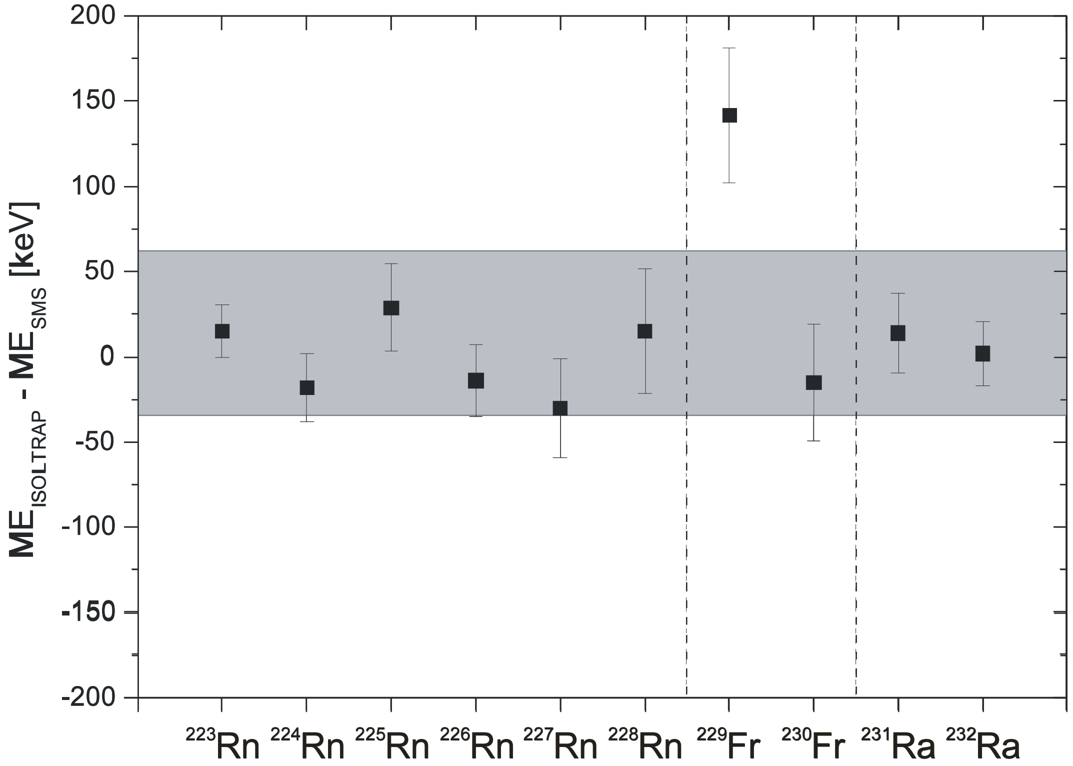
Z. Patyk

Comparison with ISOLTRAP

Z. Patyk, R. Knöbel

ISOLTRAP – data:

F. Herfurth et al., Eur. Phys. J. A 25 (2005) 17-21.
D. Neidherr et al., Phys. Rev. Lett. 102 (2009) 112501.
C. Weber et al., Nucl. Phys. A 803 (2008) 1.



With ^{229}Fr:

$$\overline{\Delta ME} = 14 keV$$

$$\sigma_{rms} = 48 keV$$

Without ^{229}Fr:

$$\overline{\Delta ME} = -0.22 keV$$

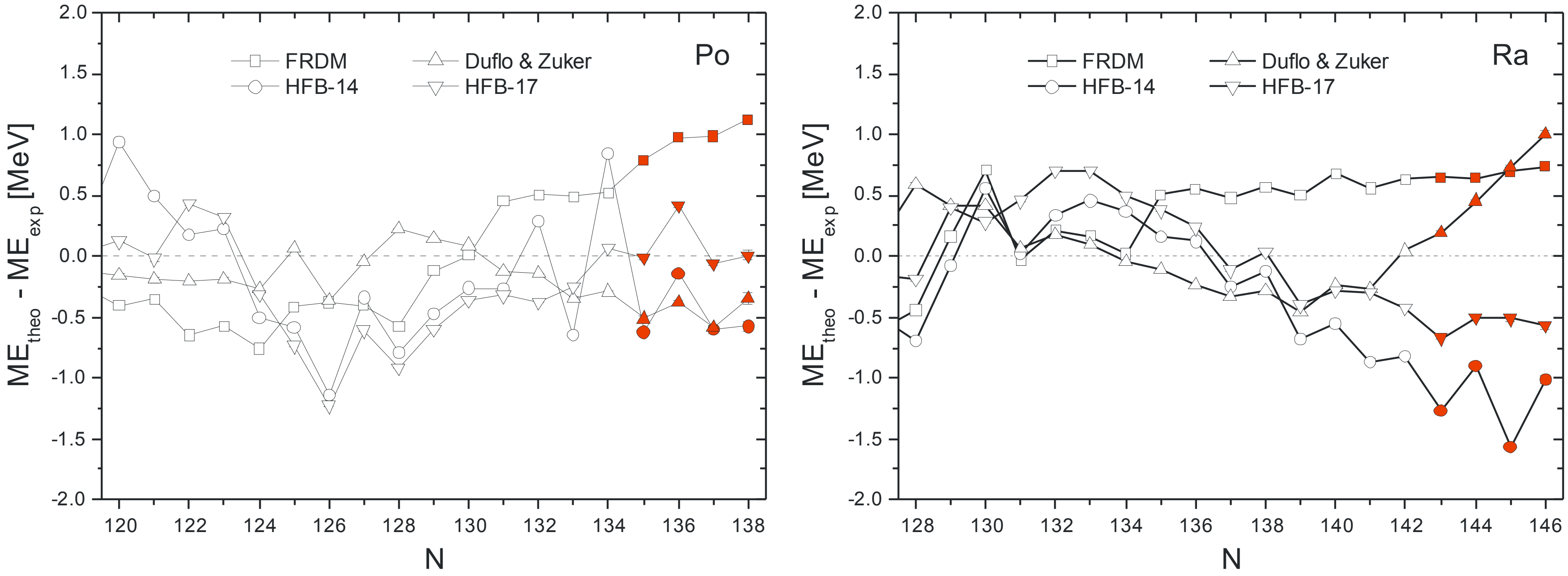
$$\sigma_{rms} = 19 keV$$

L. Chen et al., Nucl. Phys. A 882 (2012) 71.

$$\sigma_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ME_{SMS} - ME_{Isoltrap})_i^2}$$

Comparison with Mass Models

L. Chen et al., Nucl. Phys. A 882 (2012) 71.



FRDM: P. Möller et al., At. Data Nucl. Data Tables 59 (1995) 185.

HFB – 14: http://www-astro.ulb.ac.be/Nucdata/Masses/hfb14-plain,

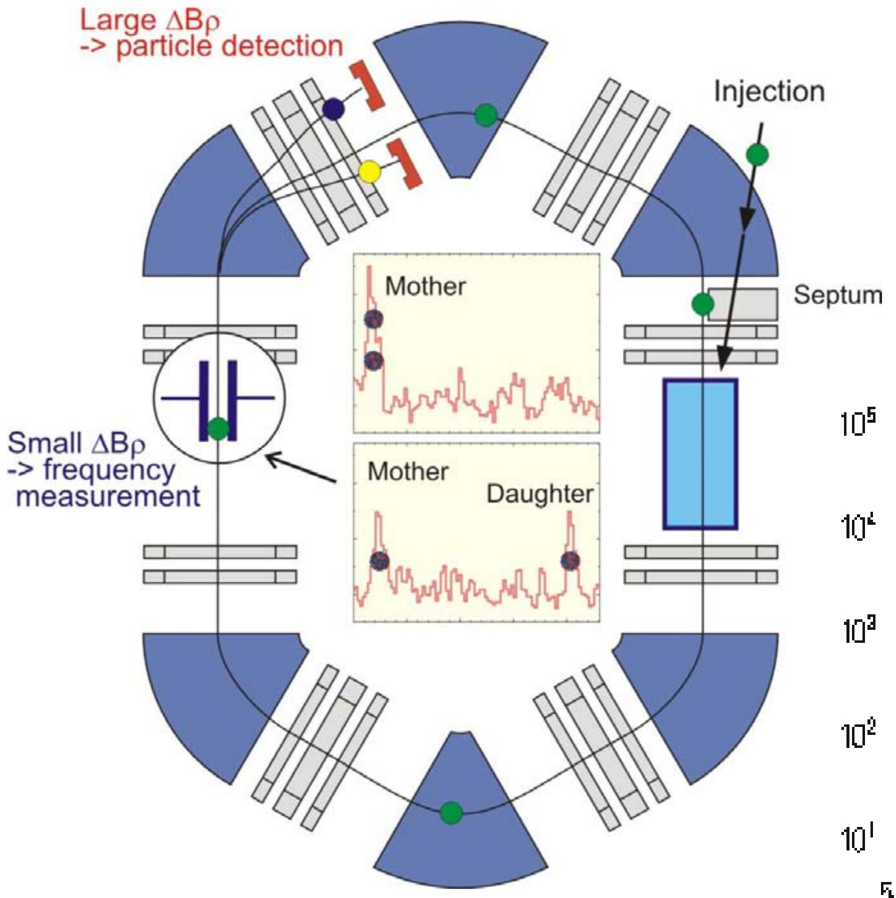
S. Goriely, M. Samyn, and J.M. Pearson, Phys. Rev. C 75 (2007) 064312 and references therein.

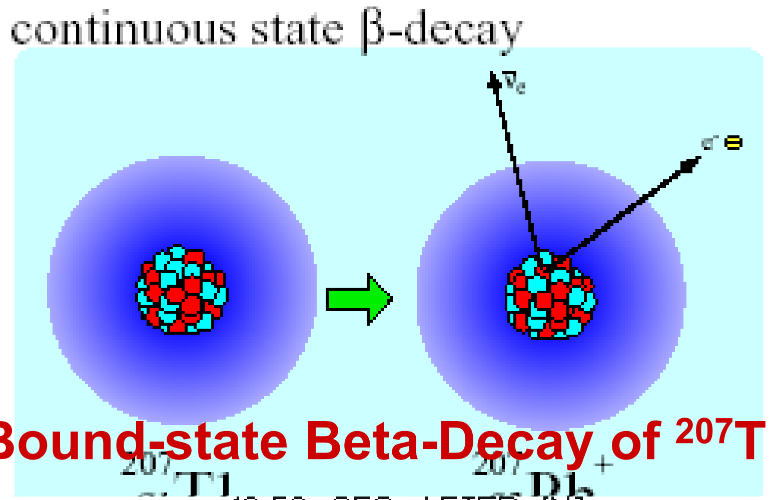
HFB – 17: S. Goriely, N. Chamel, and J.M. Pearson, Eur. Phys. J. A 42 (2009) 547-552.

Duflo & Zuker: J. Duflo, A.P. Zuker, Phys. Rev. C 52 (1995) R23.

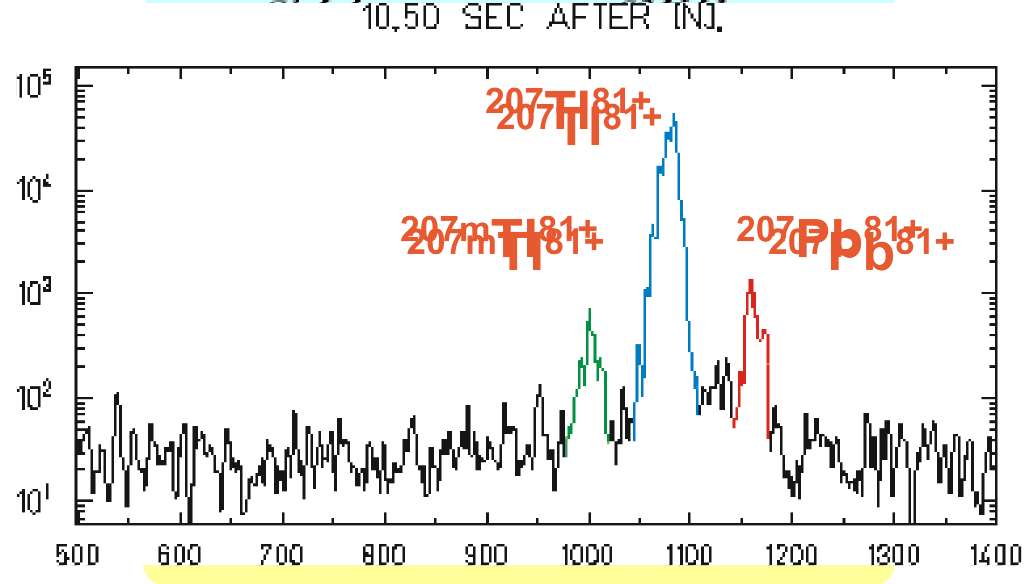
Experimental data not marked in red: G. Audi, A. H. Wapstra, C. Thibault, Nucl. Phys. A 729 (2003) 337.

Lifetime Measurements of Short-lived Nuclei Applying Stochastic and Electronic Cooling





Bound-state Beta-Decay of $^{207}Tl^{81+}$



T. Otsubo, Phys. Rev. Lett. 100, 164801 (2008)

D. Boutin PhD

Measured Nuclear Electron-Capture of H-like & He-like ^{140}Pr and ^{142}Pm Ions

EC Decay Rates

Results for ^{140}Pr

Experiment

$\lambda_{EC}(\text{H-like}) / \lambda_{EC}(\text{He-like}) = \mathbf{1.49(8)}$

Theory

Relative probability of EC Decay

Neutral ^{140}Pr: P = 2.381

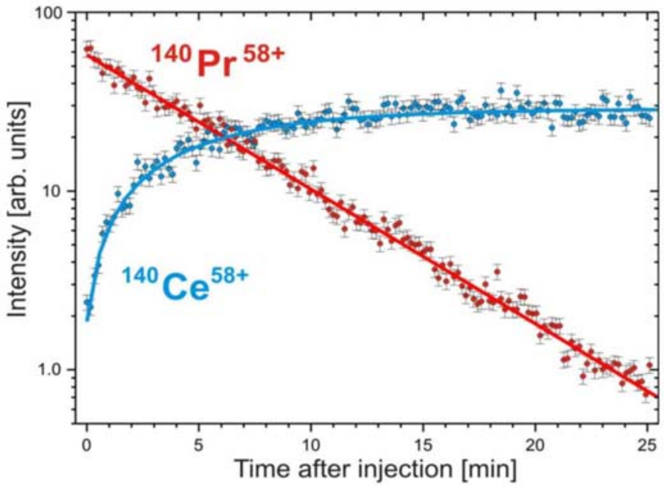
He-like ^{140}Pr: P = 2

H-like ^{140}Pr: P = 3

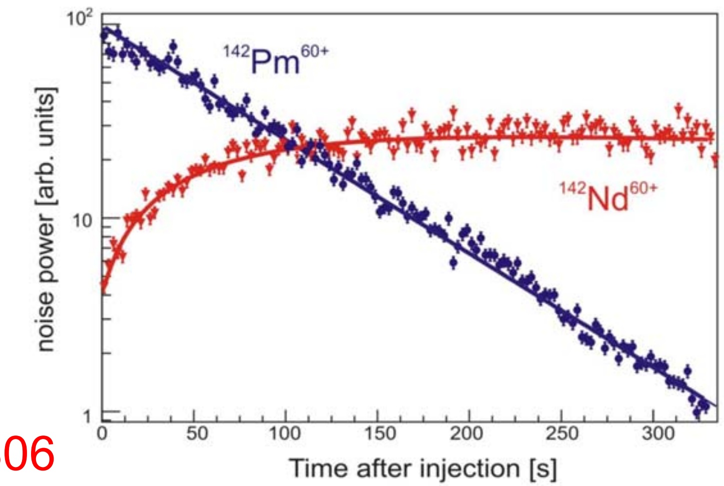
Experiment ^{142}Pm

$\lambda_{EC}(\text{H-like}) / \lambda_{EC}(\text{He-like}) = \mathbf{1.44(6)}$

Yu.A. Litvinov et al., Phys. Rev. Lett. 99 (2007) 262501



N. Winckler et al., Phys. Lett. B679 (2009) 36



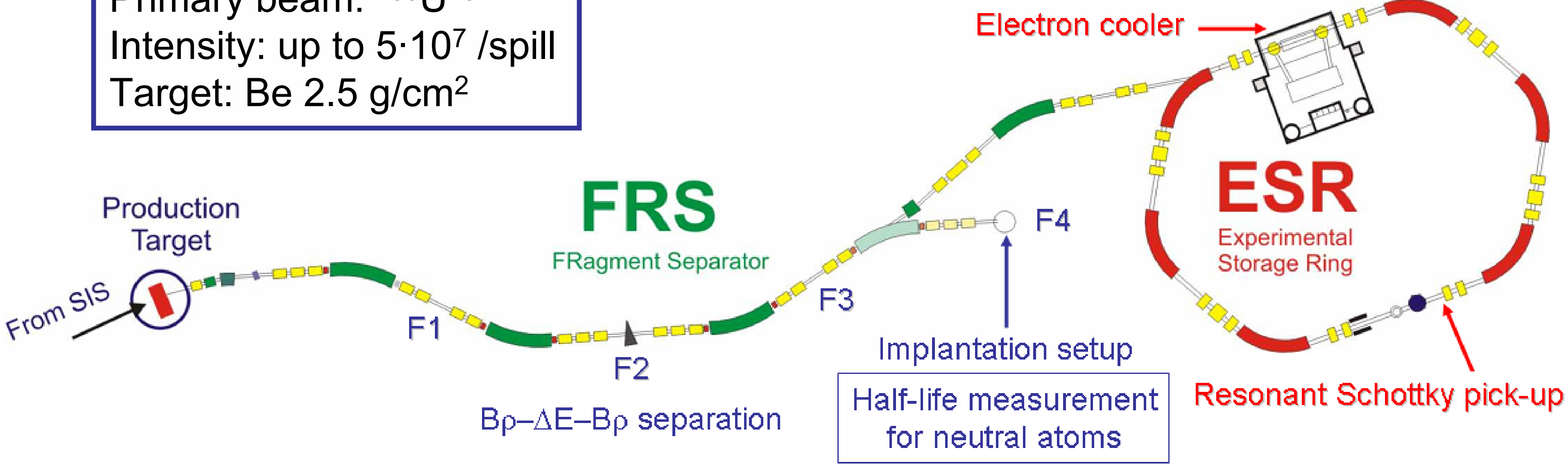
Experiment: N. Winckler (PhD)

Theory: Z. Patyk et al.PR C77 (2008) 014306

Half-life of Neutral α-Emitters

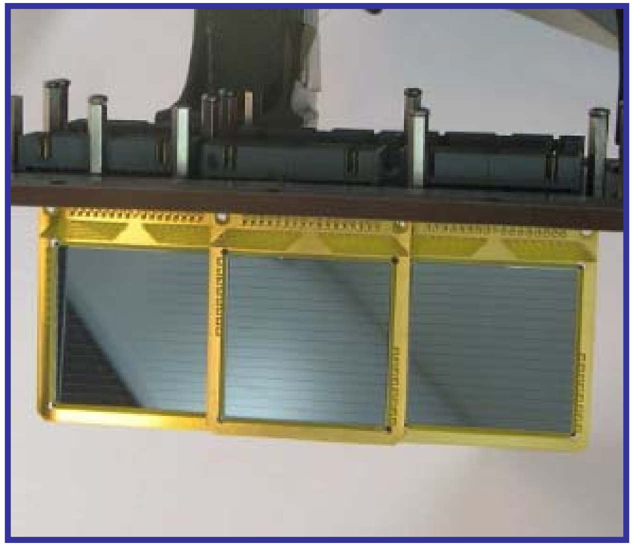
Primary beam: $^{238}U^{73+}$
Intensity: up to $5 \cdot 10^7$ /spill
Target: Be 2.5 g/cm^2

Half-life measurement for stored bare and few electrons ions



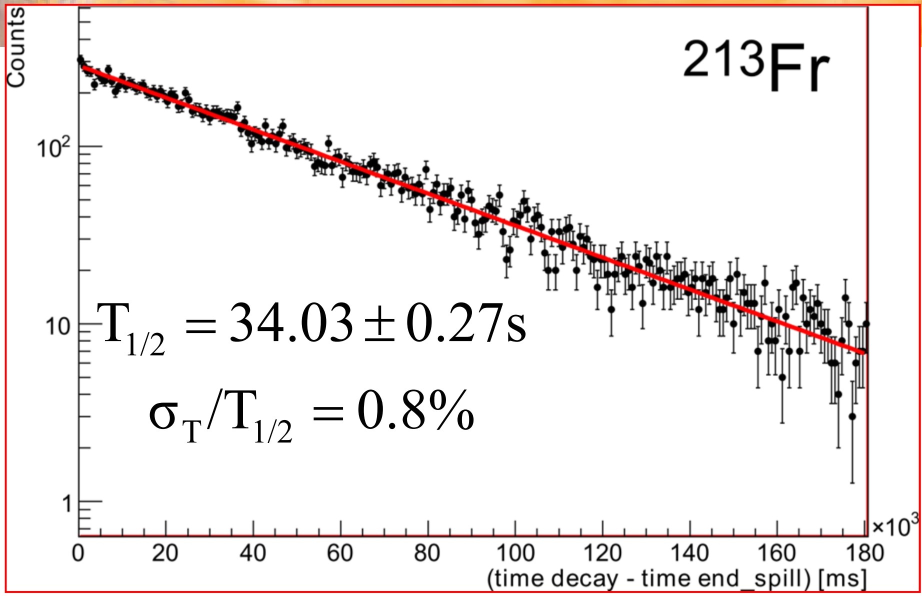
<u>Double-sided strip detectors:</u>

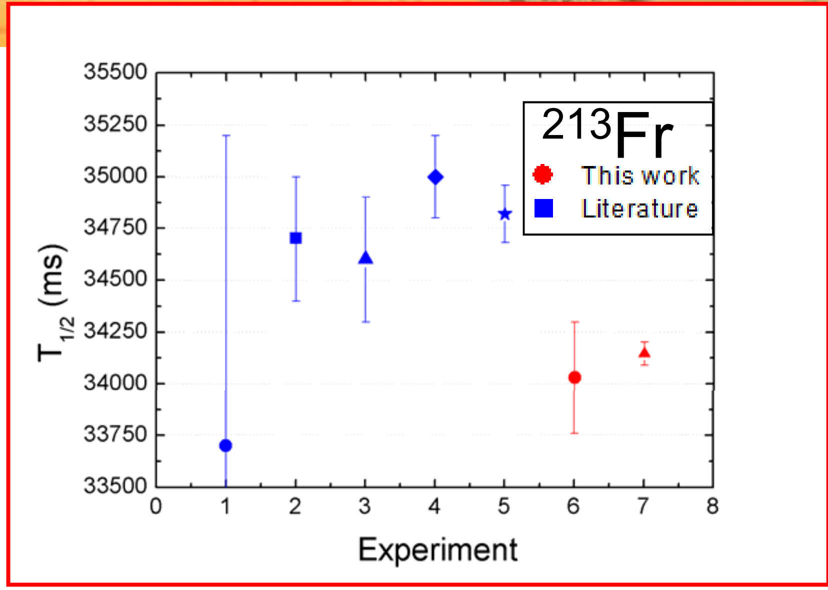
- **<u>surface: 5x5 cm^2</u>**
- **<u>thickness 1 mm</u>**
- **<u>2x16 3.1 mm strips</u>**
- **<u>time resolution: 25 ns</u>**

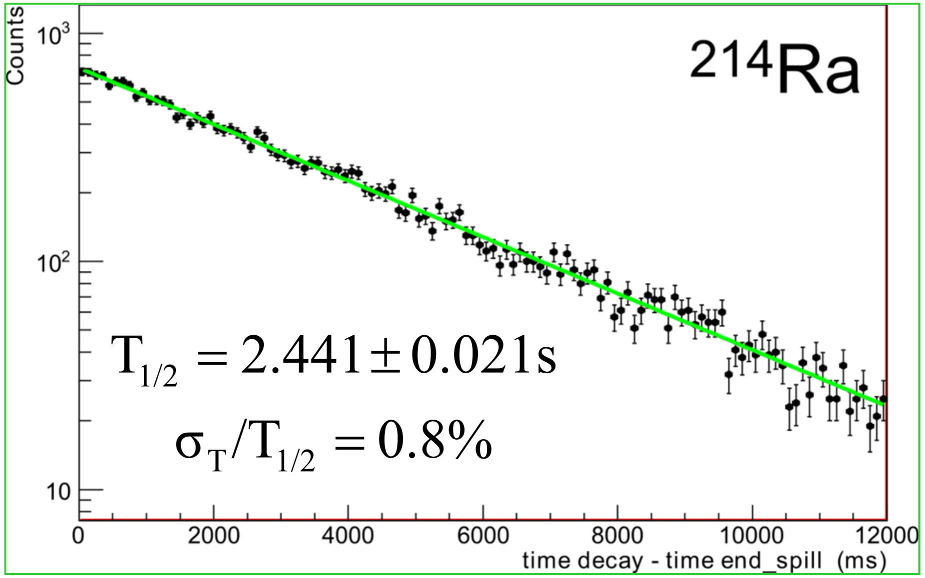


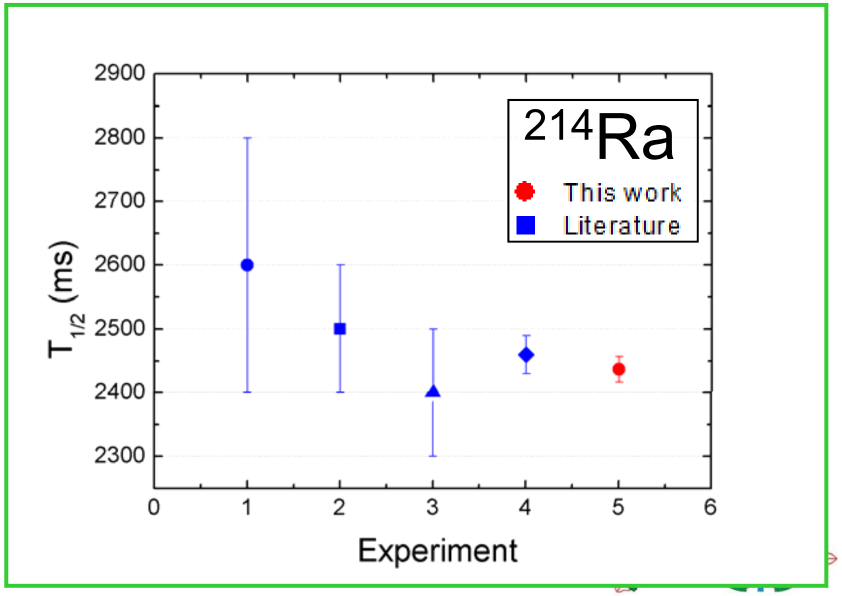
Half-life of neutral ^{213}Fr and ^{214}Ra

Fabio Farinon PhD Oct. 2011









Half-life of H-like and Neutral ^{213}Fr

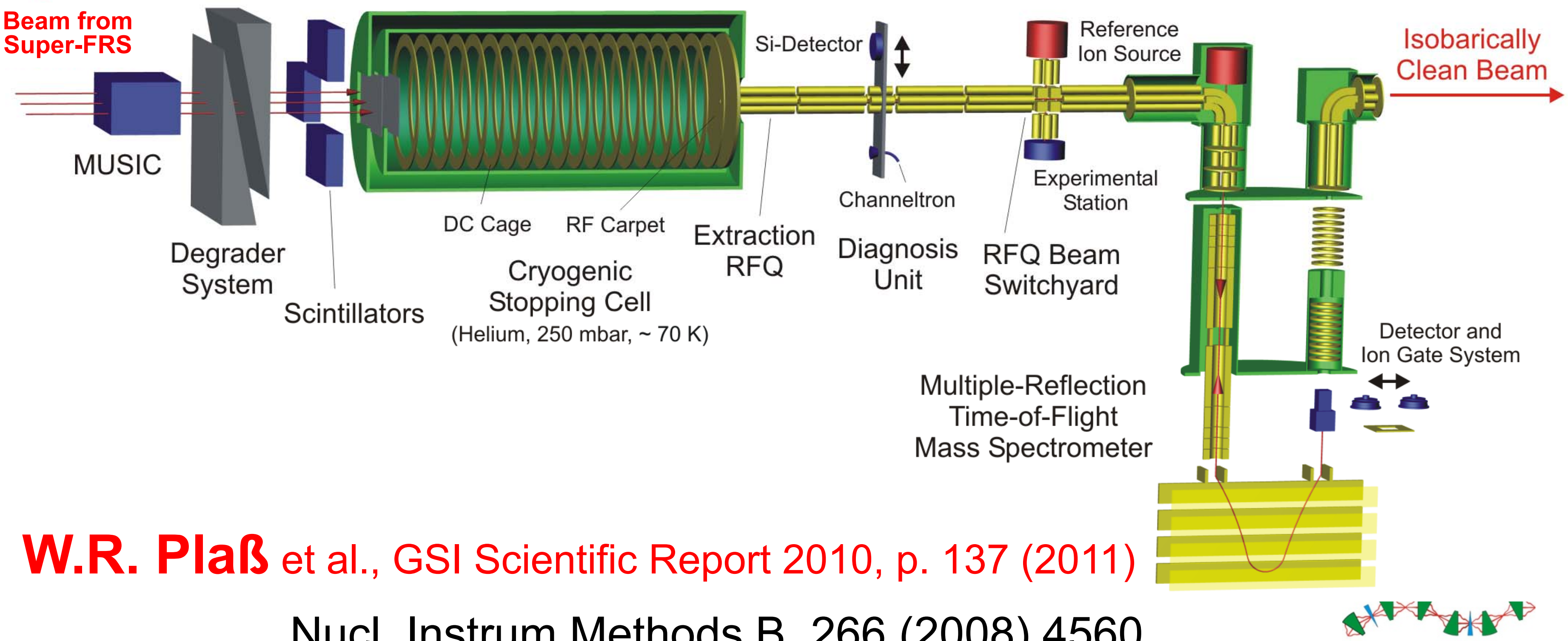
	neutral ^{213}Fr		
	Decay events	$T_{1/2} \pm \sigma_T$ (s)	χ_r^2
FRS (GSI)	36885	34.03 ± 0.27	1.18
LNS (ITALY)	~ 620000	34.160 ± 0.058	0.98

	H-like ^{213}Fr		
	Decay events	$T_{1/2} \pm \sigma_T$ (s)	χ_r^2
ESR (GSI) many-particle method	~ 500	34.4 ± 1.6	1.7
ESR (GSI) single-particle method	36	34 ± 6	3.5

The results of the pilot experiment at the ESR are a strong evidence against the predictions of the theoretical paper from Erma ($\Delta\lambda / \lambda \sim 34$ %).
(A. Erma, Phys. Rev. **105**, 1957).

FRS Ion Catcher

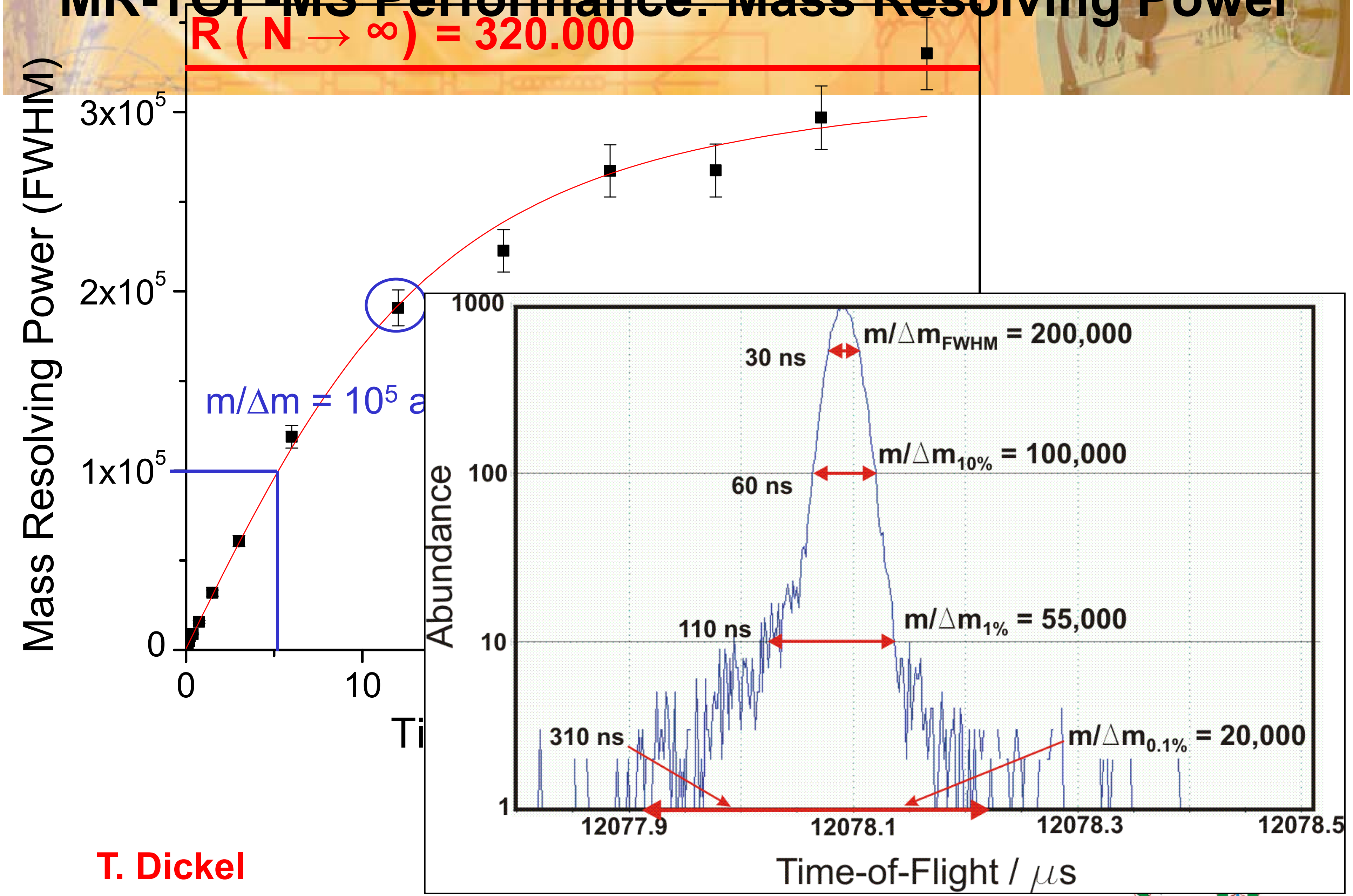
~ GeV/u	~ MeV/u	~ eV	~ keV
Fragment Separator FRS Production, separation and range-bunching	**Cryogenic Stopping Cell** Stopping, thermalization, extraction	**RFQ Beam Line** Ion cooling, transmission, differential pumping, isotope separation, diagnosis, beam distribution introduction of reference ions	**Multiple-reflection TOF-MS** Ion identification, isobar separation direct mass measurements



W.R. Plaß et al., GSI Scientific Report 2010, p. 137 (2011)

Nucl. Instrum.Methods B, 266 (2008) 4560.

MR-TOF-MS Performance: Mass Resolving Power



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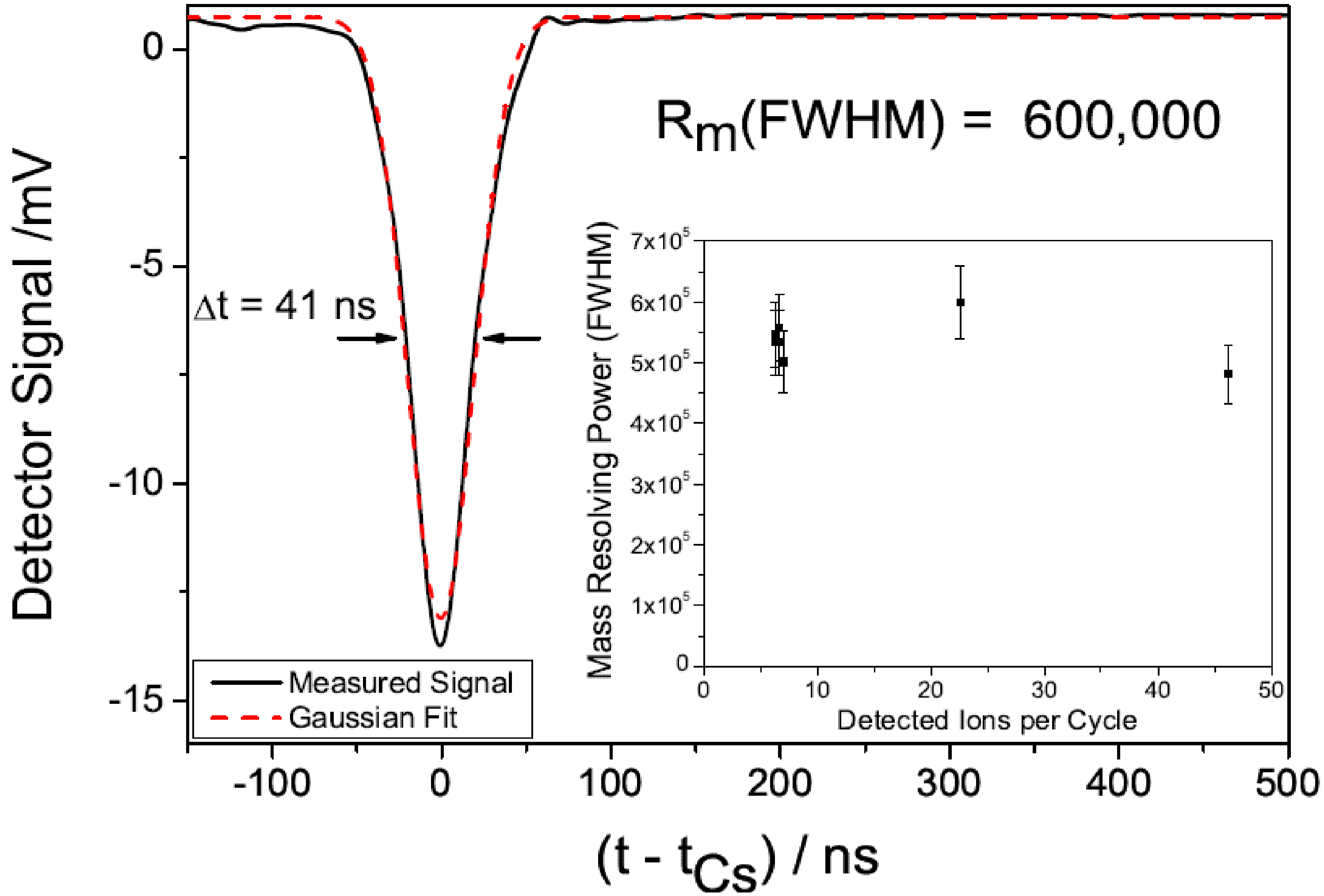
W.R. Plass

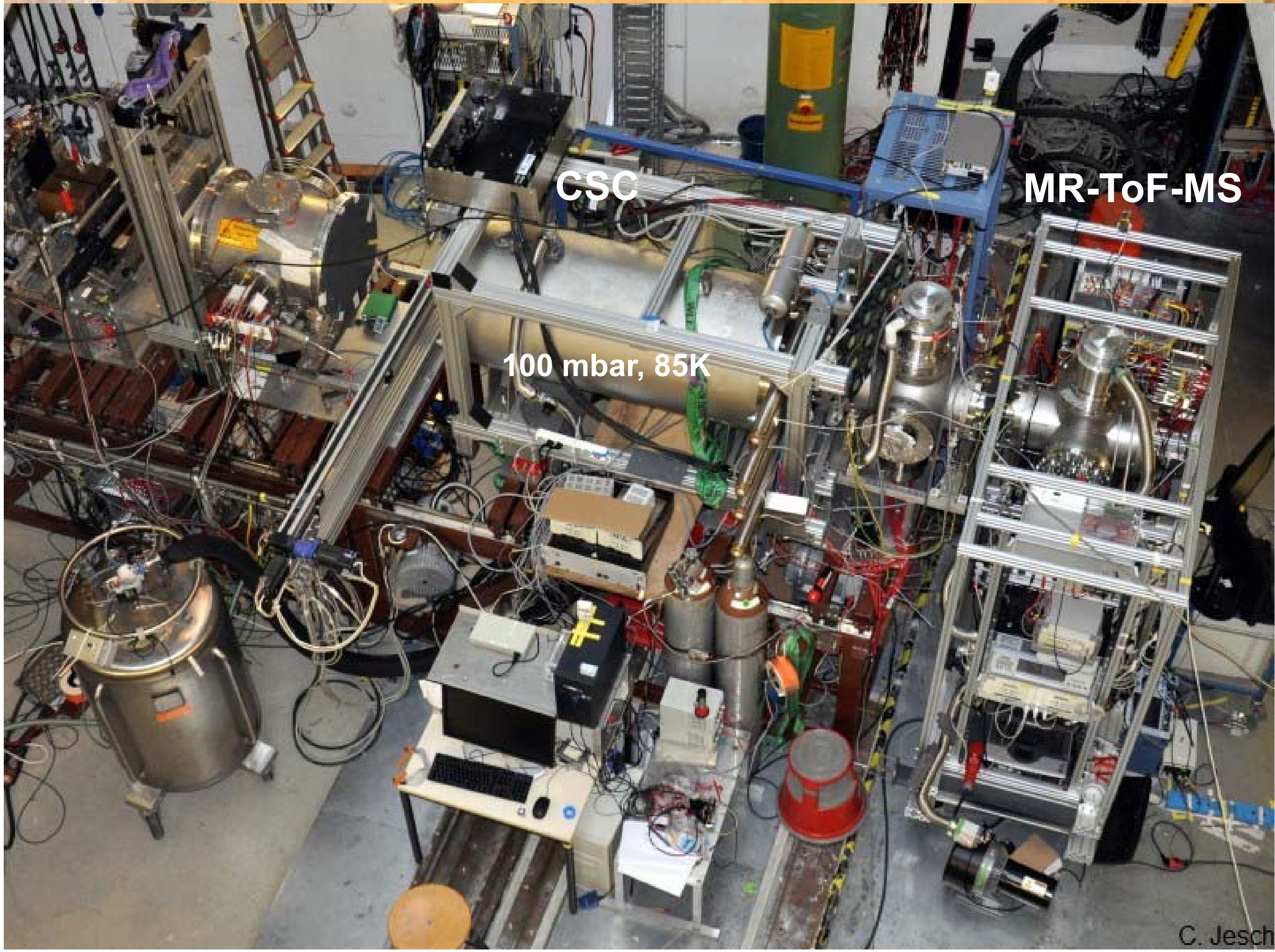
MR-TOF-MS Performance: Mass Resolving Power



T. Dickel
W.R. Plass

GSI SCIENTIFIC REPORT 2010 PHN-NUSTAR-FRS-08

First 1 GeV/u ^{238}U Run with Cryogenic Stopping Cell & MR-TOF-MS with FRS October 2011



CSC and MR-ToF-MS online at the final focal plane at the FRS

First Results:

Short-lived projectile fragments (^{223}Th,^{221}Ac) from 1 GeV/u 238U have been accepted and transmitted with high efficiency.

The combination of the two devices open a novel field for studies with exotic nuclei.

Summary

- Mass-, Lifetime Measurements of stored exotic nuclei have contributed significantly to the basic knowledge of matter.

- The discovery of 60 new neutron-rich isotopes have opened up a new field for nuclear structure physics and astrophysics.

- The Ion Catcher consisting of a cryogenic gas stopping cell and the MR-Tof open a new field for spectroscopy with low-energy cooled reaction products at in-flight separators like FRS, Super-FRS. SHIP and LEB.

Acknowledgements

IONAS Group at JLU Gießen

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R. Knöbel, J. Lang, M. Petrick, W.R. Plaß, M.P. Reiter,
A.-K. Rink, C. Scheidenberger, B. Sun, W. Lippert, M. Yavor

FRS Ion Catcher / S411 Collaboration

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R. Knöbel, J. Kurcewicz, J. Lang, I.D. Moore, C. Nociforo,
H. Penttilä, S. Pietri, W.R. Plaß, A. Prochazka, S. Purushothaman,
M. Ranjan, M.P. Reiter, S. Rinta-Antila, C. Scheidenberger,
M. Takechi, H. Weick, J.S. Winfield

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university of groningen

UNIVERSITY OF JYVÄSKYLÄ

C. Jesch