Applying Heavy-Ion Storage Rings for Precision Experiments at the Intersection of Atomic and Nuclear Physics

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Seminar Moscow State University
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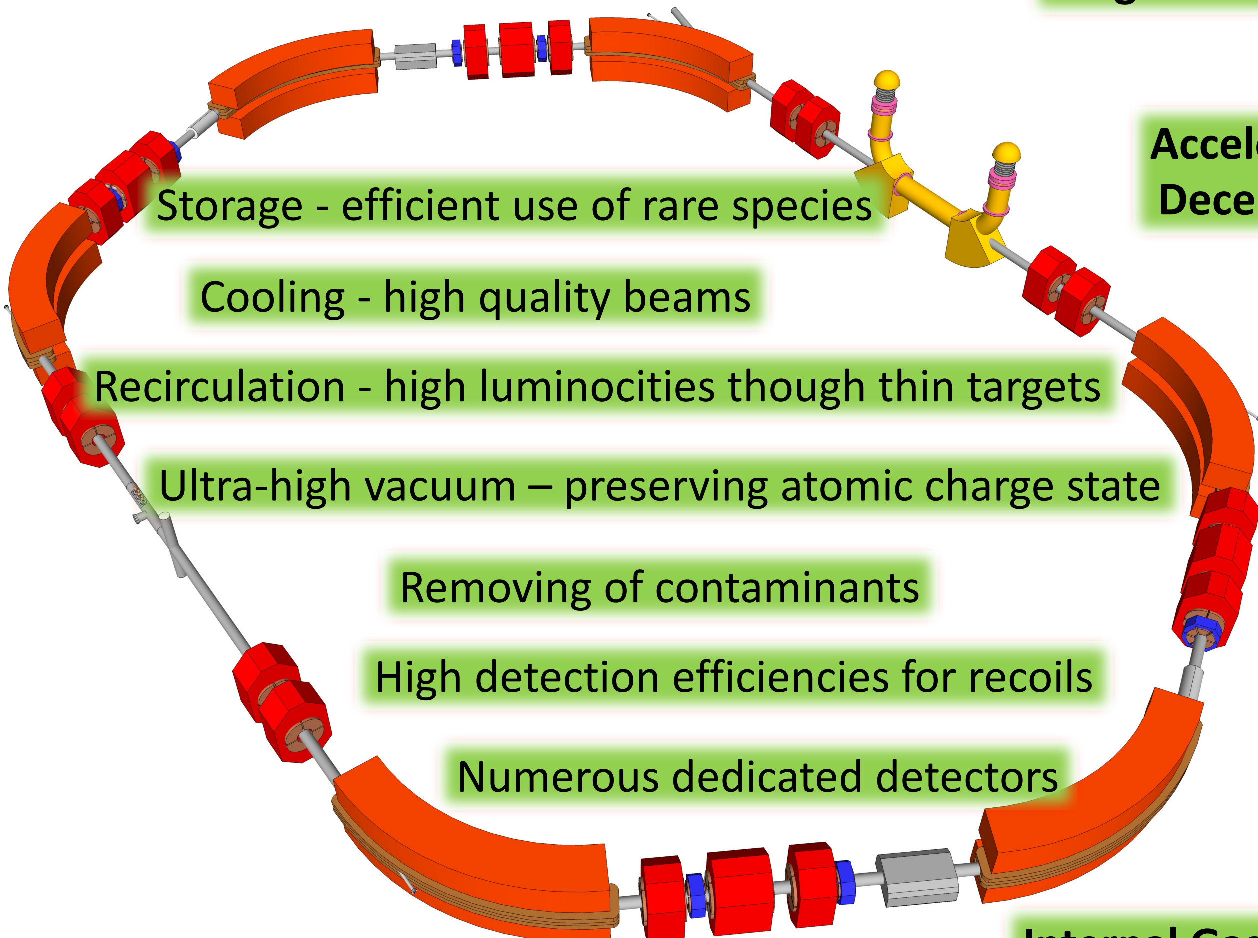
Why storage rings? - Versatile Capabilities



Storage - efficient use of rare species

Cooling - high quality beams

Recirculation - high luminocities though thin targets

Ultra-high vacuum – preserving atomic charge state

Removing of contaminants

High detection efficiencies for recoils

Numerous dedicated detectors

Large Acceptance

Beam Accumulation

Acceleration/ Deceleration

UHV

Beam Cooling:
- Stochastic
- Electron
- (Laser)

Beam Bunching

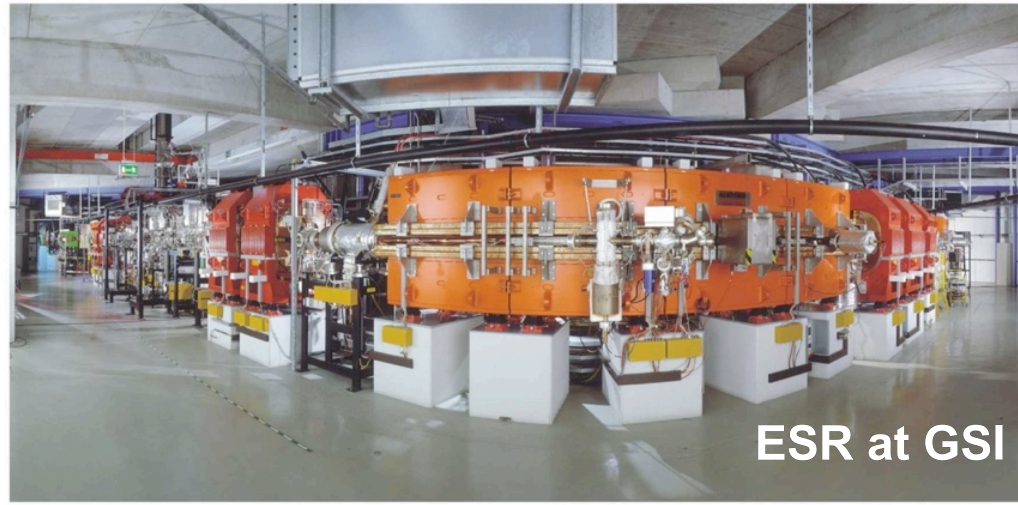
Various targets:
- Electrons
- Photons
- Atoms
- (Ions)
- (Neutrons)

Detection:
- Electrons
- Photons
- Recoils

Internal Gas-Jet Target

Non-destructive particle detection

Physics at Storage Rings



Storage rings stay for:
Single-particle sensitivity
Broad-band measurements
High atomic charge states
High resolving power

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Photos: M. Lestinsky, A. Zschau, GSI; IMP Lanzhou; RIKEN

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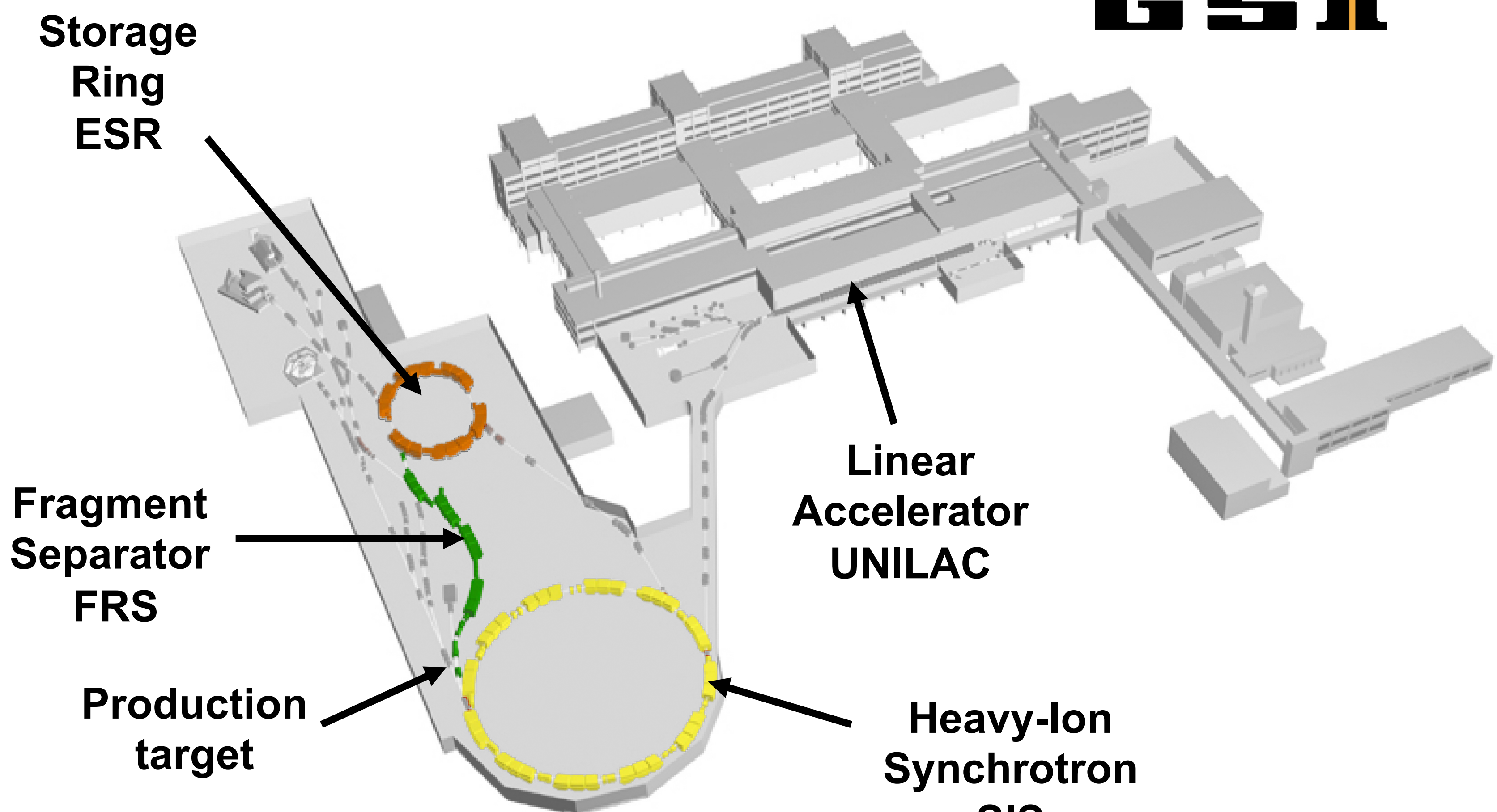
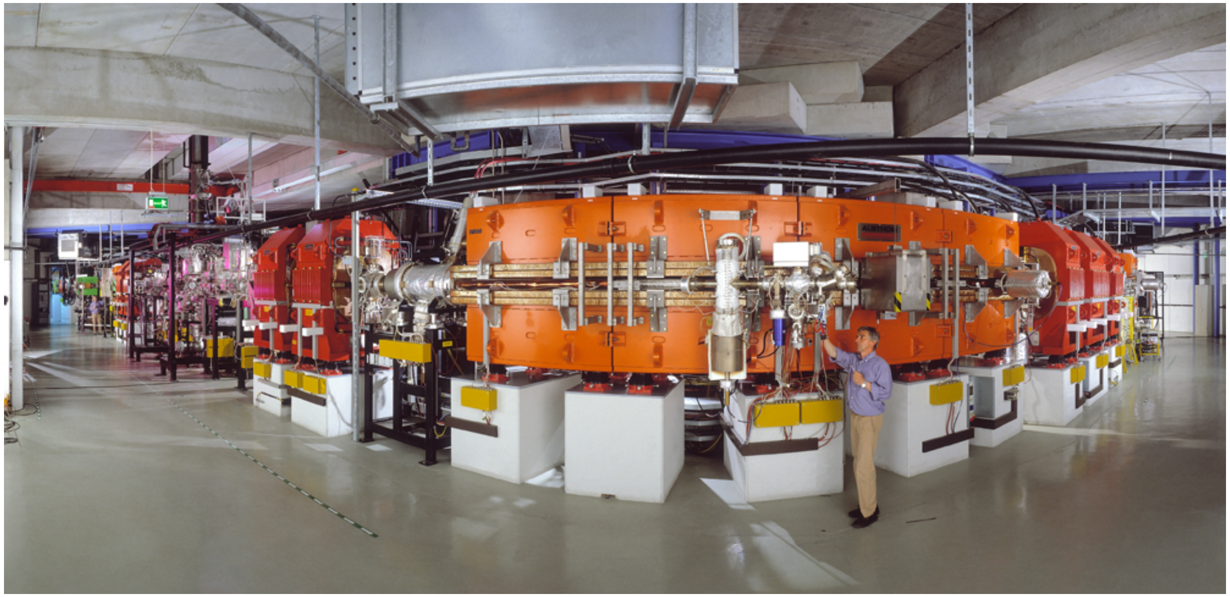
Physics with Storage Rings

Mass measurements
Nuclear structure through transfer reactions
Long-lived isomeric states
Atomic effects on nuclear half-lives
Nuclear effects on atomic decay rates
Exotic decay modes (NEEC/NEET, unbound states, …)
Di-electronic recombination on exotic nuclei
Purification of secondary beams from contaminants
Nuclear magnetic moments
Neutron–induced reactions
Astrophysical reactions
….

Radioactive Ion Beam Facility at GSI



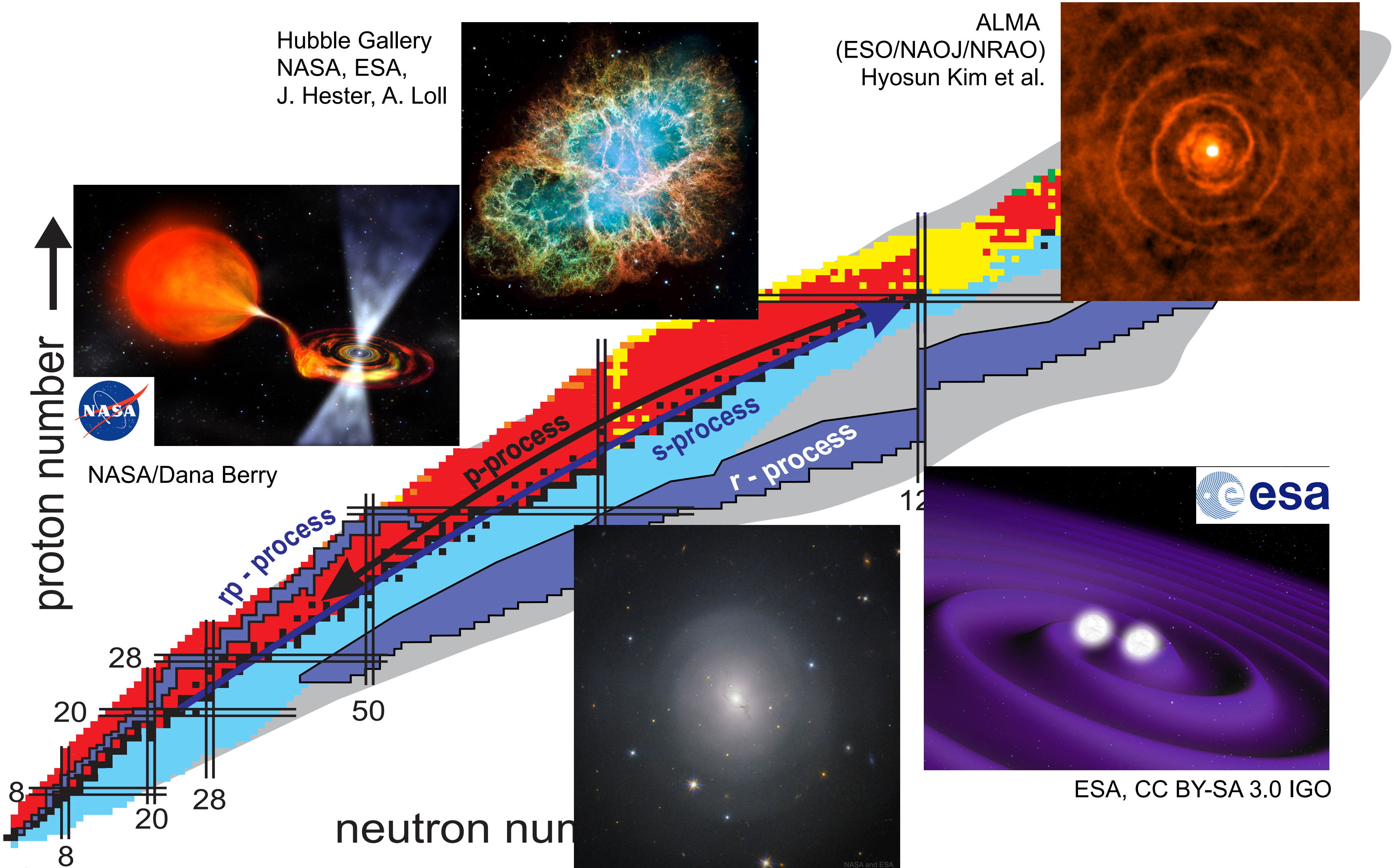
Storage ring facilities at GSI



Experimental Storage Ring (ESR)

In operation since 1990
Circumference = 108.3 m
UH Vacuum = 10^{-10}—10^{-12} mbar
Electron, stochastic cooling
Energy range = 3 – 400 MeV/u
Slow and fast extraction

Where and how was gold cooked?



Hubble Gallery
NASA, ESA,
J. Hester, A. Loll

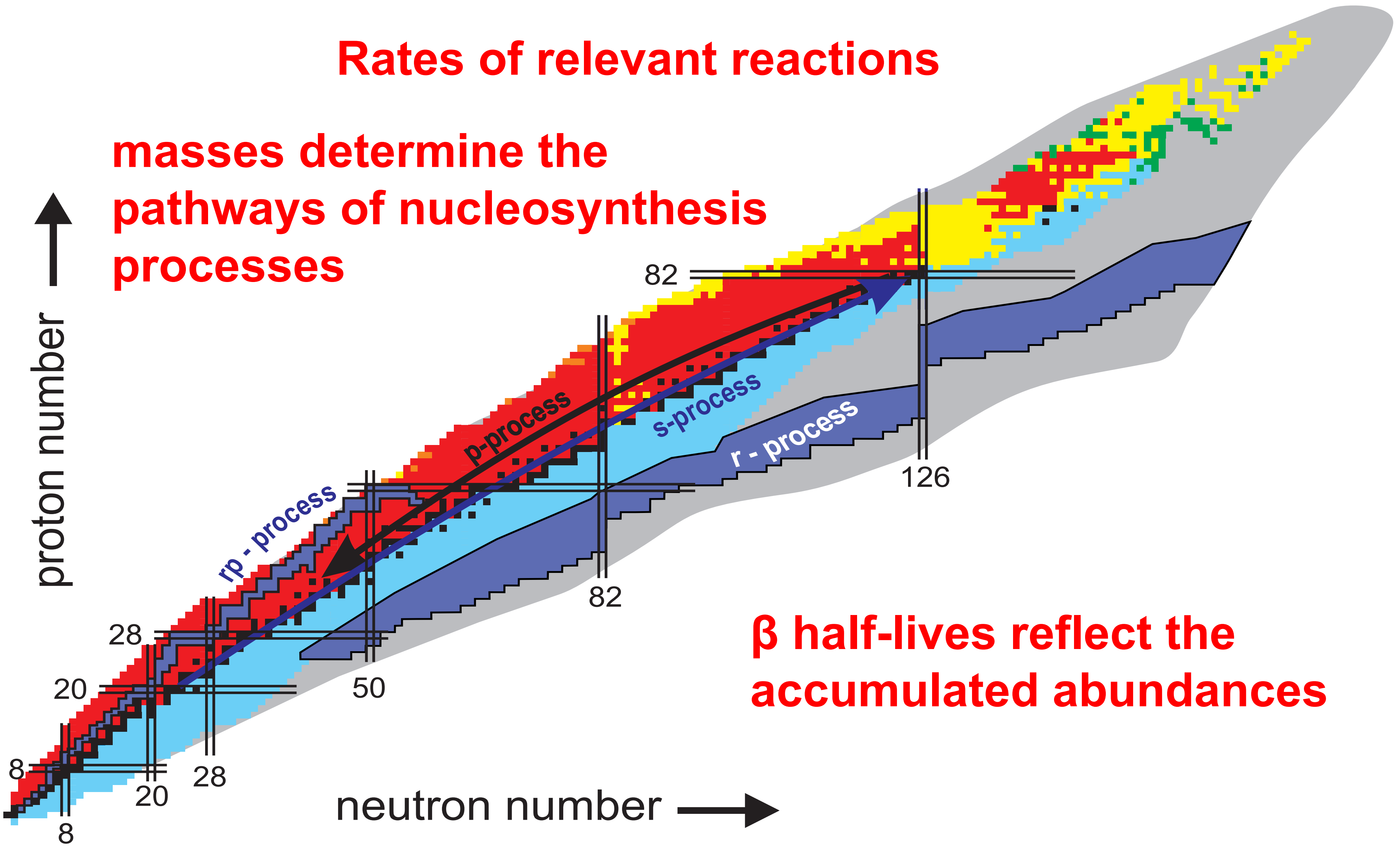
ALMA
(ESO/NAOJ/NRAO)
Hyosun Kim et al.

NASA/Dana Berry

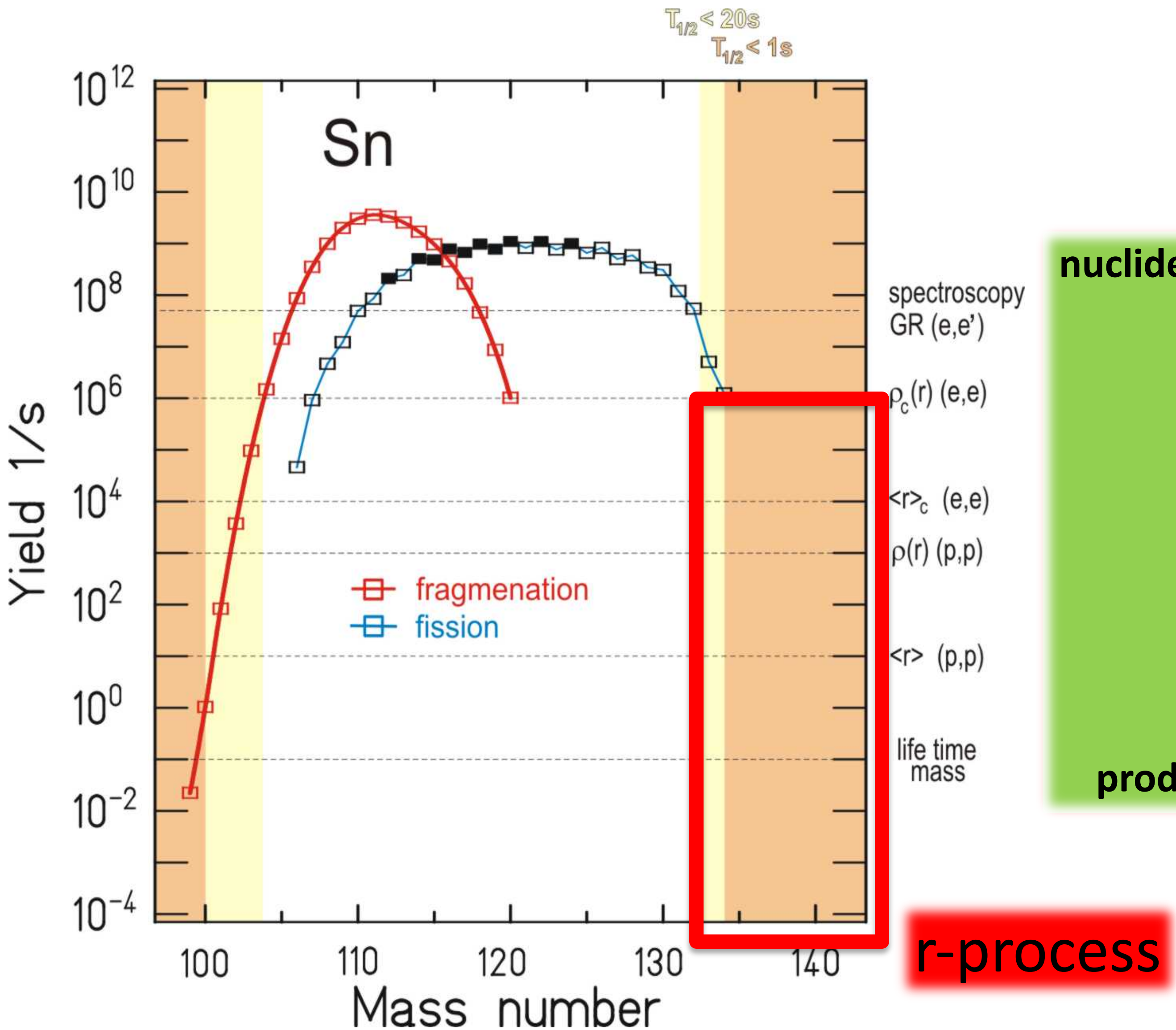
ESA, CC BY-SA 3.0 IGO

Hubble Gallery, NASA, ESA

Where and how was gold cooked?



Production Cross-Sections for Tin-Isotopes



nuclides of interest today are

--as a rule--

short-lived

and

have tiny

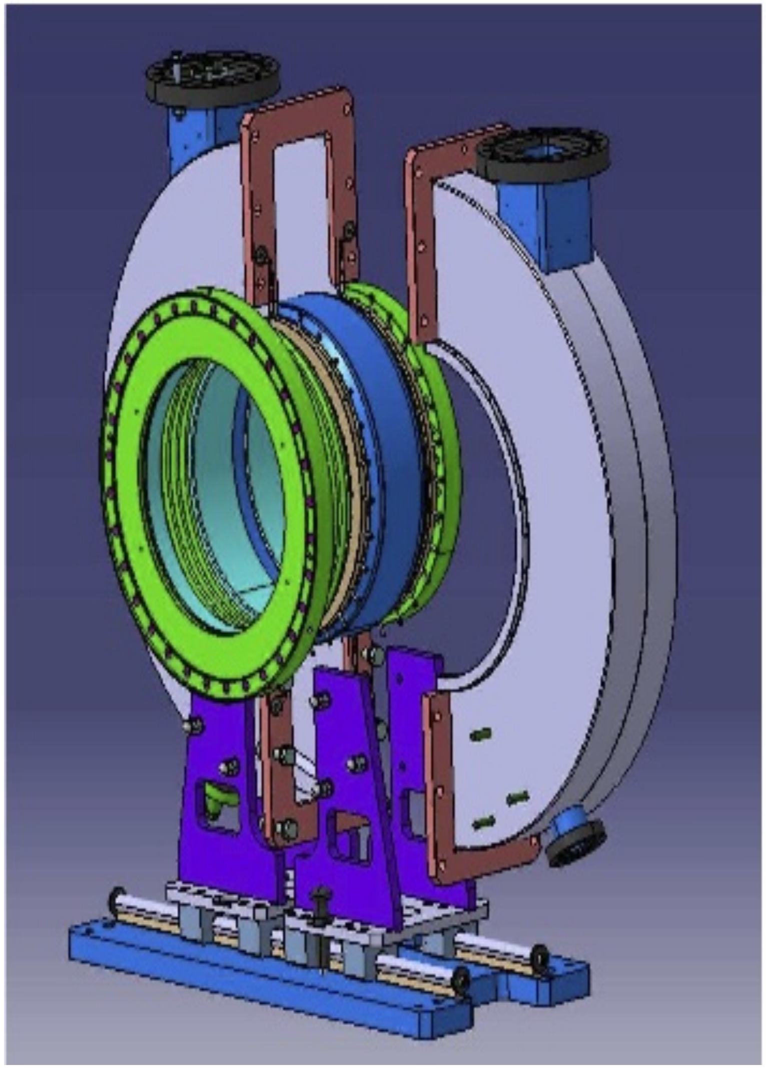
production cross-sections

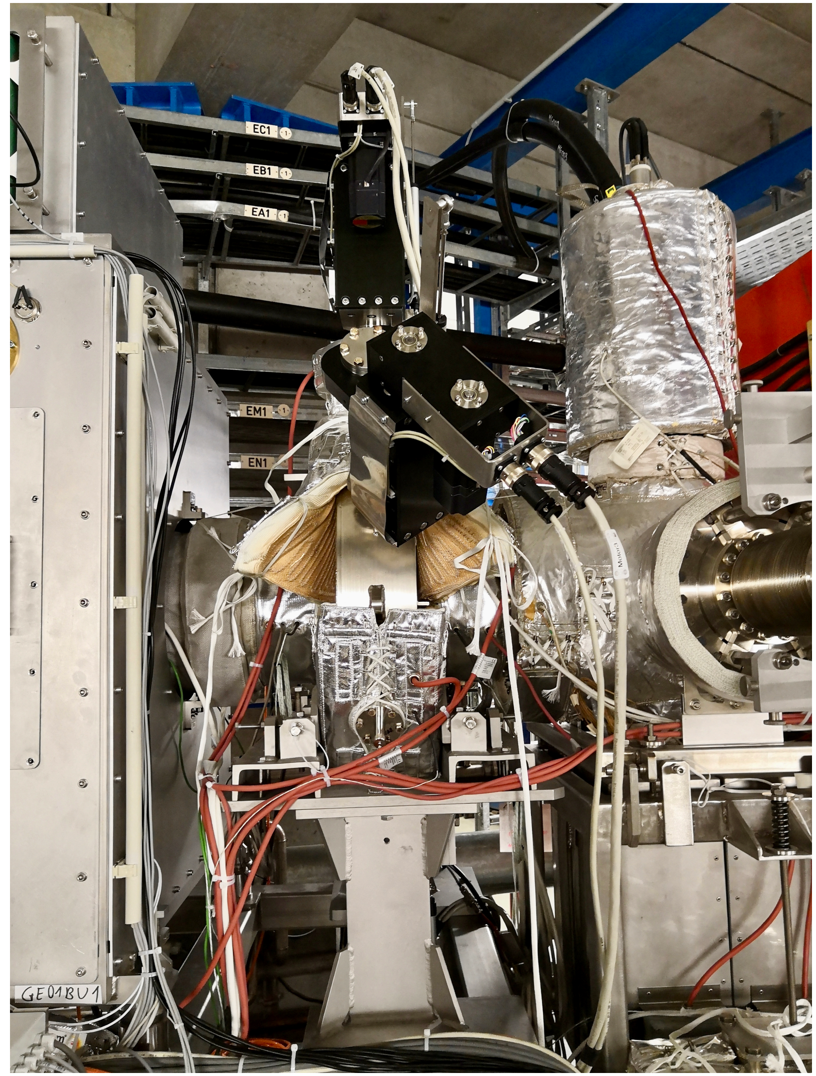
FAIR Conceptual Design Report (2002)

Courtesy: H. Geissel

Image: 4ever.eu / Mat’o

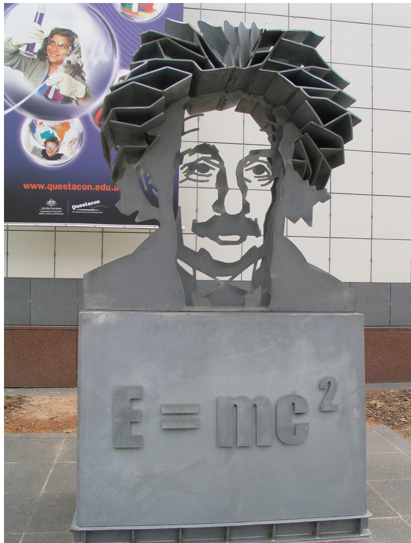
Non-Destructive Particle Detection

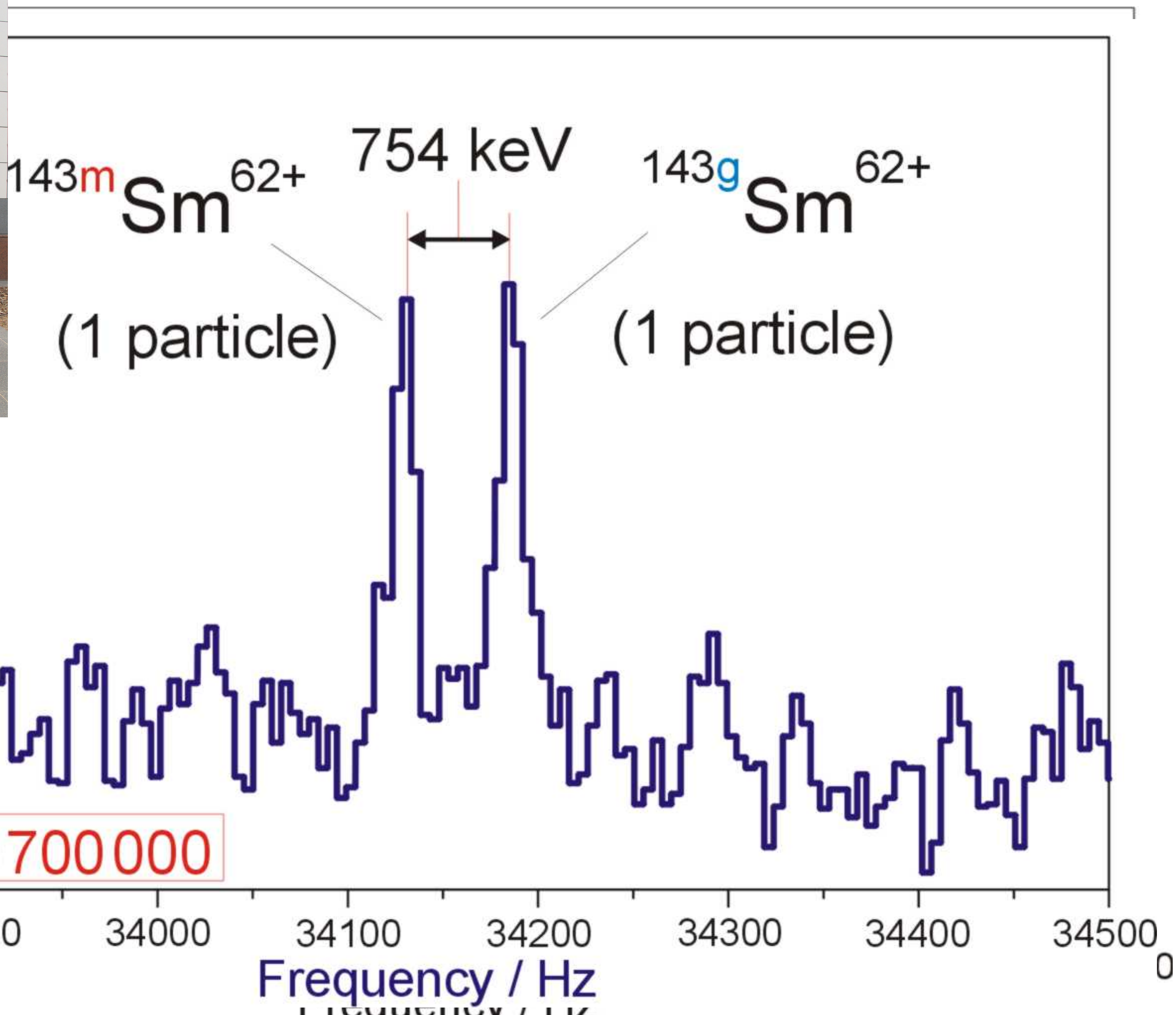




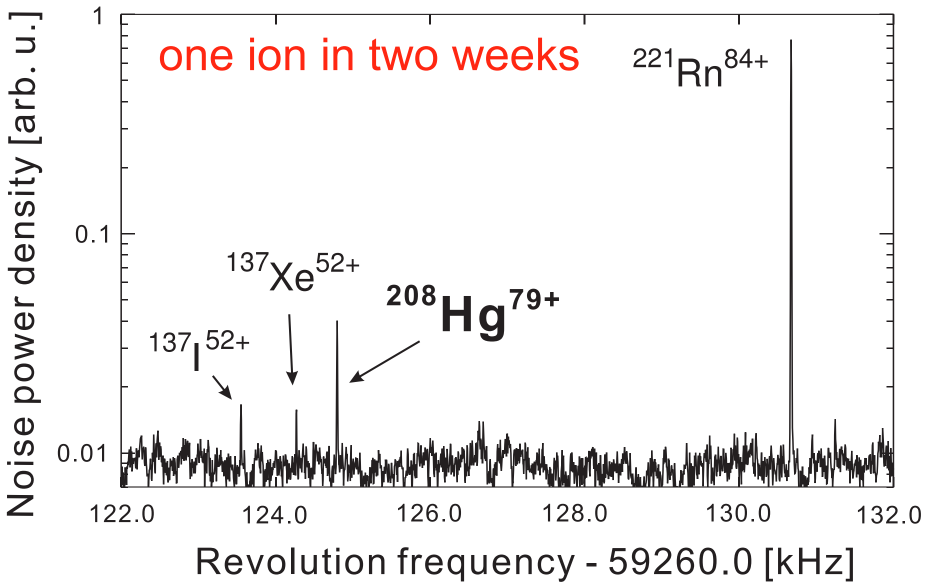
Courtesy F. Nolden and M. S. Sanjari

SMS: Broad Band Frequency Spectra





Mass Measurement of ^{208}Hg in the ESR (SMS)



$$\delta V_{pn}(Z,N) = \frac{1}{4}\Big[B(Z,N) - B(Z,N-2) - B(Z-2,N) + B(Z-2,N-2)\Big]$$

p-n interactions are sensitive to the spatial overlaps of the proton and neutron wave functions

L. Chen, et al., PRL 102 (2009) 122503

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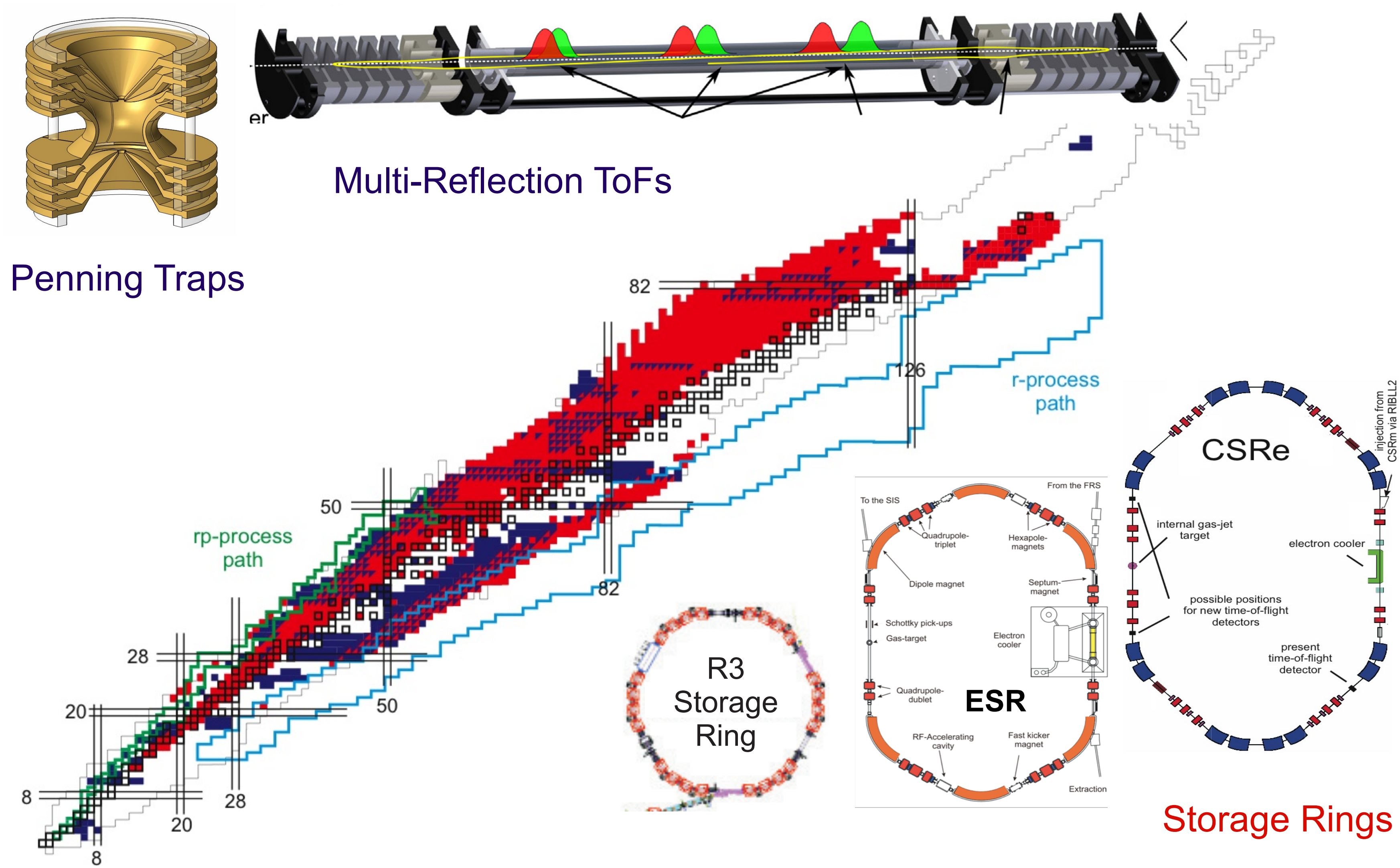
Direct Mass Measurements



K. Blaum et al., 100 Years Mass Spectrometry [Int. J. Mass Spectr. 349-350 (2013)]
Y. H. Zhang, et al., Phys. Scripta 91, 073002 (2016)

Radioactive decays of highly-charged ions

Few-electron ions
well-defined quantum-mechanical systems

New decay modes
(bound-pair-creation, bound-state beta decay, etc.)

Influence of electrons on radioactive decay

Astrophysical scenarios
high temperature = high degree of ionization

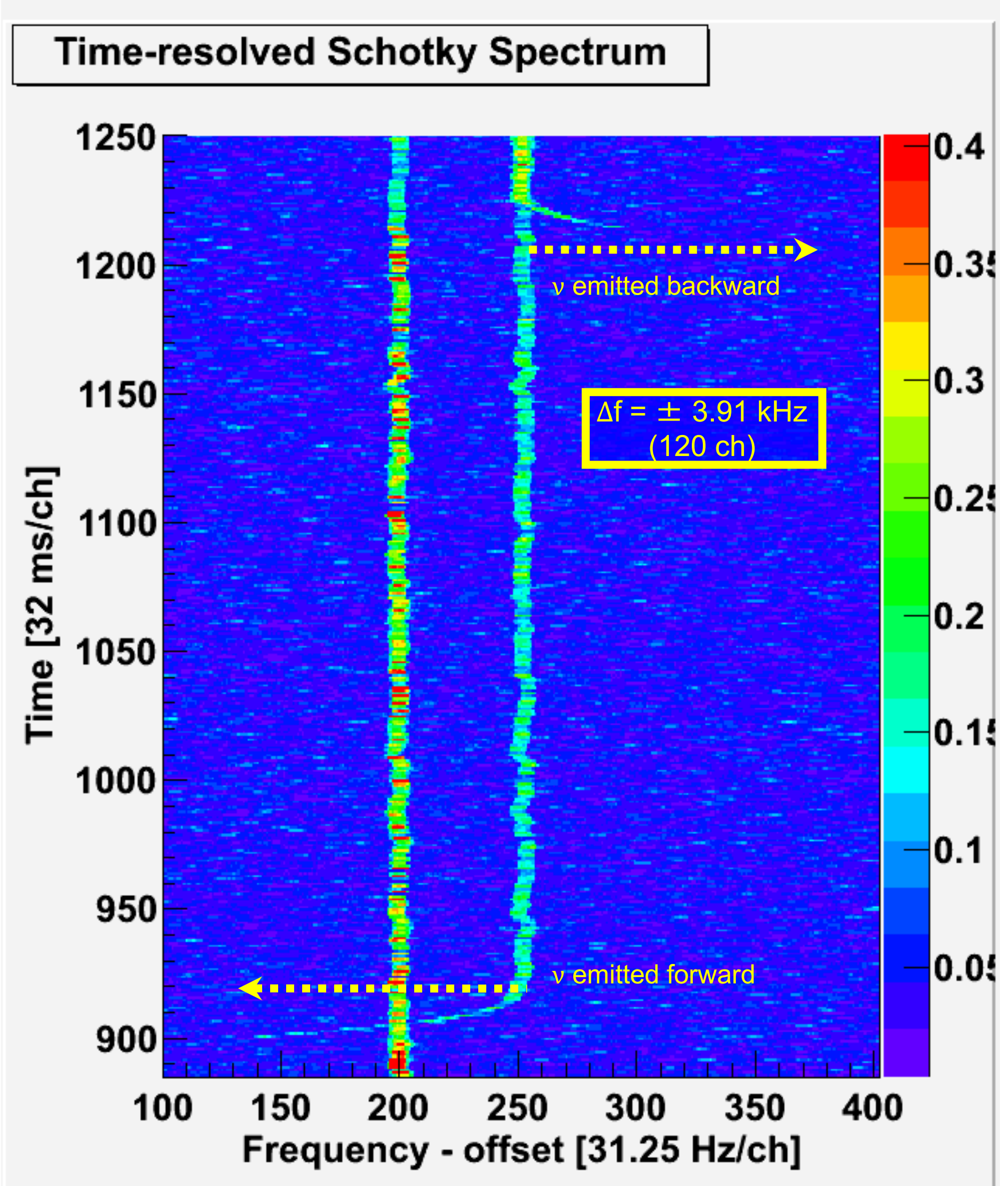
Exotic (radioactive) nuclides in high atomic charge states stored for an extended period of time

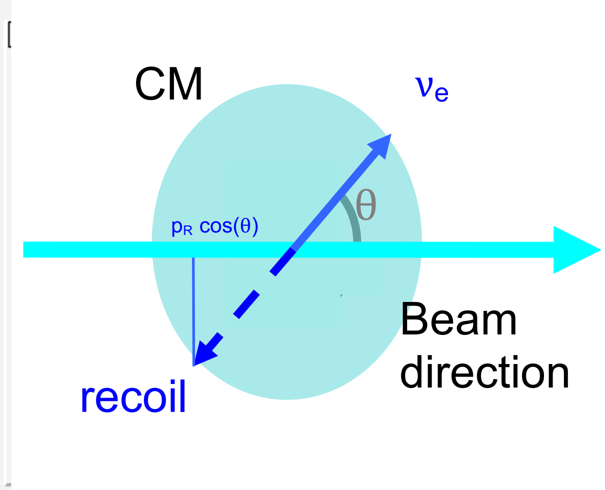
Radioactive ion beam facilities

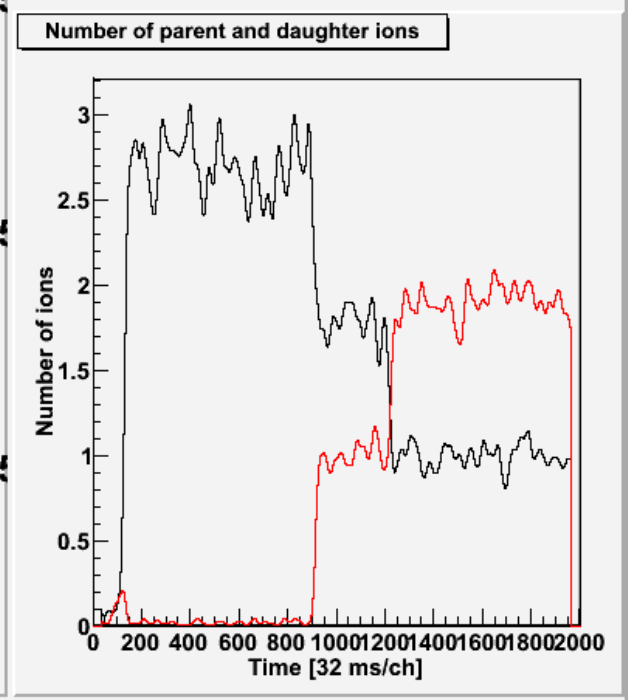
High kinetic energies or electron beam ion source

Ultra-high vacuum conditions

Three Parent He-Like ^{142}Pm Ions

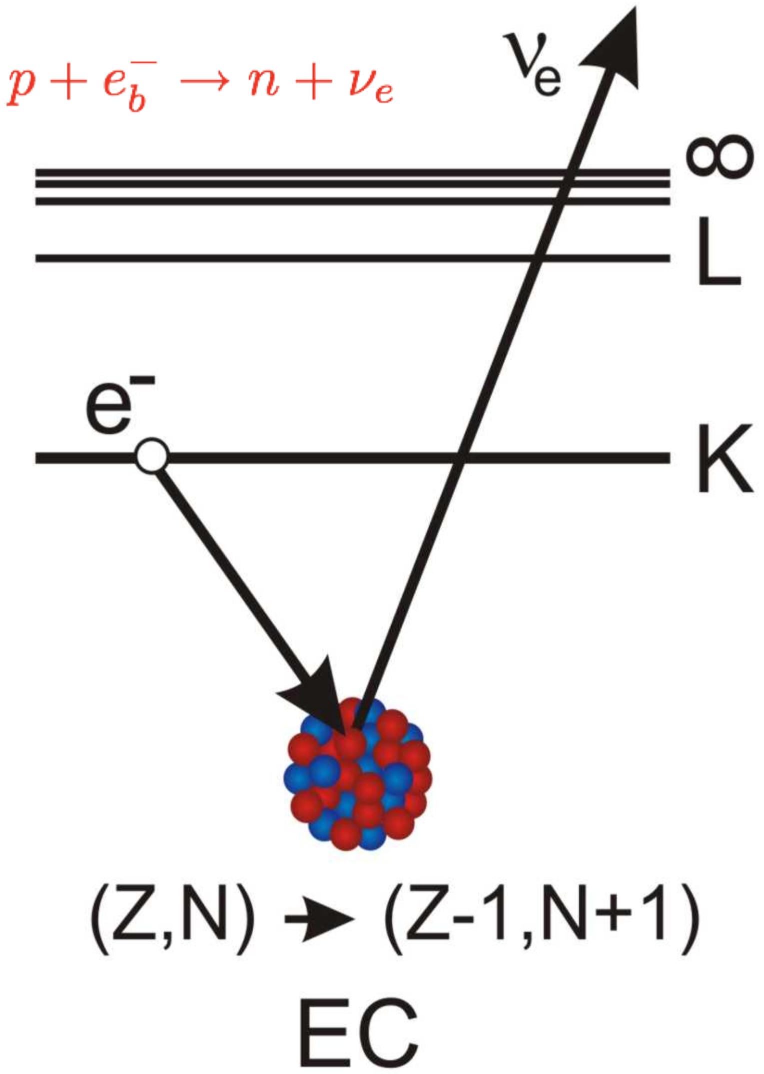




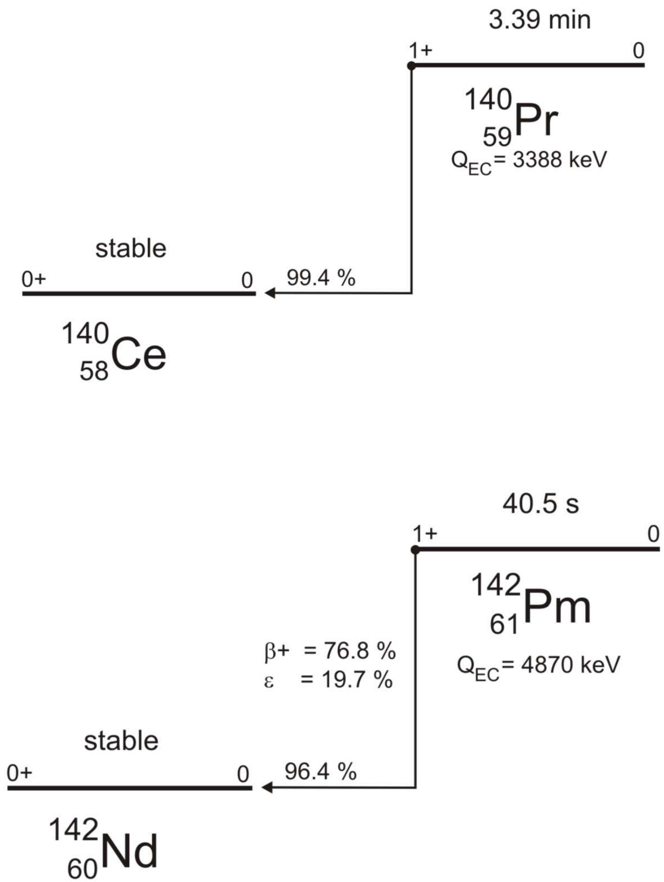


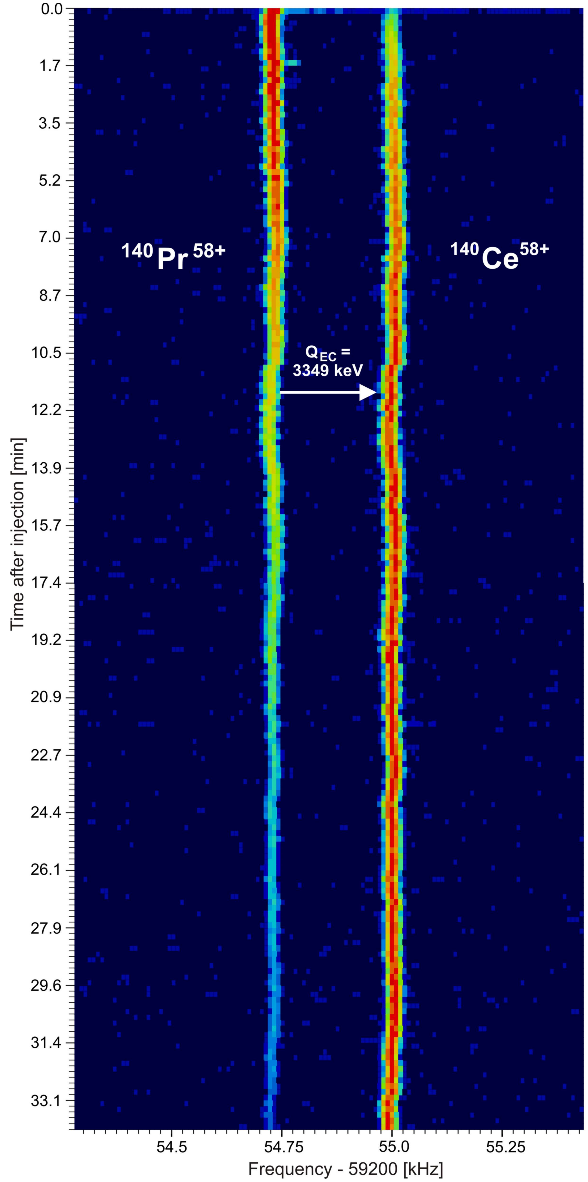
Courtesy: N. Winckler

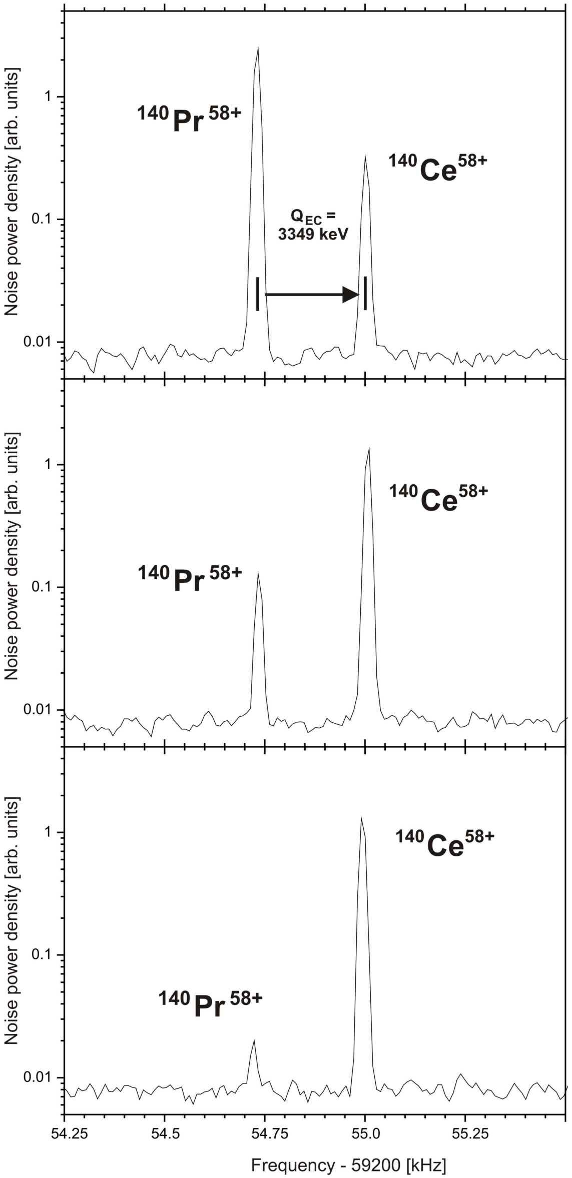
Two-Body Beta Decay



EC Decay of Few-Electron Ions







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Y. Litvinov et al., Phys. Rev. Lett. 99 (2007) 26501

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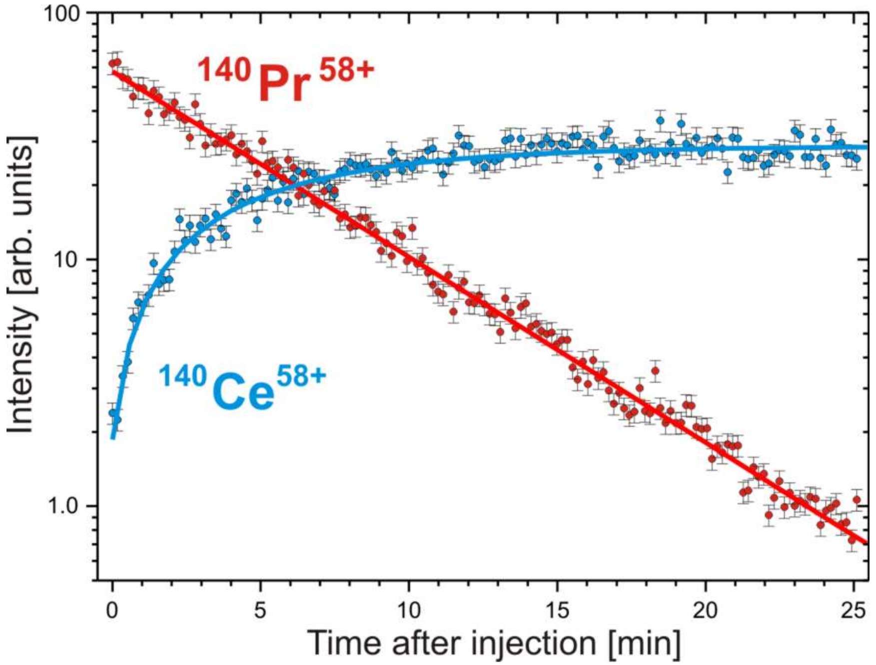
EC Decay of Few-Electron Ions

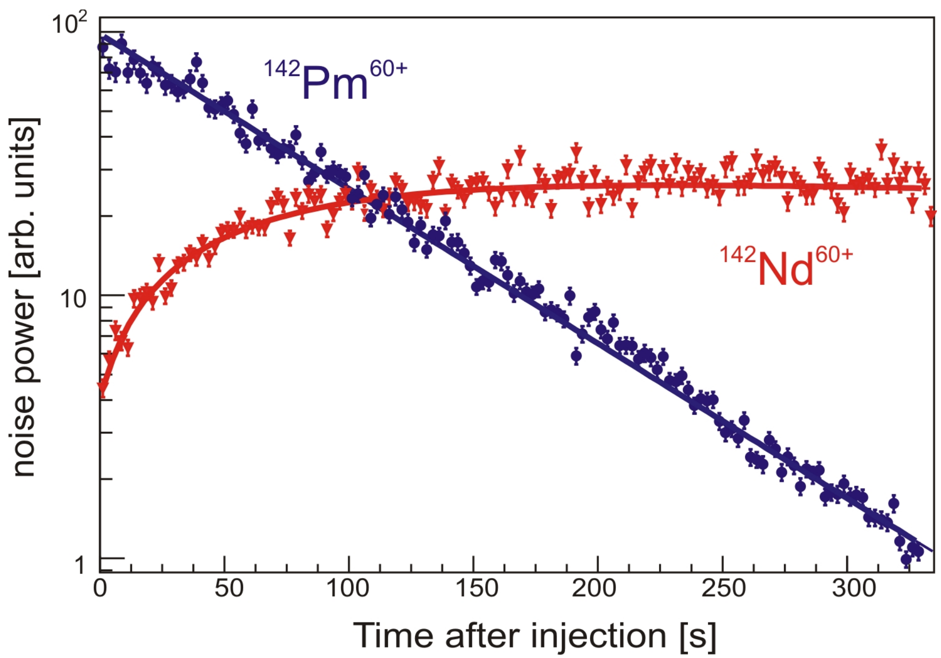
Expectations: $\lambda_{EC}(\text{H-like})/\lambda_{EC}(\text{He-like}) \approx 0.5$

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

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

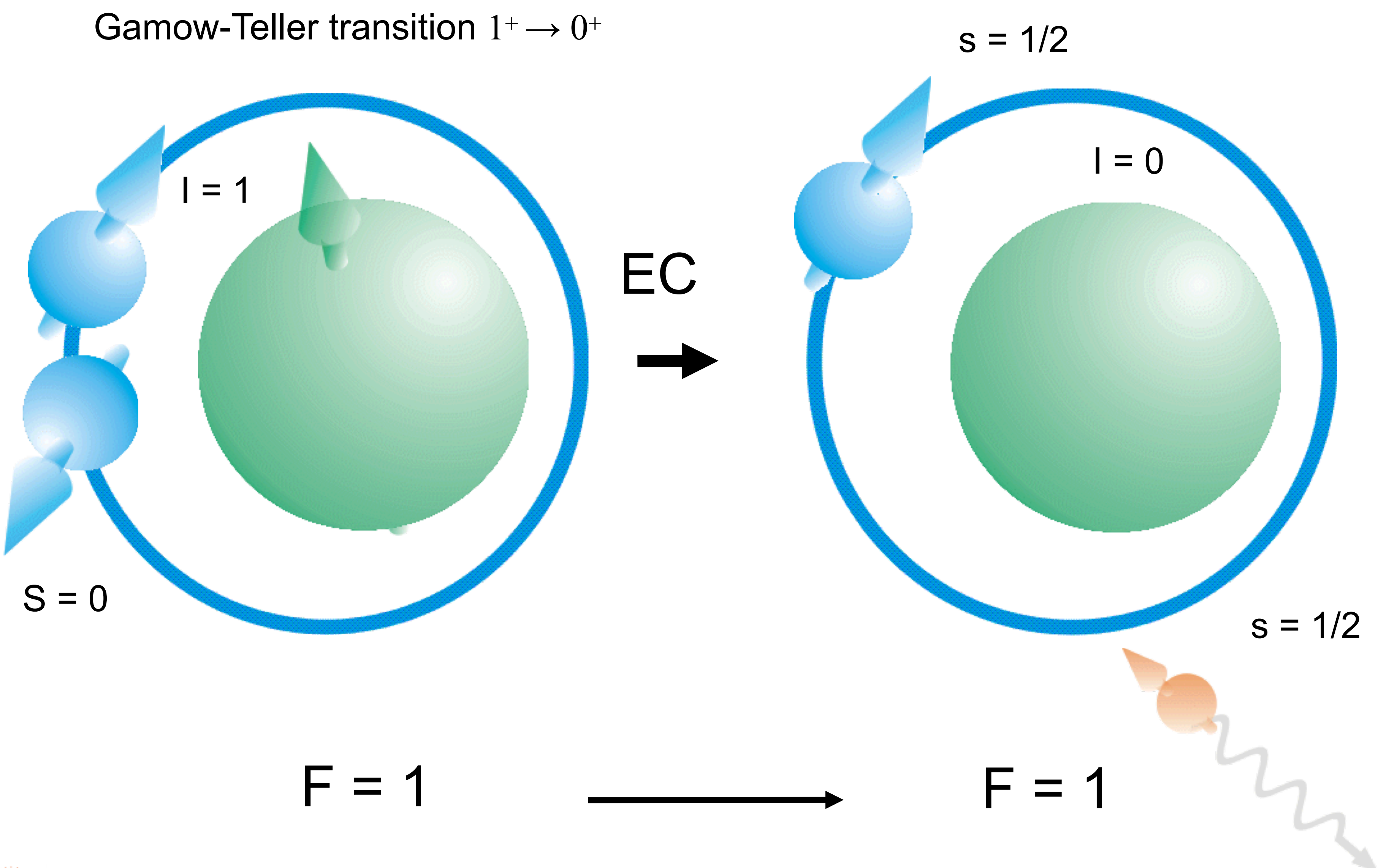


Yu.A. Litvinov et al., Phys. Rev. Lett. 99 (2007) 262501



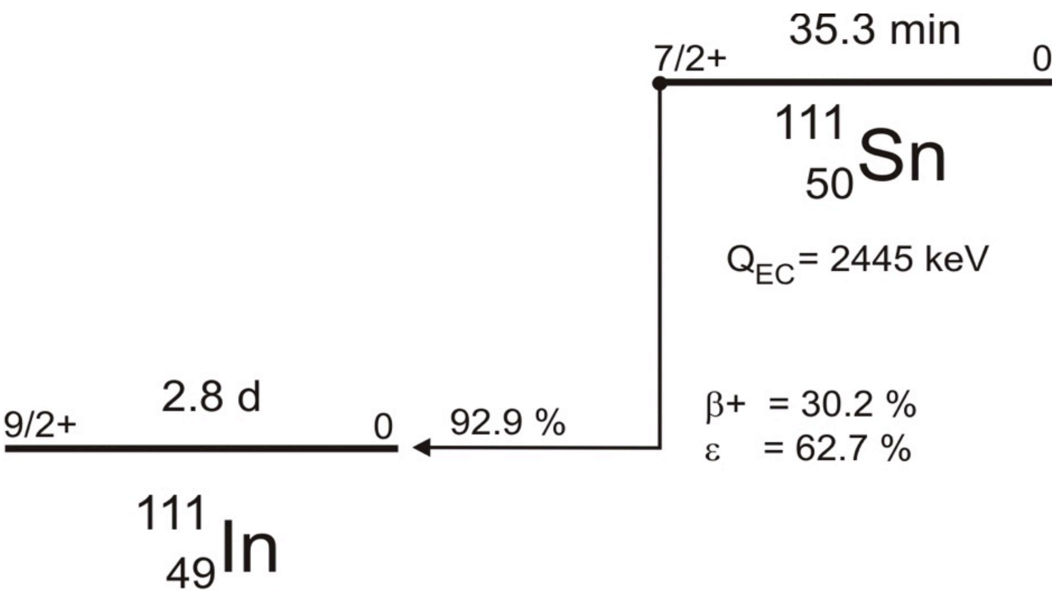
N. Winckler et al., Phys. Lett. B579 (2009) 36

EC Decay of He-like Ions



Z. Patyk et al., Phys. Rev. C 77 (2008) 014306

EC Decay of Few-Electron Ions

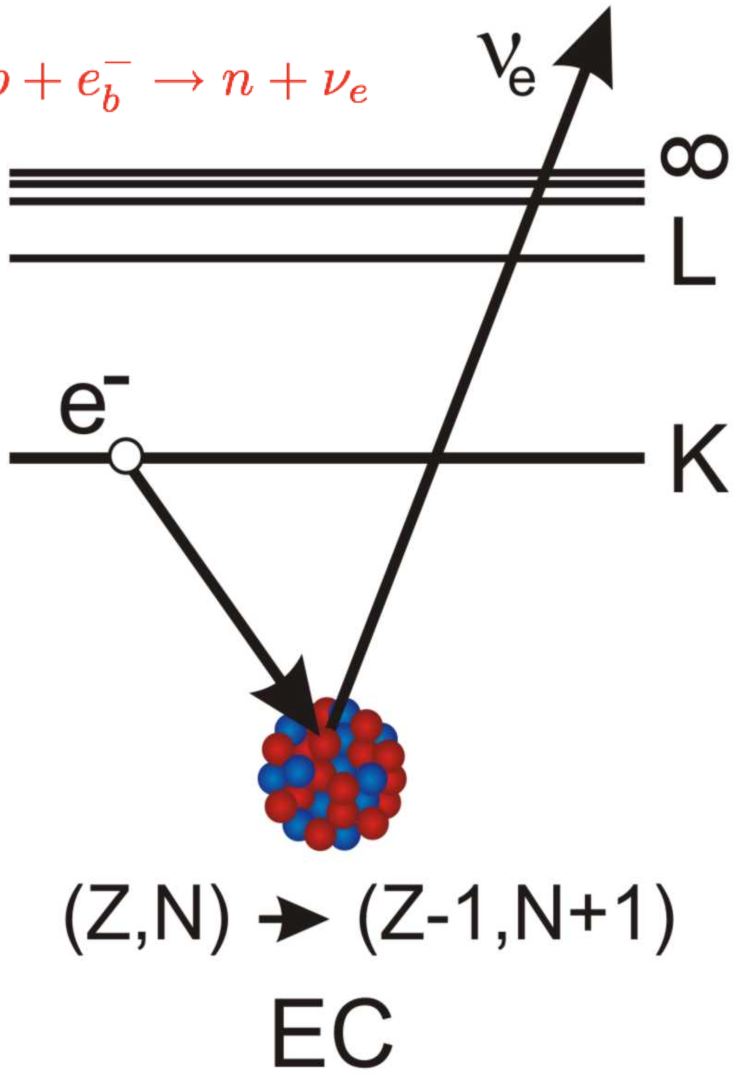


F = I + s < 4, 3

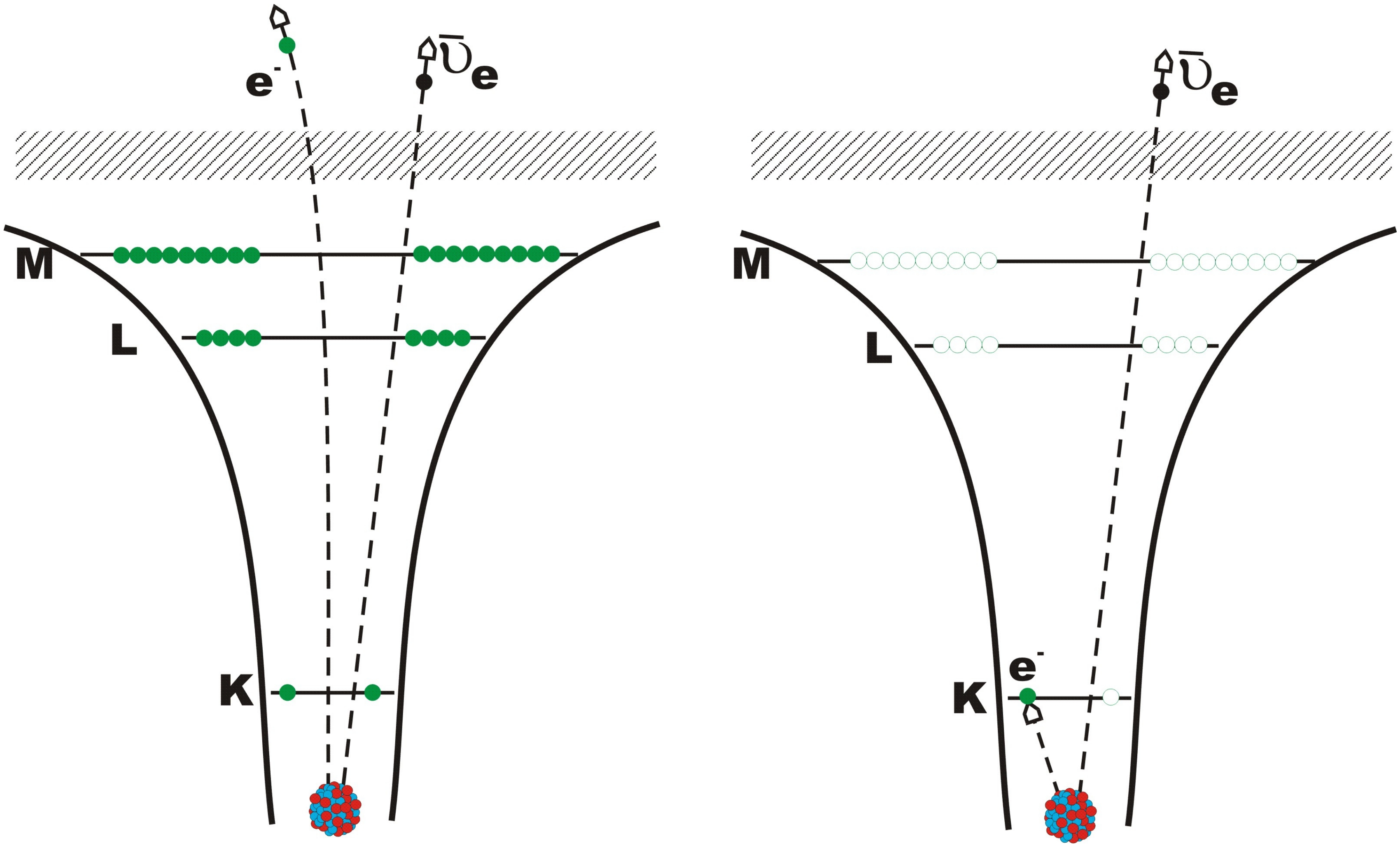
F = I + s < 5, 4

Two-Body Beta Decay

$$p + e_b^- \rightarrow n + \nu_e$$



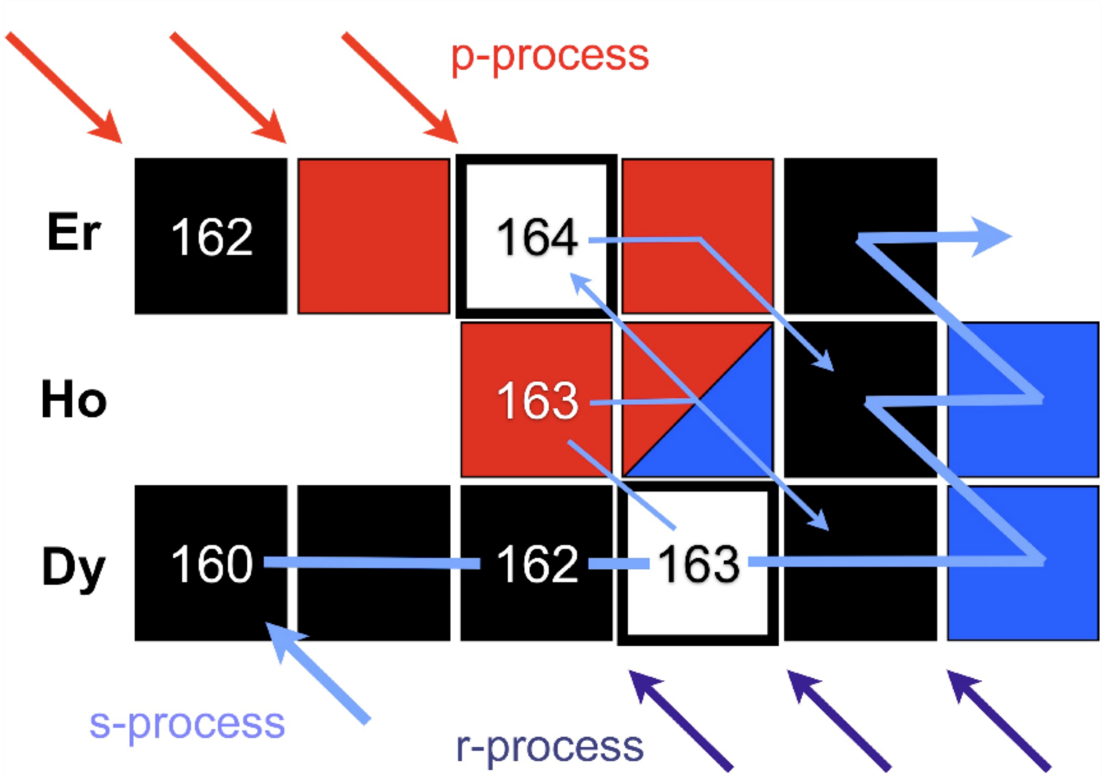
Bound-State β-decay



Y. Litvinov & F. Bosch, Rep. Prog. Phys. 74, 016301 (2011)

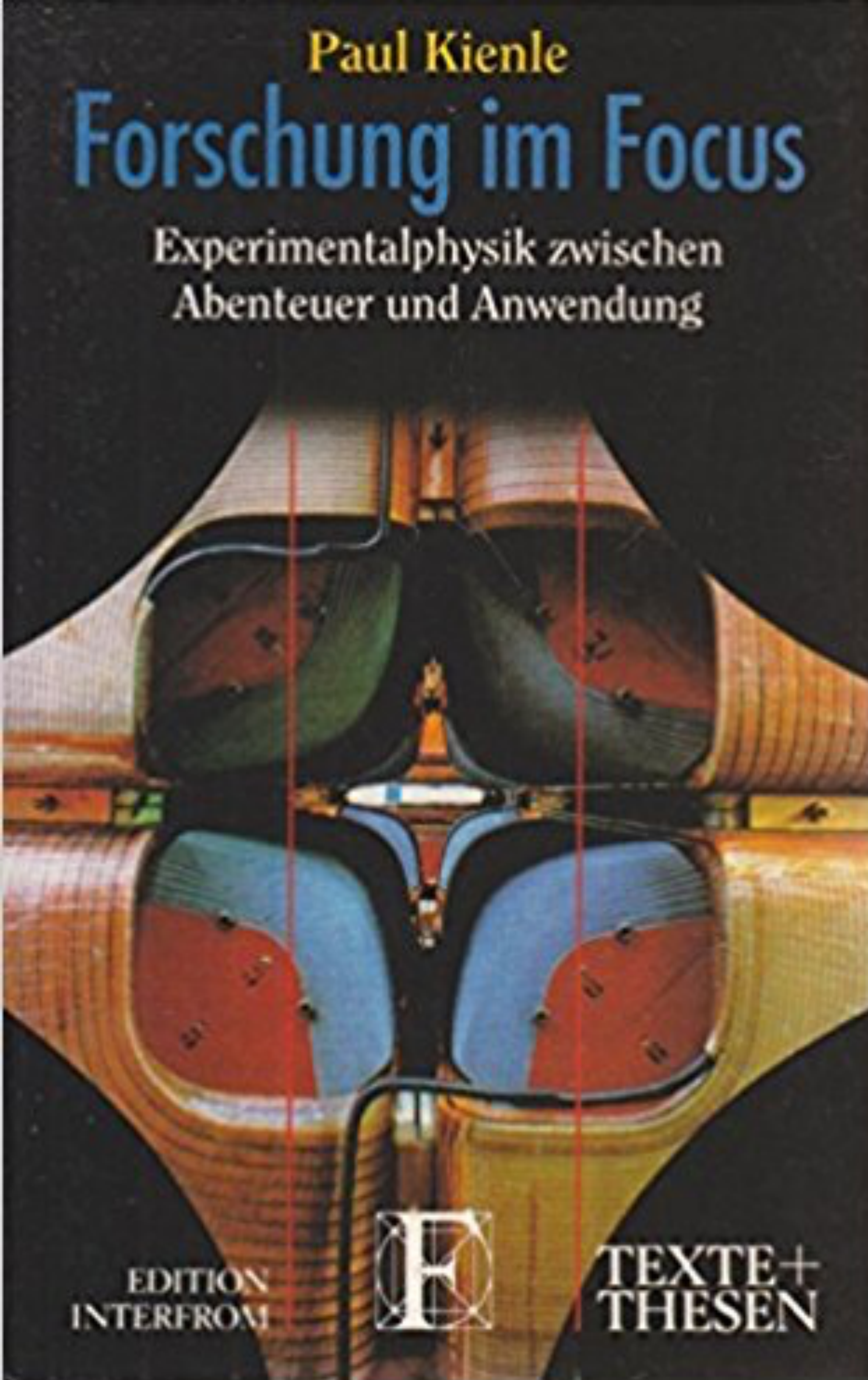
Bound-State β-decay of ^{163}Dy

s process: slow neutron capture and β- decay near valley of β stability at kT = 30 keV; → high atomic charge state → bound-state β decay



$T_{1/2}$ = 48 days

branchings caused by bound-state β decay



Paul Kienle
(1931-2013)

Bound-State Beta Decay of ^{205}Tl Nuclei

Proposal for an experiment to be conducted at FRS/ESR

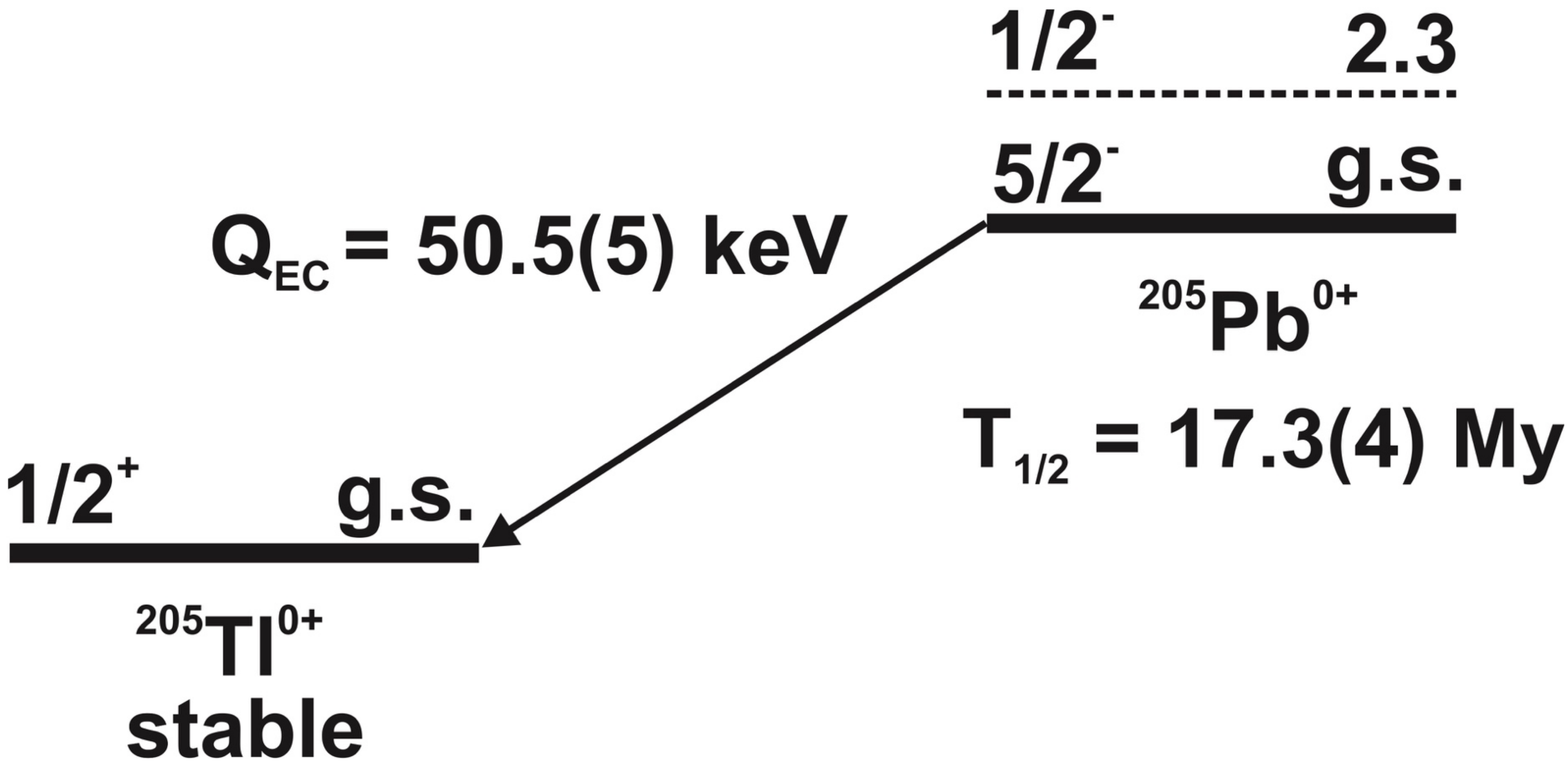
Measurement of the bound-state beta decay of bare ^{205}Tl ions

Updated from previously accepted proposal E100

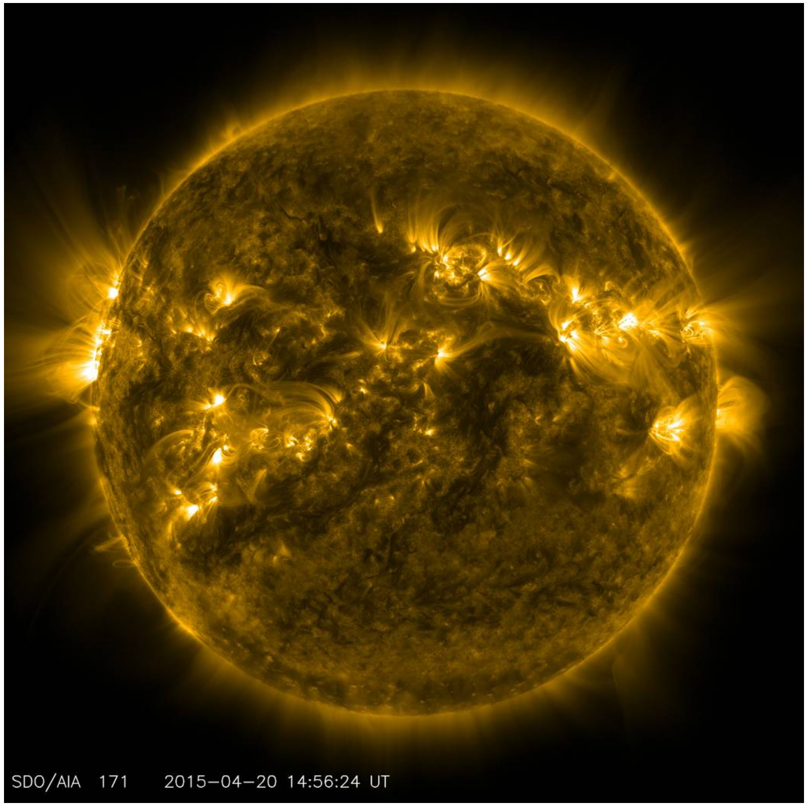
For the LOREX, NucCAR, SPARC and ILIMA Collaborations

Regarding the proposal "Measurement of the bound-state beta decay of bare ^{205}Tl ions" (Proposal E121), the G-PAC recommends this proposal with ***highest priority (A)*** *and that* ***21 shifts of main beam time*** *be allocated for this measurement.*

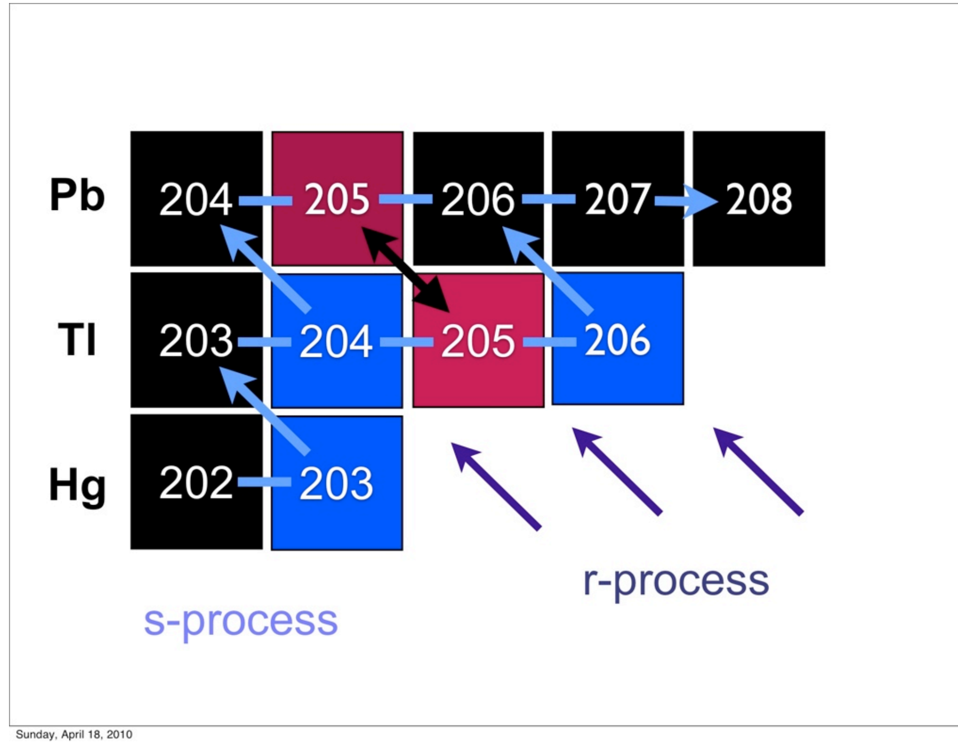
Bound-State Beta Decay of ^{205}Tl Nuclei



Bound-State Beta Decay of ^{205}Tl Nuclei



NASA/SDO

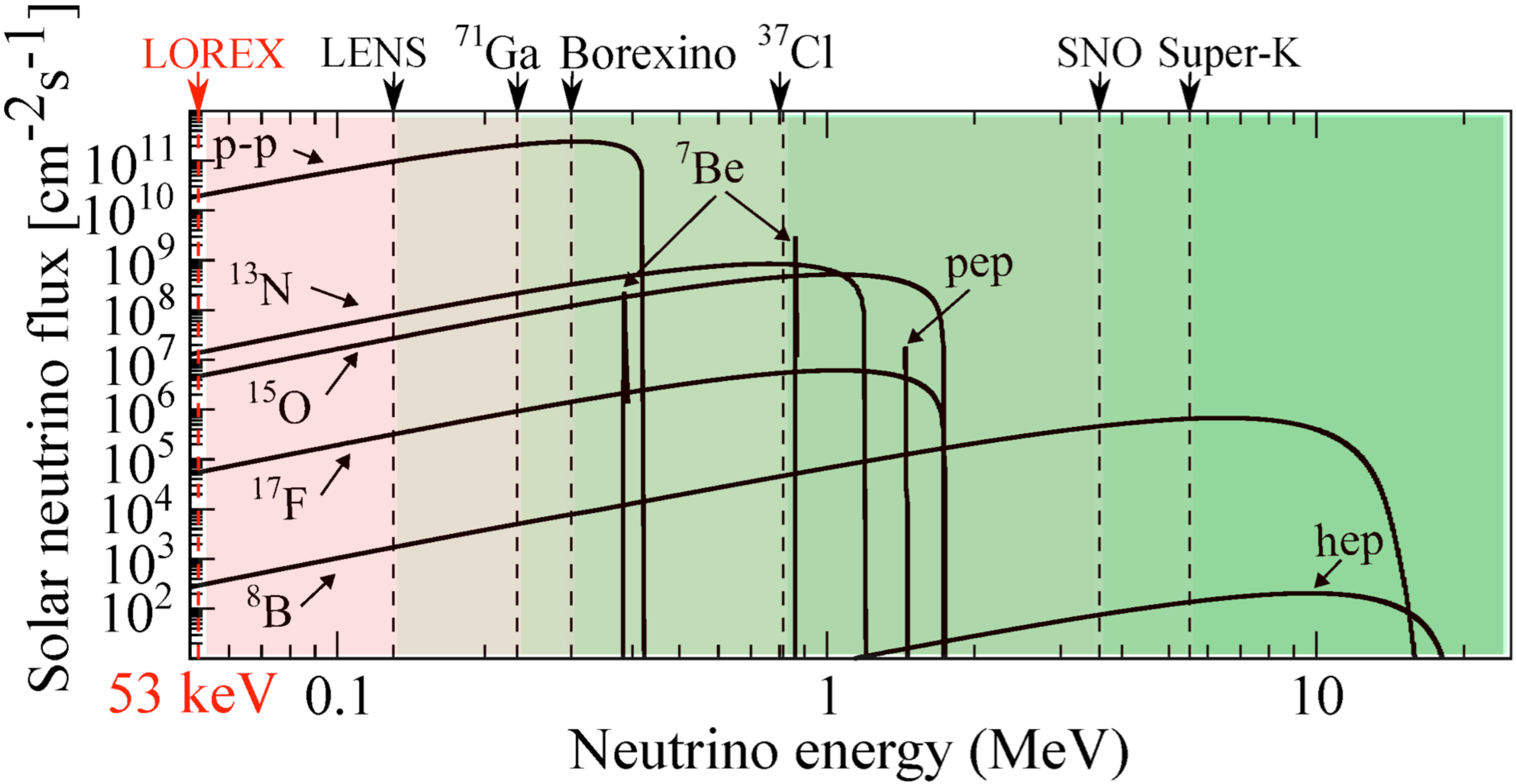


Termination of s-process

Fate of ^{205}Pb in early Solar system

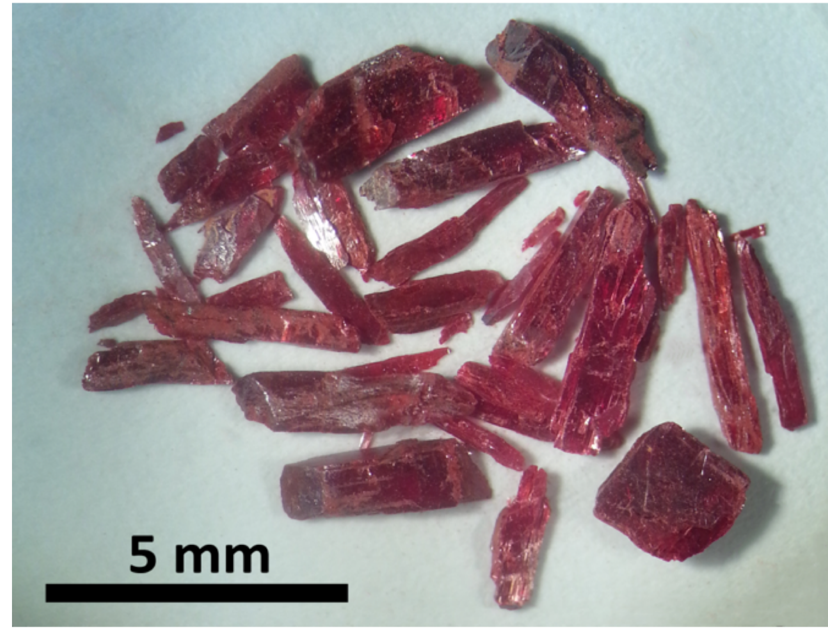
Detection of Solar pp-neutrinos

Solar Neutrino Flux

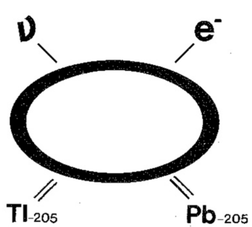


Courtesy R. J. Chen and R. Singh Sidhu

Lorandite $TlAsS_2$ Mineral



Age = 4.31(2) Ma



LOREX Project

EMMI

December 2019

EMMI Rapid Reaction Task Force on The LOREX Project

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M. Pavicevic et al., NIM A895, 62 (2018)

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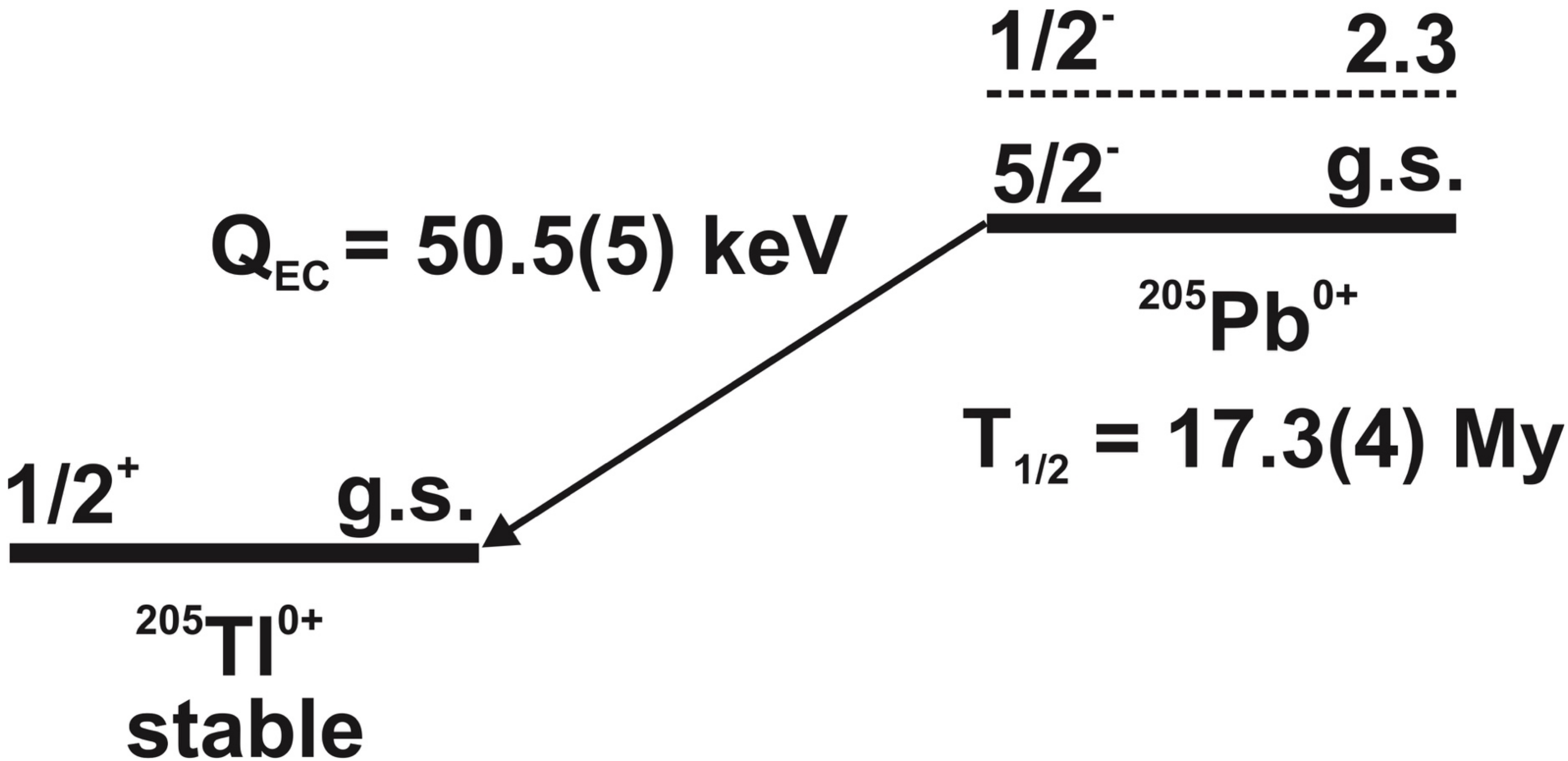
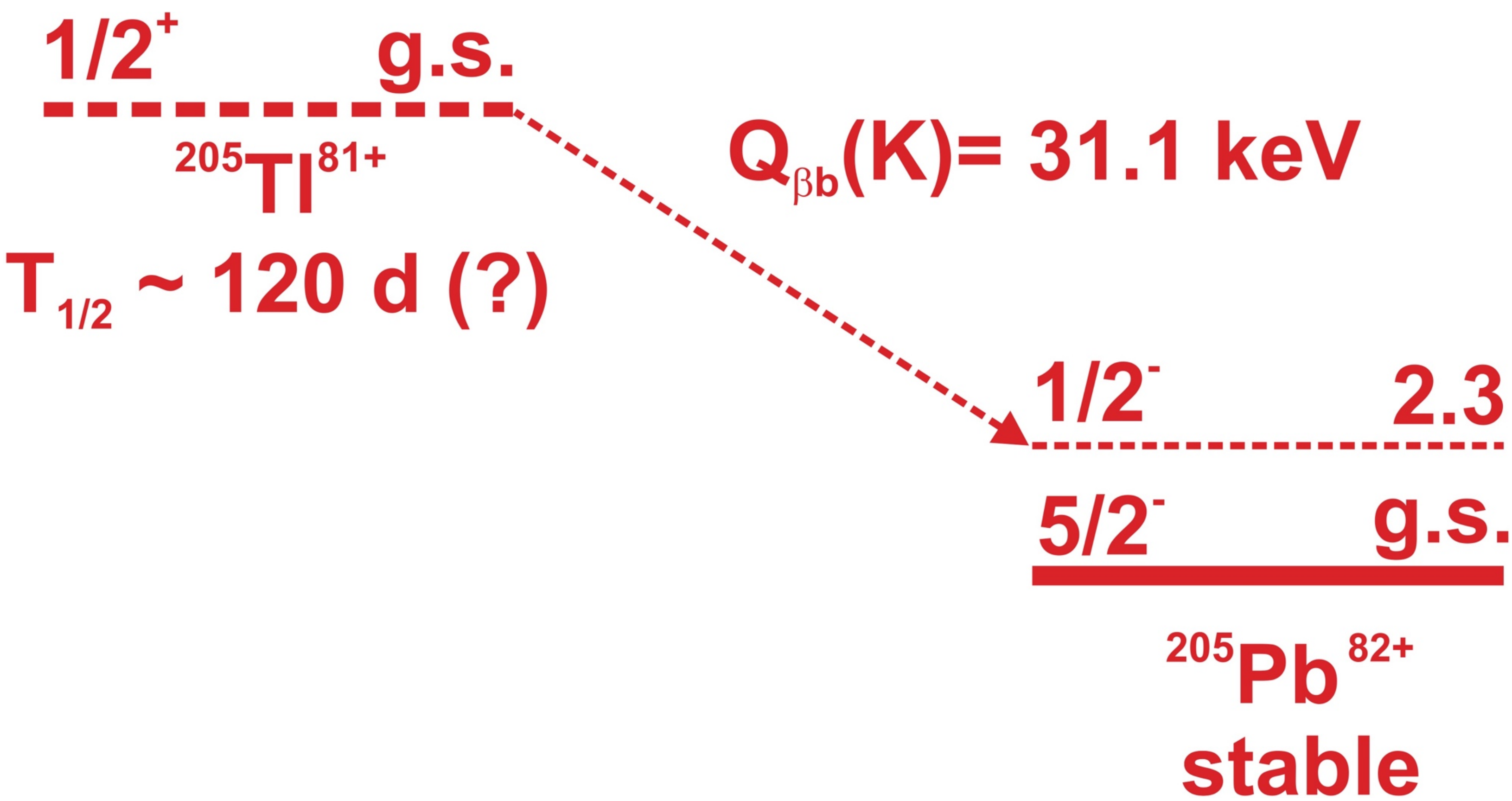
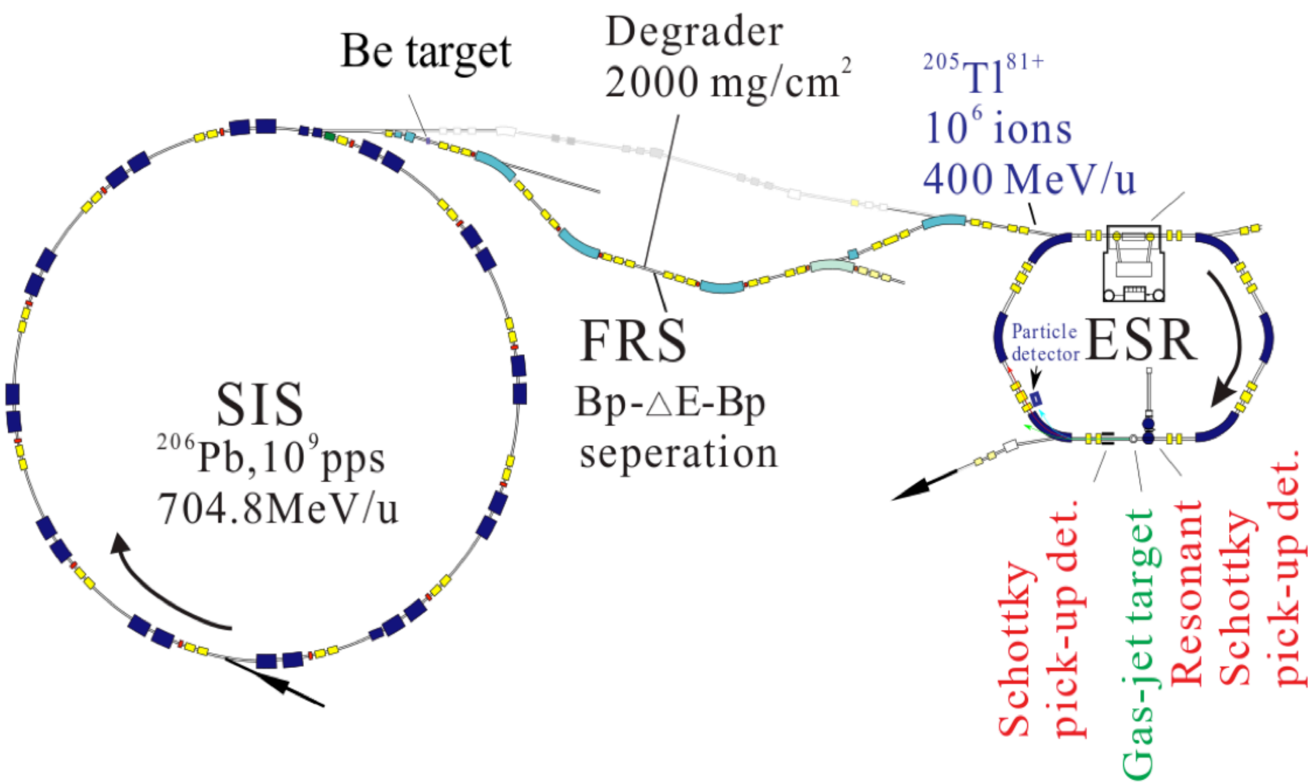
Bound-State Beta Decay of ^{205}Tl Nuclei



Bound-State Beta Decay of ^{205}Tl Nuclei



Experiment during the COVID19
23.03 – 01.04 – 06.04



Enriched ^{206}Pb beam

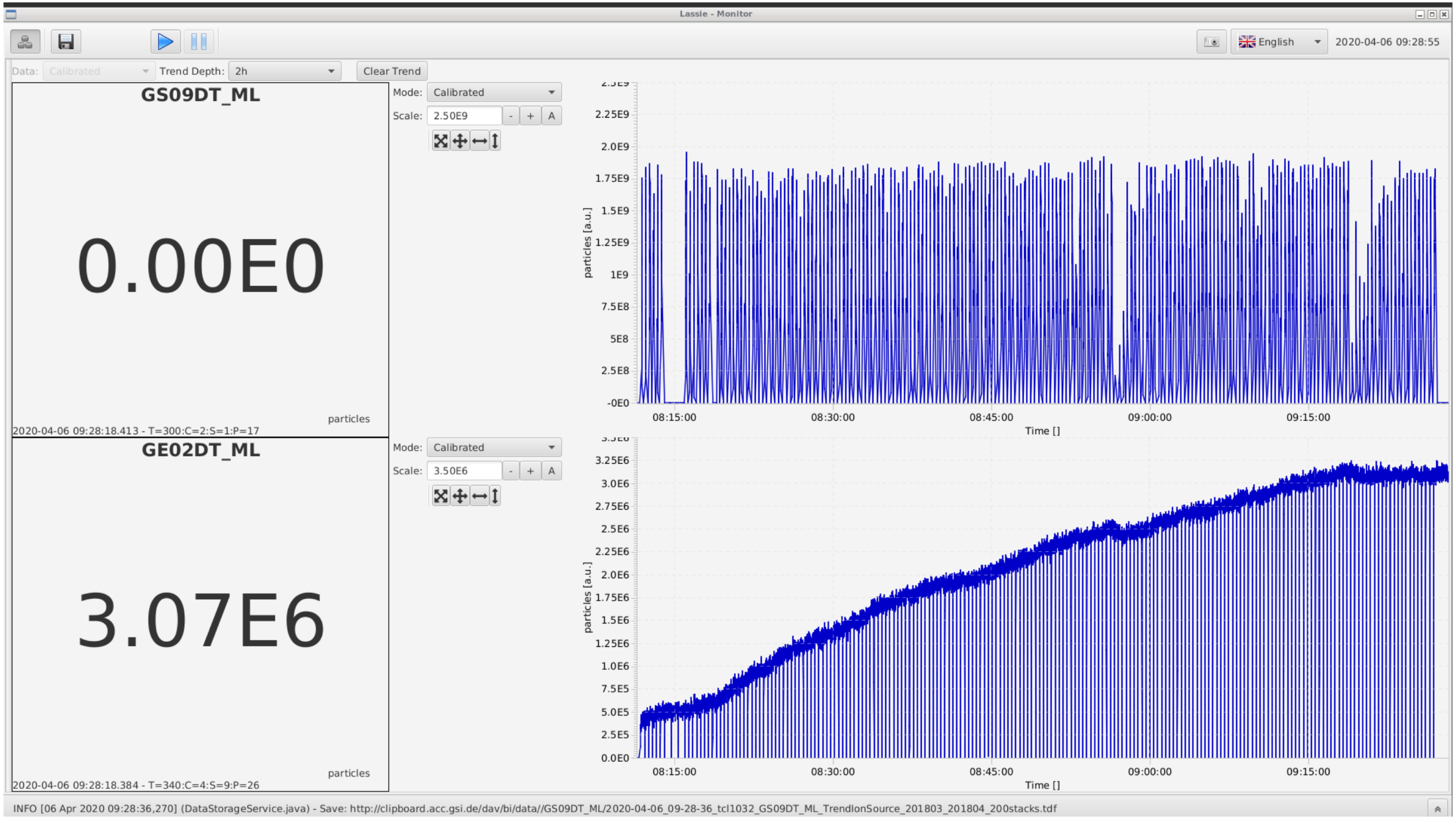
Separation from $^{205}Pb^{81+}$
$I(^{205}Tl^{81+})/I(^{205}Pb^{81+})= 1/15$

Accumulation

Long breeding time

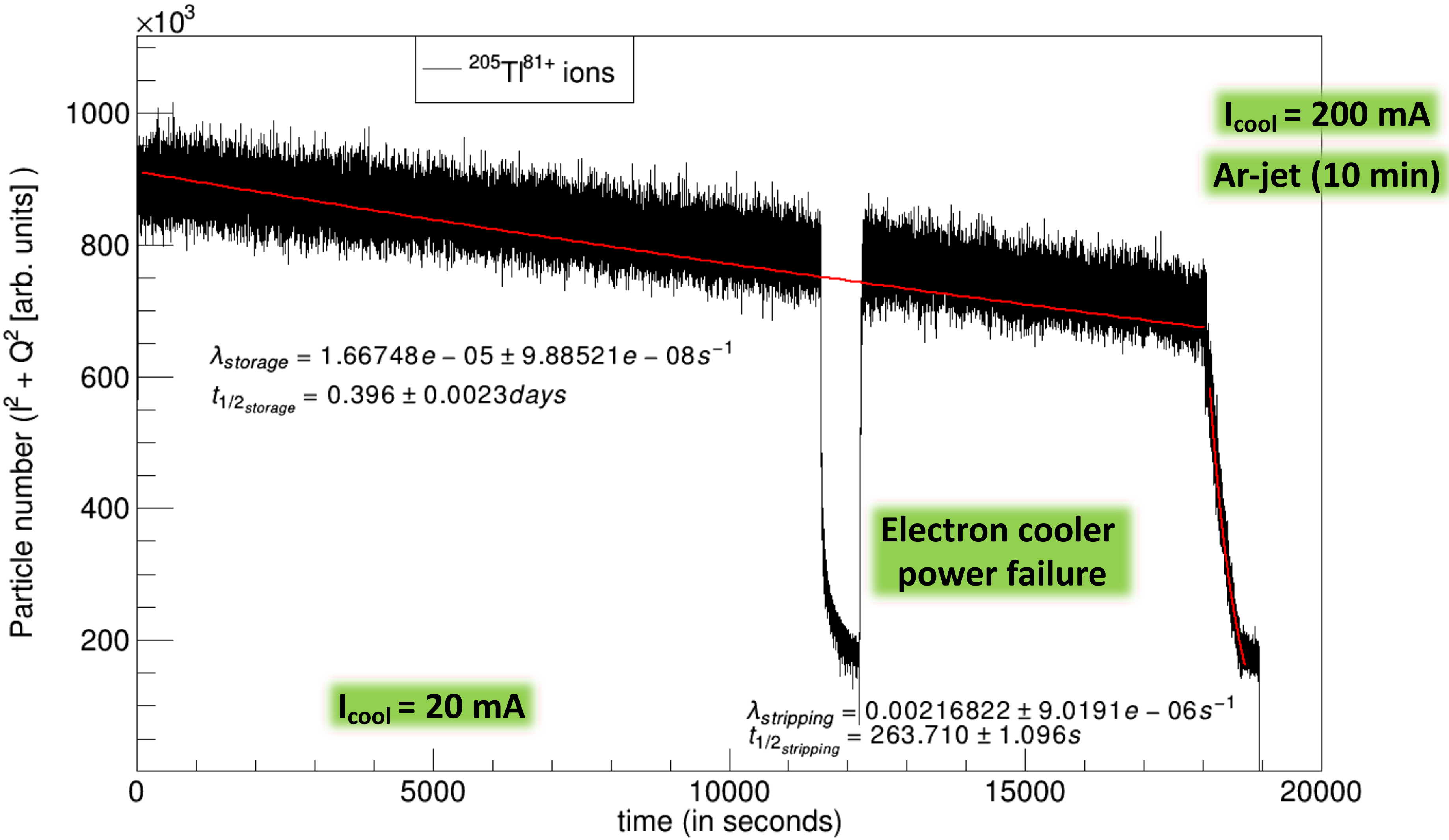
Separation of decay daughter ions from parent ions

Accumulation of $^{205}Tl^{81+}$ beam in the ESR



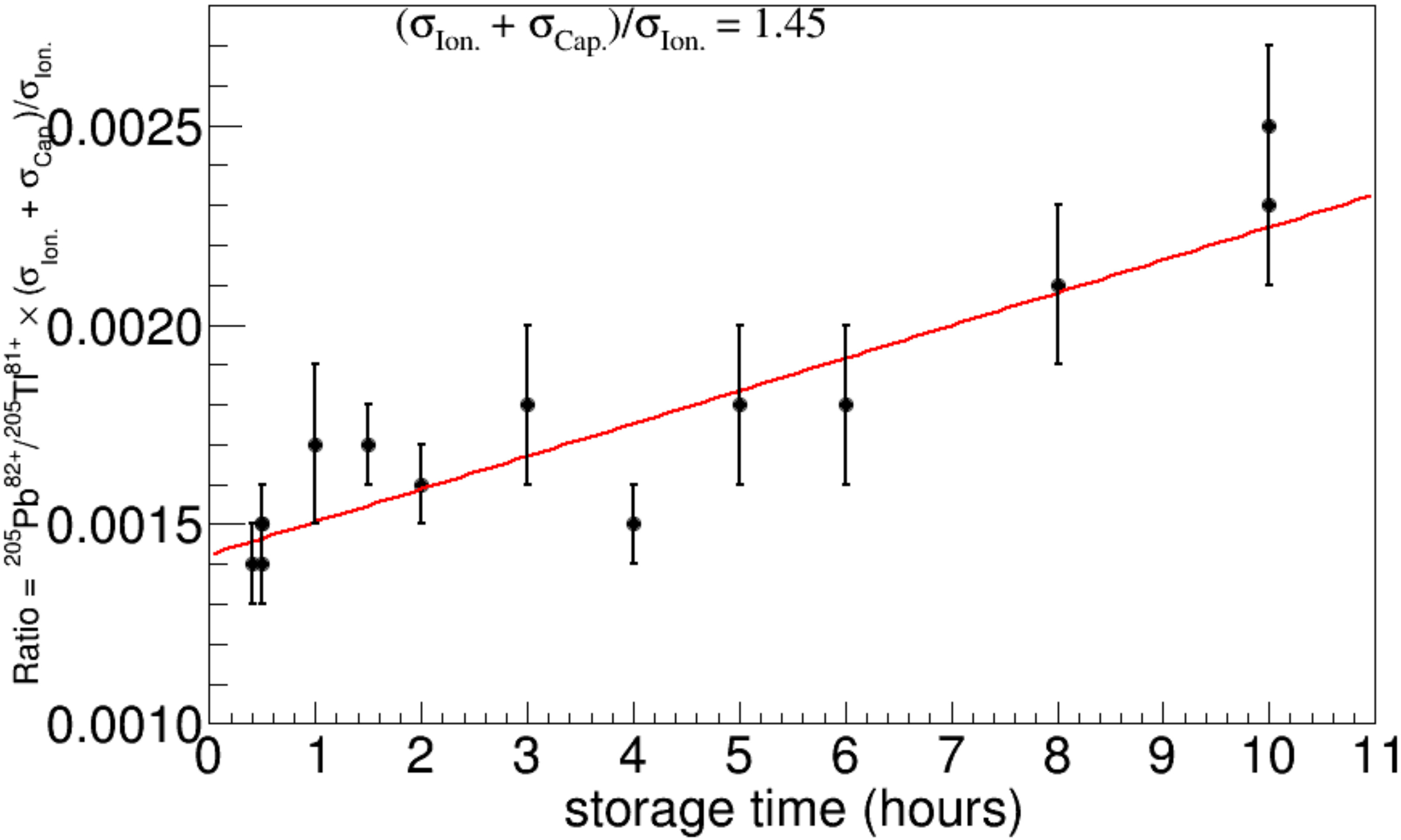
Courtesy R. J. Chen and R. Singh Sidhu

Typical Measurement (5 Hours)



Courtesy R. J. Chen and R. Singh Sidhu

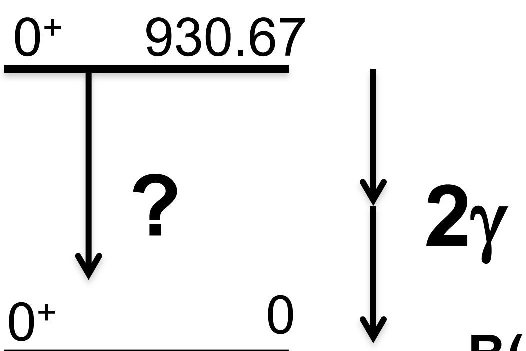
Preliminary Results



Courtesy R. J. Chen and R. Singh Sidhu

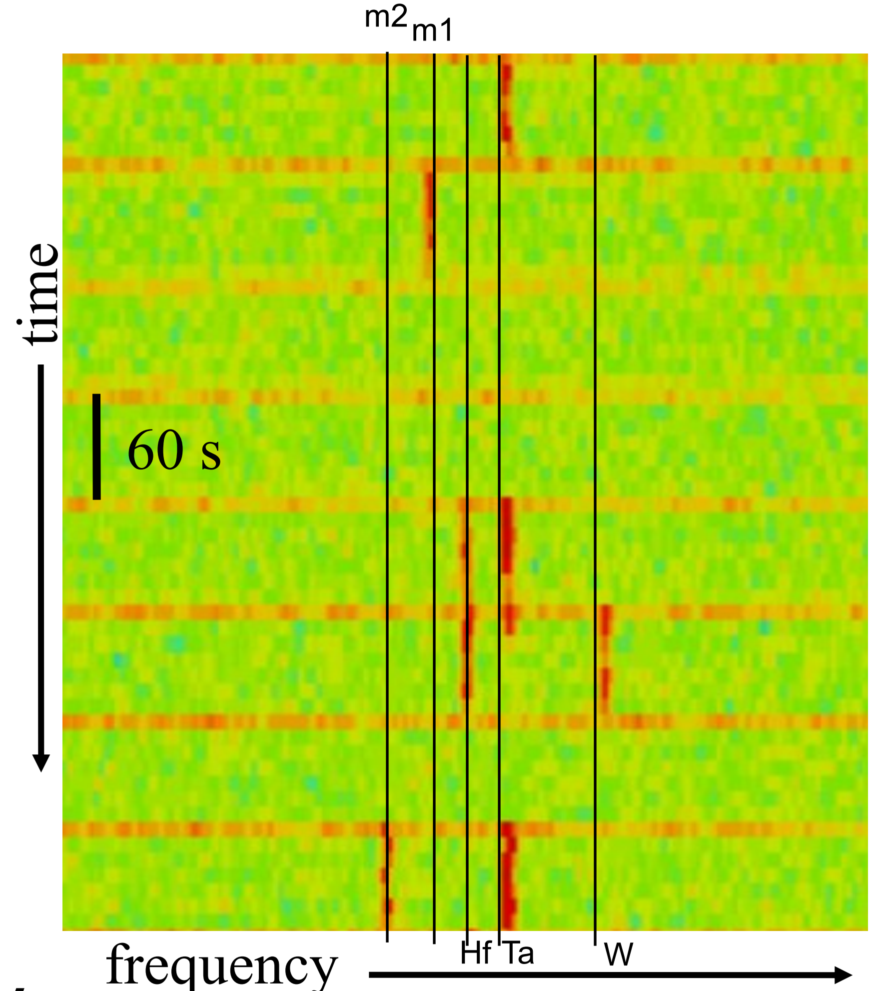
Further Physics Cases

- Search for very rare high-K isomers
- Studies of $0^+ \rightarrow 0^+$ transitions
- EC-decay of Li-like ions
- Alpha-decay of few-electron ions
- Search for exotic decay modes (NEEC, bound-state e^+e^-...)



$^{196}Pb^{82+}$

$B(K)=101.336$ keV
$E(0^+_2)=930.67$ keV
1032 keV



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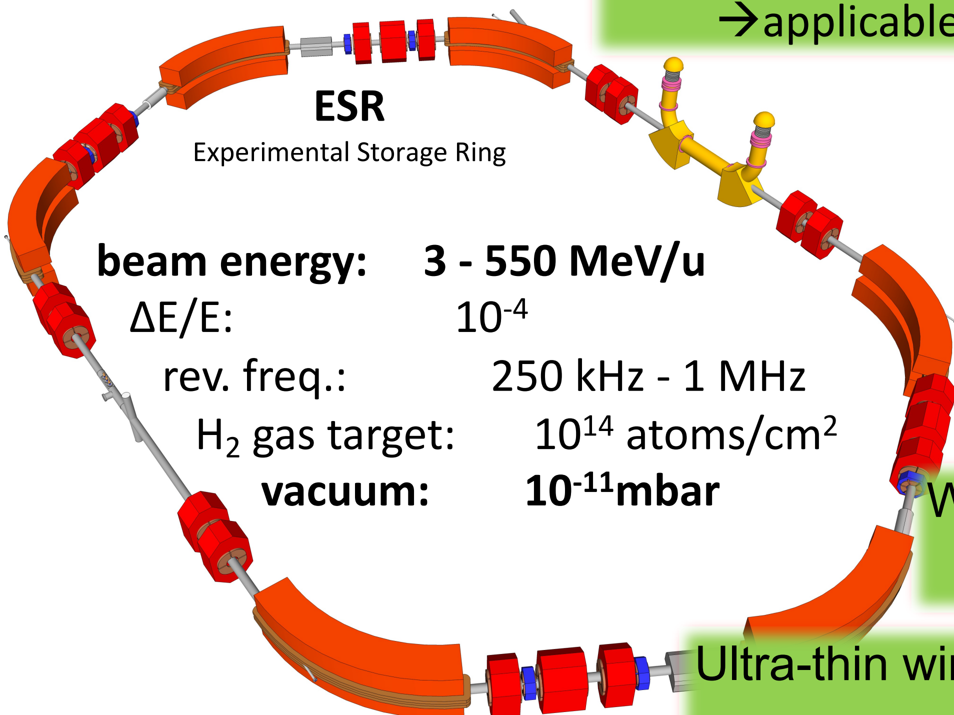
M.W. Reed, et al., Phys. Rev. Lett. 105 (2010) 172501

Nuclear reaction studies in a storage ring



in-flight fragmentation at FRS
→applicable to radioactive nuclei

deceleration of beams
→Gamow window

High revolution frequency
→ high luminosity even with thin targets

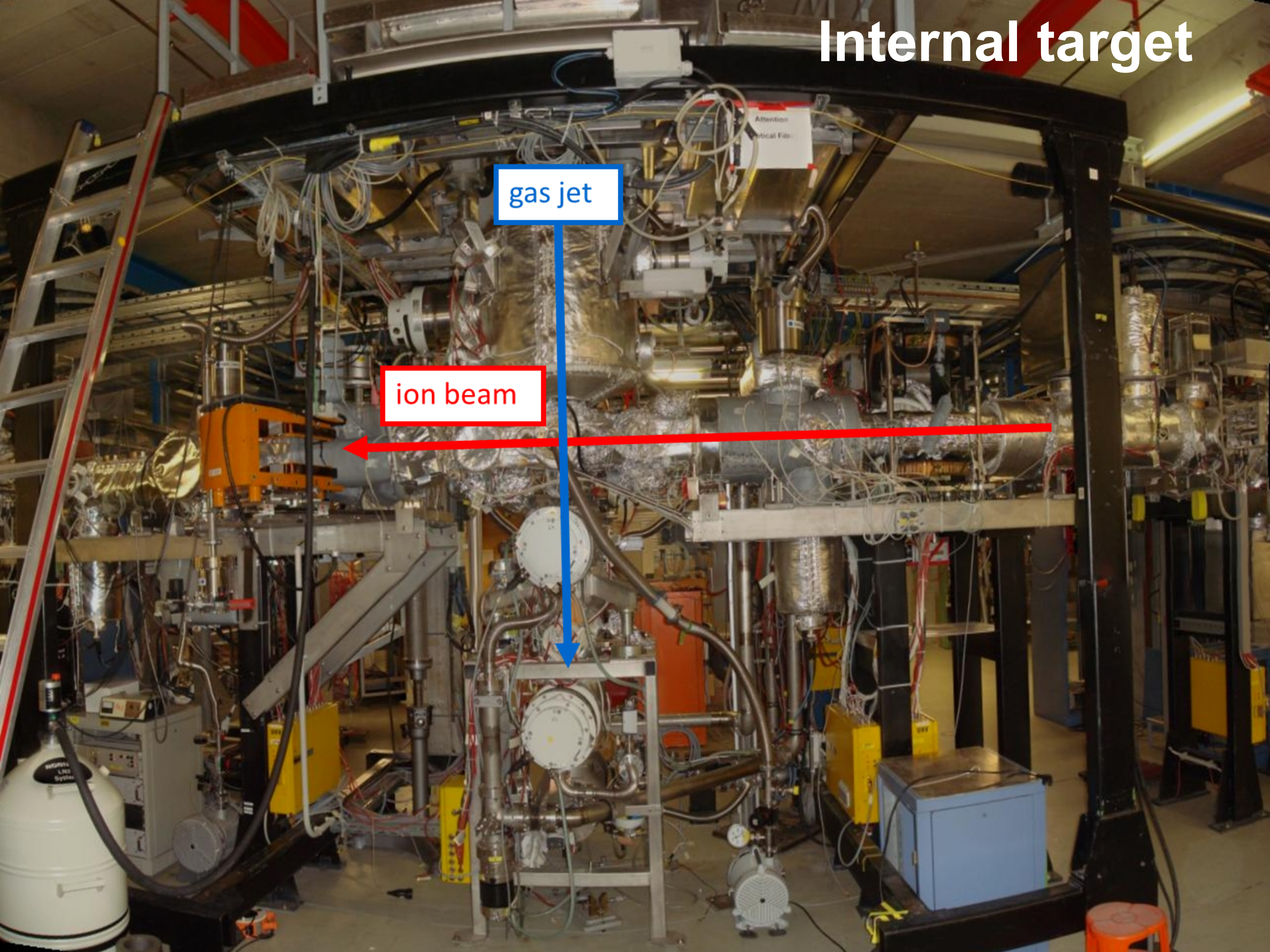
Well-known atomic charge-exchange rates
→in-situ luminosity monitor

Ultra-thin windowless gas targets and electron cooling
→ excellent energy resolution

Detection of ions via in-ring particle detectors, clean beam and target
→low background, high efficiency

very efficient use of exotic beams for high resolution experiments

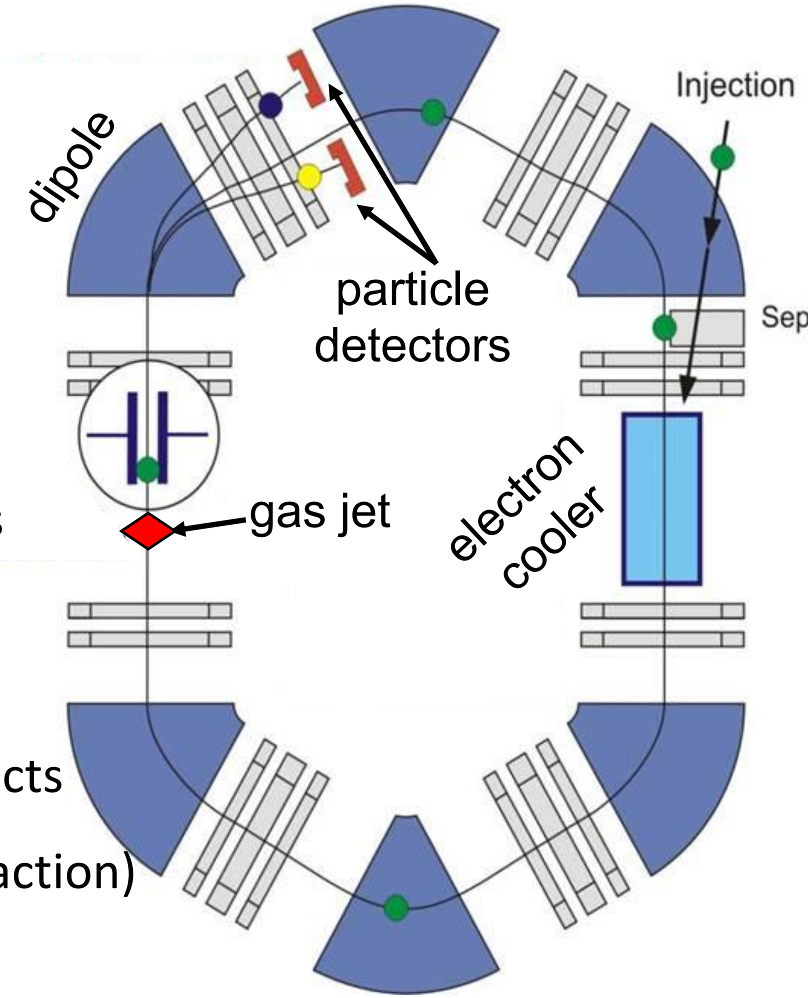
Internal target



Proton-Capture Reactions in the ESR

refill ring periodically

- injection of ions @ >100 MeV/u
  - ✓ **fully stripped ions**
- deceleration & cooling of the beam
  - ✓ **E = 3 - 10 MeV/u**
- activate internal **hydrogen target**
  - ✓ proton & electron capture reactions
  - ✓ separated by dipole
  - ✓ particle detectors on…
    - … inner tracks for (p,γ) products
    - … outer tracks for e^- capture products
- beam life time (residual gas + target interaction)
  - ➢ intensity goes down



ESR

Jan Glorius: "A recycling recoil separator"

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Courtesy J. Glorius

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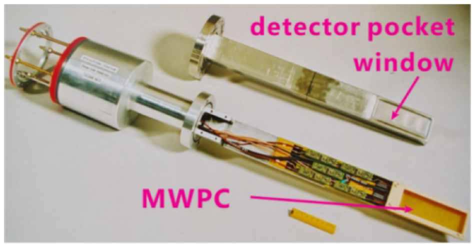
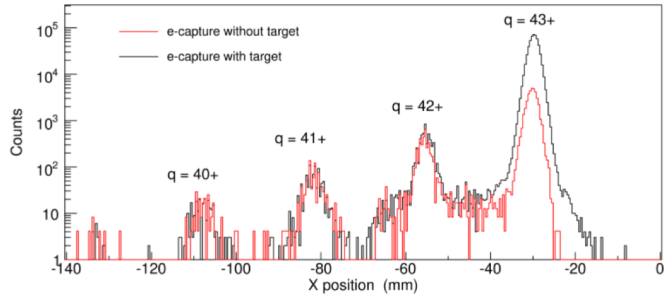
In-Situ Luminosity Monitoring

total e^- capture rate [NRC + REC]

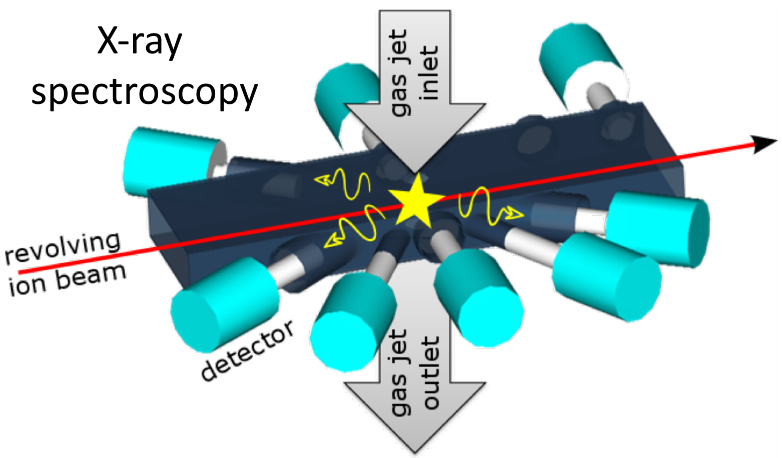
measured by particle detection

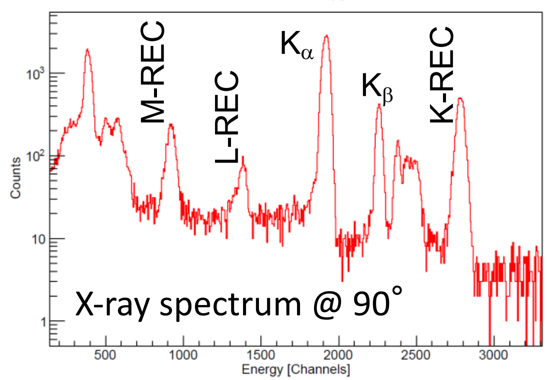


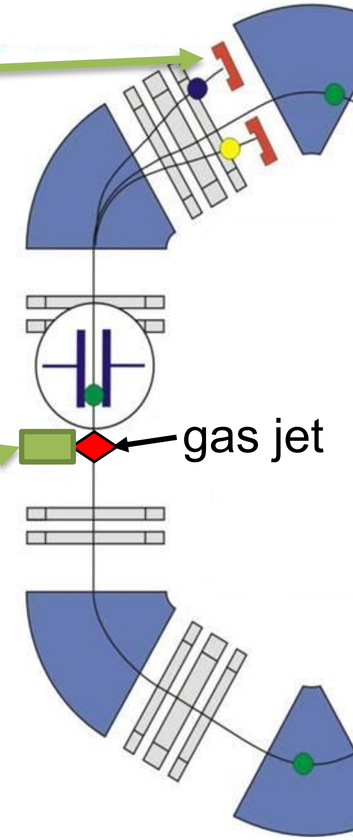


radiative e^- capture rate [REC]

X-ray spectroscopy

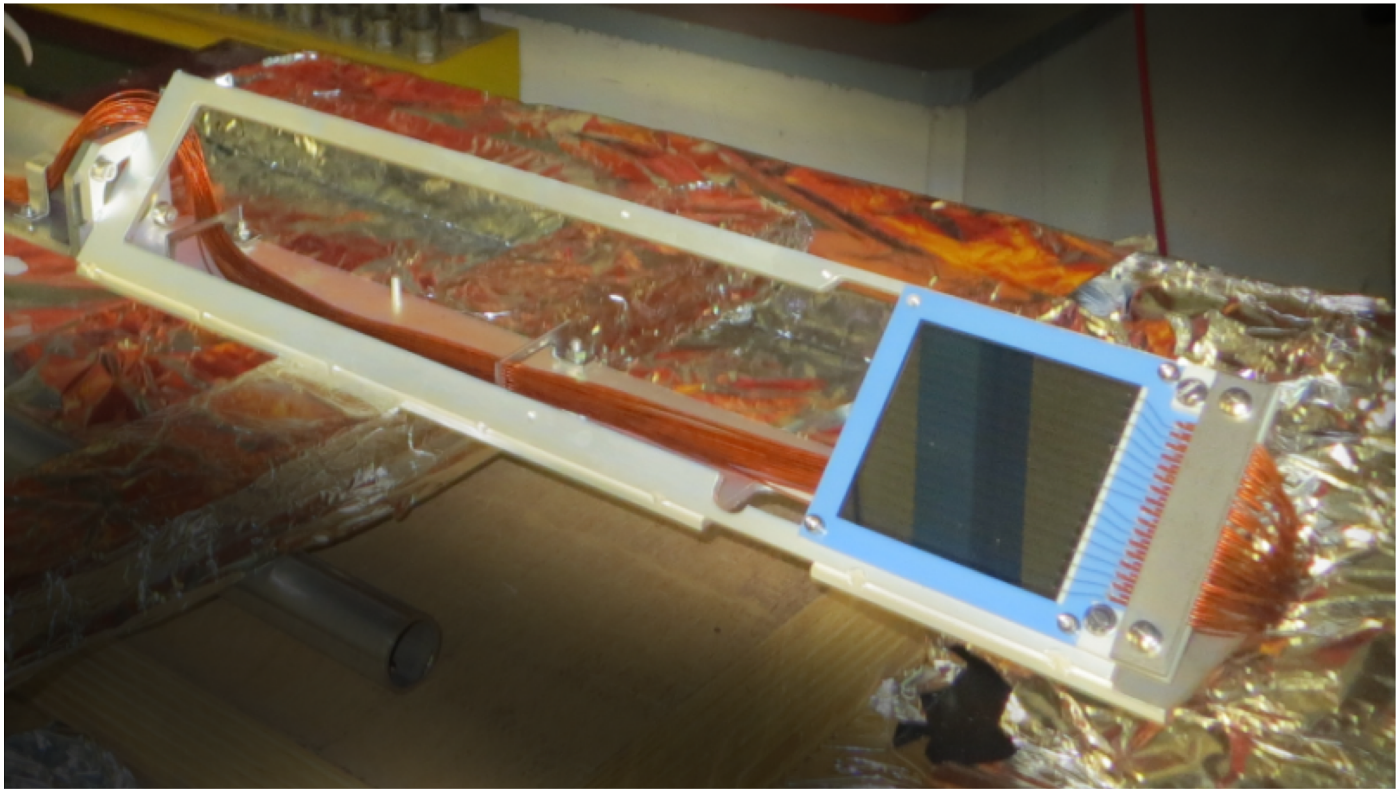






In-Vacuum Particle Detectors

- Double Sided Si Strip Detector (DSSSD)
  - ✓ x & y segmentation
  - ✓ 500 μm thickness (ions are stopped)
  - ✓ ultra thin dead layer of 0.3 μm
- compatible to UHV conditions
  - ✓ low outgassing rate
  - ✓ bakeable at T > 125°C



Federal Ministry of Education and Research

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Courtesy J. Glorius

HELMHOLTZ GSI

ESR Test Beam Time 2016 $^{124}Xe(p,g)^{125}Cs$

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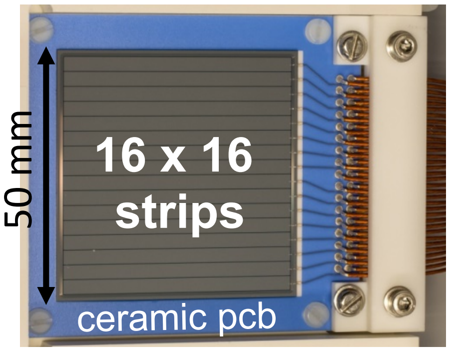
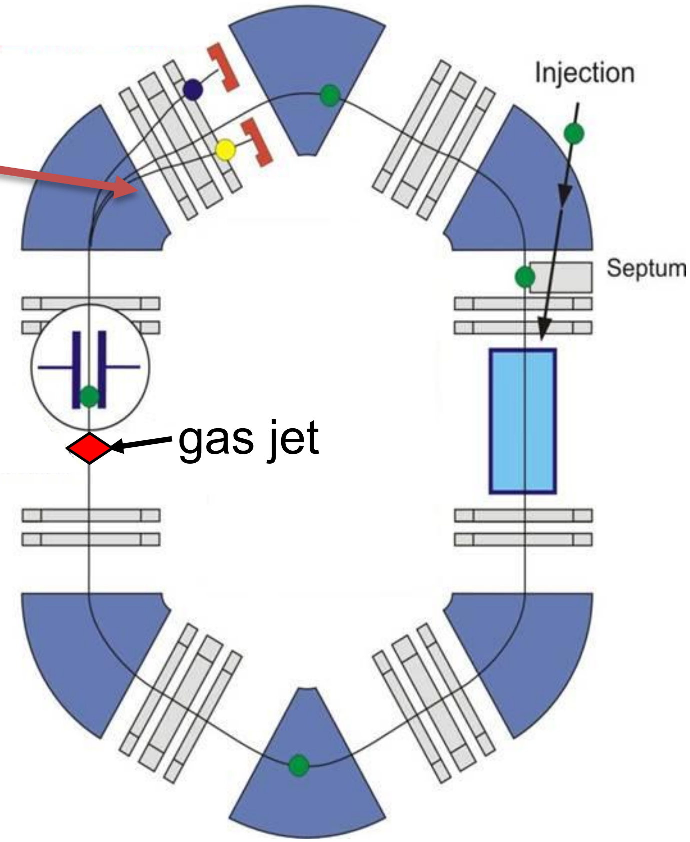
2^{nd} generation detectors

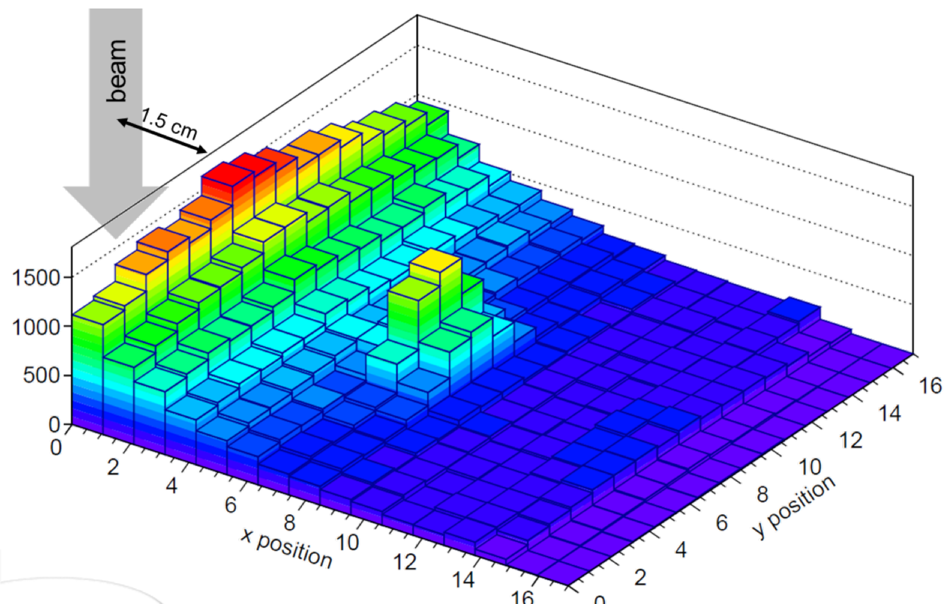


UHV compatible

$^{124}Xe(p,\gamma)$



ESR



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Courtesy J. Glorius

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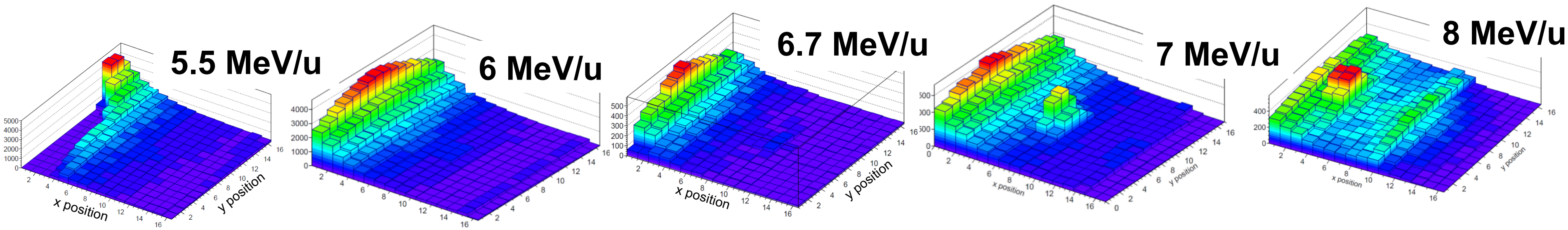
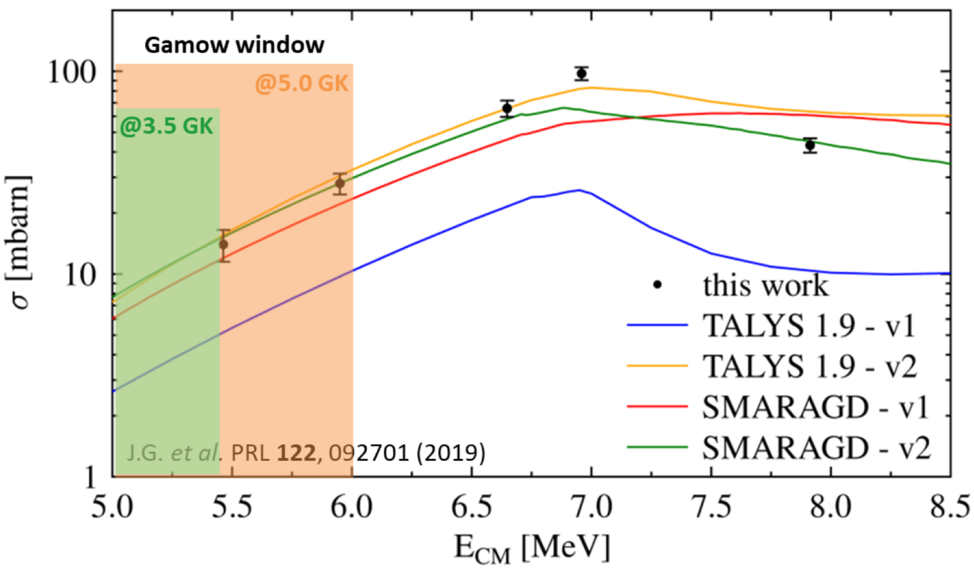
^{124}Xe(p,g) - Results





PHYSICAL REVIEW LETTERS **122,** 092701 (2019)

**Approaching the Gamow Window with Stored Ions:
Direct Measurement of ^{124}Xe(p,γ) in the ESR Storage Ri**

J. Glorius,[1,*] C. Langer,[2] Z. Slavkovská,[2] L. Bott,[2] C. Brandau,[1,3] B. Brückner,[2] K. Blaum,[4]
T. Davinson,[7] P. Erbacher,[2] S. Fiebiger,[2] T. Gaßner,[1] K. Göbel,[2] M. Groothuis,[2] A. Gumberidz
R. Hess,[1] R. Hensch,[2] P. Hillmann,[2] P.-M. Hillenbrand,[1] O. Hinrichs,[2] B. Jurado,[9] T. Kaus
T. Kisselbach,[2] N. Klapper,[2] C. Kozhuharov,[1] D. Kurtulgil,[2] G. Lane,[10] C. Lederer-Woods,[7] M
Yu. A. Litvinov,[1] B. Löher,[11,1] F. Nolden,[1] N. Petridis,[1] U. Popp,[1] T. Rauscher,[12,13] M. Reed,[10] R
D. Savran,[1] H. Simon,[1] U. Spillmann,[1] M. Steck,[1] T. Stöhlker,[1,14] J. Stumm,[2] A. Surzhykov,[15,16
A. Taremi Zadeh,[2] B. Thomas,[2] S. Yu. Torilov,[17] H. Törnqvist,[1,11] M. Träger,[1] C. Trageser,[1,3]
M. Volknandt,[2] H. Weick,[1] M. Weigand,[2] C. Wolf,[2] P. J. Woods,[7] and Y. M.

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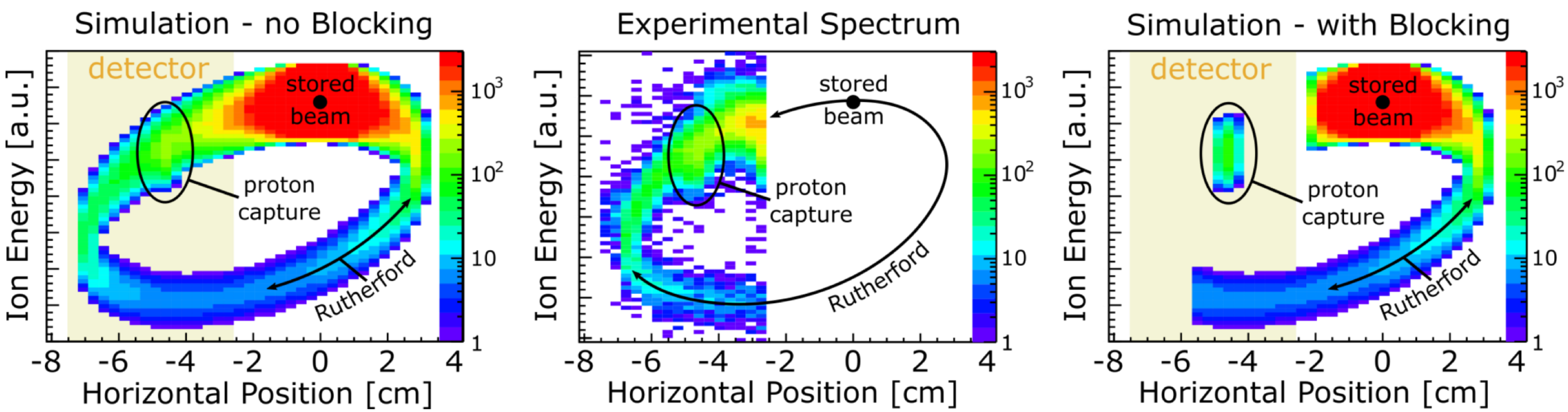
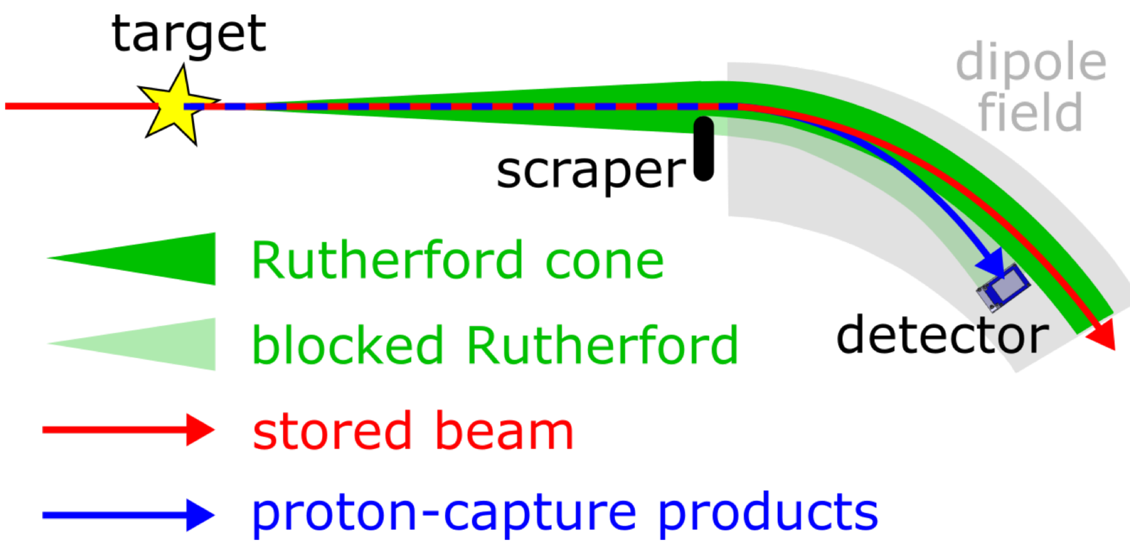
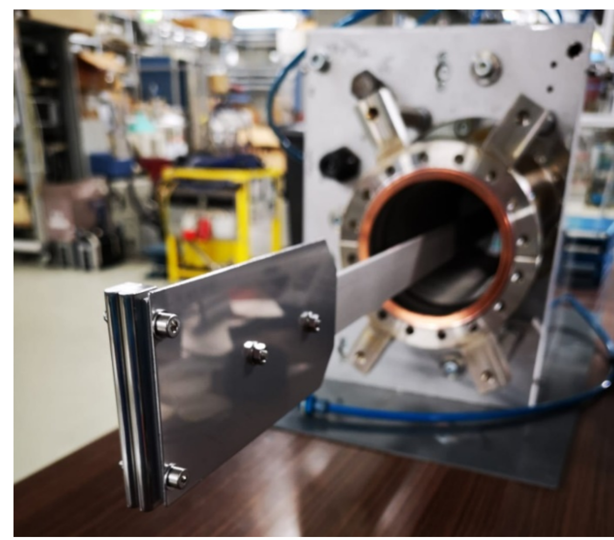
J. Glorius, et al., PRL 122, 092701 (2019)

Towards background free measurement





work of Laszlo Varga

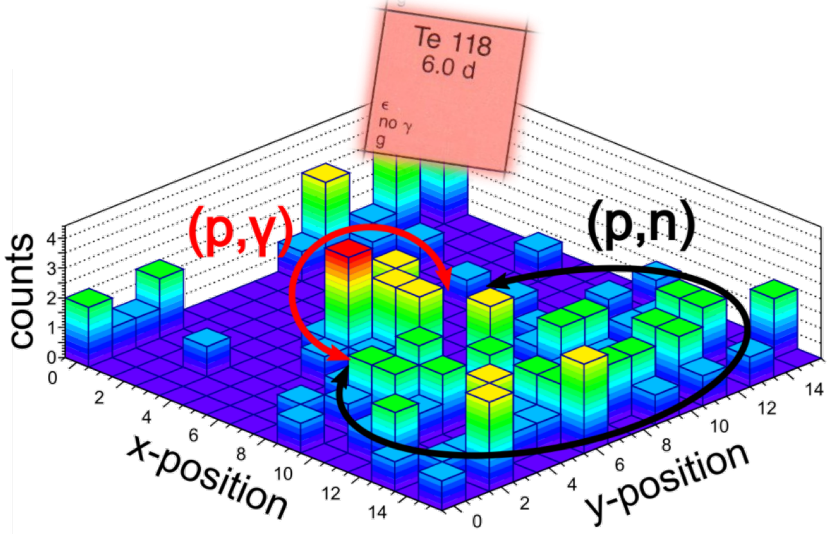


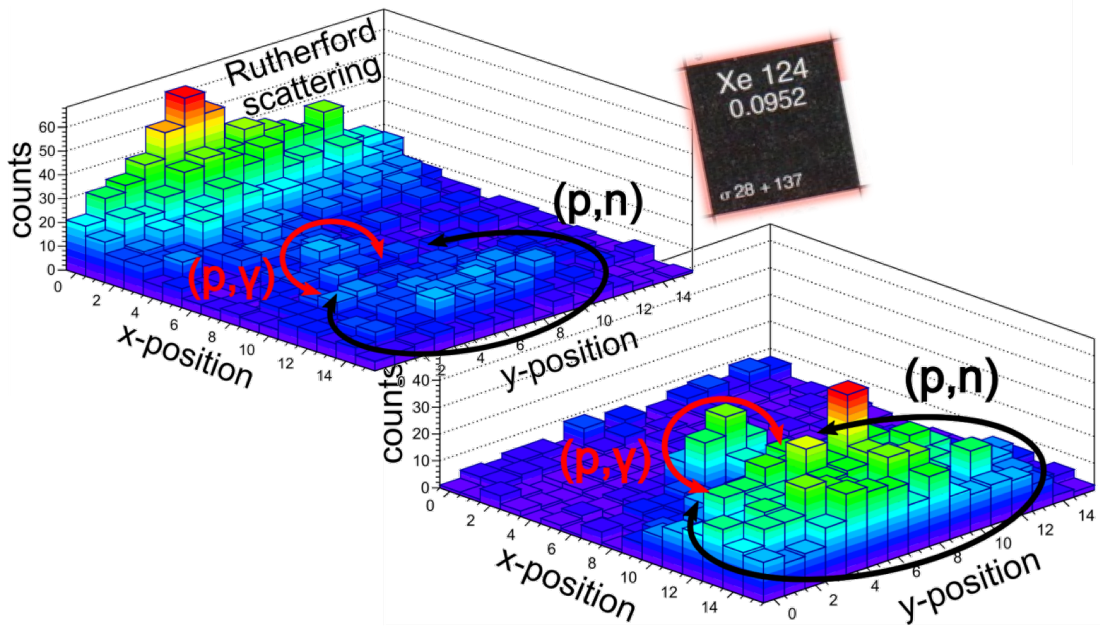
Courtesy J. Glorius and L. Varga

Experiment during the COVID19
17.03 – 22.03

study of radioactive ^{118}Te (6 days half-life)

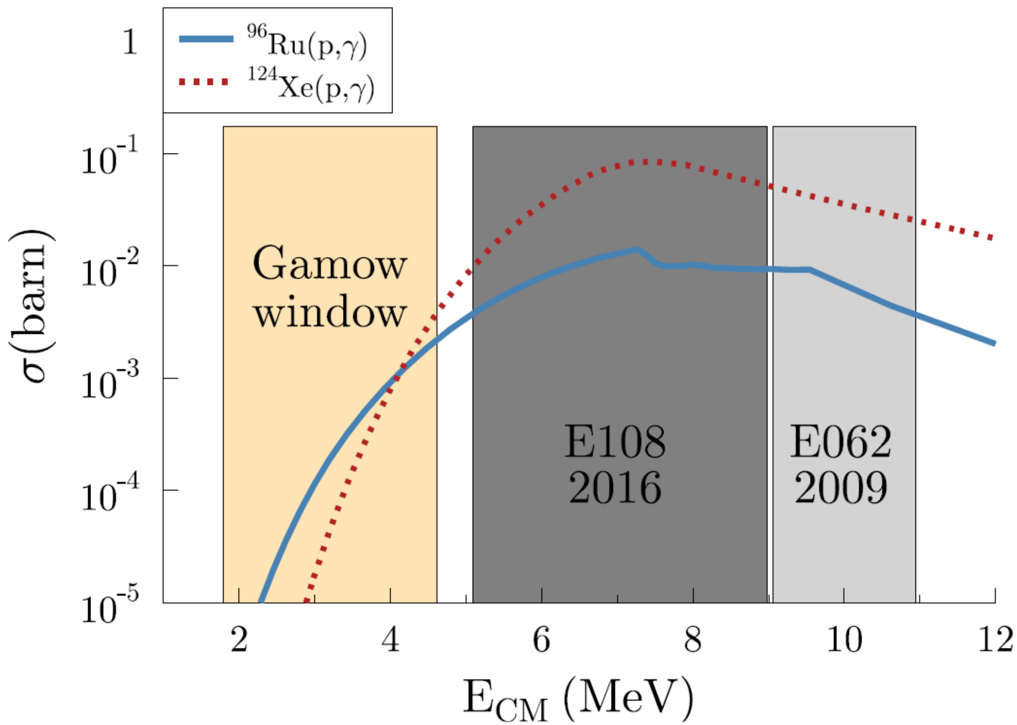
~10^5 $^{118}Te^{52+}$ ions available at 10 MeV/u





Rutherford blocking technique clearly demonstrated with primary ^{124}Xe beam

First Proton Capture Reaction on Stored Radioactive Beam

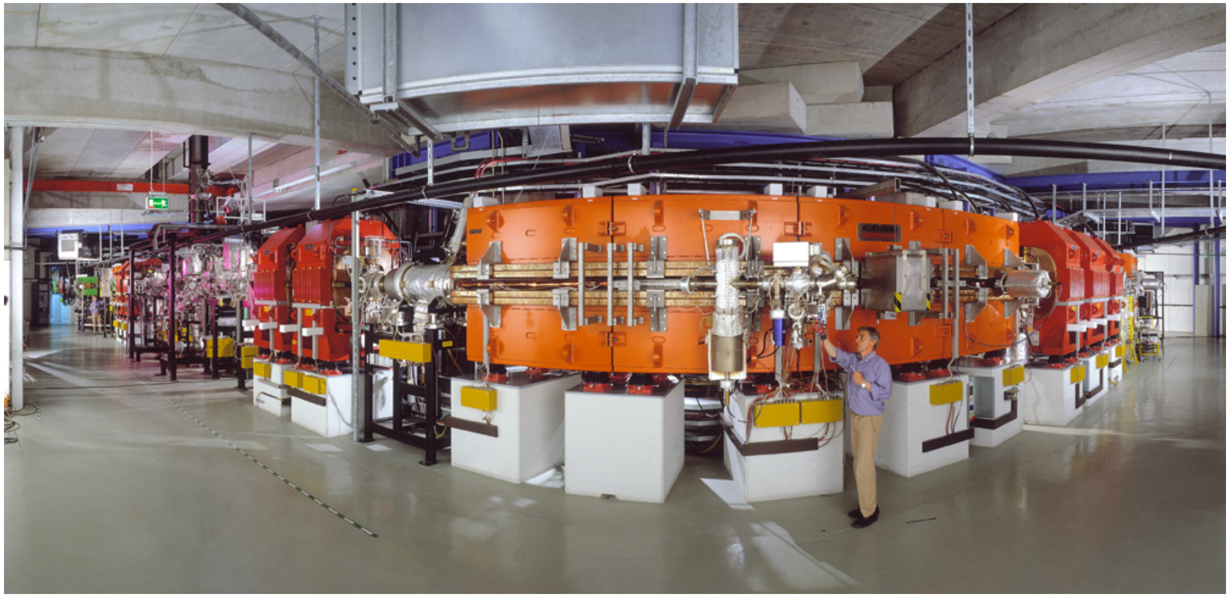


E127 R. Reifarth et al.

NucAR

*Regarding the proposal "Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process" (Proposal E127), the G-PAC recommends this proposal with **highest priority (A)** and that **15 shifts of main beam time** be allocated for this measurement.*

Storage ring facilities at GSI



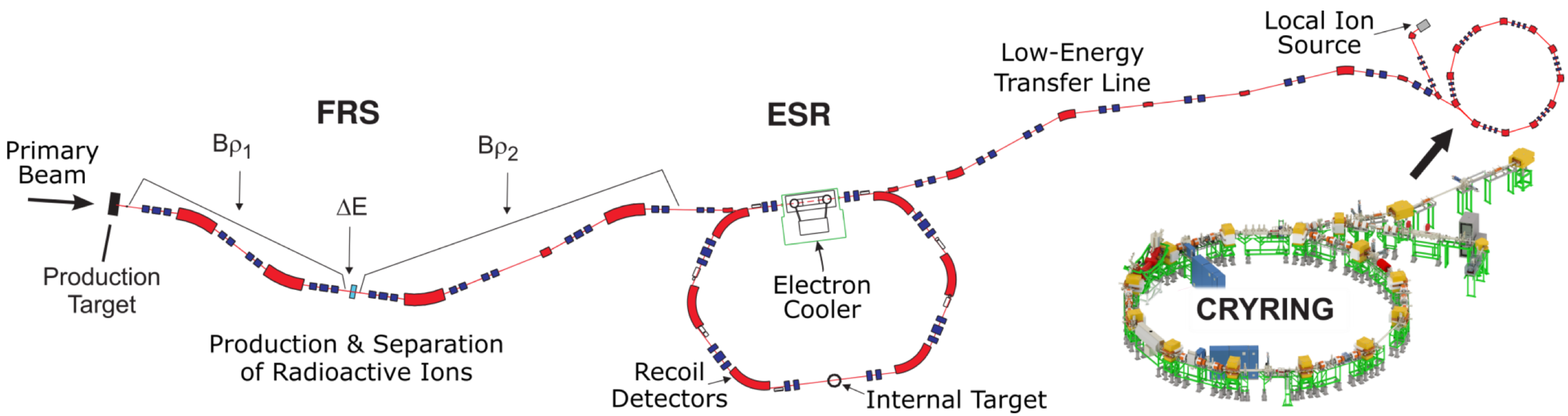
Experimental Storage Ring (ESR)

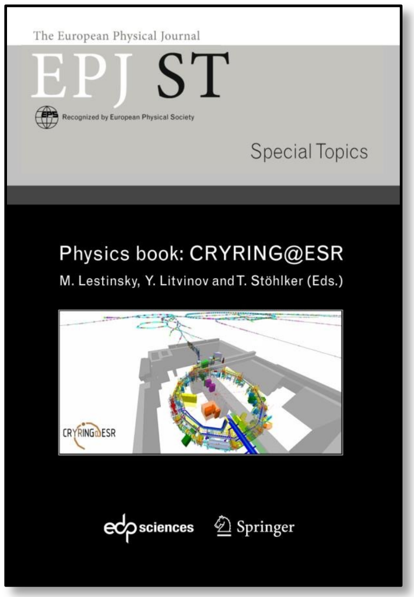
In operation since 1990
Circumference = 108.3 m
UH Vacuum = 10^{-10}—10^{-12} mbar
Electron, stochastic cooling
Energy range = 3 – 400 MeV/u
Slow and fast extraction

CRYRING
(transported from Stockholm University)

Start of operation (local source) – 2019
Start of operation (beams from ESR) – 2020
Circumference = 54.15 m
XH Vacuum = 10^{-11}—10^{-12} mbar
Electron cooling
Energy range = ~0.1 – 15 MeV/u
Slow and fast extraction

The CRYRING@ESR facility





M. Lestinsky, GSI, Darmstadt

M. Lestinsky et al., EPJ ST 225, 797 (2016)

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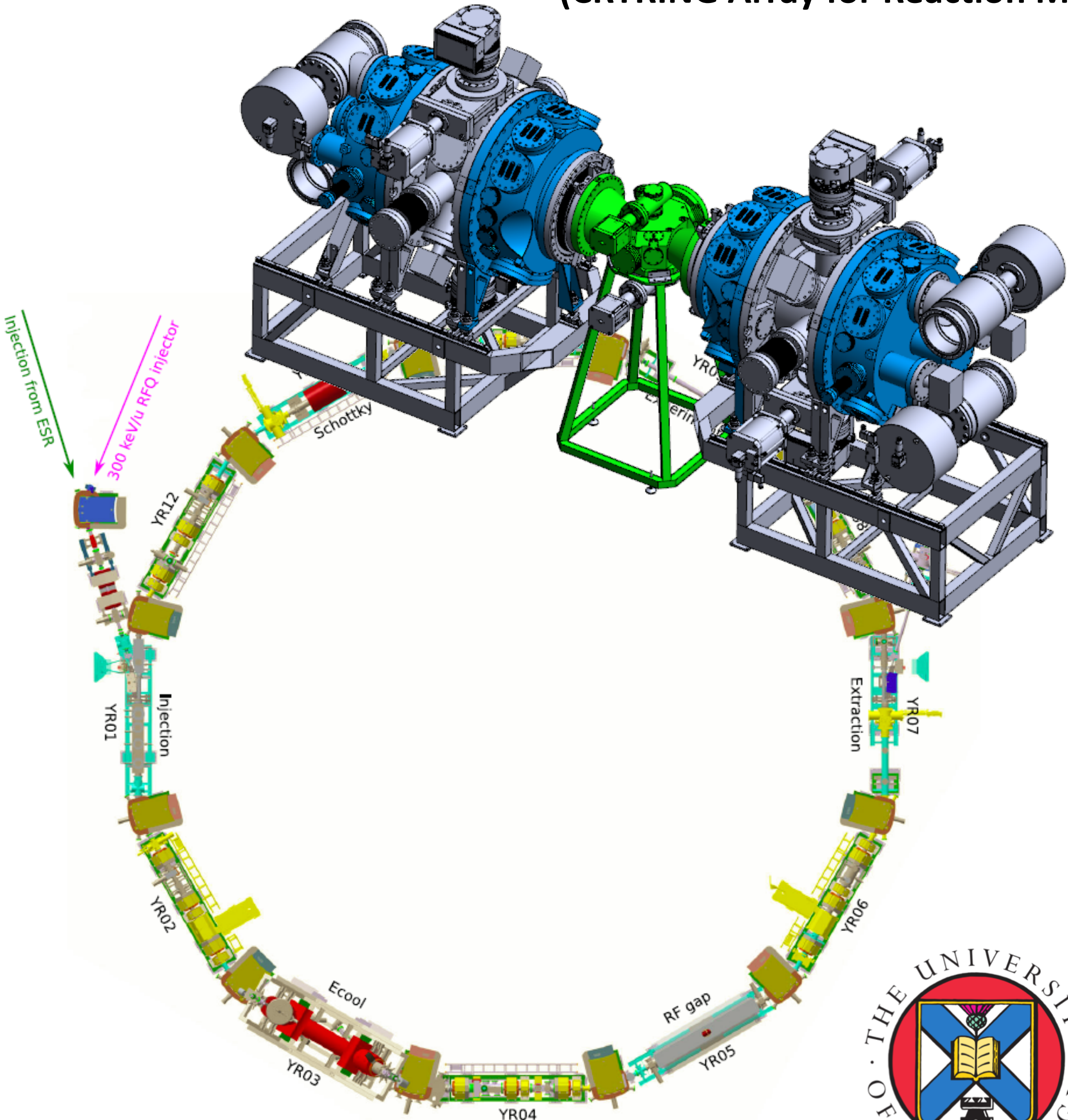
CARME @ CRYRING

(CRYRING Array for Reaction MEasurements)



Measure nuclear reactions directly at Big Bang energies

Novae physics

Reactions for p-process

Reactions for rp-process

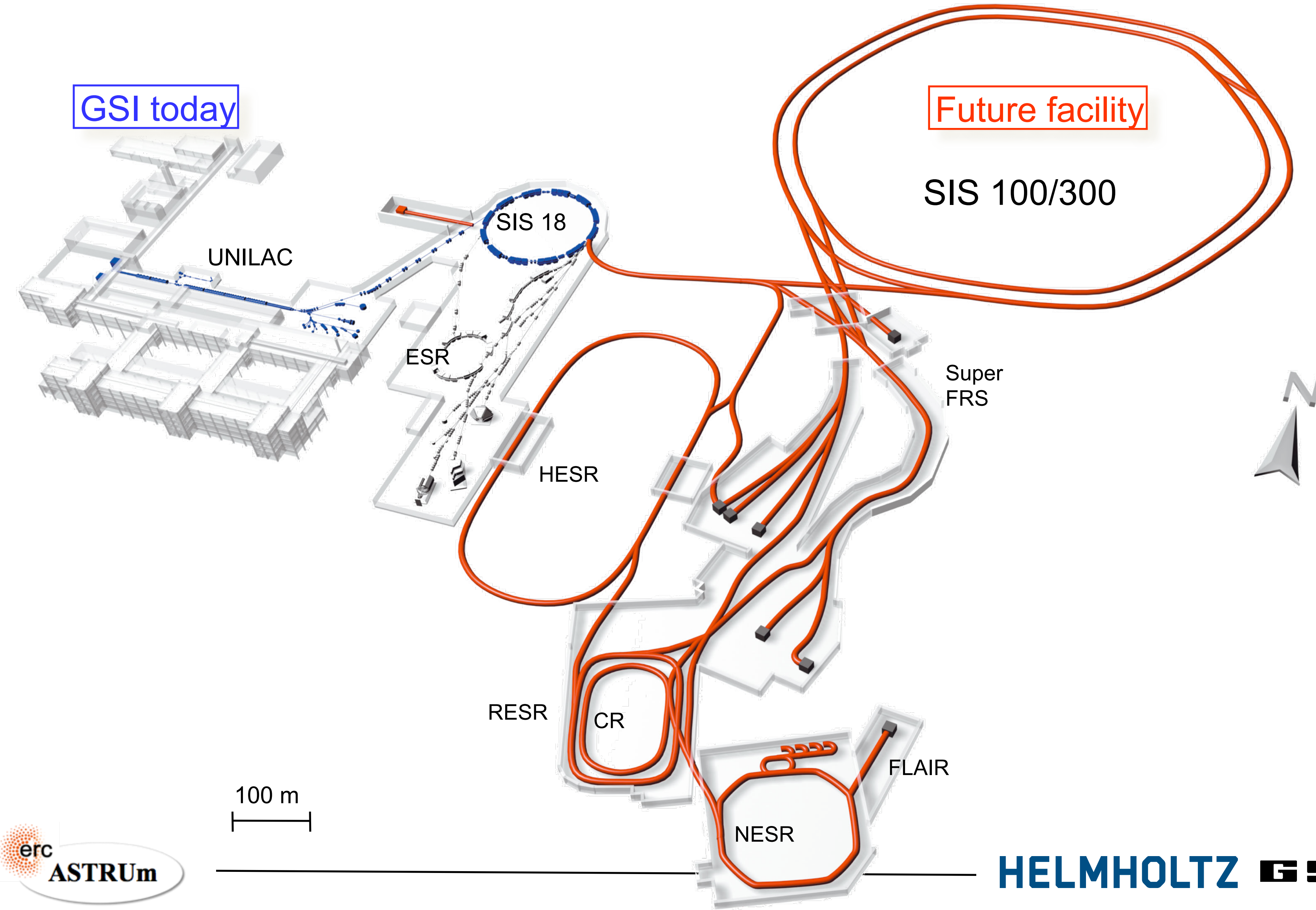
.....

Neutron-induced reactions (surrogate method)

B. Jurado, ERC AG „NECTAR“

Courtesy C. Bruno, T. Davinson, P. Woods

FAIR - Facility for Antiproton and Ion Research



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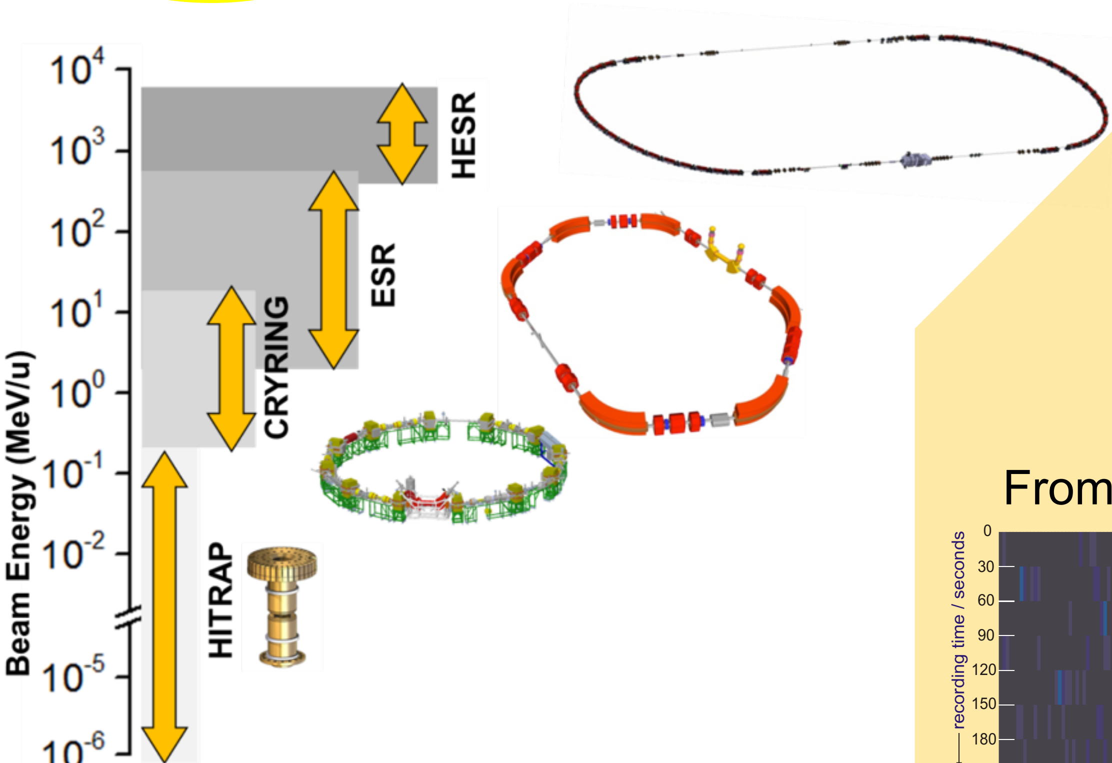
Ion Beam Facilities / Trapping & Storage

Worldwide Unique !

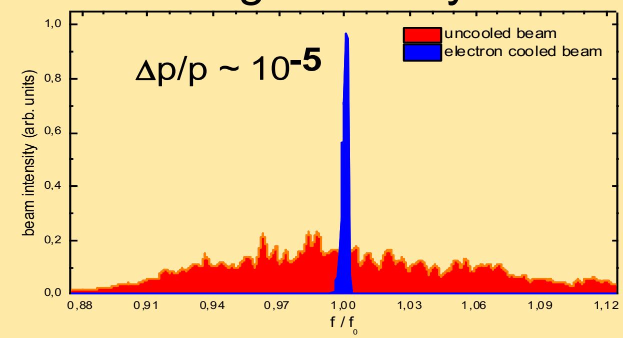
Stored and Cooled

Highly-Charged Ions (e.g. U^{92+}) and Exotic Nuclei

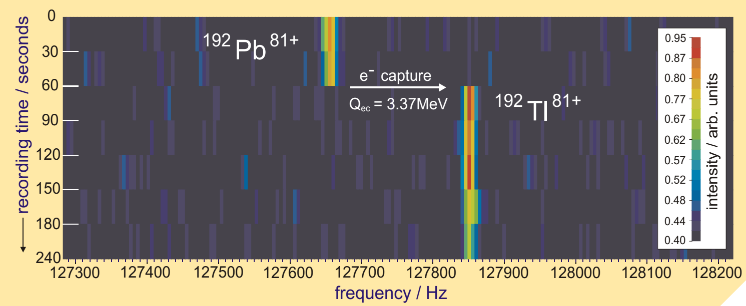
From Rest to Relativistic Energies (up to 4.9 GeV/u)



Cooling: The Key for Precision



From Single Ions to Highest Intensities



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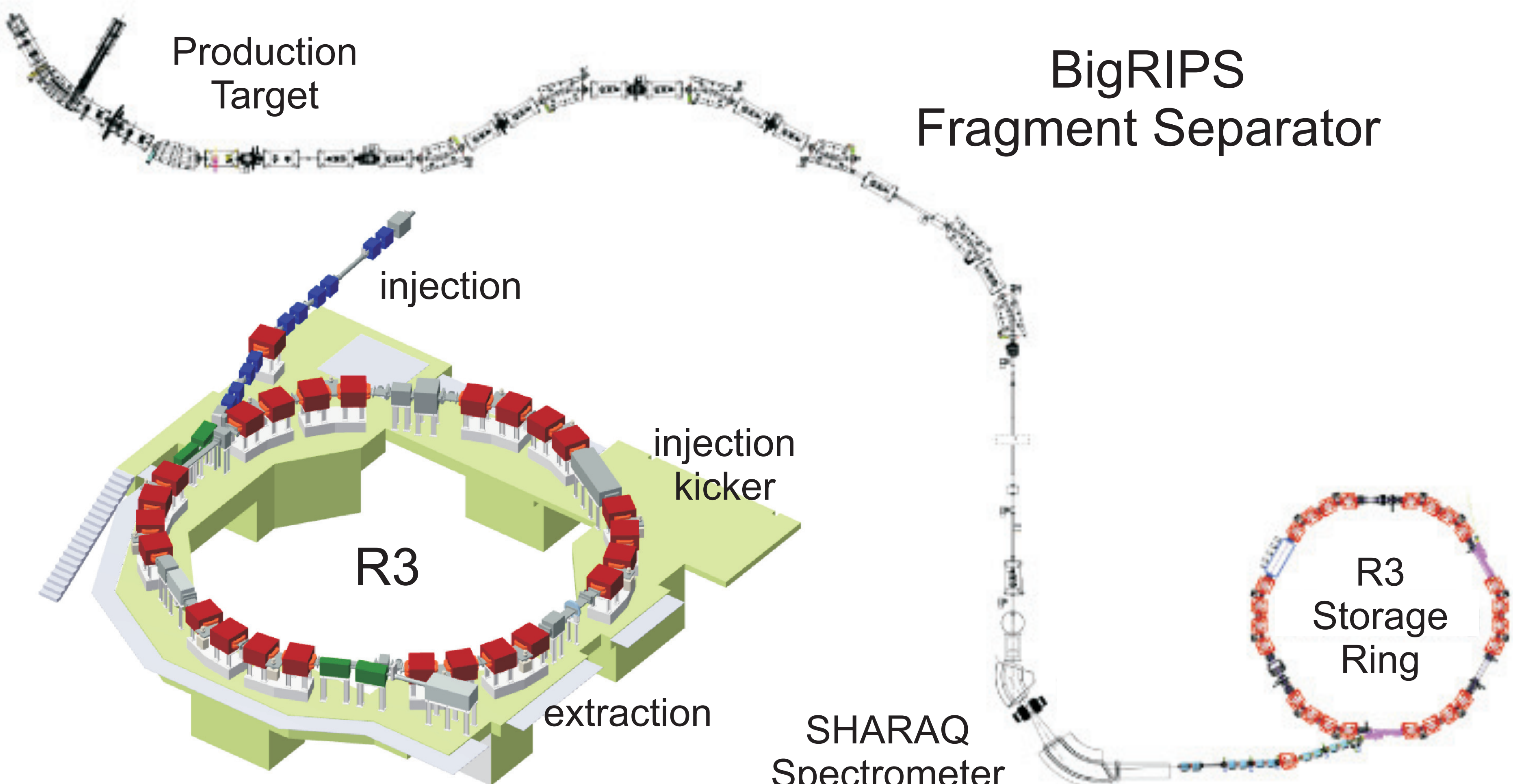
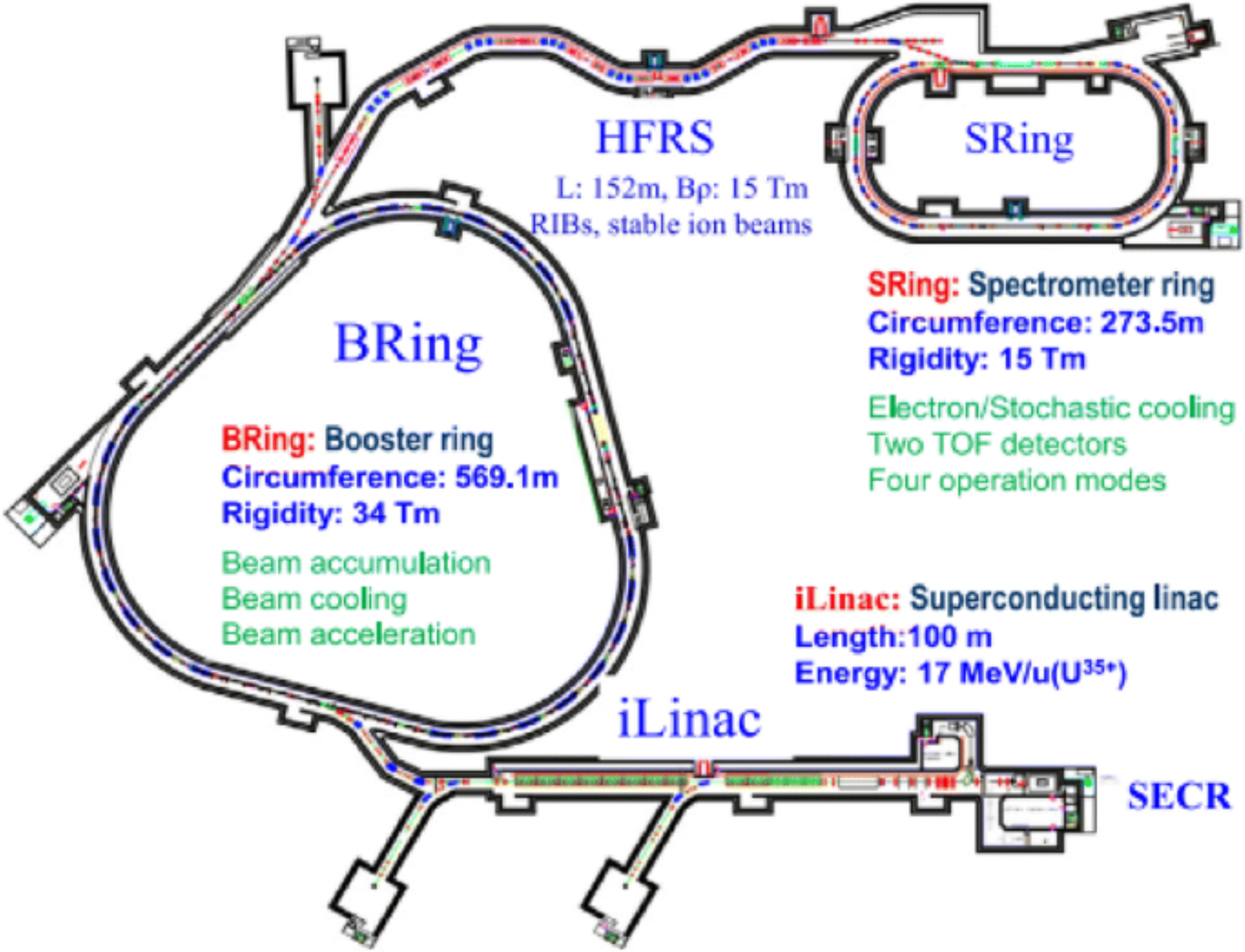
BigRIPS + R3 Setup in RIKEN



HIAF – High Intensity Heavy Ion Accelerator Facility



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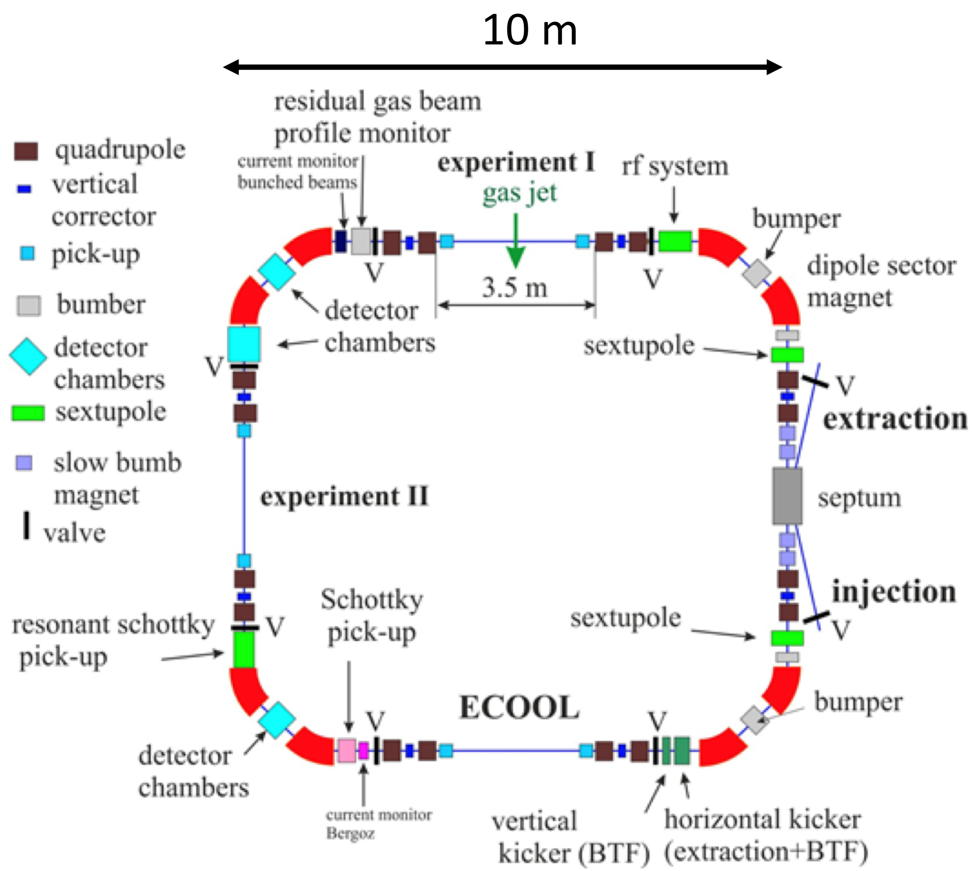
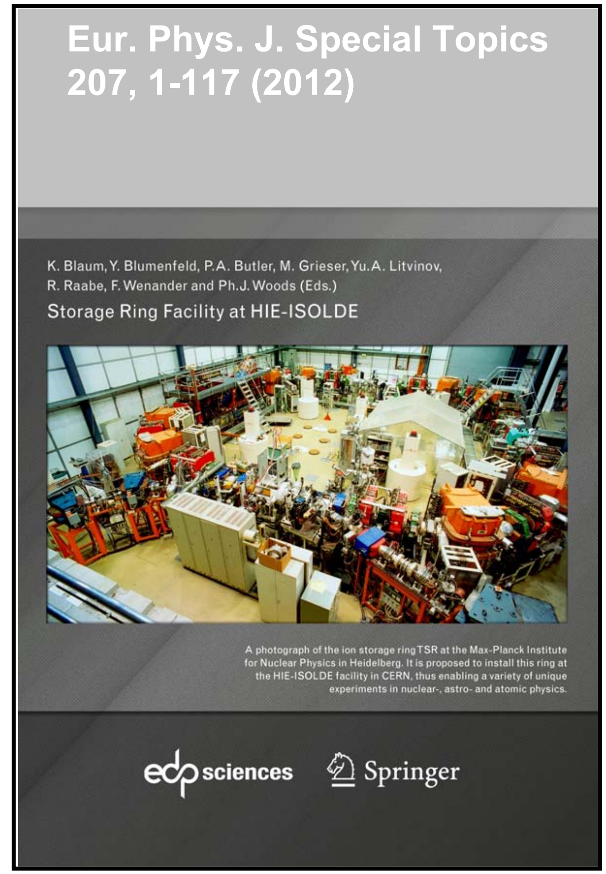
Outlook 2: Storage ring at ISOLDE

A new compact storage ring for light and heavy ions

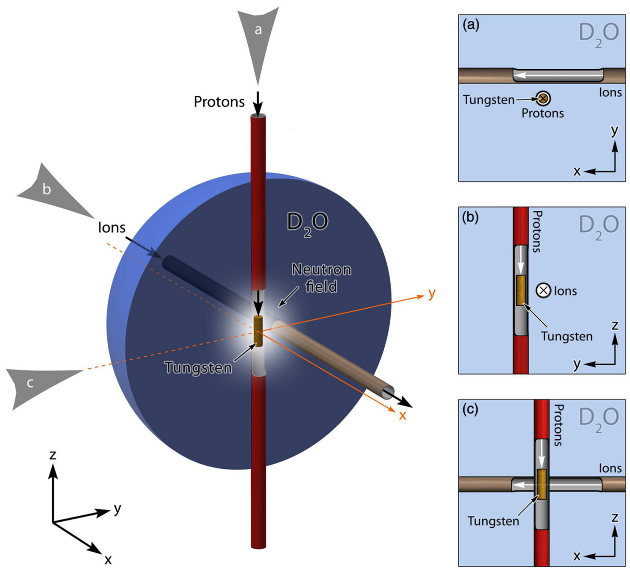


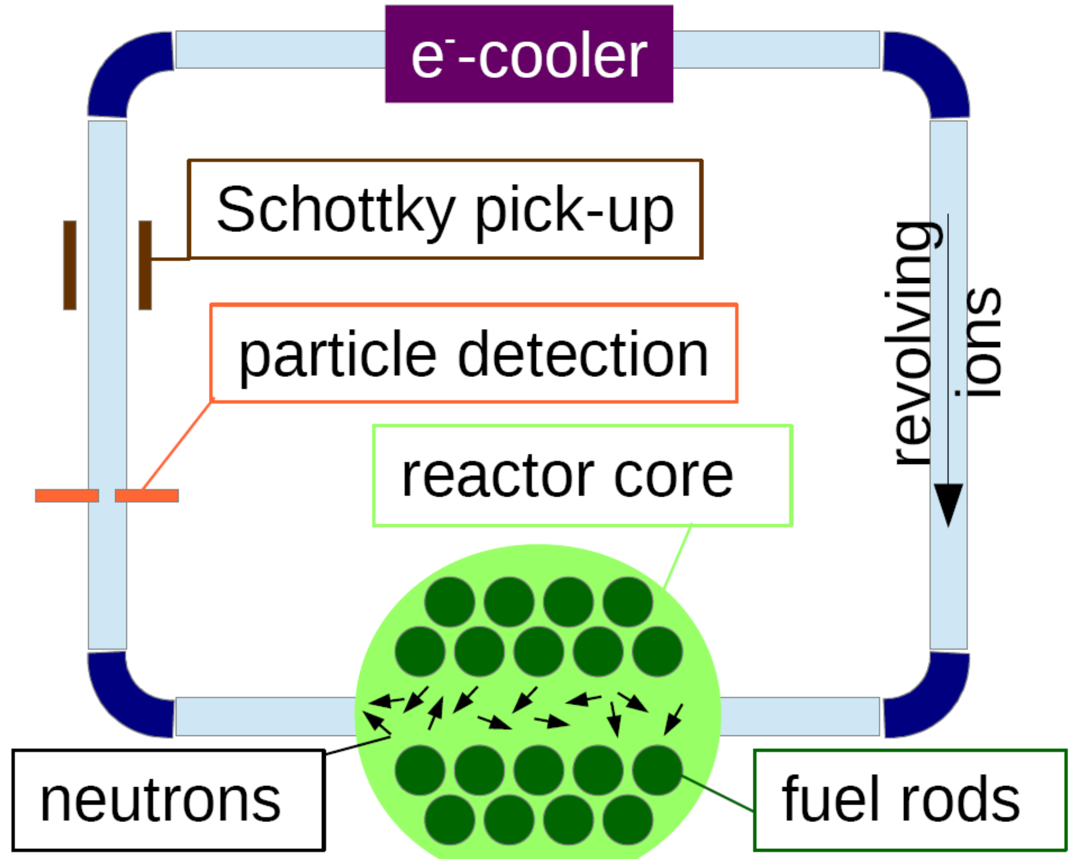


Courtesy M. Grieser, E. Siesling

Outlook 3: Neutron-induced reactions

- Neutron flux: 10^{14} n/cm^2/s ->
- Neutron target: 2 10^{10} n/cm^2
- 10^7 ions, 1 MHz: 10^{13} ions/s
- Counts per day: 20 σ / mb





Reifarth & Litvinov , Phys. Rev ST Accelerator and Beams, 17 (2014) 014701
Reifarth et al., Phys. Rev ST Accelerator and Beams, 20 (2017) 044701

Courtesy R. Reifarth

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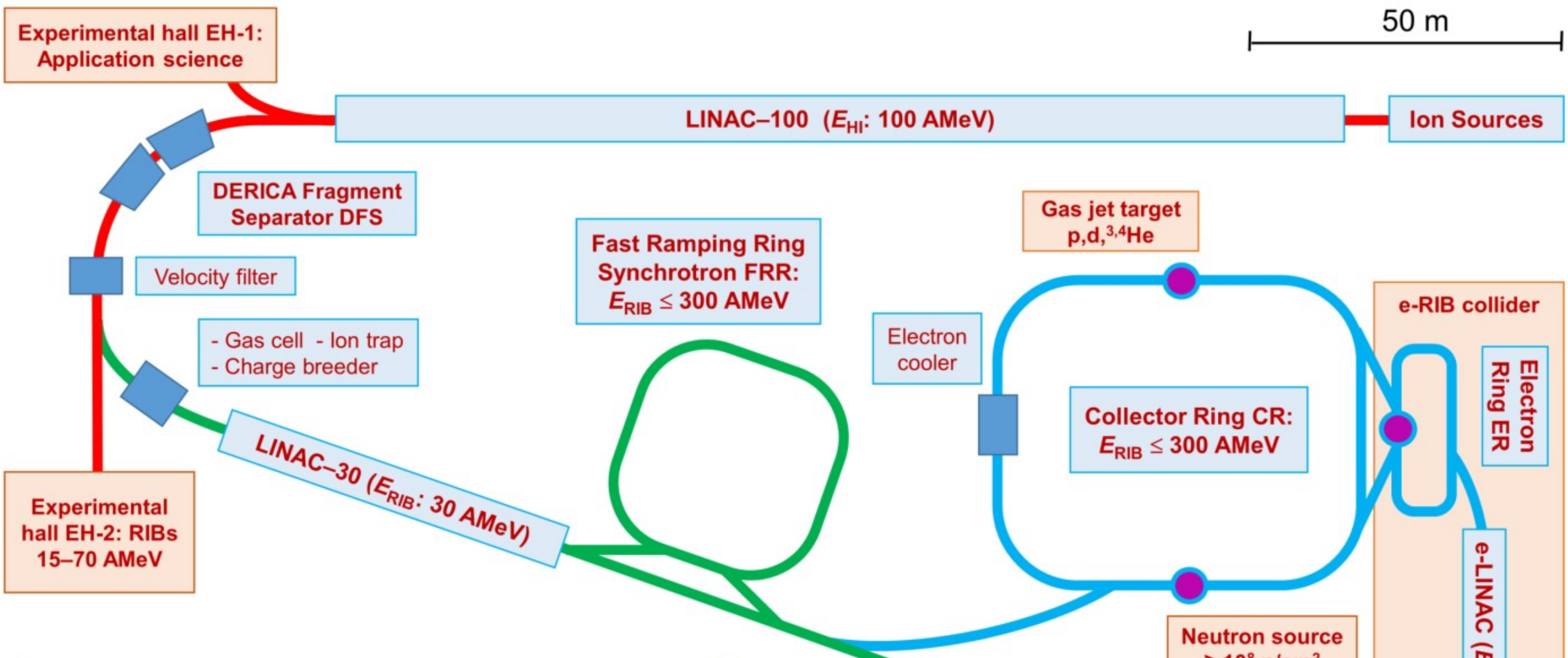
The DERICA Project



Stage 2:	Buildings, LINAC–100, DFS, EH-1,2	2022-2027
Stage 3:	LINAC–30 relocation, FRR, EH-3	2024-2029
Stage 4:	CR, e-RIB collider, ring experiments	2026-2031

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L. Grigorenko, et al., Phys. Uspechi 189 (2019) 721

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North American Storage Rings and Neutron Captures Workshop

28-30 June, 2021
Virtual Meeting hosted through Zoom and Gather.Town

Many thanks to our collaborators from all over the world !!!

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sparc
Stored Particles Atomic Physics Research Collaboration

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THE UNIVERSITY OF EDINBURGH

GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN

RIKEN

TUM

CENBG

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