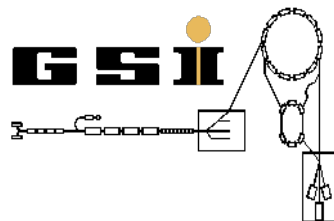


Precision Experiments at Heavy-Ion Storage Rings

Yury A. Litvinov

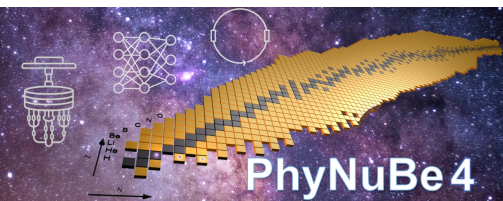
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES



中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences



www.gsi.de/astrum



4th PhyNuBe school: Innovative Technologies, Theories, and Methodologies in Nuclear Physics
"Paul Langevin", Haute-Maurienne-Vanoise-Alpen, Aussois, France
17-22 May 2026

HELMHOLTZ **GSI**

CRYRING at GSI



ESR at GSI



- Single-particle sensitivity
- High revolution frequencies
- Broad-band measurements
- High atomic charge states
- High resolving power

R3 at RIKEN



CSR实验环闭环

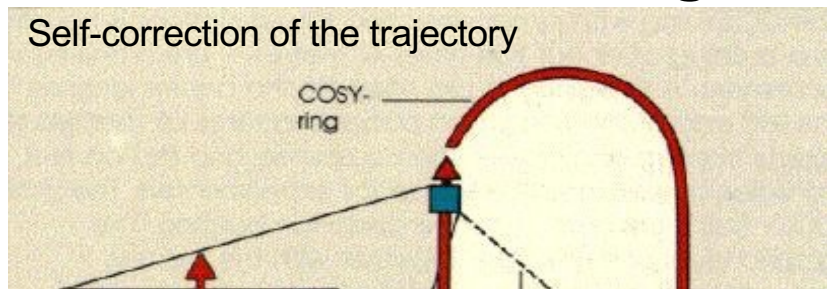
CSRe at IMP

Cooling techniques applied at ion rings

- Lasers = transfer of momentum
- Electrons = mixing of temperatures
- Stochastic = self-correction

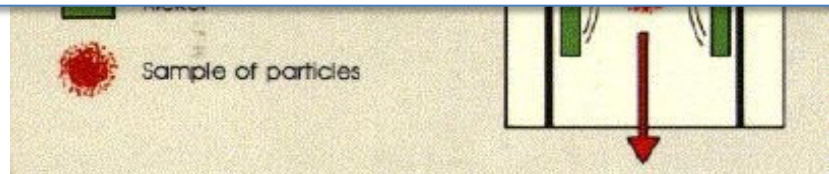


Stochastic Cooling of Secondary Beams



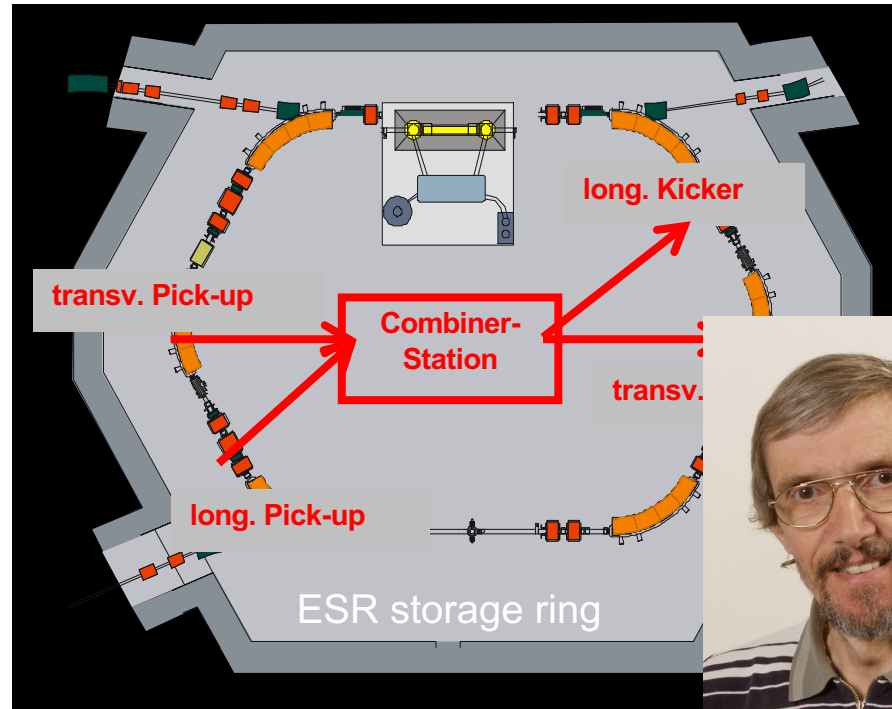
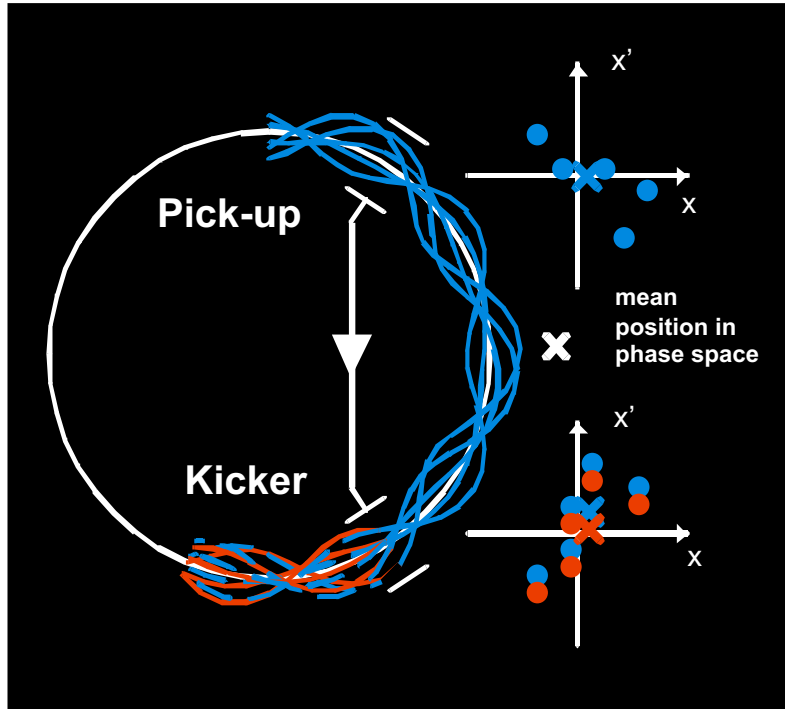
Simon van der Meer
1925 - 2011

Why do you need to send the signal to the opposite side of the ring? Why cannot one simply wait until the beam comes back after full revolution?



Nobel prize 1984: S. van der Meer and C. Rubbia

Stochastic cooling (self-correction of trajectory)

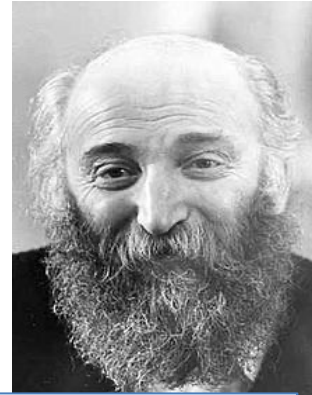
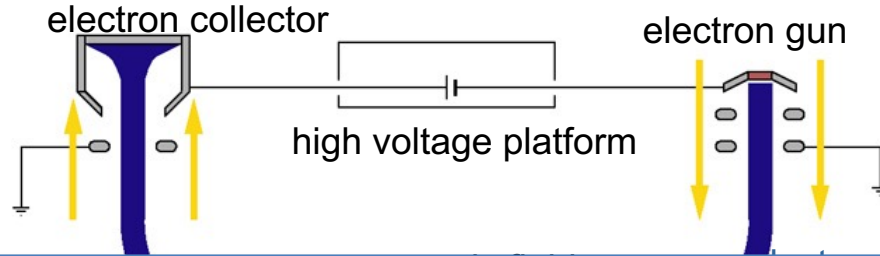


Stochastic cooling is in particular efficient for hot ion beams

Cooling time τ scales as $N_{\text{ion}} / \text{bandwidth}$

Fritz Nolden 2023⁺

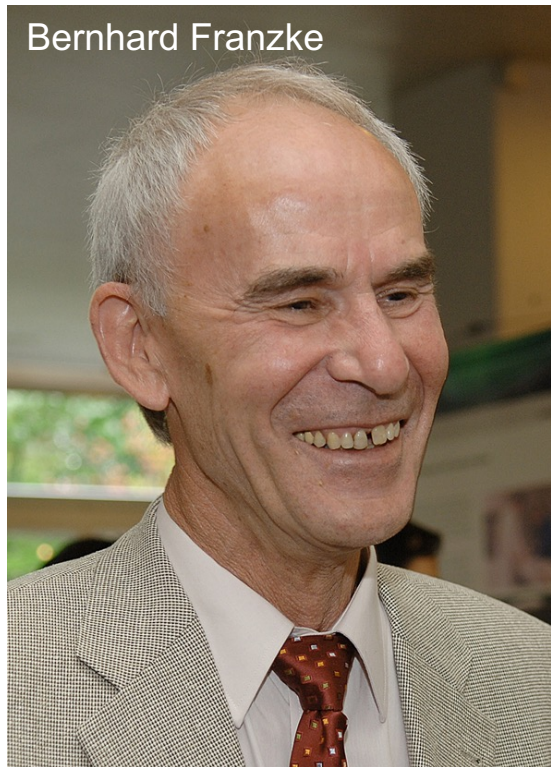
Electron Cooling of Secondary Beams



The cross-section for recombination of electrons with highly-charged ions diverges at zero relative velocity. Why stored ions do simply not recombine and get lost from the ring?

1985: Proposal for Schottky Mass Spectrometry at the ESR

Bernhard Franzke



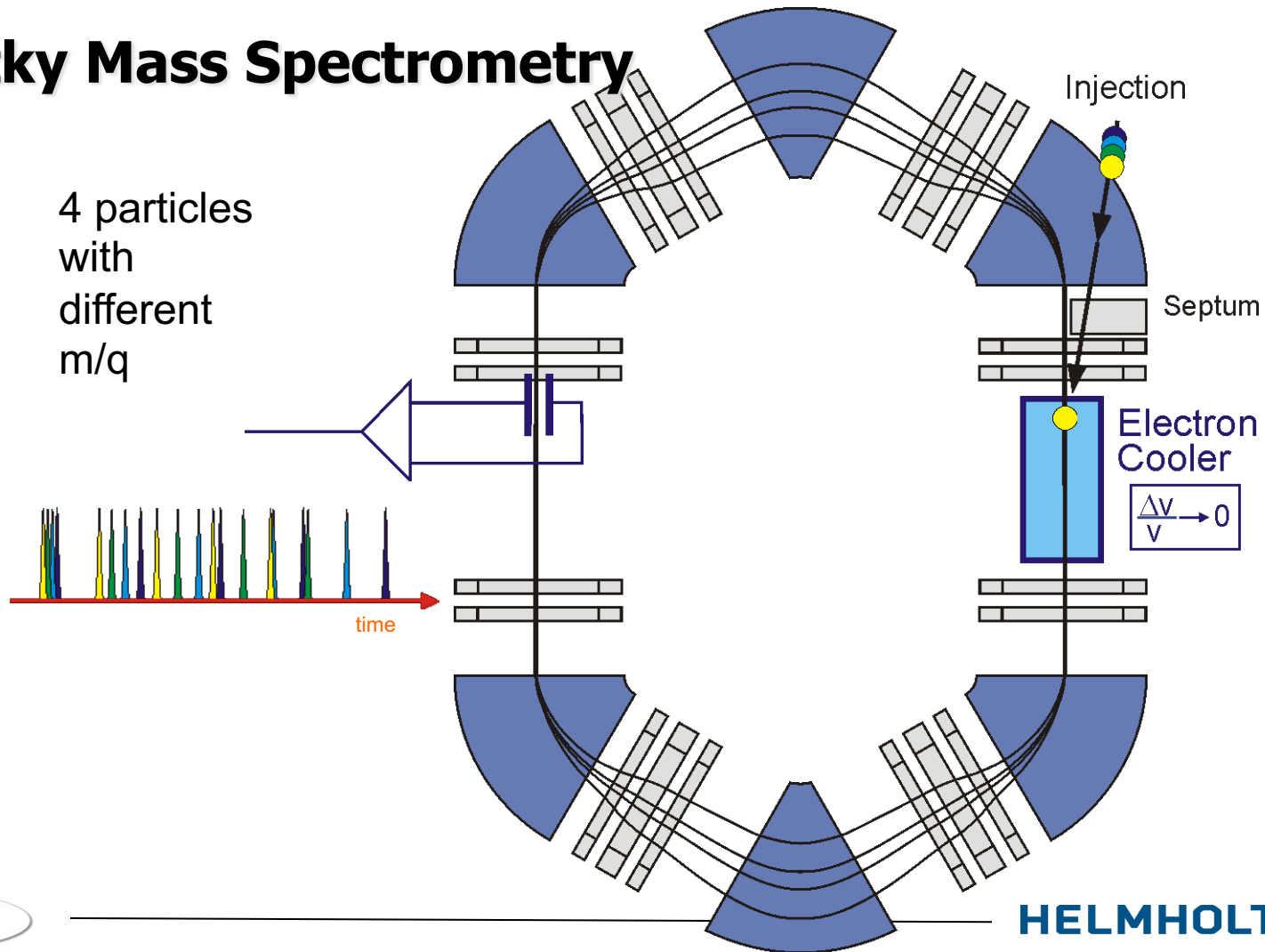
Gottfried
Münzenberg
2024⁺



Hans
Geissel
2024⁺

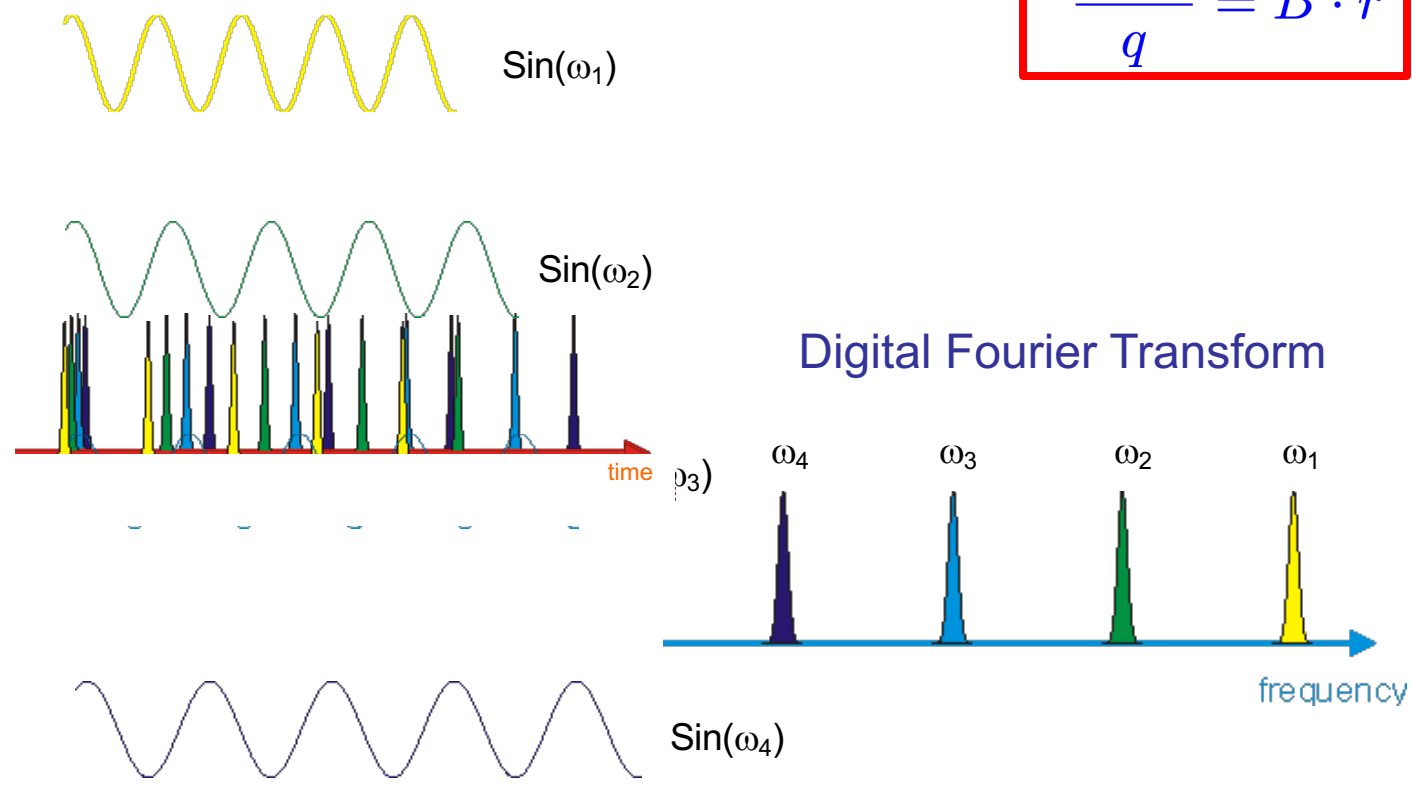


Schottky Mass Spectrometry

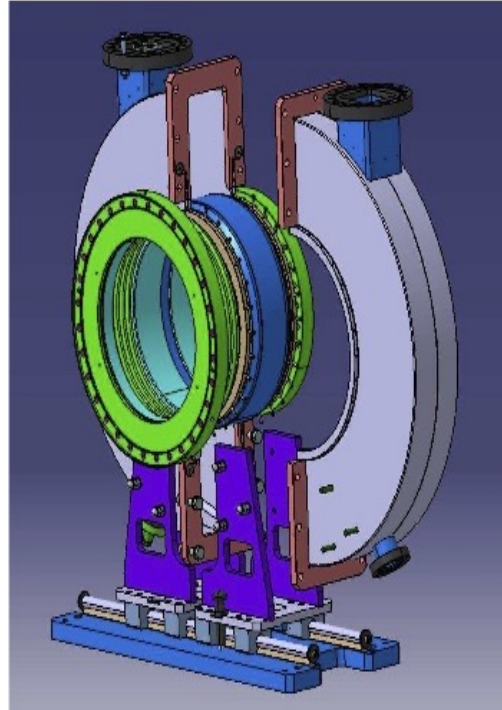
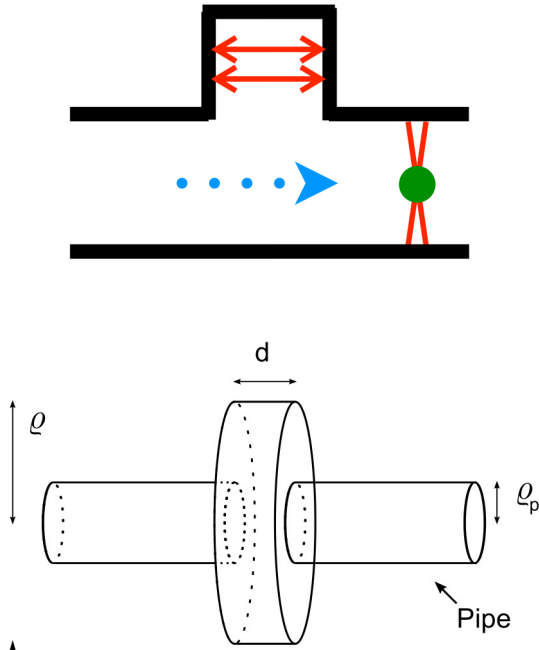


Schottky Mass Spectrometry

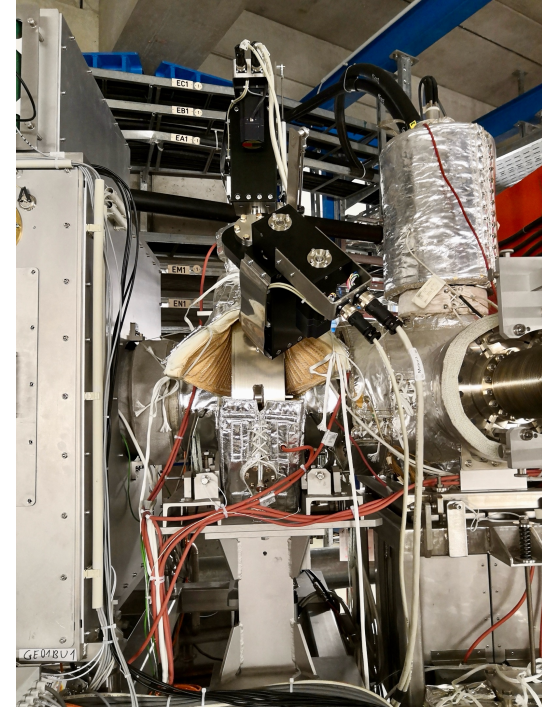
$$\frac{m \cdot v}{q} = B \cdot r$$



Non-Destructive Particle Detection



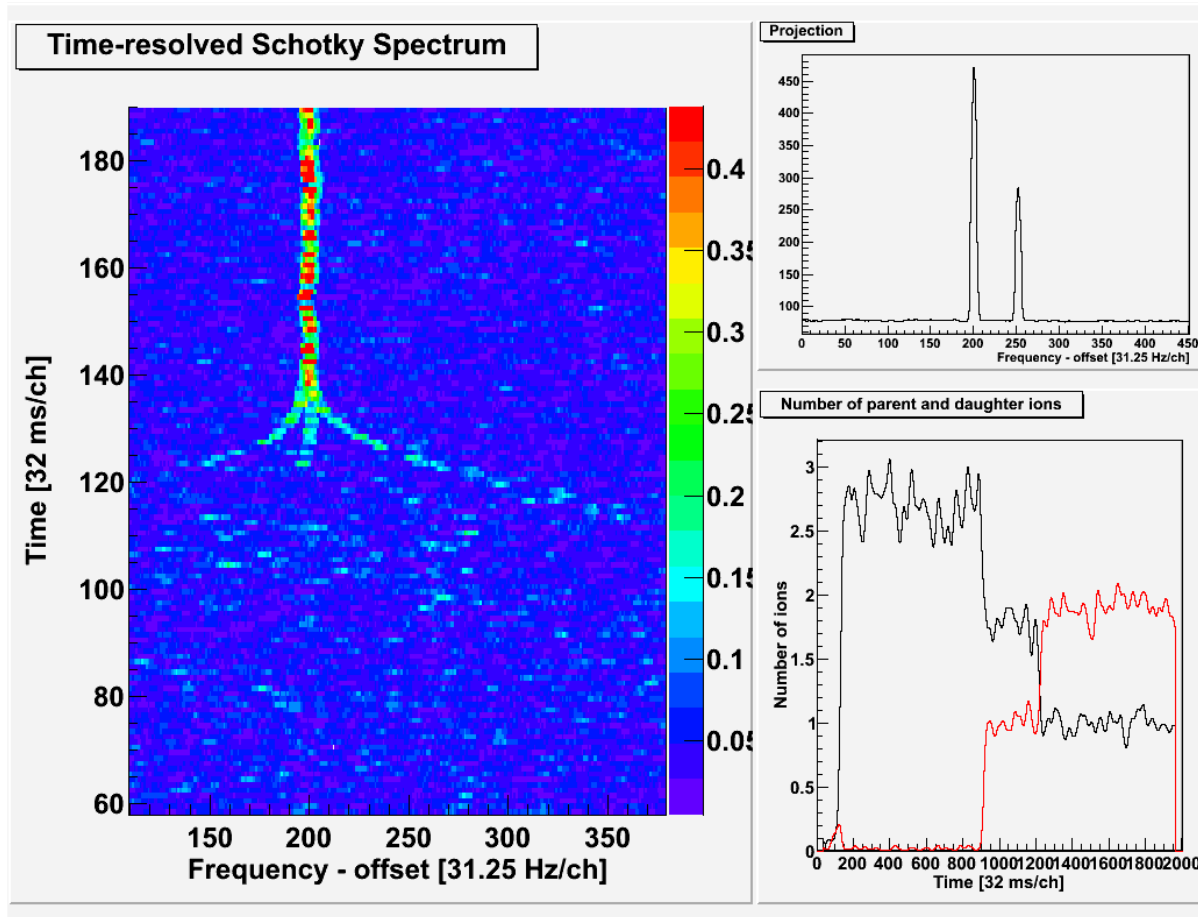
F. Nolden et al., Nucl. Instr. Meth. A (2011)

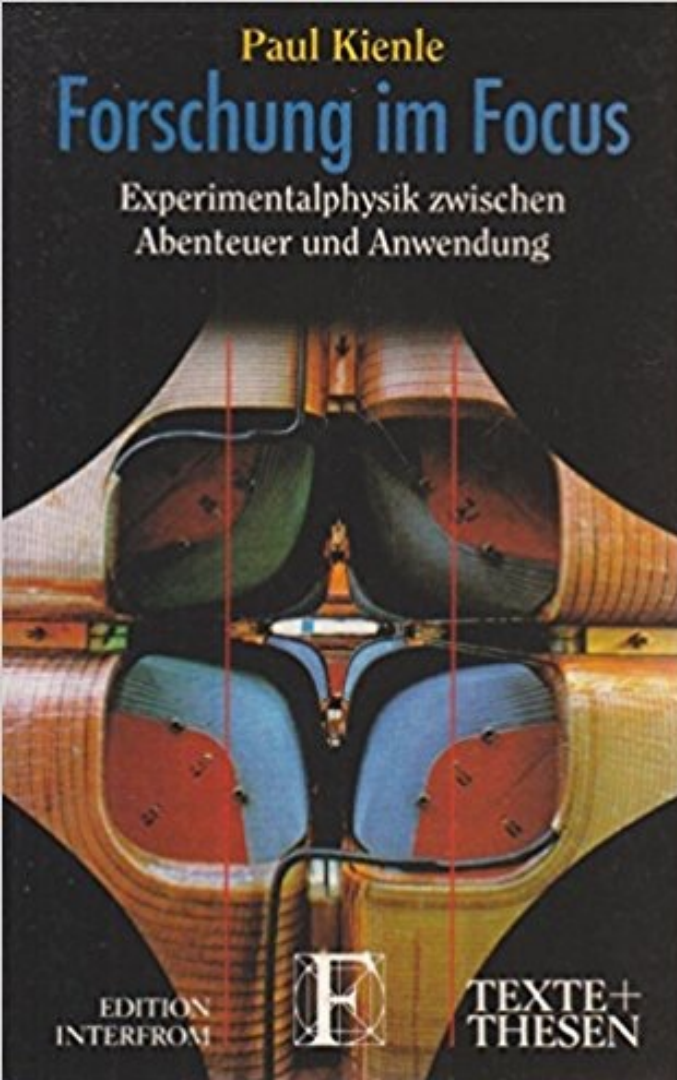


S. Sanjari et al., Rev. Sci. Instr. (2020)

The goal: to measure non-destructively the revolution frequency of a single ion within a few milliseconds

Three Parent He-Like ^{142}Pm Ions



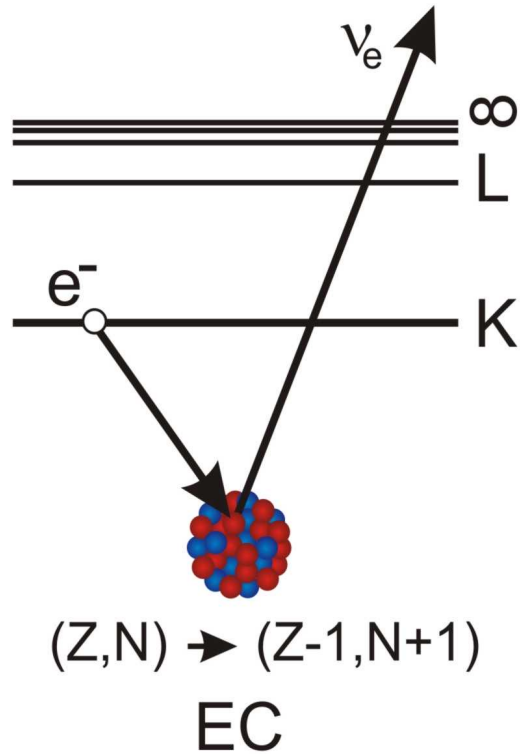


Weak decays of highly-charged ions

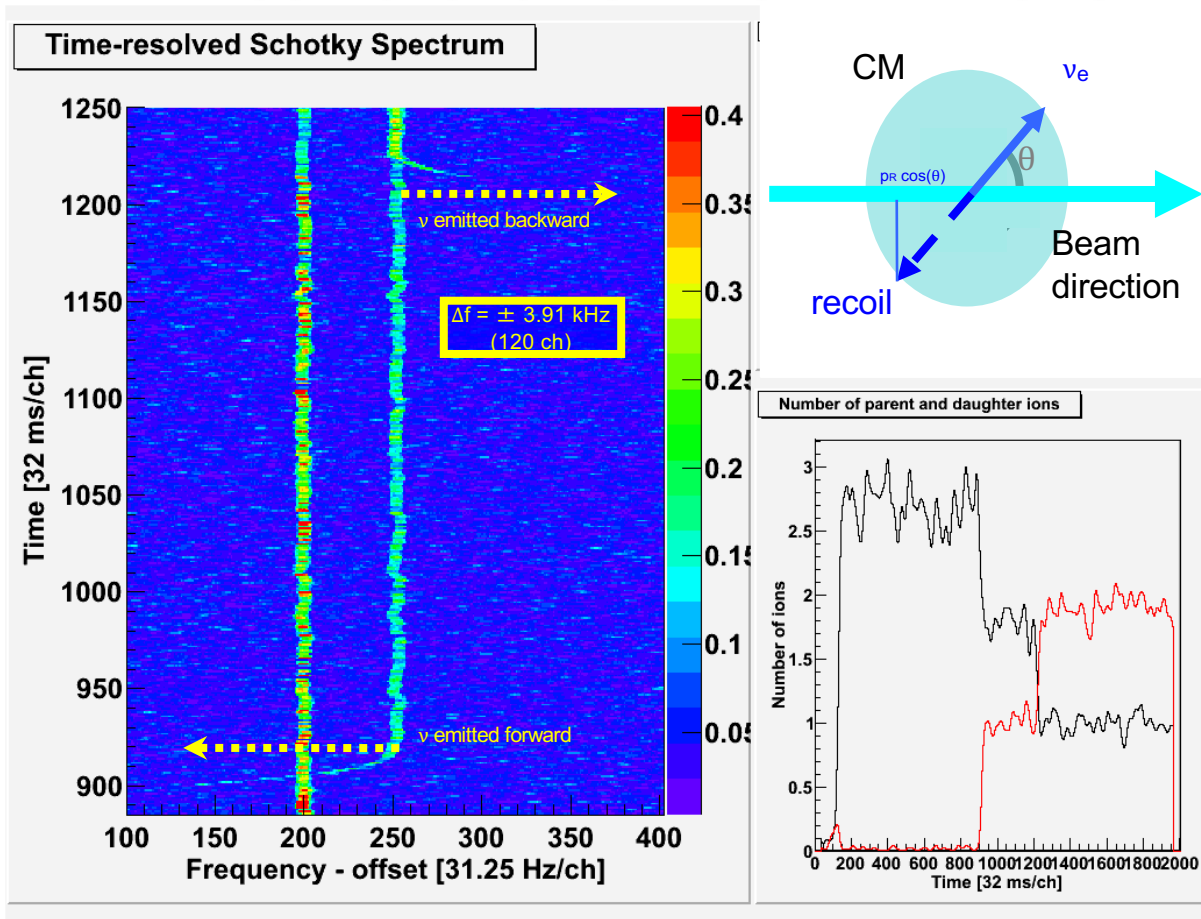


**Paul Kienle
(1931-2013)**

Two-Body Beta Decay

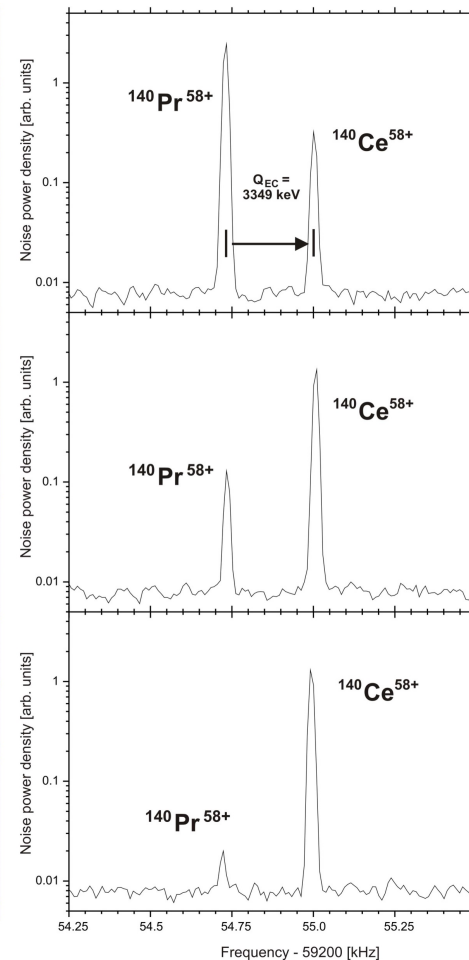
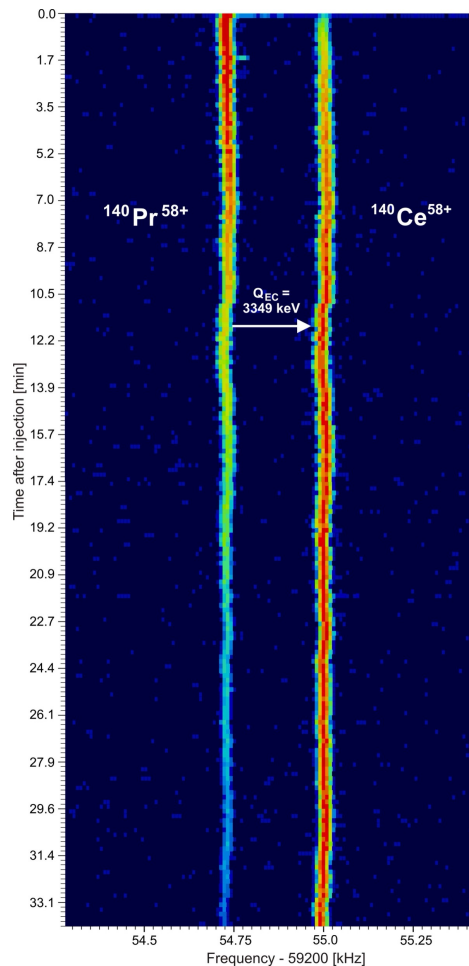
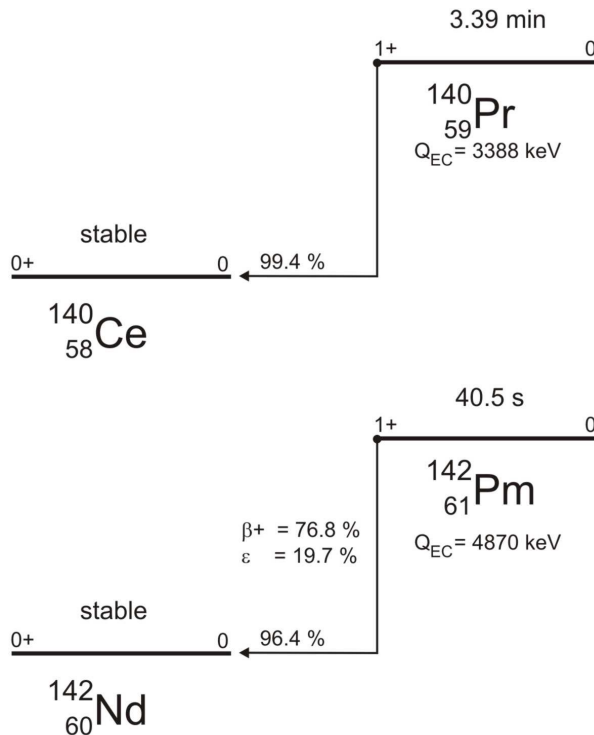


Three Parent He-Like ^{142}Pm Ions



Orbital electron capture

Allowed Gamow-Teller Transitions



Orbital electron capture

Conventional EC-theory:

W.Bambynek et al., Rev. Mod. Phys 49, 1977

S-electron density at the nucleus:

$$|f_s(0)|^2 \propto 1/n^3$$

Simple scaling:

$$P_{EC} \text{ (neutral atom)} \propto 2 \sum 1/n^3 = 2.4$$

$$P_K \text{ (H-like)} \propto 1 * 1/1^3 = 1$$

$$P_K \text{ (He-like)} \propto 2 * 1/1^3 = 2$$

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

Precise calculations including electron-electron correlations:

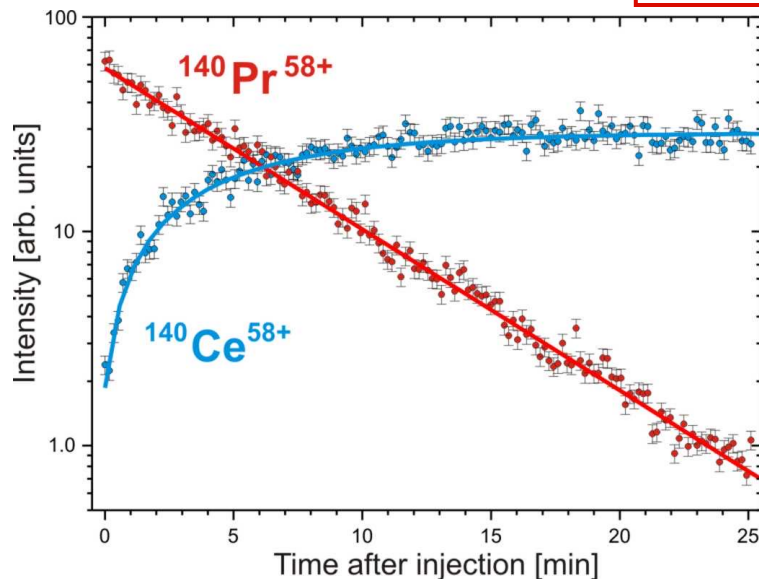
$$\lambda_{EC}(\text{H-like})/\lambda_{EC}(\text{He-like}) \approx 0.41$$

Orbital electron capture of few-electron ions



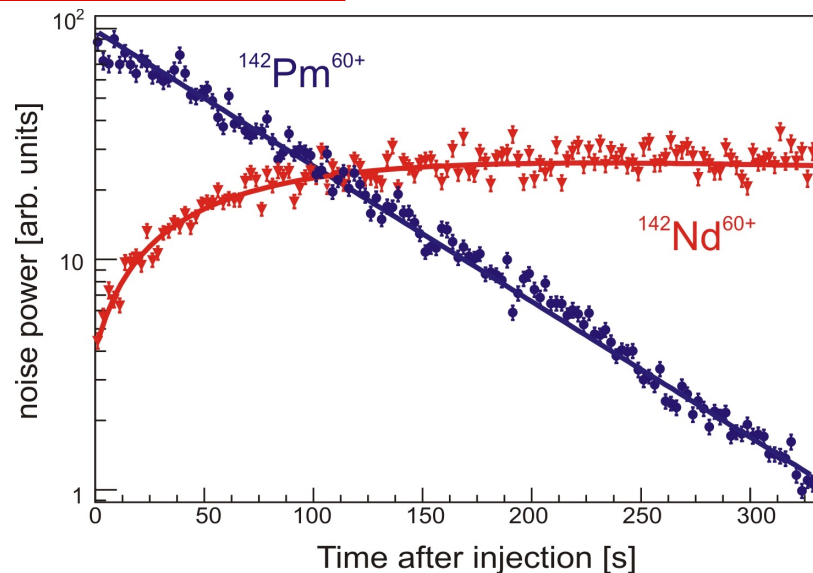
Expectations:

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



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

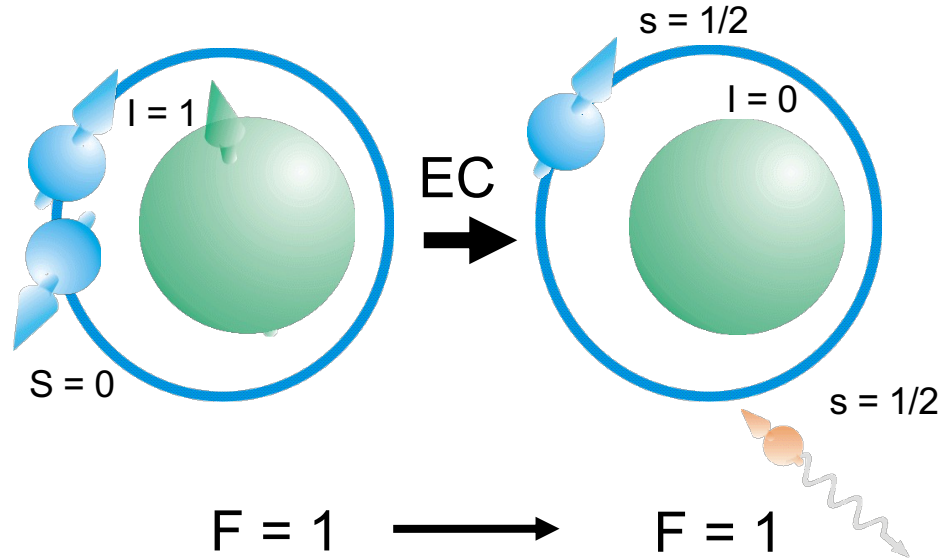
Yu.A. Litvinov et al., Phys. Rev. Lett. 99 (2007) 262501



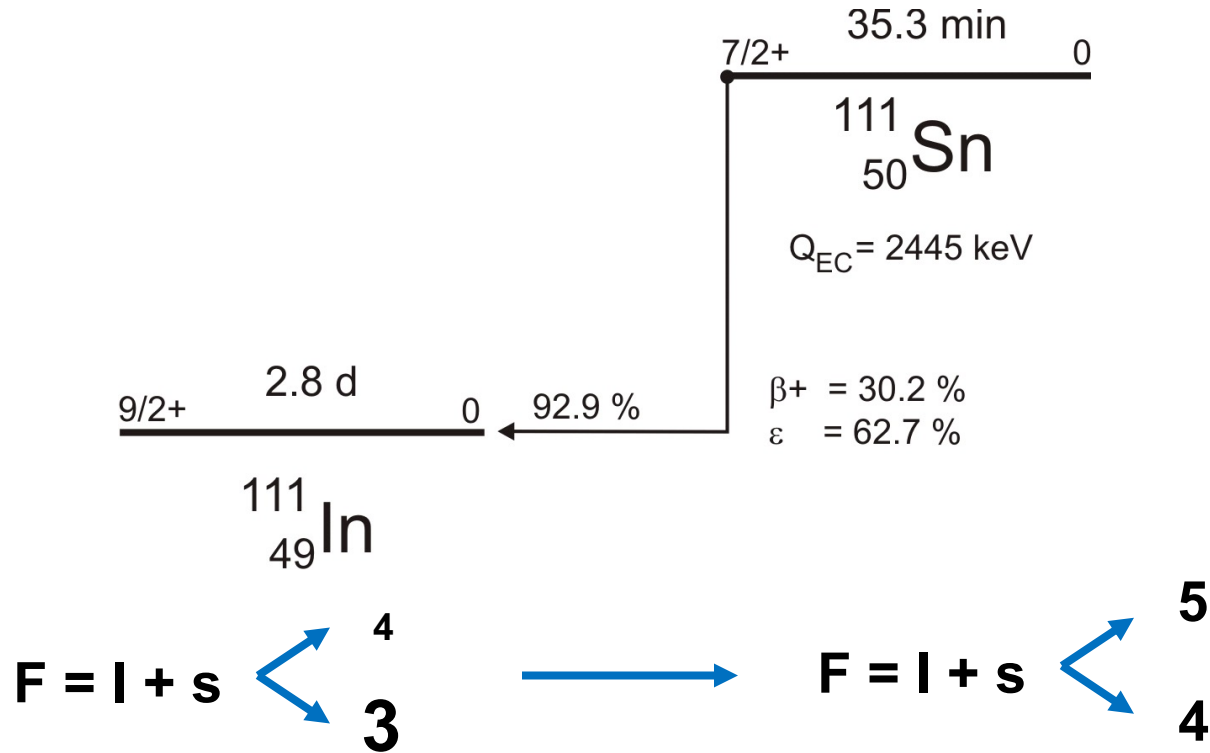
$$\lambda_{\text{EC}}(\text{H-like})/\lambda_{\text{EC}}(\text{He-like}) = 1.44(6)$$

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

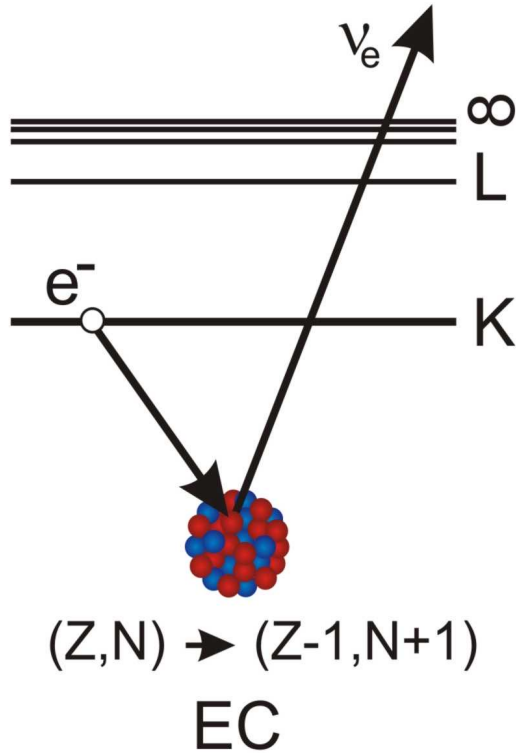
Orbital electron capture of few-electron ions



Electron Capture in Hydrogen-like Ions

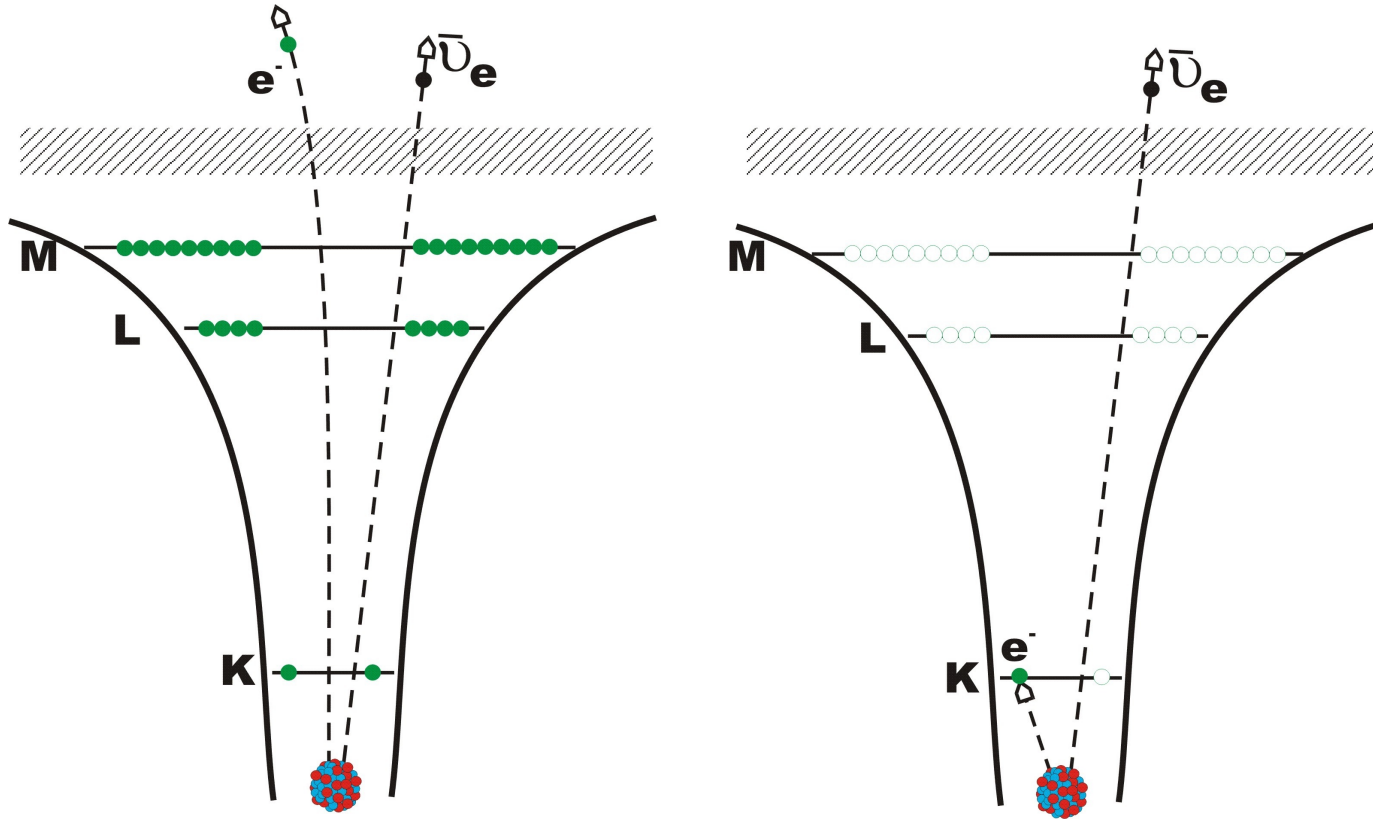


Two-Body Beta Decay



Time reversal

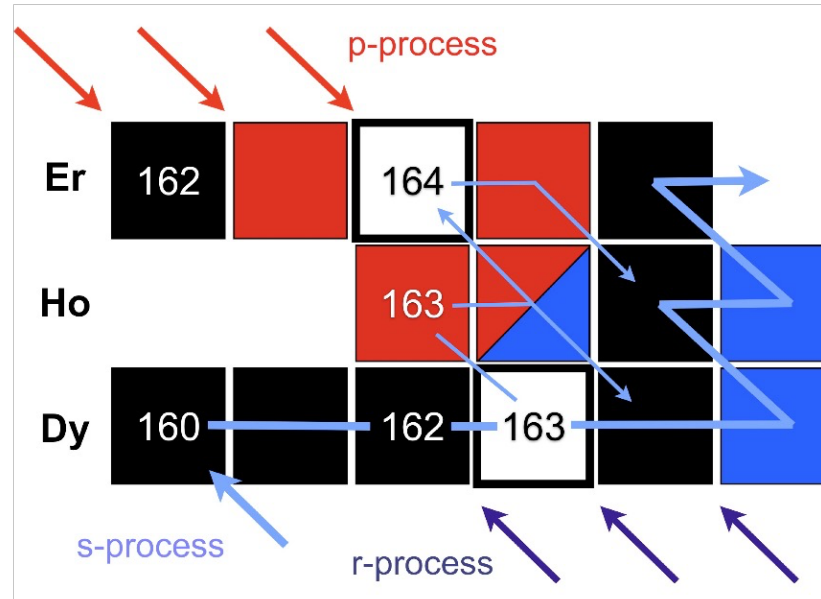
Bound-State β -decay



R. Daudel et al., J. Phys. Le Rad. 8 (1947) 238
J. Bahcall, Phys. Rev. 124 (1961) 495

Bound-State β -decay of ^{163}Dy

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

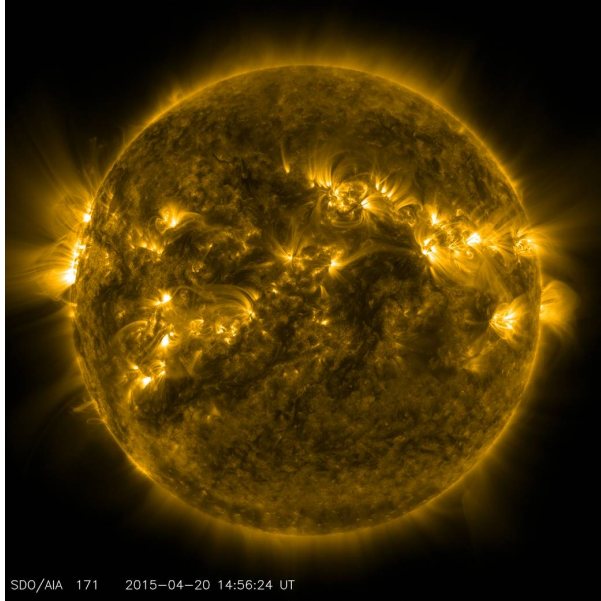


Fritz Bosch
(1940-2016)

$T_{1/2} = 48$ days

branchings caused by bound-state β decay

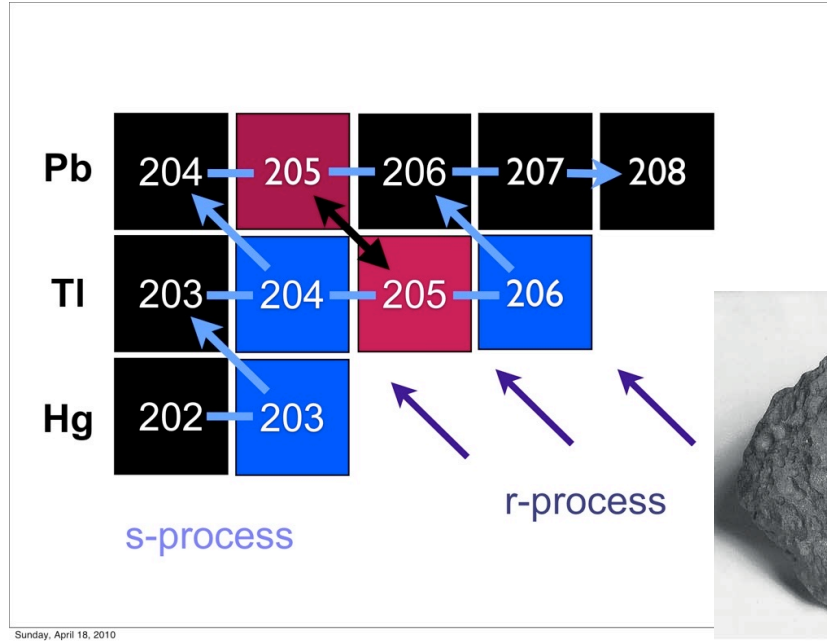
Bound-State Beta Decay of ^{205}Tl Nuclei



SDO/AIA 171 2015-04-20 14:56:24 UT



NASA/SDO



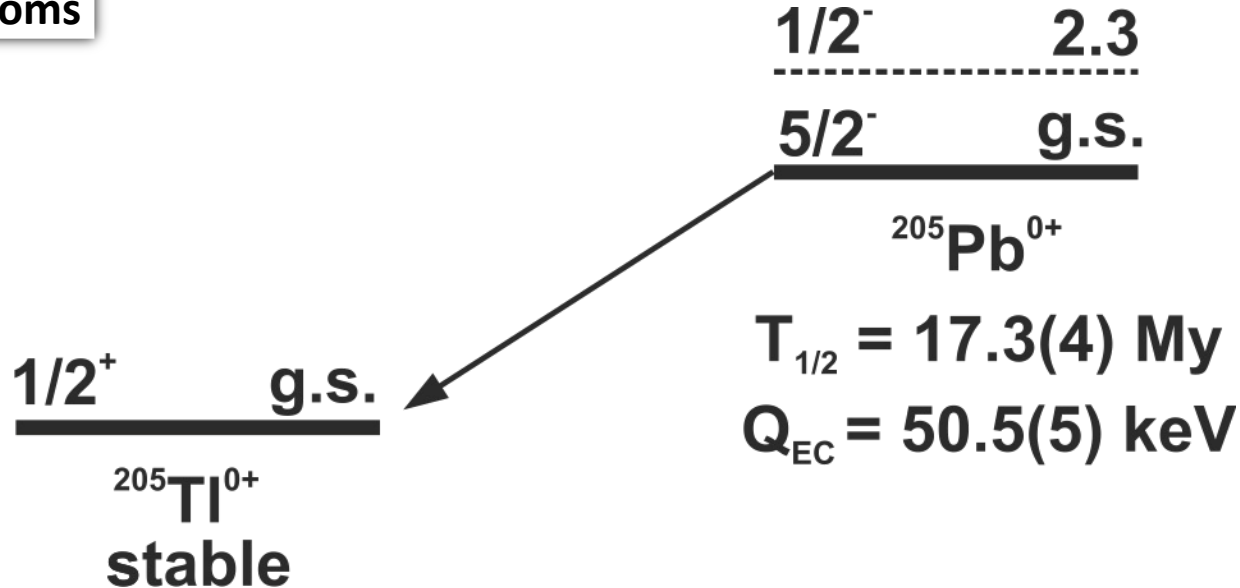
Termination of s-process nucleosynthesis

Time needed for the Solar system to build

Long-term averaged Solar neutrino flux

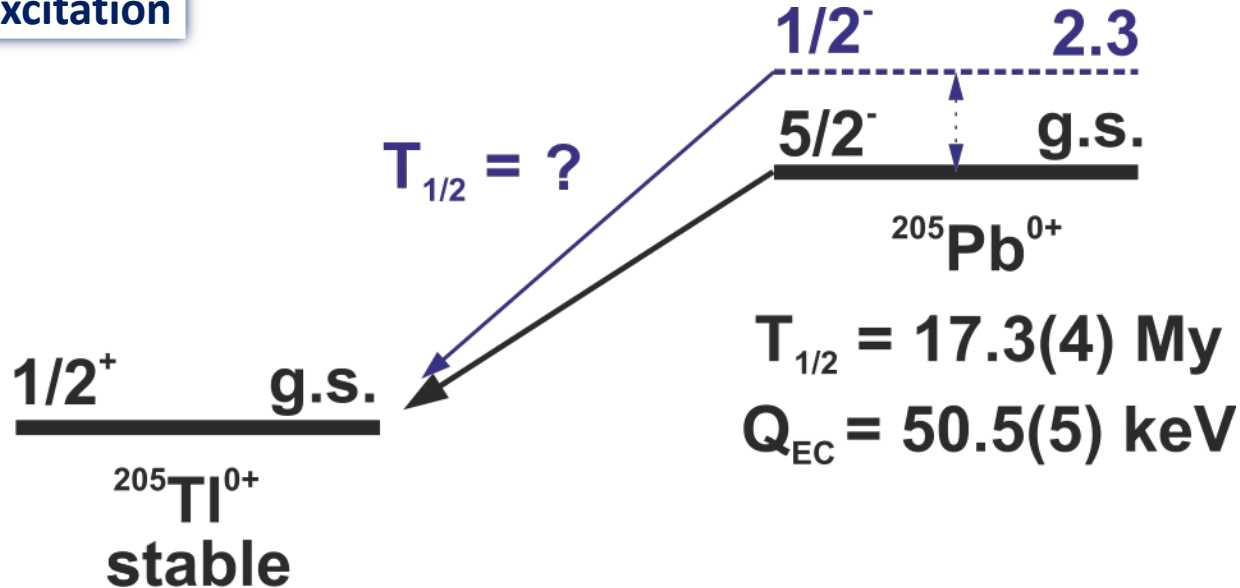
Bound-State Beta Decay of ^{205}TI Nuclei

Neutral atoms

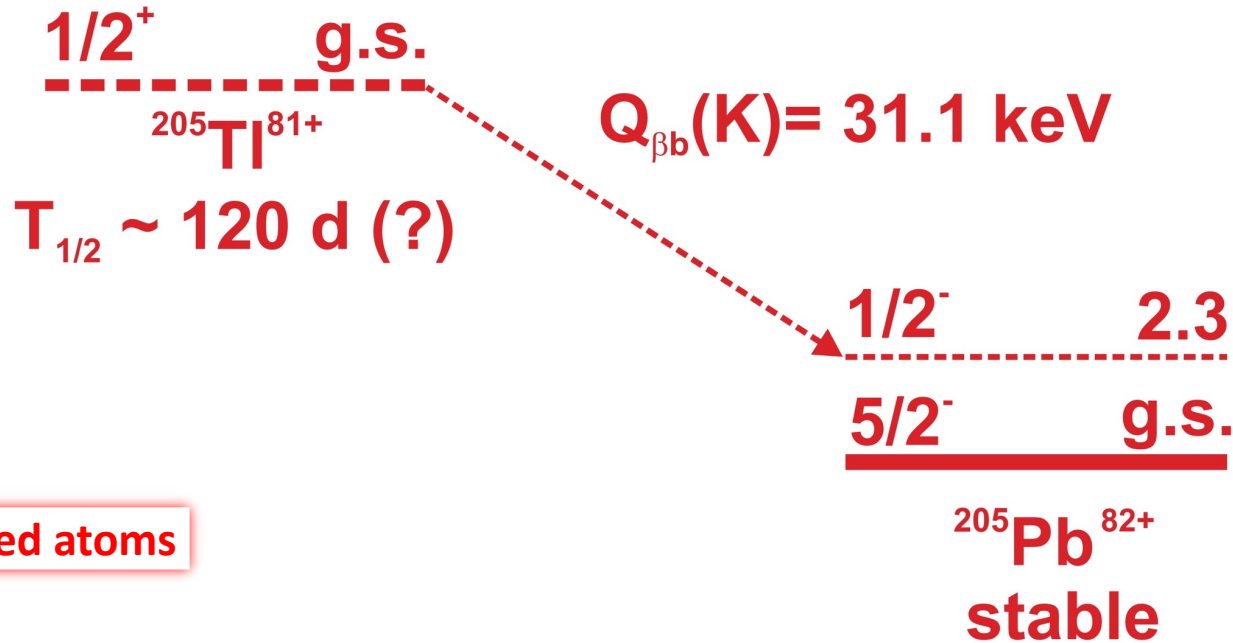


Bound-State Beta Decay of ^{205}TI Nuclei

Thermal excitation



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



Fully ionized atoms

Experiment during the COVID19

23.03 – 01.04 – 06.04



Enriched ^{206}Pb beam

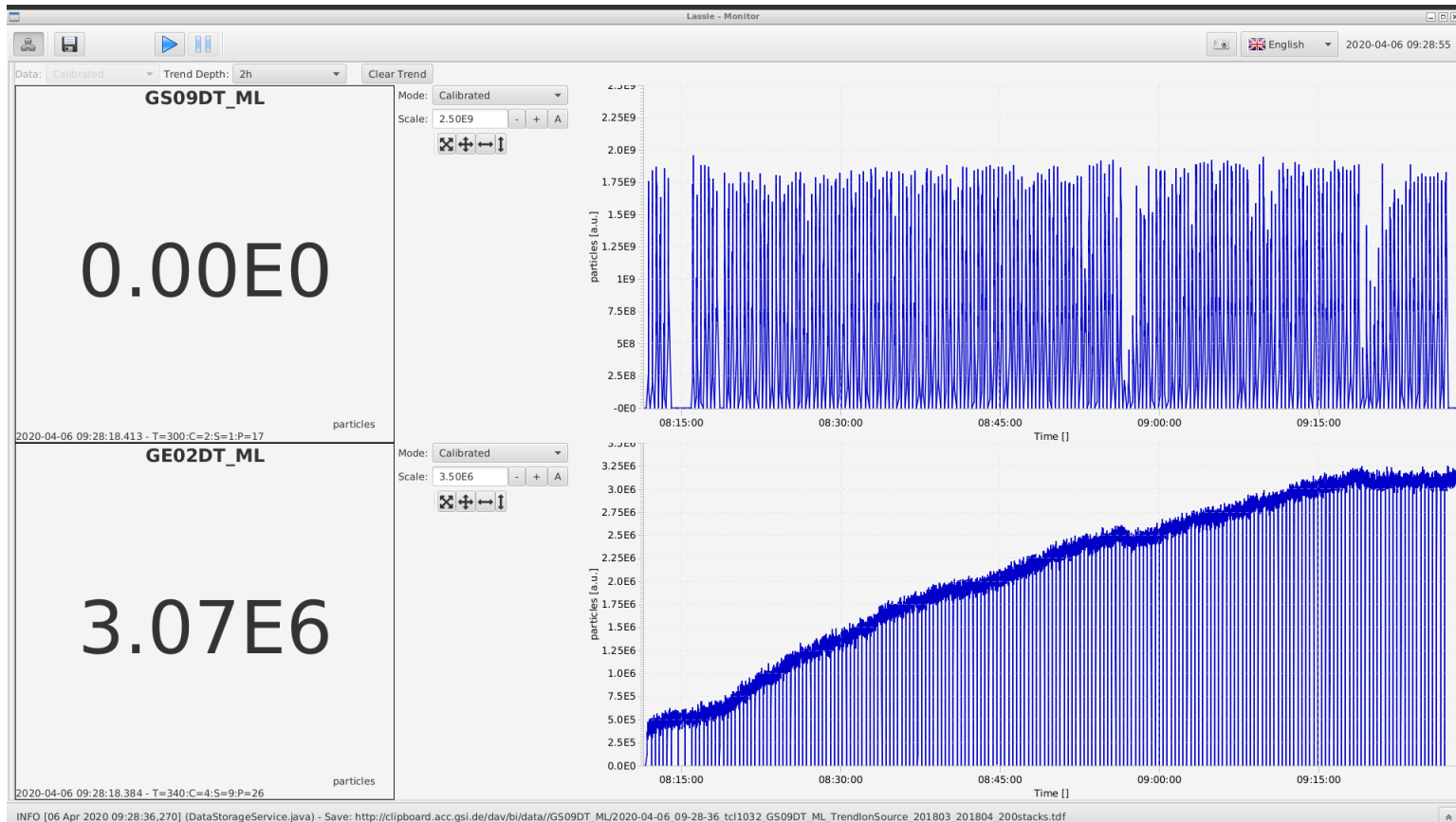
Separation from $^{205}\text{Pb}^{81+}$
 $I(^{205}\text{Tl}^{81+})/I(^{205}\text{Pb}^{81+}) = 1/1000$

Accumulation

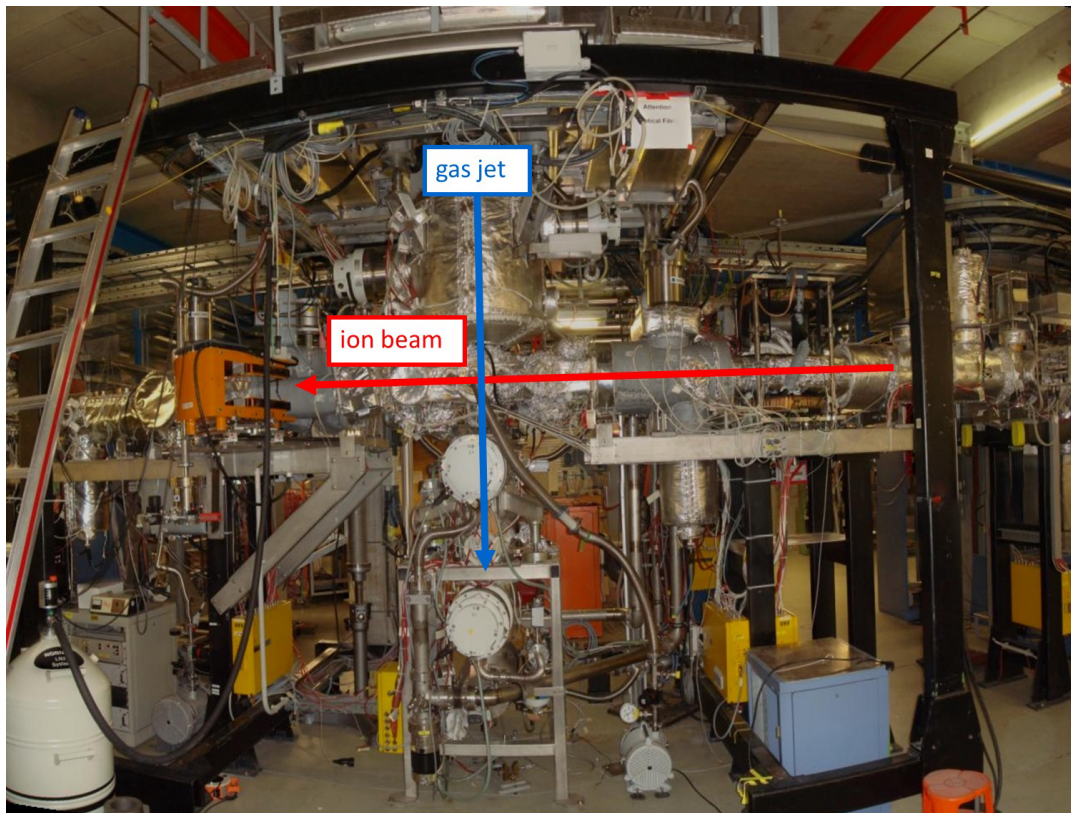
Breeding time of hours

Separation of decay
daughter ions from
parent ions
(50 keV @ 205 GeV)

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

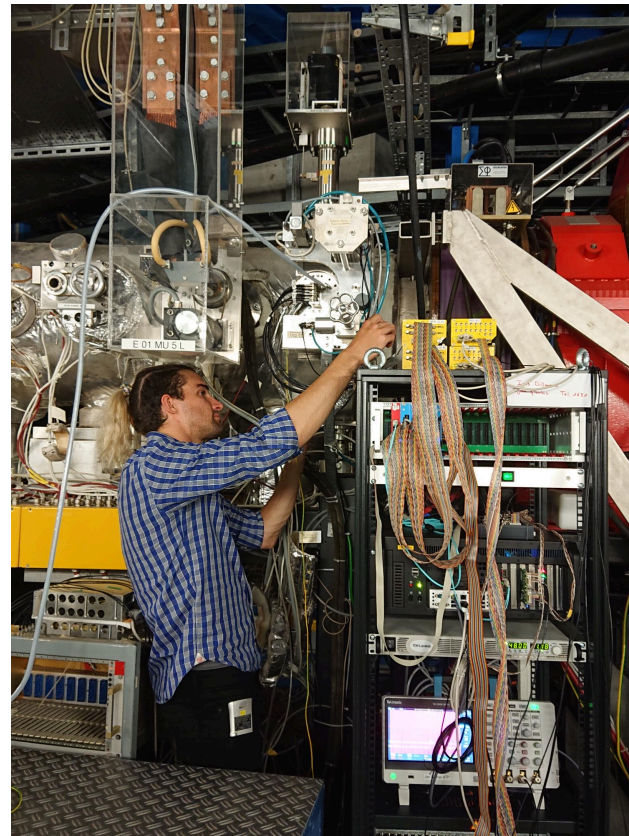


Internal gas-jet target

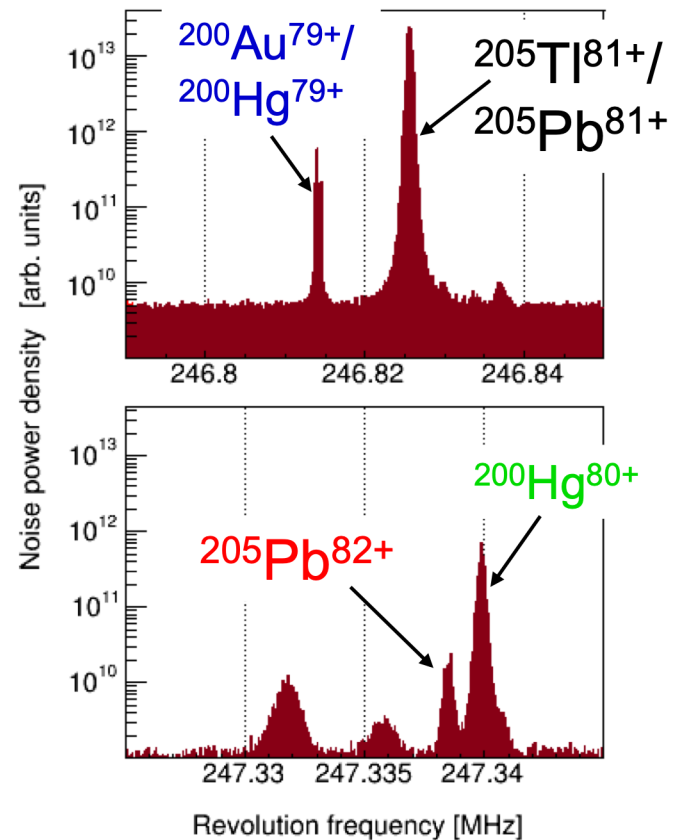
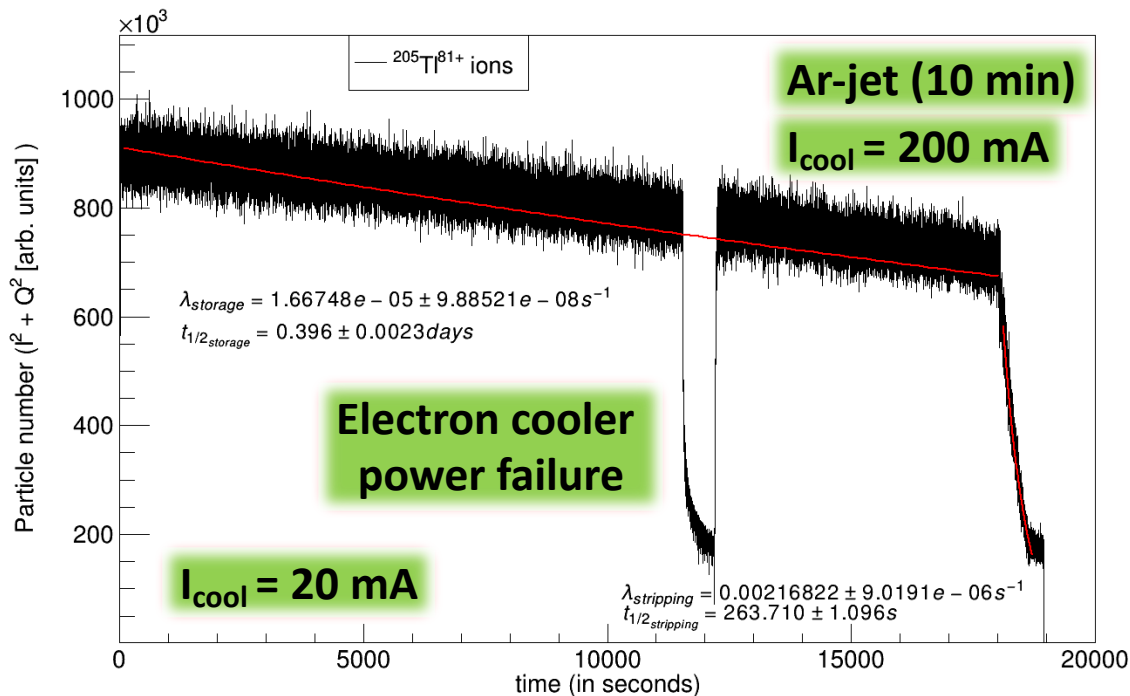


16

Particle detectors

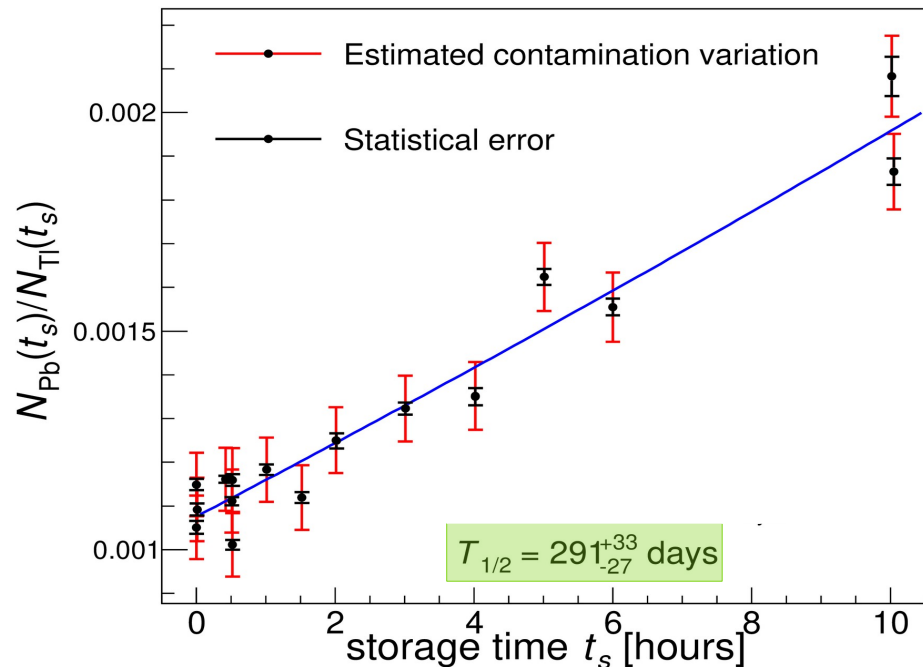


Typical Measurement (5 Hours)



Half-life of fully-ionized $^{205}\text{Tl}^{81+}$

Theory predictions



ATOMIC DATA AND NUCLEAR DATA TABLES **36**, 375–409 (1987)

BETA-DECAY RATES OF HIGHLY IONIZED HEAVY ATOMS IN STELLAR INTERIORS*

K. TAKAHASHI

University of California, Institute of Geophysics and Planetary Physics
Lawrence Livermore National Laboratory, Livermore, California 94550

and

K. YOKOI†

Kernforschungszentrum Karlsruhe GmbH, Institut für Kernphysik III
D-7500 Karlsruhe, Federal Republic of Germany

$T_{1/2} = 120$ d

PHYSICAL REVIEW C **104**, 024304 (2021)

Investigation of bound state β^- decay half-lives of bare atoms

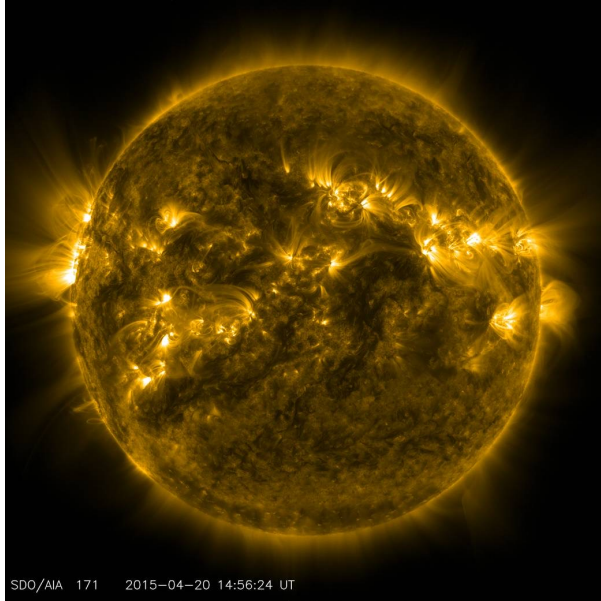
Shuo Liu, Chao Gao, and Chang Xu^{*}

School of Physics, Nanjing University, Nanjing 210093, China

(Received 9 June 2021; accepted 21 July 2021; published 2 August 2021)

$T_{1/2} = 52.4$ d

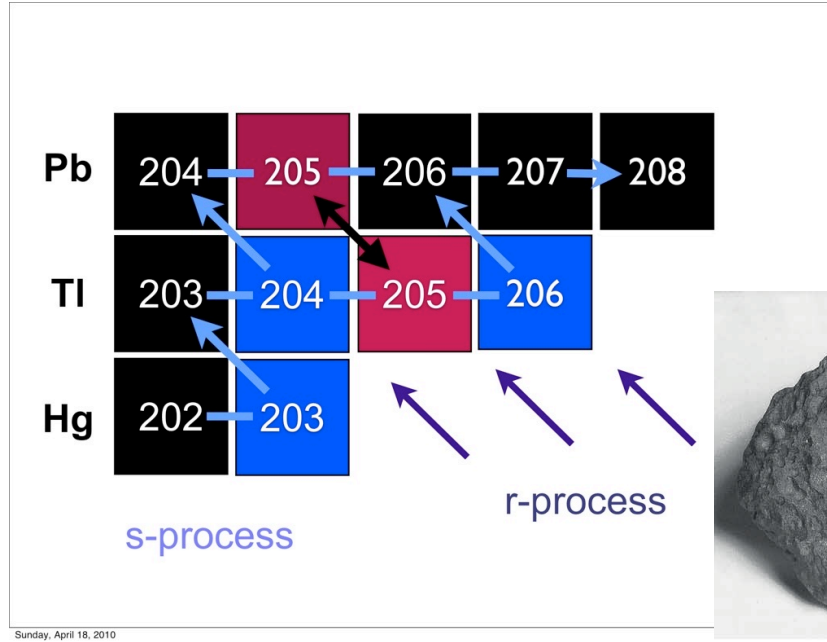
Bound-State Beta Decay of ^{205}Tl Nuclei



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NASA/SDO



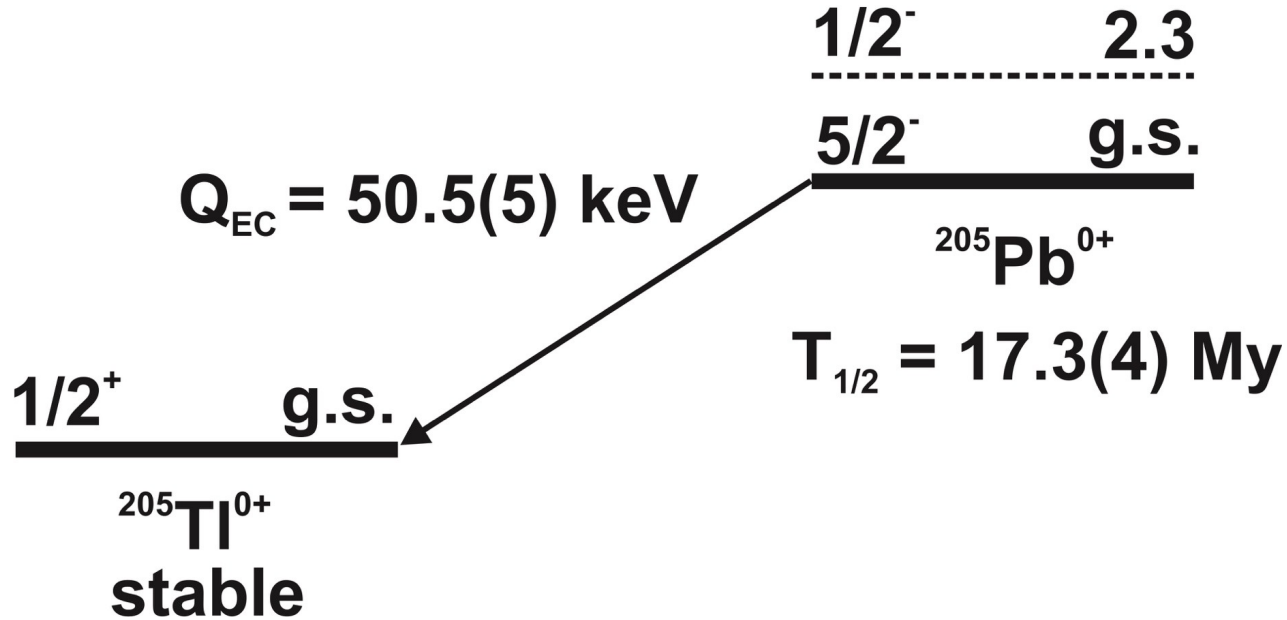
A
4 cm
D'Orbigny

Termination of s-process nucleosynthesis

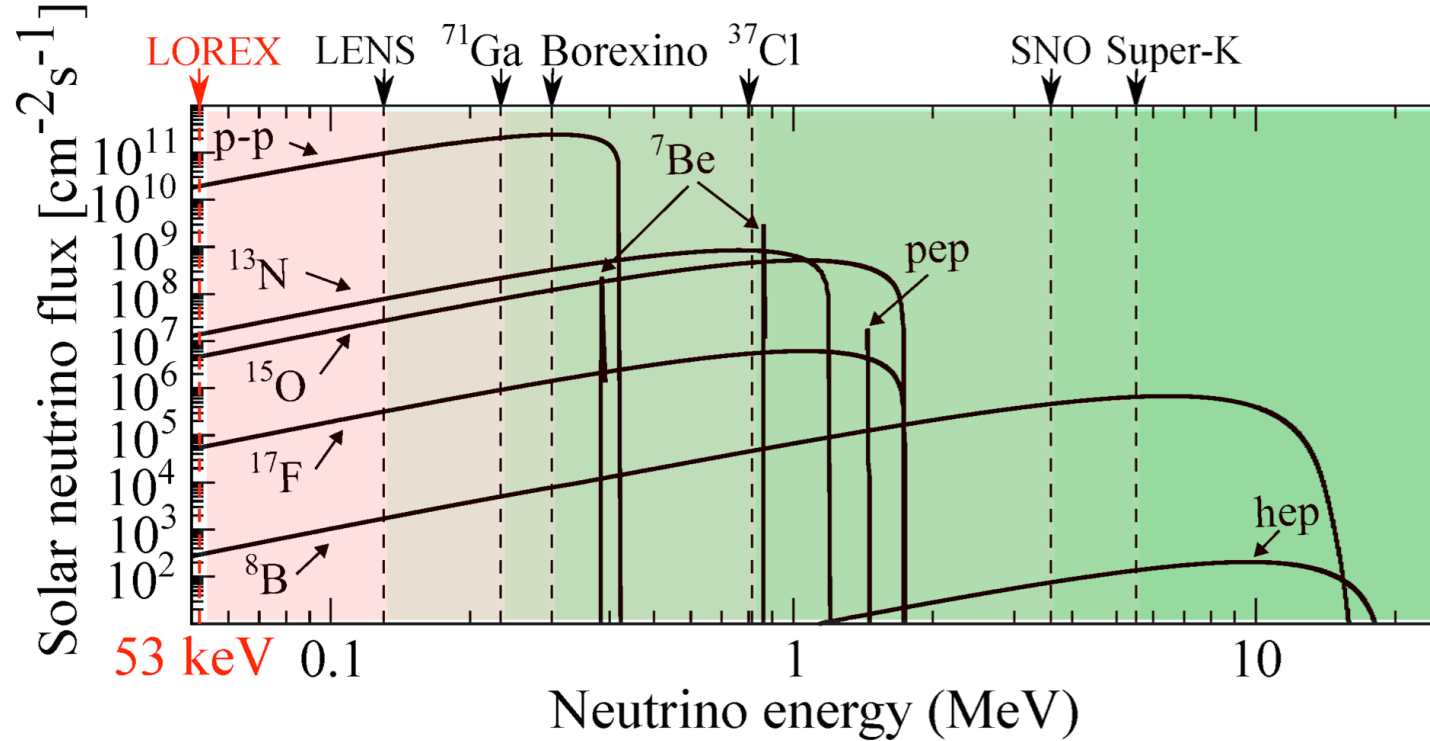
Time needed for the Solar system to build

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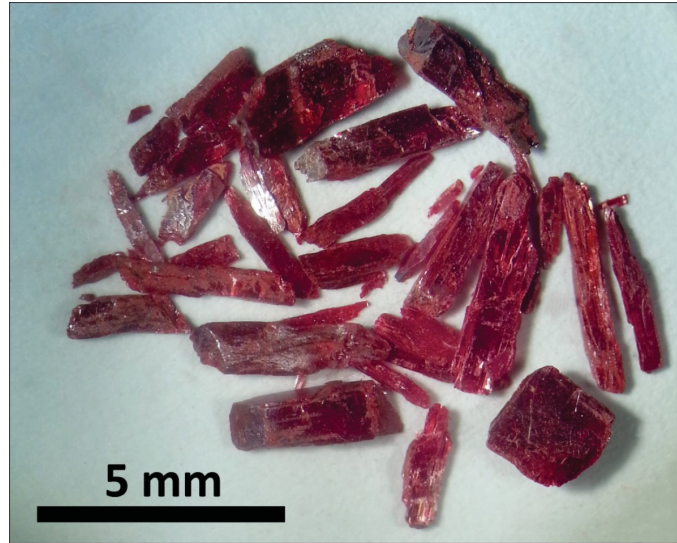
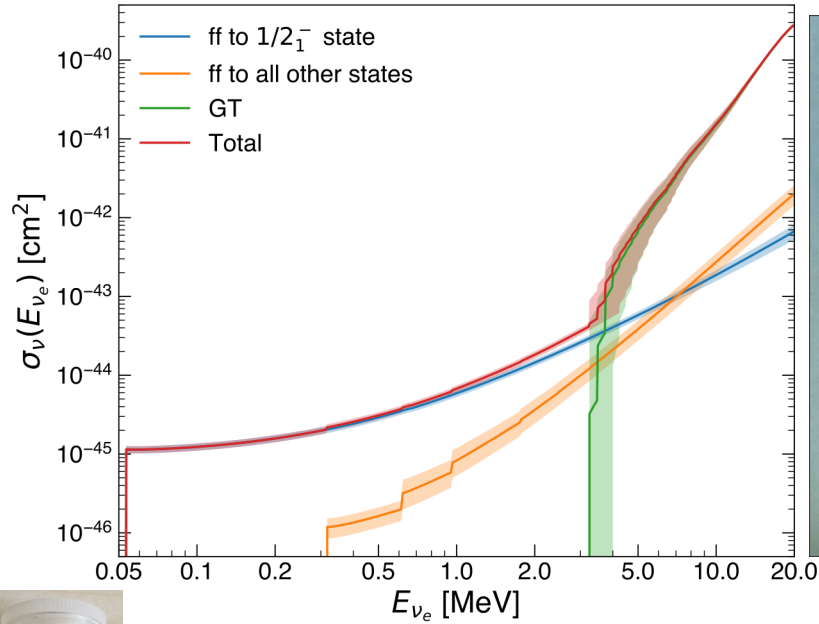
Bound-State Beta Decay of ^{205}Tl Nuclei



Solar Neutrino Flux

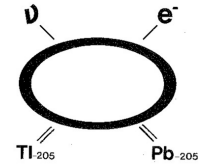


Solar neutrino capture probabilities



Lorandite - TlAsS_2

Age of lorandite
 $T = 4.31(2)$ My



LOREX Project

LOREX – 146 SNU (before)
22(7) ${}^{205}\text{Pb}$ atoms/g

92(10) SNU (now)
14(4) ${}^{205}\text{Pb}$ atoms/g

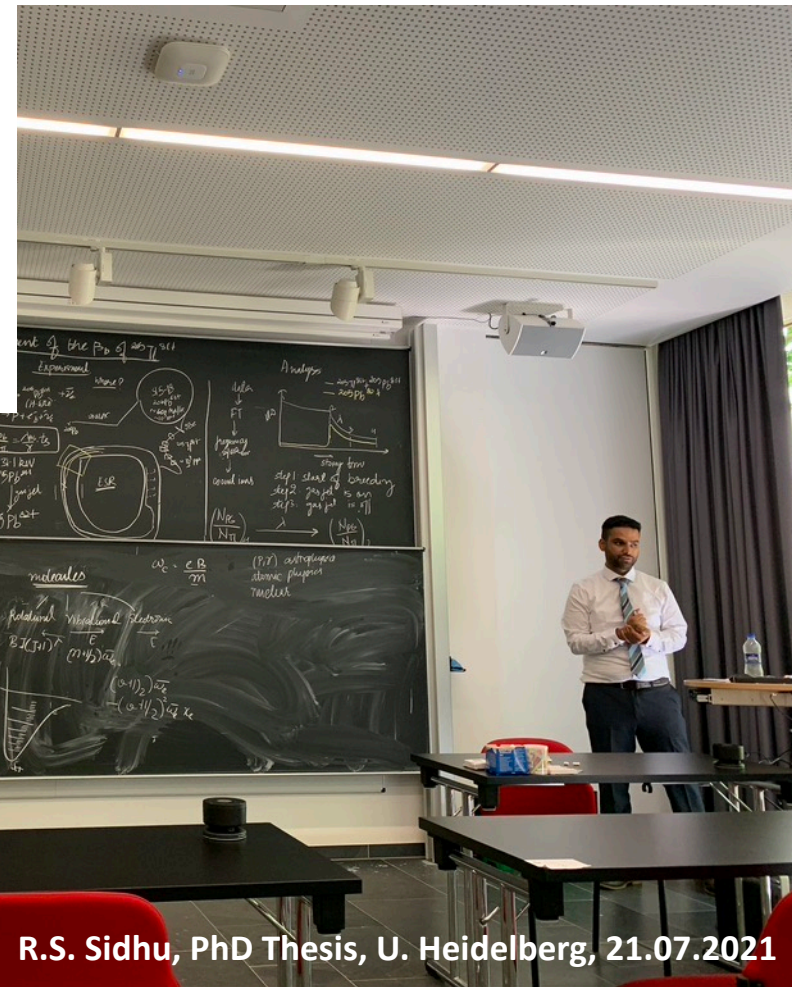
About 1 kg of pure lorandite is stored in Felsenkeller (HZDR)



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

Bound-State Beta Decay of $^{205}\text{Tl}^{81+}$ Ions and the LOREX Project

R. S. Sidhu^{1,2,3,†} G. Leckenby^{4,5} R. J. Chen^{2,3,6,‡} R. Mancino^{7,2,8,§} T. Neff^{9,2} Yu. A. Litvinov^{9,2,8}
 G. Martínez-Pinedo^{2,7,8} G. Amthauer⁹ M. Bai² K. Blaum³ B. Boev^{9,10} F. Bosch^{2,*} C. Brandau^{9,2}
 V. Cvetković¹¹ T. Dickel^{9,2,12} I. Dillmann^{9,2} D. Dmytriiev^{9,2} T. Faestermann^{9,14} O. Forstner^{9,2} B. Franczak²
 H. Geissel^{2,12,*} R. Gernhäuser¹⁴ J. Glorius^{9,2} C. J. Griffin^{9,4} A. Gumberidze^{9,2} E. Haettner^{9,2}
 P.-M. Hillenbrand^{9,2,15} P. Kienle^{14,*} W. Korten^{9,16} Ch. Kozhuharov^{9,2} N. Kuzminchuk² K. Langanke²
 S. Litvinov^{9,2} E. Menz^{9,2} T. Morgenroth² C. Nociforo² F. Nolden^{2,8} M. K. Pavićević⁹ N. Petridis^{9,2} U. Popp²
 S. Purushothaman^{9,2} R. Reifarth^{9,17} M. S. Sanjari^{9,2} C. Scheidenberger^{2,12,18} U. Spillmann^{9,2} M. Steck²
 Th. Stöhlker^{9,2} Y. K. Tanaka^{9,19} M. Trassinelli^{9,20} S. Trotsenko² L. Varga^{14,2} M. Wang⁶ H. Weick^{9,2} P. J. Woods¹
 T. Yamaguchi^{9,21} Y. H. Zhang⁶ J. Zhao^{9,2} and K. Zuber^{9,22}

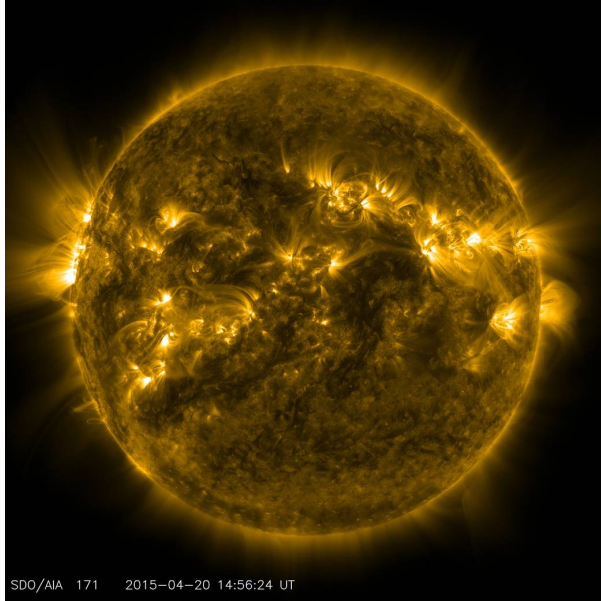


R.S. Sidhu, PhD Thesis, U. Heidelberg, 21.07.2021

**GIERSCHE Award
IoP Award**

Now, permanent faculty position at Uni Surrey

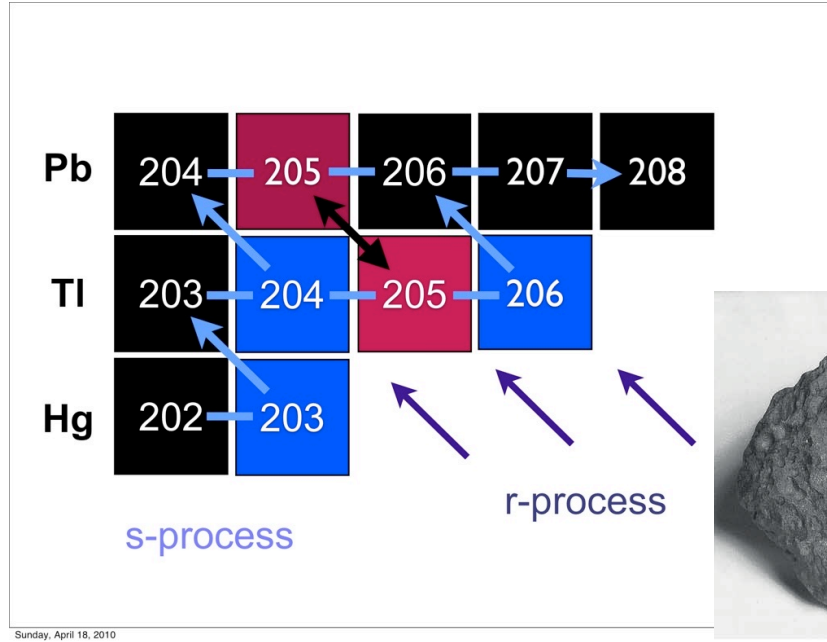
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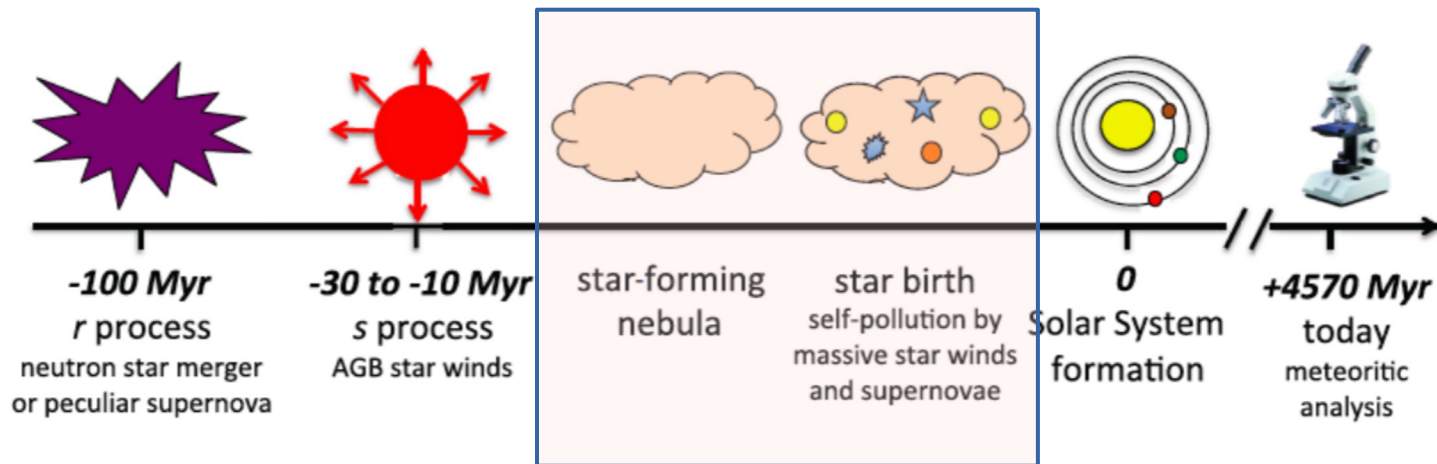


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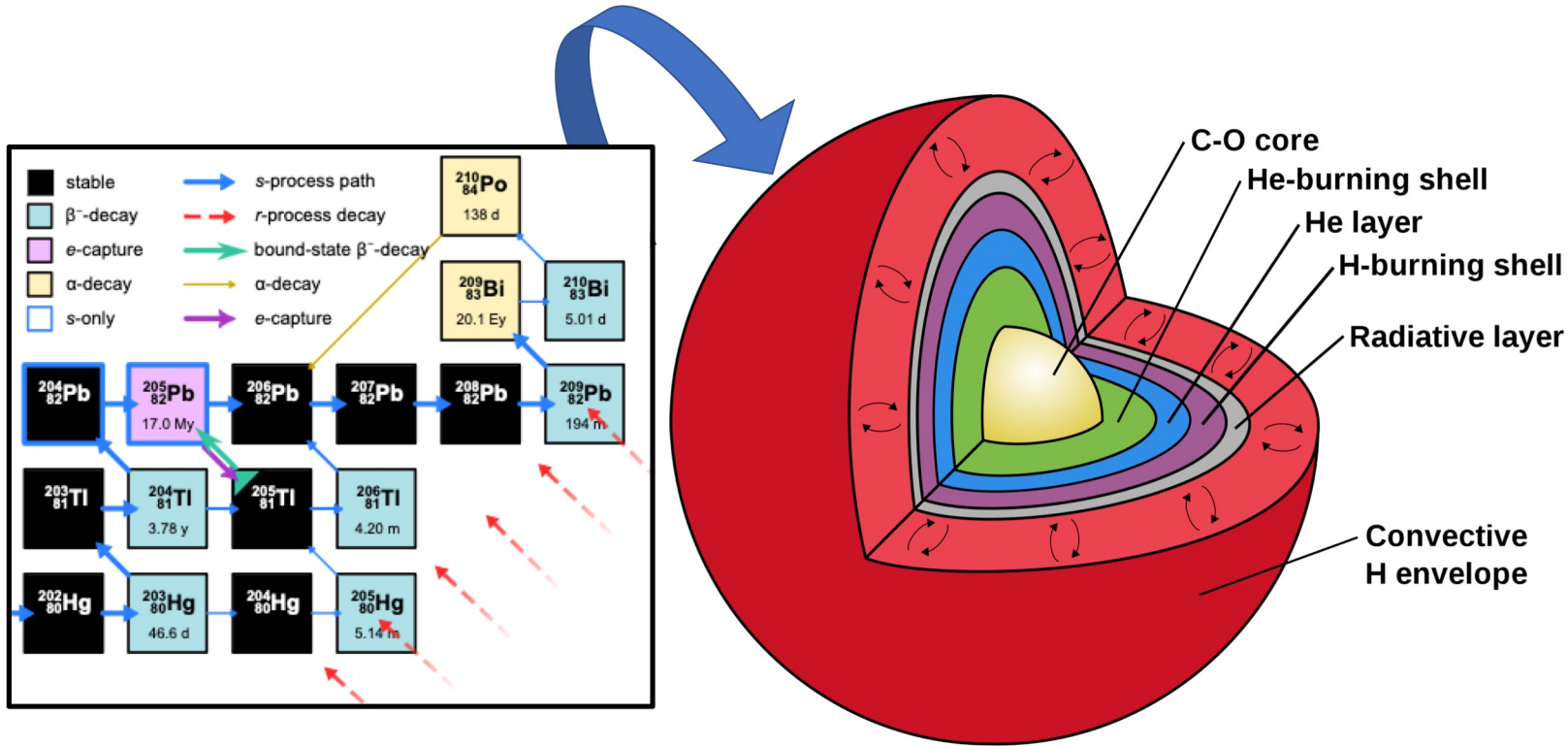
Cosmochronometers



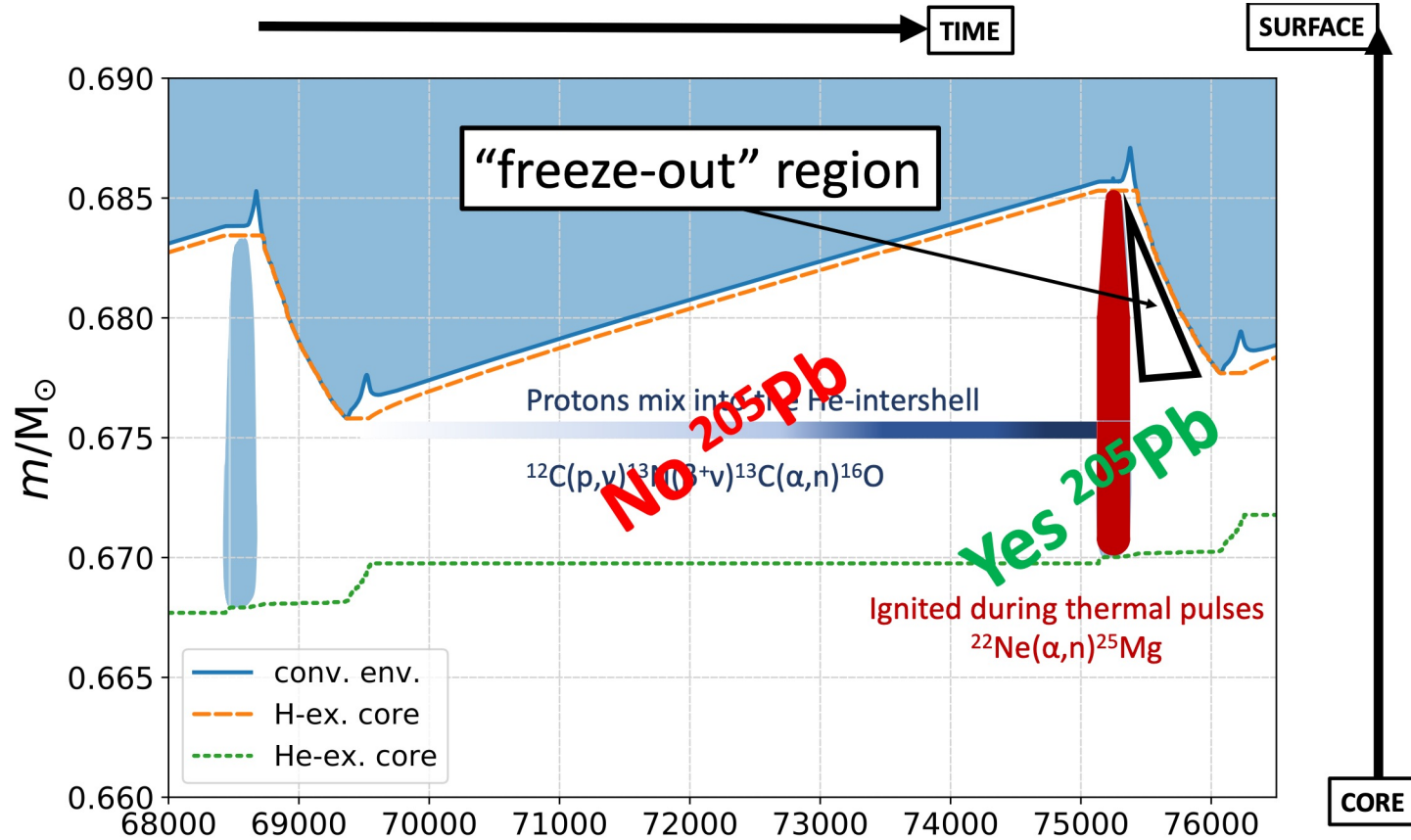
18 measurable short-lived radionuclides (SLR) ($0.1 \text{ My} < T_{1/2} < 100 \text{ My}$)
 4 are produced by the *s*-process: ^{107}Pd , ^{135}Cs , ^{182}Hf , ^{205}Pb

^{205}Pb is the only purely *s*-process SLR alive in the early solar system

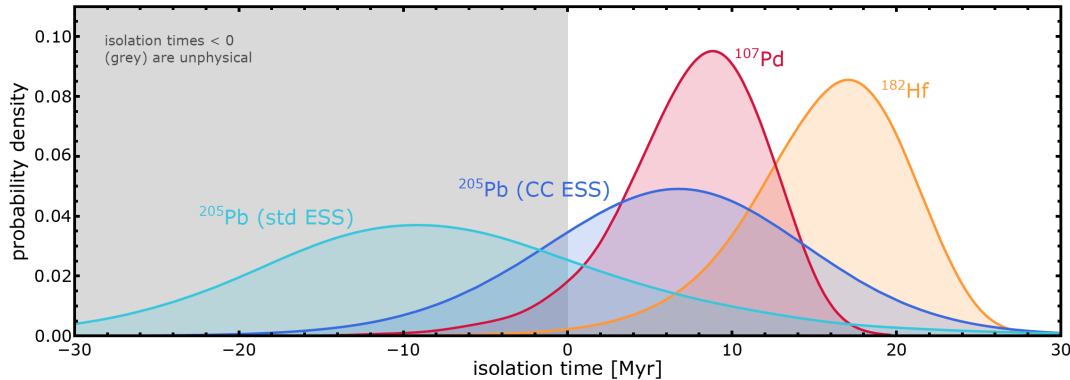
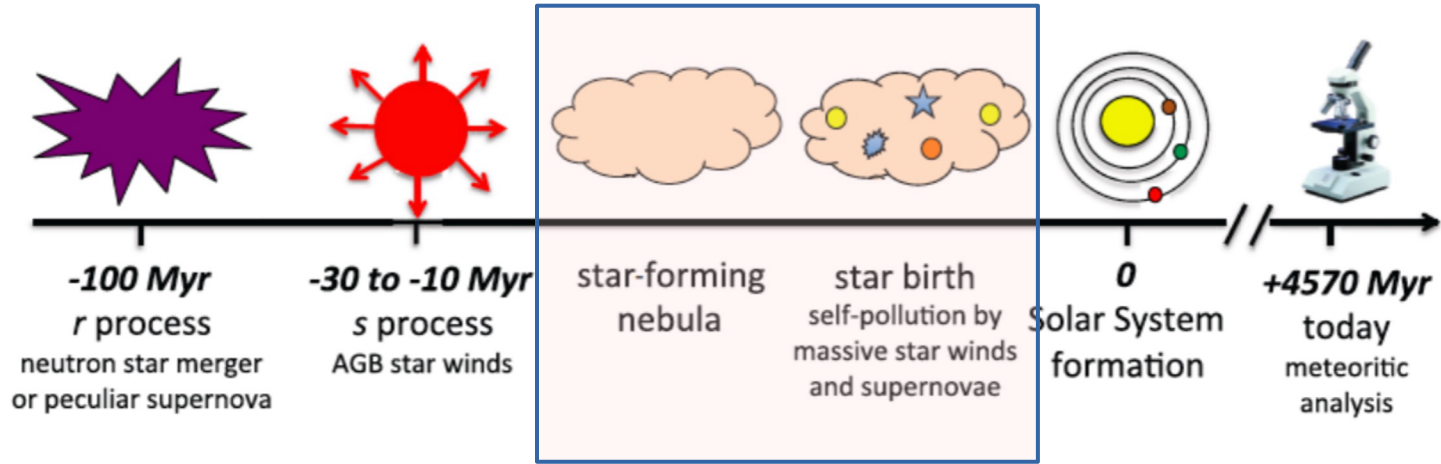
Production of ^{205}Pb in AGB stars



Production of ^{205}Pb in AGB stars



Decoupling of the solar system from interstellar medium



High-temperature ^{205}Tl decay clarifies ^{205}Pb dating in early Solar System

<https://doi.org/10.1038/s41586-024-08130-4>

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Guy Leckenby^{1,2,5}, Ragandeep Singh Sidhu^{3,4,5}, Rui Jiu Chen^{3,5,6,5}, Riccardo Mancino^{3,7,36}, Balázs Szányi^{8,9,10}, Mei Bai³, Umberto Battino^{11,12}, Klaus Blaum⁵, Carsten Brandau^{3,13}, Sergio Cristallo^{14,15}, Timo Dickel^{3,16}, Iris Dillmann^{1,17}, Dmytro Dmytriiev^{3,18}, Thomas Faester¹⁹, Oliver Forstner^{3,20}, Bernhard Franczak³, Hans Geisse^{3,16}, Roman Gernhäuser¹⁹, Jan Glorius³, Chris Griffin¹, Alexandre Gumberidze³, Emma Haettner³, Pierre-Michel Hillenbrand^{3,13}, Amanda Karakas^{21,22,23}, Tejpreet Kaur²⁴, Wolfram Korten²⁵, Christoph Kozhuharov³, Natalia Kuzminchuk³, Karlheinz Langanke³, Sergey Litvinov³, Yuri A. Litvinov^{3,26,5}, Maria Lugaro^{9,10,21,27,5}, Gabriel Martínez-Pinedo^{3,7,26}, Esther Menz³, Bradley Meyer²⁸, Tino Morgenroth³, Thomas Neff³, Chiara Nociforo³, Nikolaos Petridis³, Marco Pignatarì^{9,10,11}, Ulrich Popp³, Sivaji Purushothaman³, René Reifarh^{29,30}, Shahab Sanjari^{3,31}, Christoph Scheidenberger^{3,16,32}, Uwe Spillmann³, Markus Steck³, Thomas Stöhlker^{3,20}, Yoshiki K. Tanaka³³, Martino Trassinelli³⁴, Sergiy Trotsenko³, László Varga^{3,37}, Diego Vescovi^{14,15,29}, Meng Wang⁶, Helmut Weick³, Andrés Yagüe López³⁰, Takayuki Yamaguchi³⁵, Yuhu Zhang⁶ & Jianwei Zhao³

UBC PhD Award
GENCO Young Researcher Prize
SPARC PhD Prize
Gordon Conference Best Poster
DPG SMUK Prize

G. Leckenby, PhD Thesis, University of British Columbia, 2024

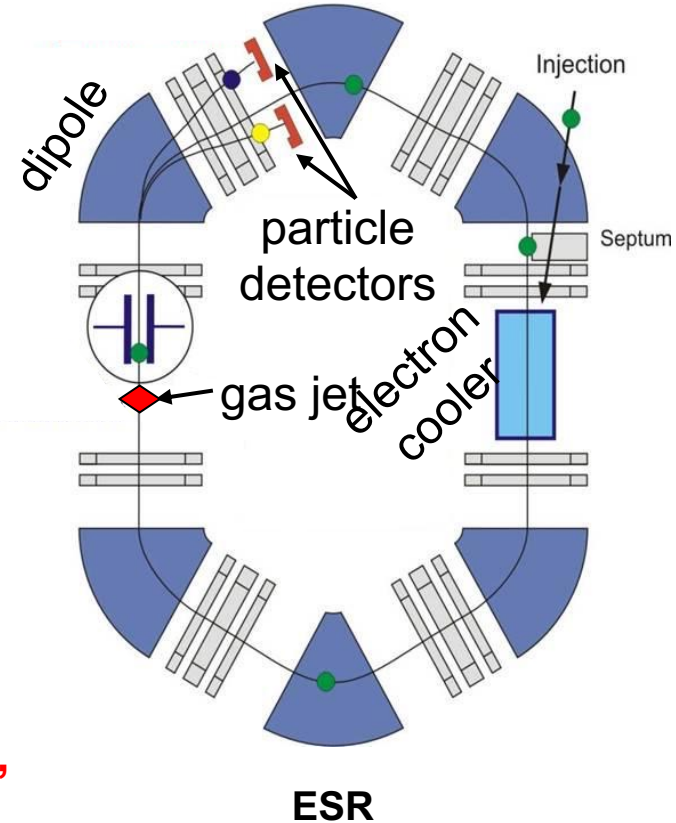
Now, MSC fellowship postdoctoral researcher at JCLAB in Bordeaux



Danielle Adams for TRIUMF

Proton-Capture Reactions in the ESR

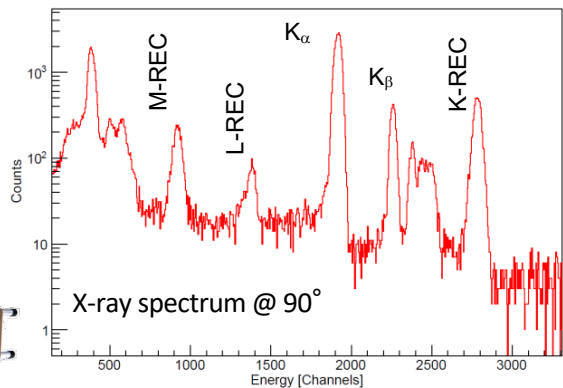
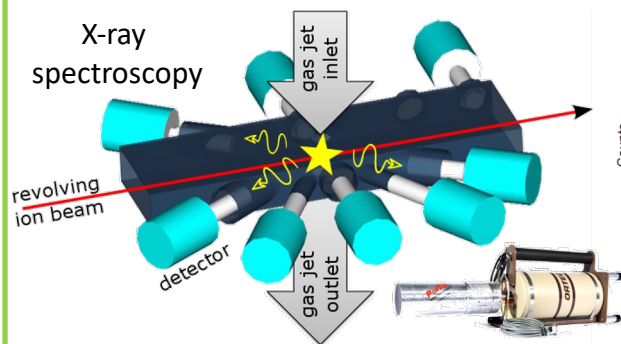
- refill ring periodically
- injection of ions @ >100 MeV/u
 - ✓ **fully stripped ions**
 - deceleration & cooling of the beam
 - ✓ **$E = 3 - 10$ MeV/u**
 - activate internal **hydrogen target**
 - ✓ proton & electron capture reactions
 - ✓ separated by dipole
 - ✓ particle detectors on...
 - ... inner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



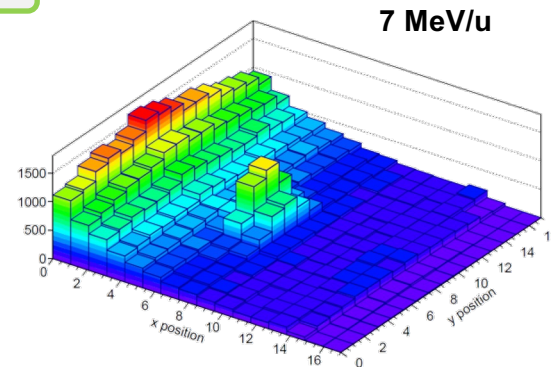
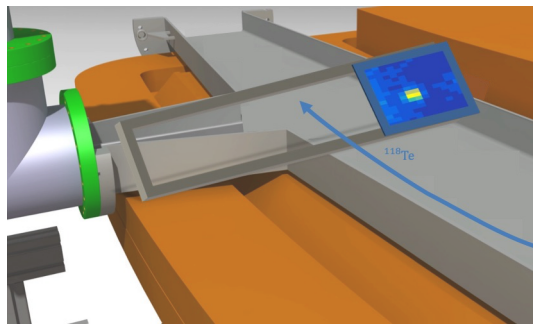
Jan Glorius: “A recycling recoil separator”

Proton-Induced Reactions in the Experimental Storage Ring

radiative e^- capture rate [REC]

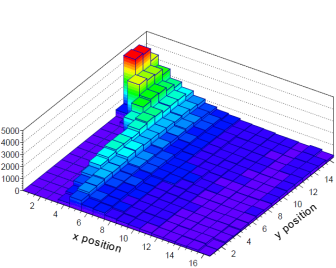


(p,g) and (p,n) reaction products

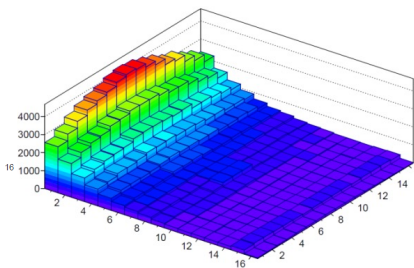


Towards background free measurement

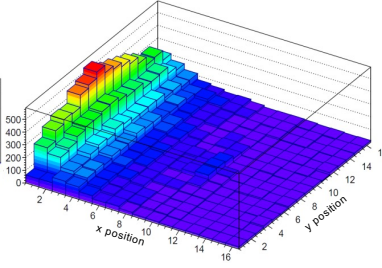
5.5 MeV/u



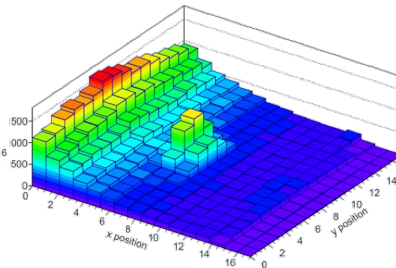
6 MeV/u



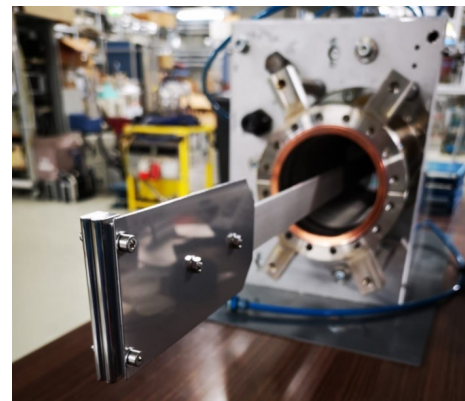
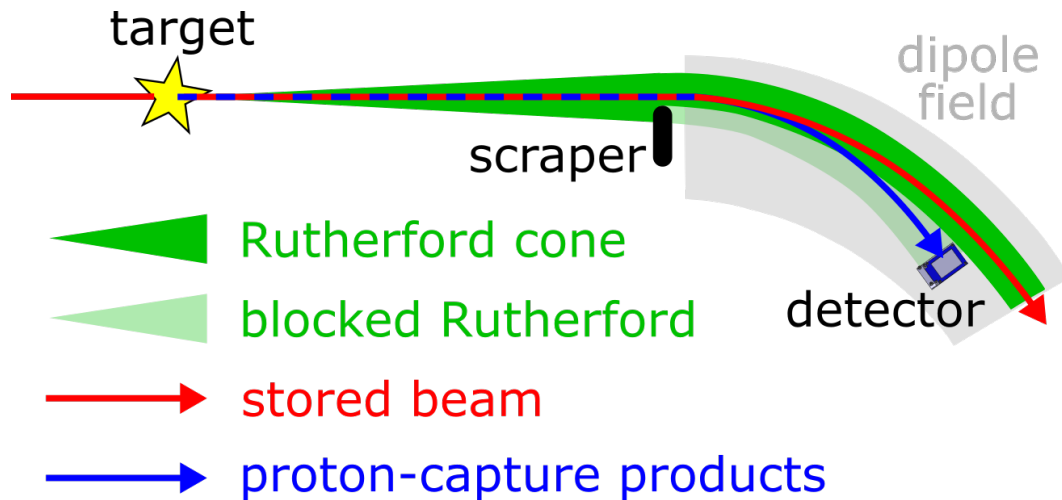
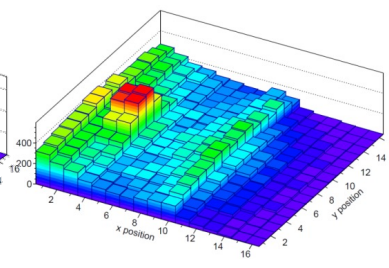
6.7 MeV/u



7 MeV/u



8 MeV/u



Proton-Induced Reactions in the Experimental Storage Ring

ERASE vs no-ERASE: $^{124}\text{Xe}(p,x)$

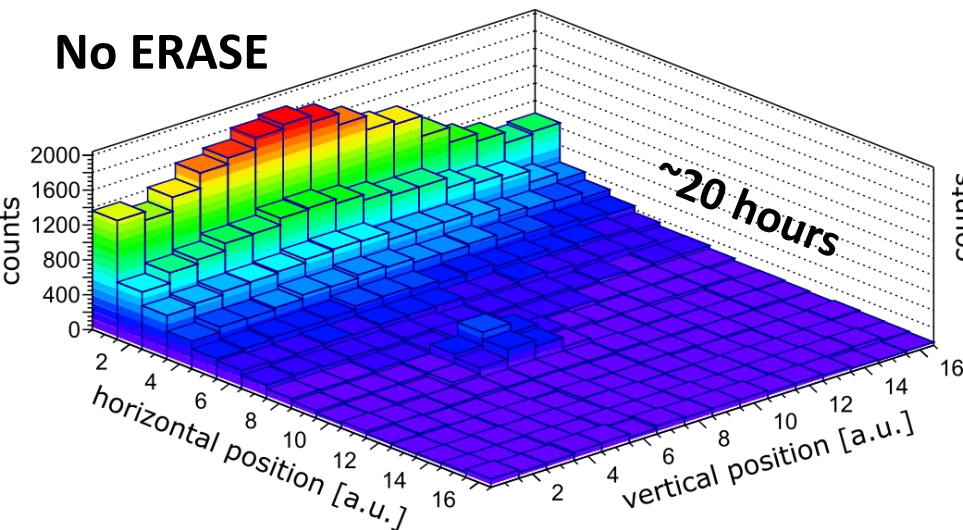
$^{124}\text{Xe}(p,\gamma)$

- 10^7 bare ions stored
- cooled and decelerated to 7 MeV/u

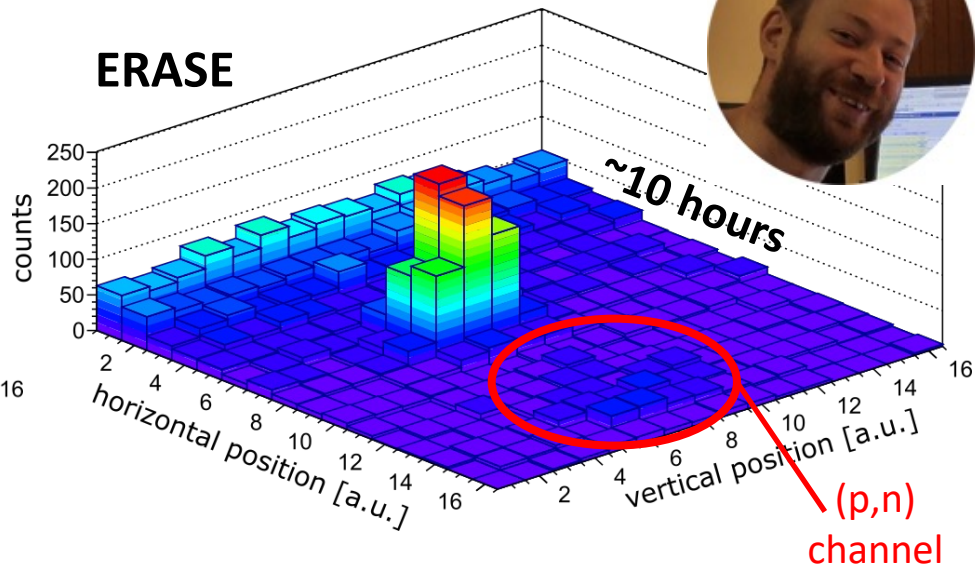
nearly background-free measurement
maximized experimental sensitivity

**(p,n) reaction channel measured
simultaneously**

No ERASE

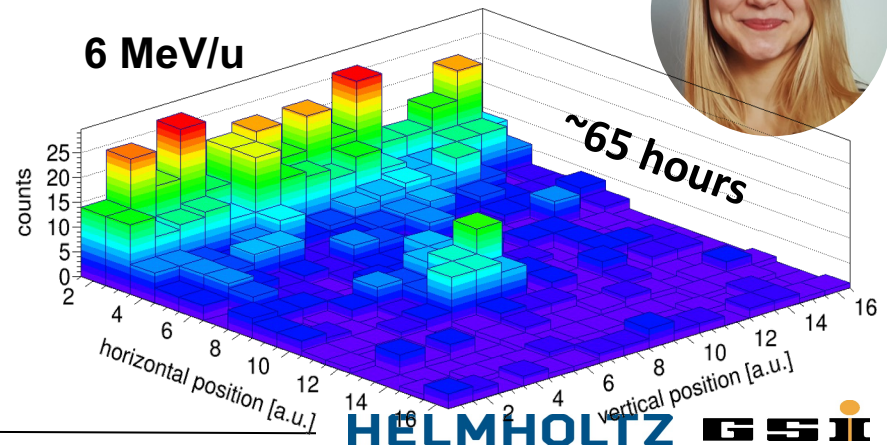
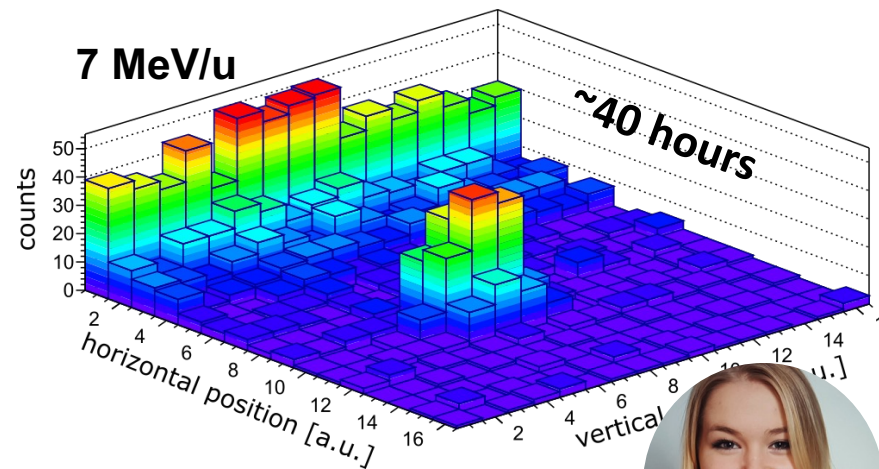
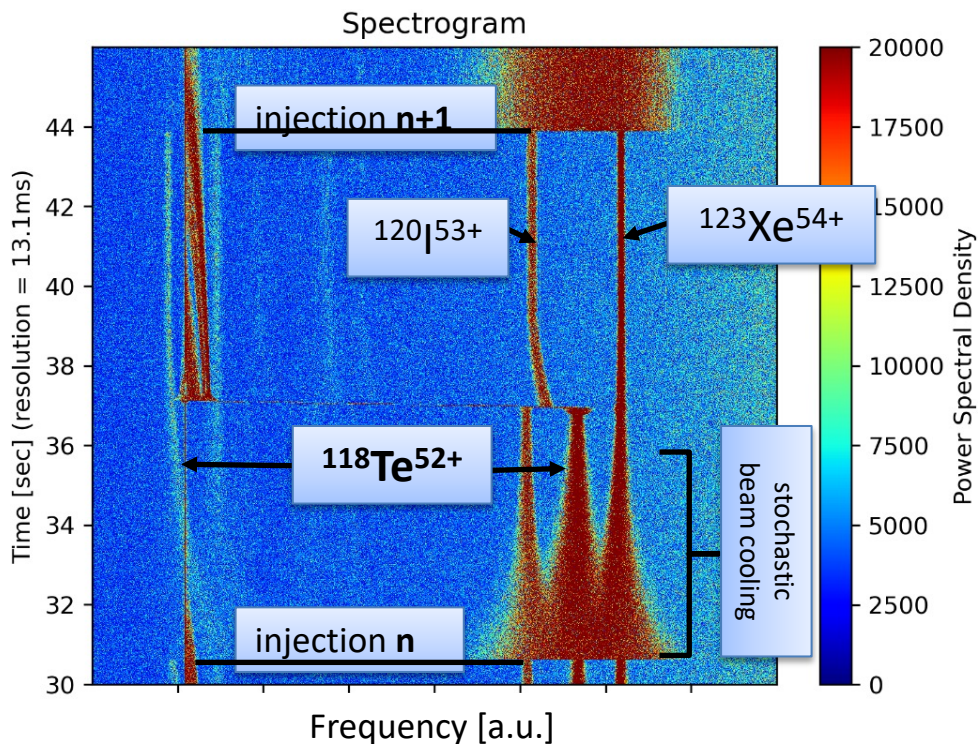


ERASE

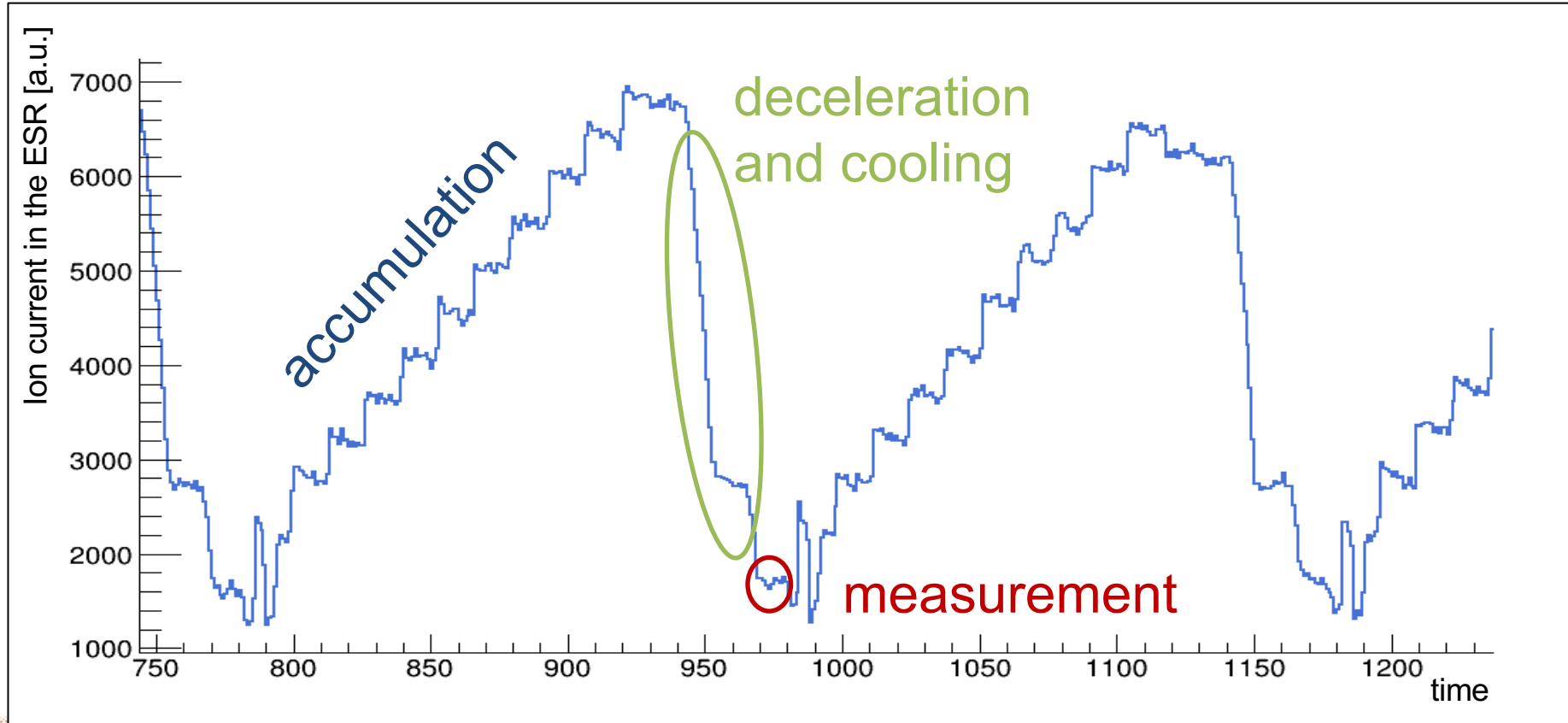


Proton-Induced Reactions in the Experimental Storage Ring

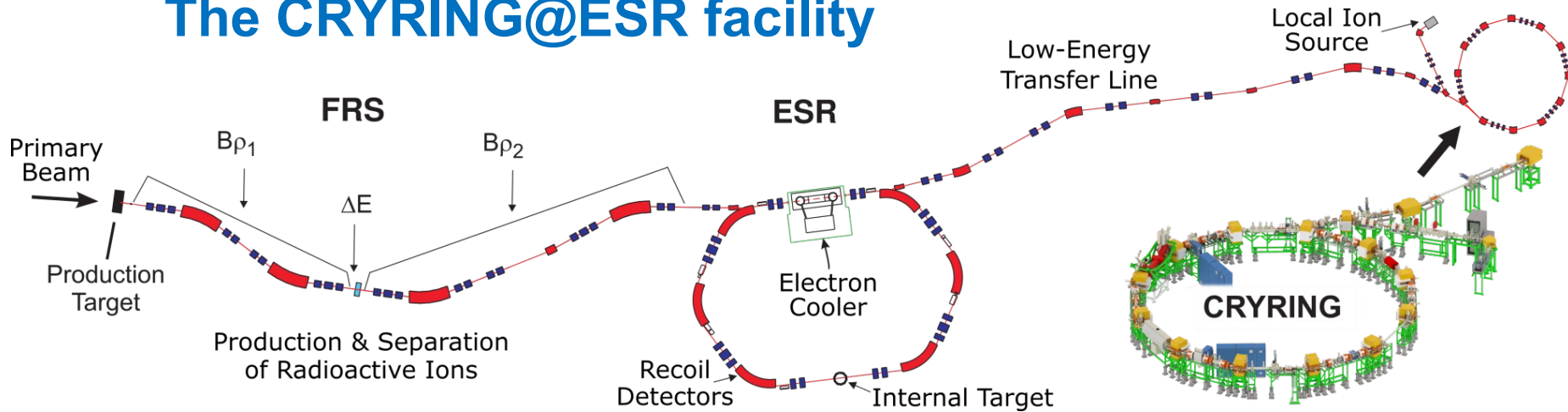
First study on radioactive ion beam



Proton capture on radioactive ^{118}Te



The CRYRING@ESR facility



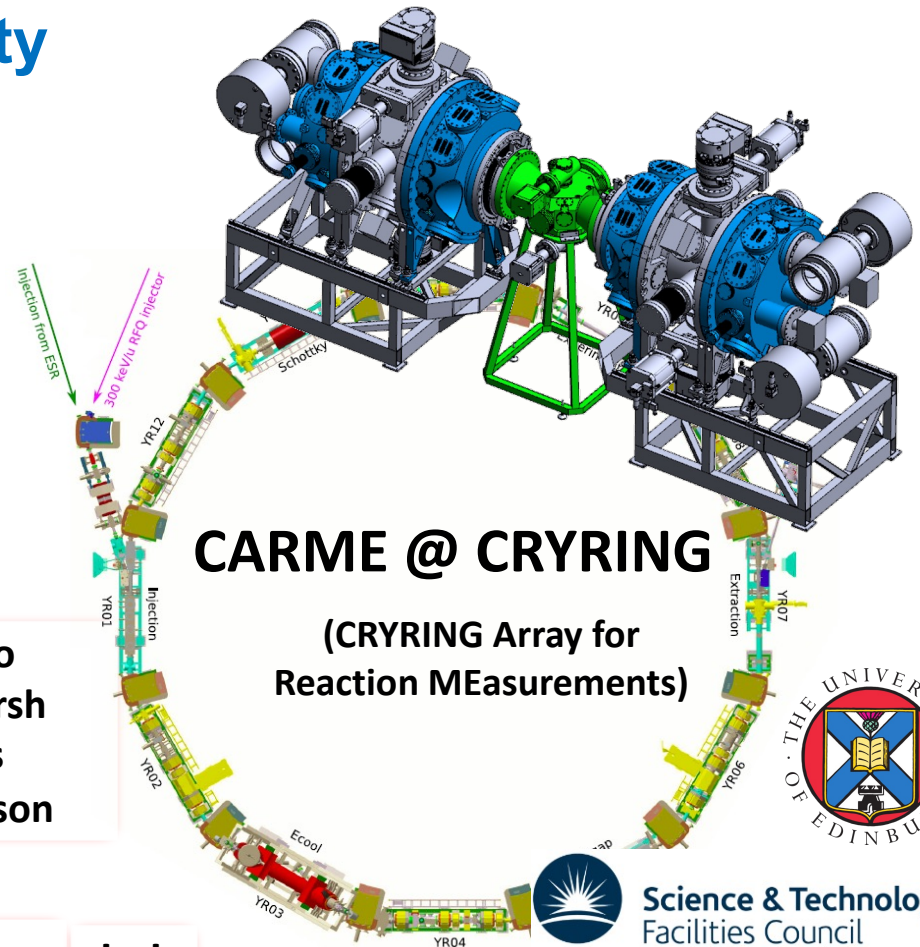
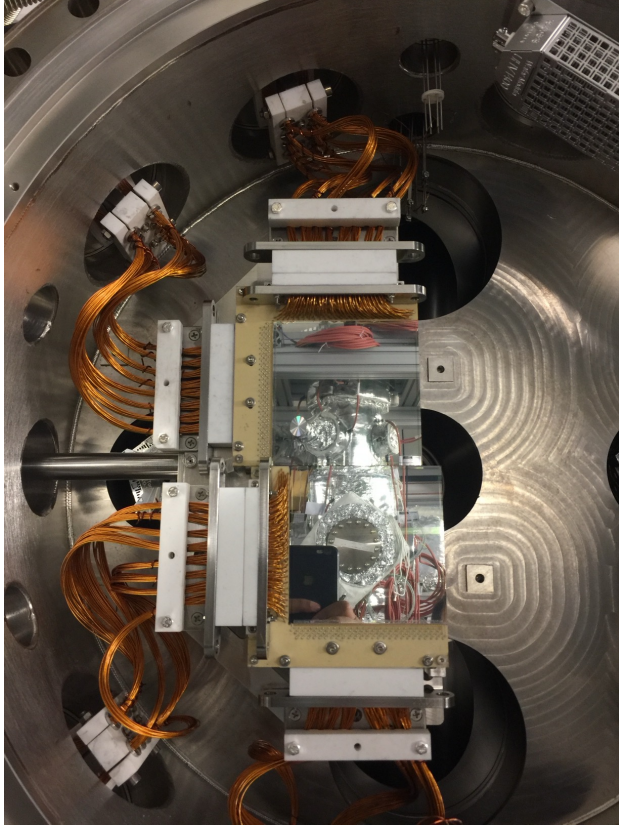
CRYRING (transported from Stockholm University)

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



M. Lestinsky, GSI, Darmstadt

The CRYRING@ESR facility



Carlo Bruno
Jordan Marsh
Phil Woods
Tom Davinson

${}^7\text{Li}+p$

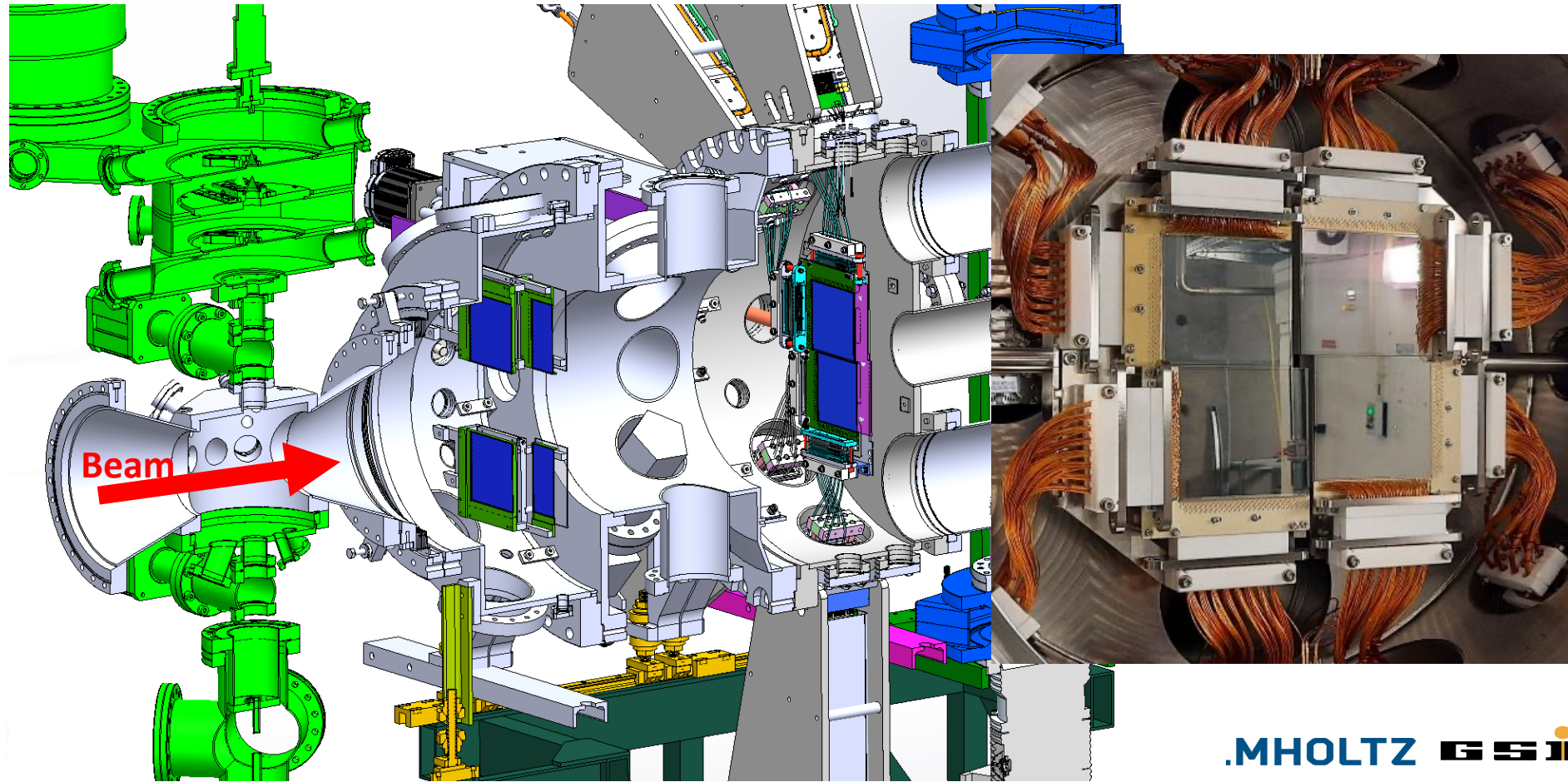
$d+d$



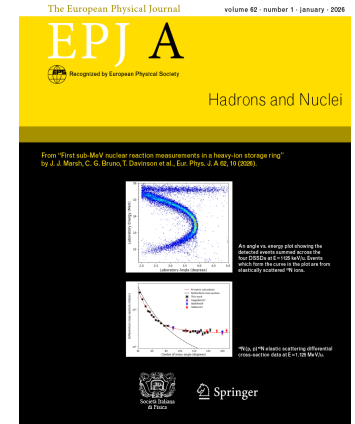
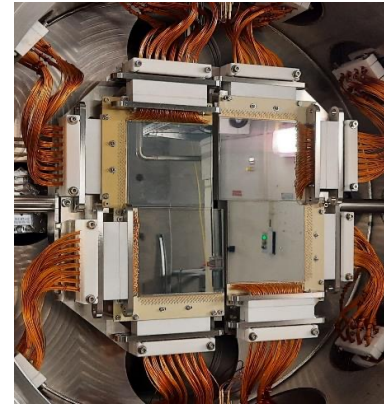
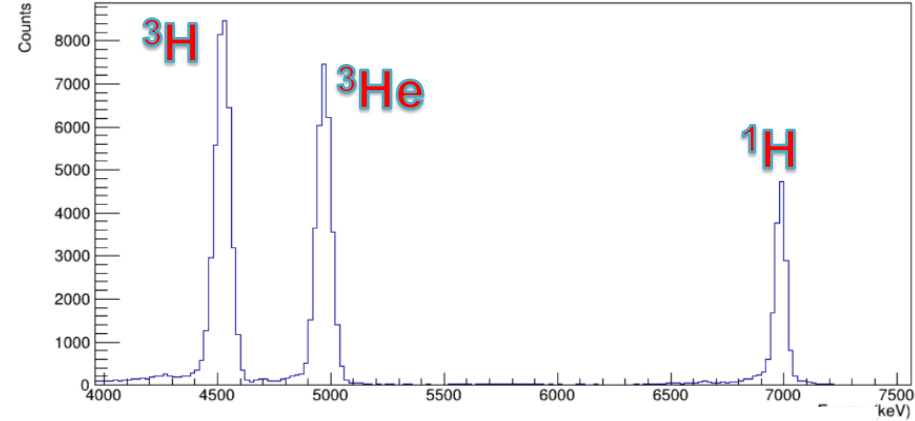
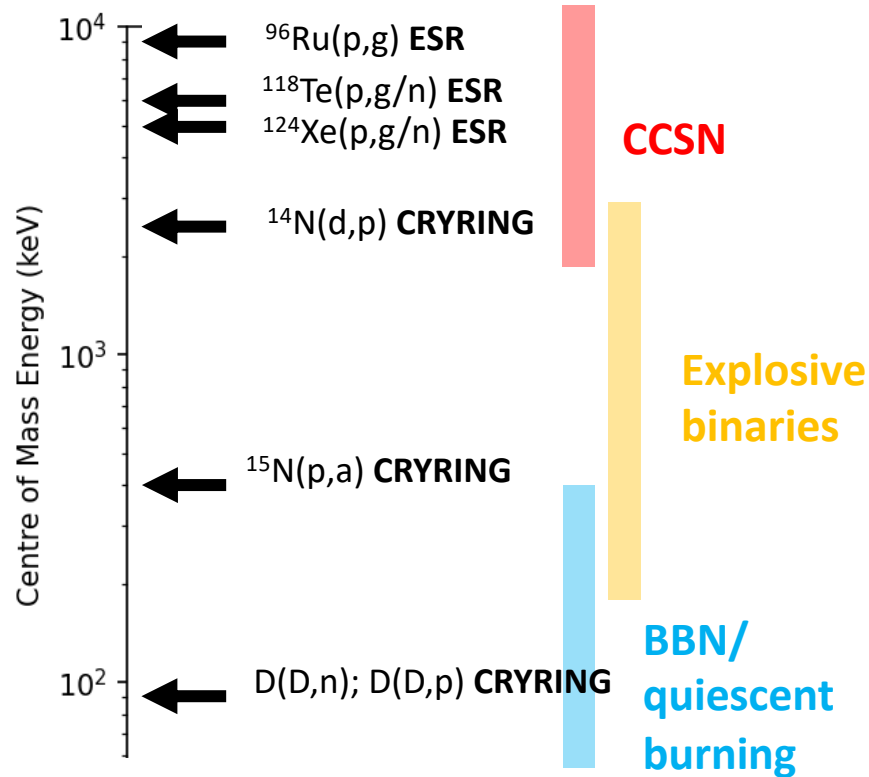
Science & Technology
Facilities Council

HELMHOLTZ 

CARME array



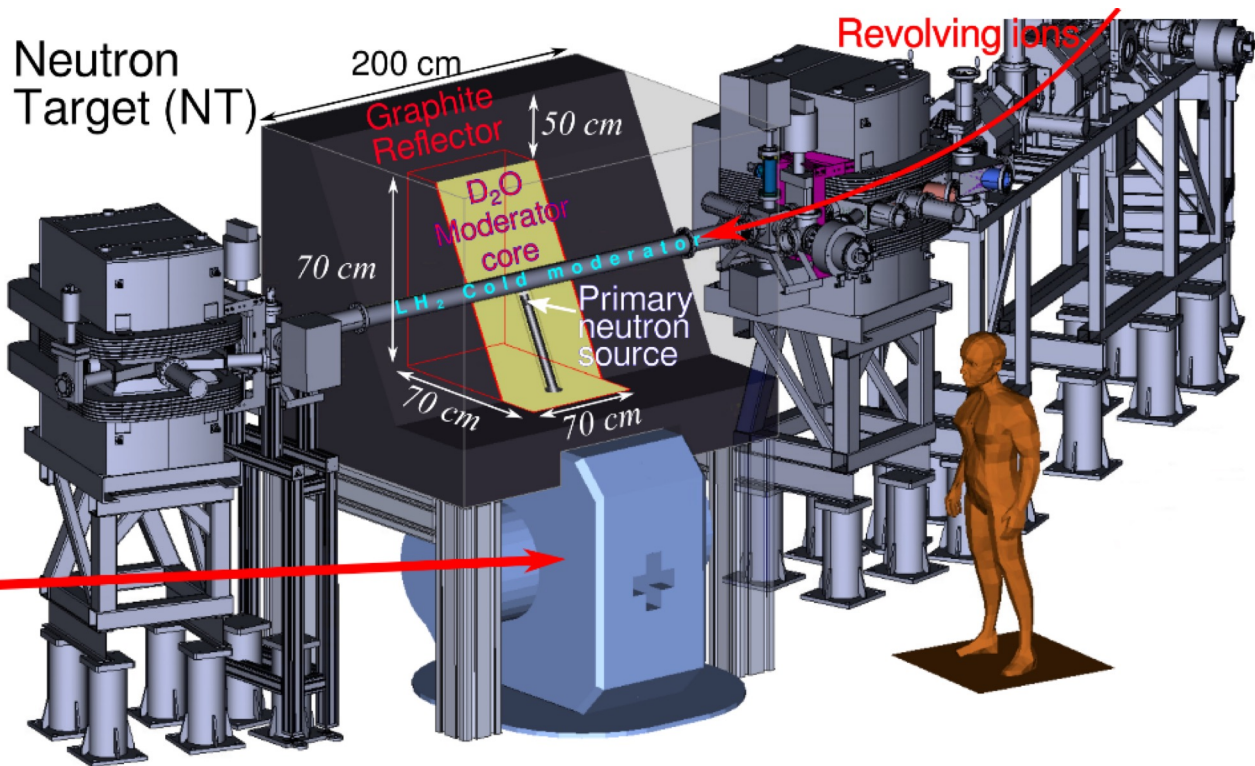
Commissioning and first results with CARME



J. Marsh et al., EPJ A 62, 10 (2026)

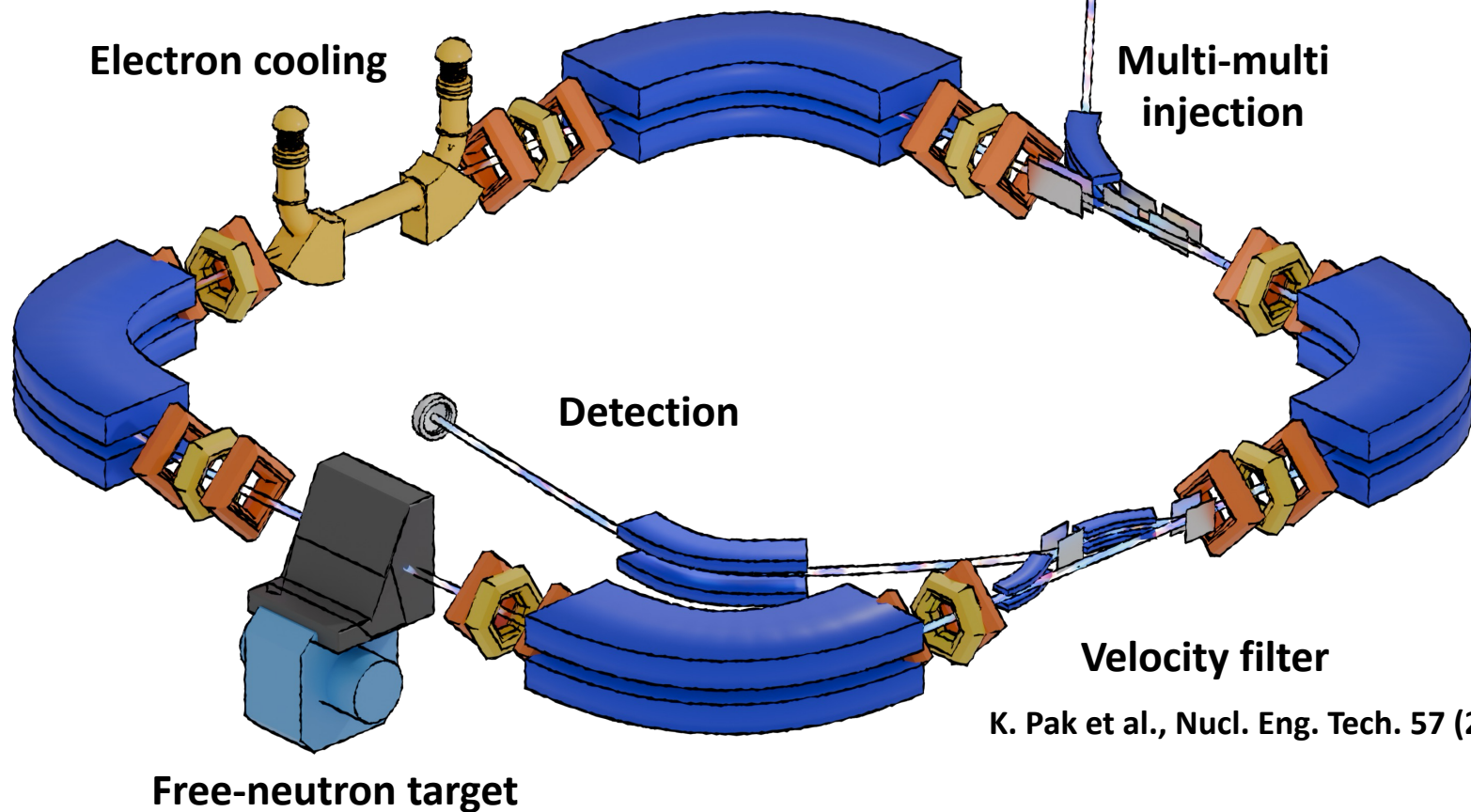
Neutron captures in inverse kinematics

NRING NT Conceptual Design



Free-neutron target at CRYRING

Why storage rings? - Versatile Capabilities



K. Pak et al., Nucl. Eng. Tech. 57 (2025) 103392

Why storage rings? - Versatile Capabilities

Nuclear Excitation by (target) Electron Capture

Nuclear Excitation by (free) Electron Capture

Electron Capture in H- and Li-like Ions

Alpha decay of highly-charged ions

Transfer reactions

Long-lived isomeric states

Di-electronic recombination on exotic nuclei

Giant resonances

Astrophysical reactions for BBN and

Novae, rp- and nup-processes

Surrogate (n,g) reaction studies

ERC SG Bruno

ERC AG Jurado

Electron-Ion scattering (future)

Neutron-induced reactions (future)

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



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Established by the European Commission

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und Forschung