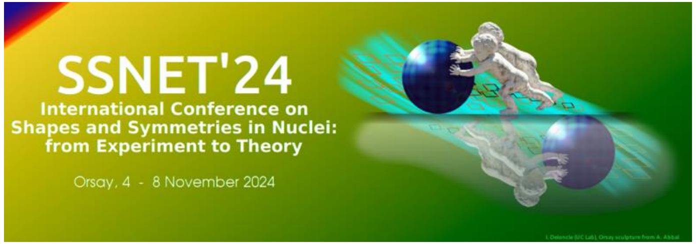
Highly charged radioactive ions – the intersection of nuclear structure, atomic physics and astrophysics

Yury A. Litvinov

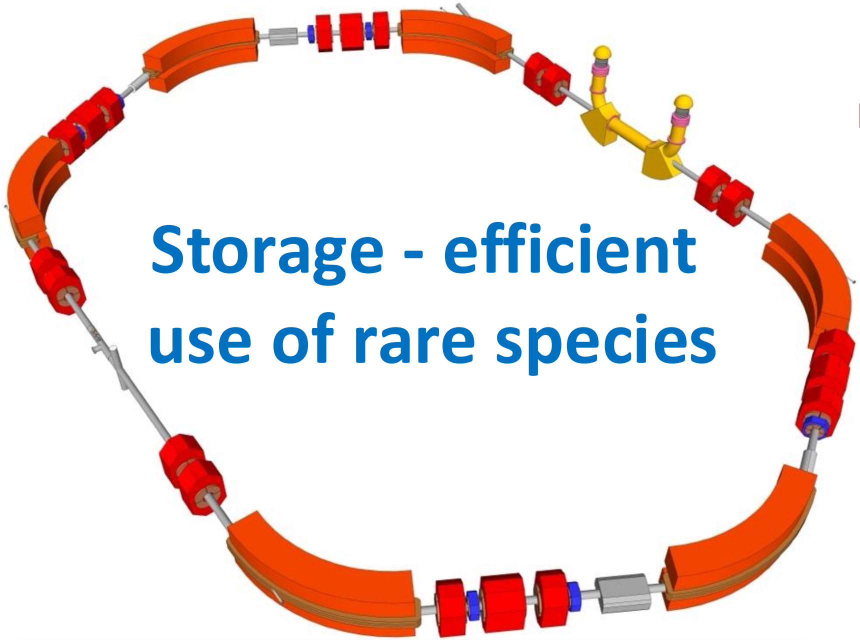


www.gsi.de/astrum

SSNET'24 International Conference on
Shapes and Symmetries in Nuclei: from Experiment to Theory
4-8 November, 2024
IJCLab, Orsay, France

Heavy-Ion Storage Rings - Versatile Instruments

Dedicated beam preparation and manipulation techniques



Storage - efficient use of rare species

A huge trap – more than 100 m circumference, aperture size – 25 cm

Nuclear reaction inevitably leads to large momentum spread of the secondary beam

Beam cooling - high quality beams

Isochronous mode – high mass resolution

Small production rates of secondary beams

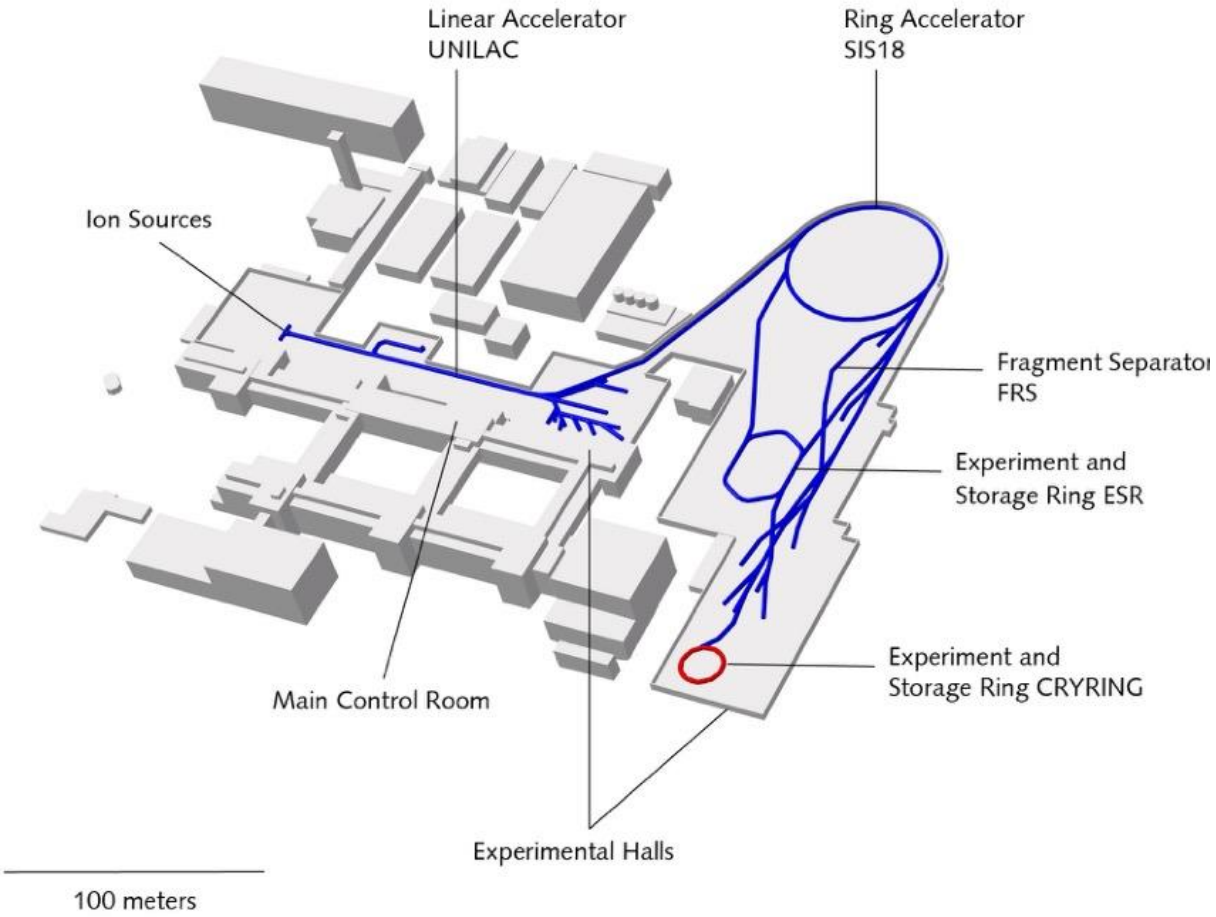
Accumulation techniques

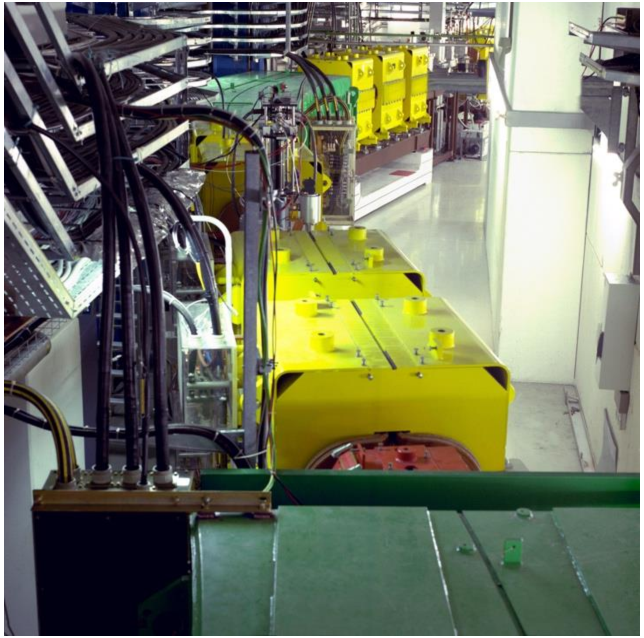
Single-particle sensitivity detection

Short-lived species

Instantaneous detection

Radioactive Ion Beam Facility at GSI





GSI FAIR Phase-0 Research Program

Picture: GSI, Darmstadt

Experimental Storage Ring ESR in Darmstadt, Germany

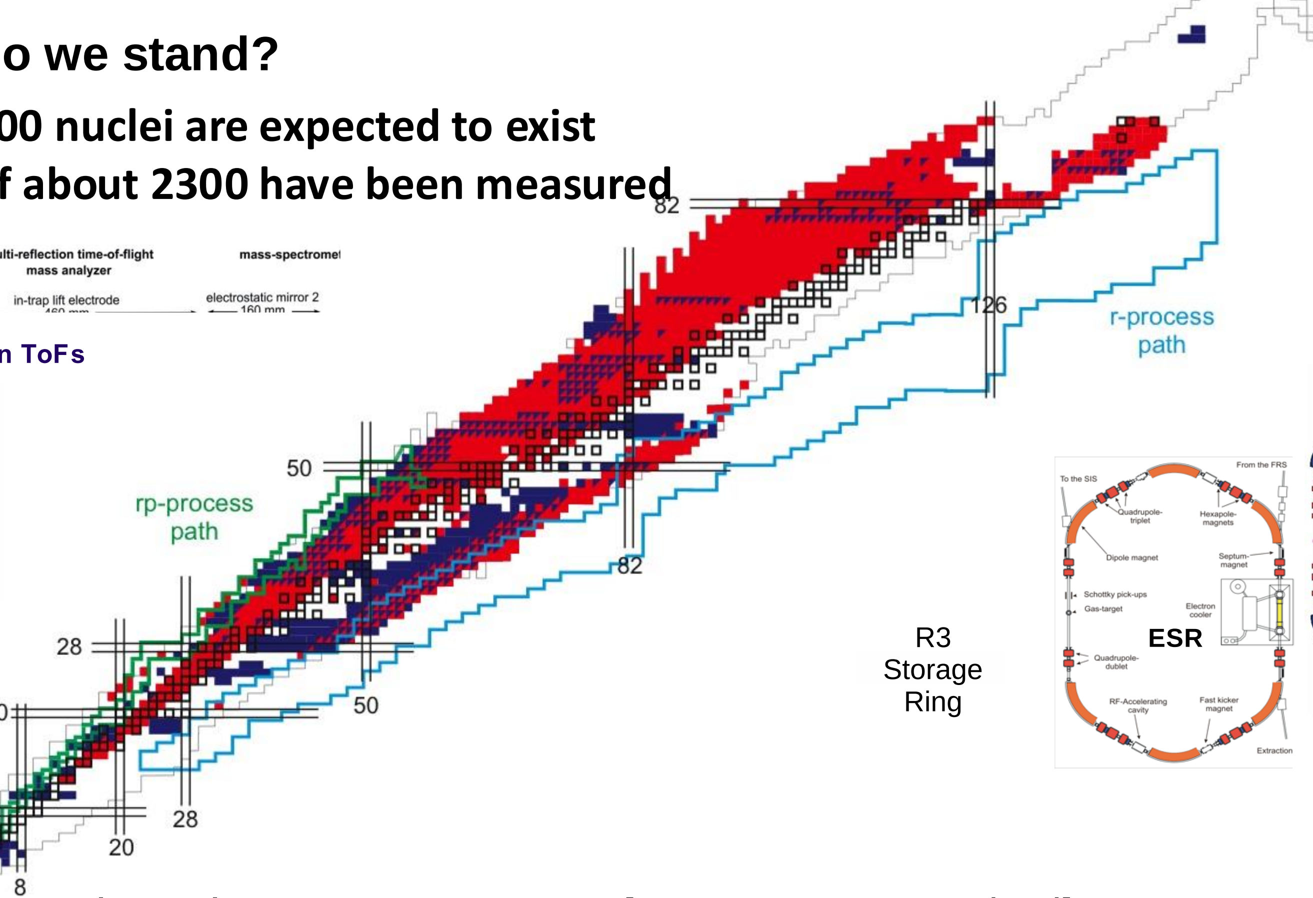
Photos: A. Zschau, GSI; IMPCAS Lanzhou

Direct Mass Measurements on the Chart of the Nuclides

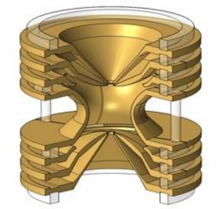
Where do we stand?

About 7000 nuclei are expected to exist

Masses of about 2300 have been measured

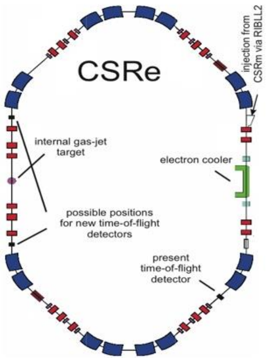


Multi-Reflection ToFs



Penning Traps

R3
Storage
Ring



Storage Rings

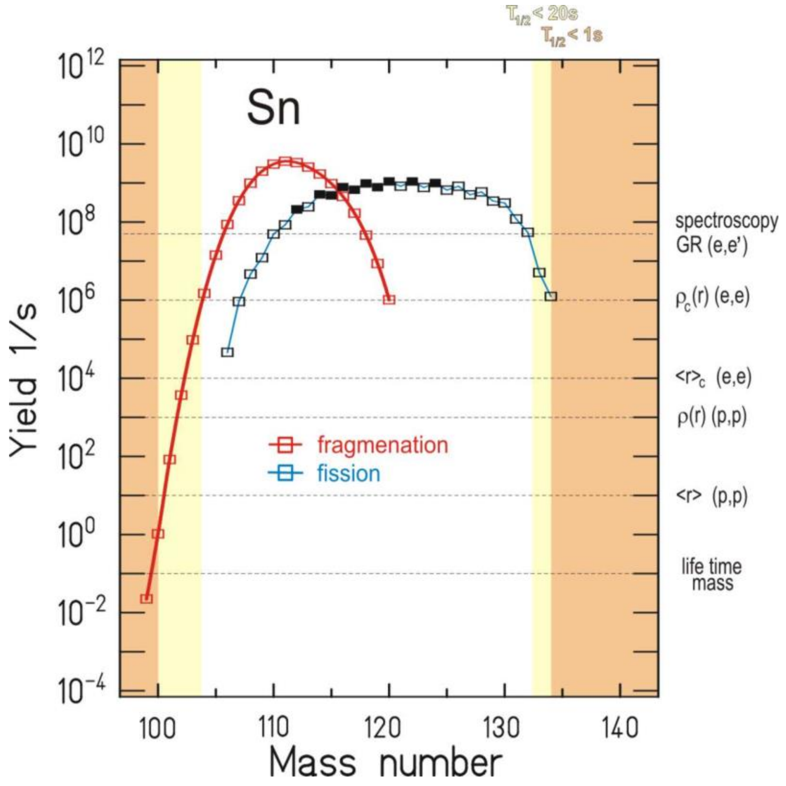
K. Blaum et al., 100 Years Mass Spectrometry [Int. J. Mass Spectr. 349-350 (2013)]
T. Yamaguchi et al., Prog. Part. Nucl. Phys. 120, 103882 (2021)

Characteristics of mass spectrometry techniques

Why do not we measure them all?

Mass spectrometry techniques:
- Bandwidth
- Resolving power
- Speed
- Sensitivity

Ultimate goal to combine all 4 characteristics

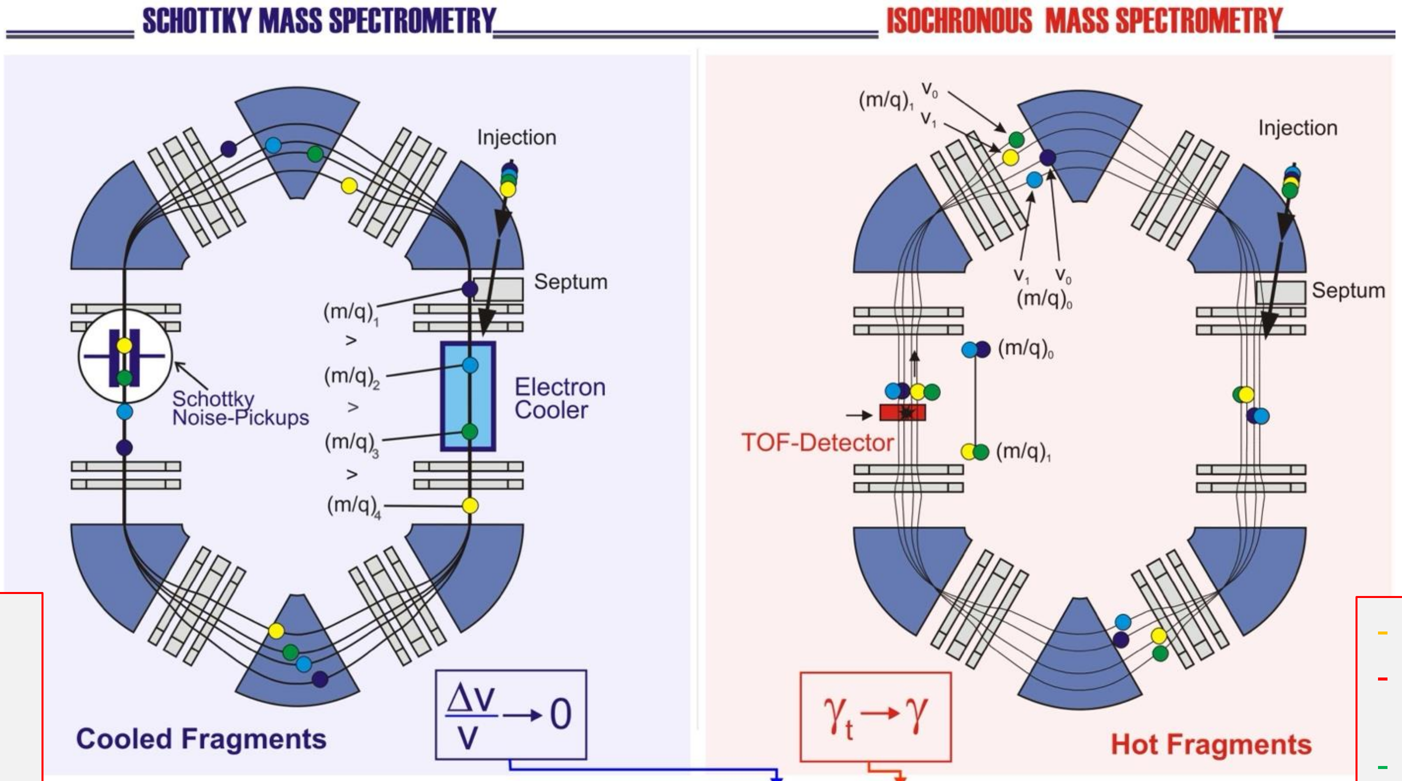


Schottky and Isochronous Storage Ring Mass Spectrometry

Cooling: Takes time

Non-Destructive Detection (Schottky detectors)

- Bandwidth
- Resolving power
- Speed
- Sensitivity



Destructive Detectors (foil-based Secondary electron detectors)

No cooling

- Bandwidth
- Resolving power
- Speed
- Sensitivity

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

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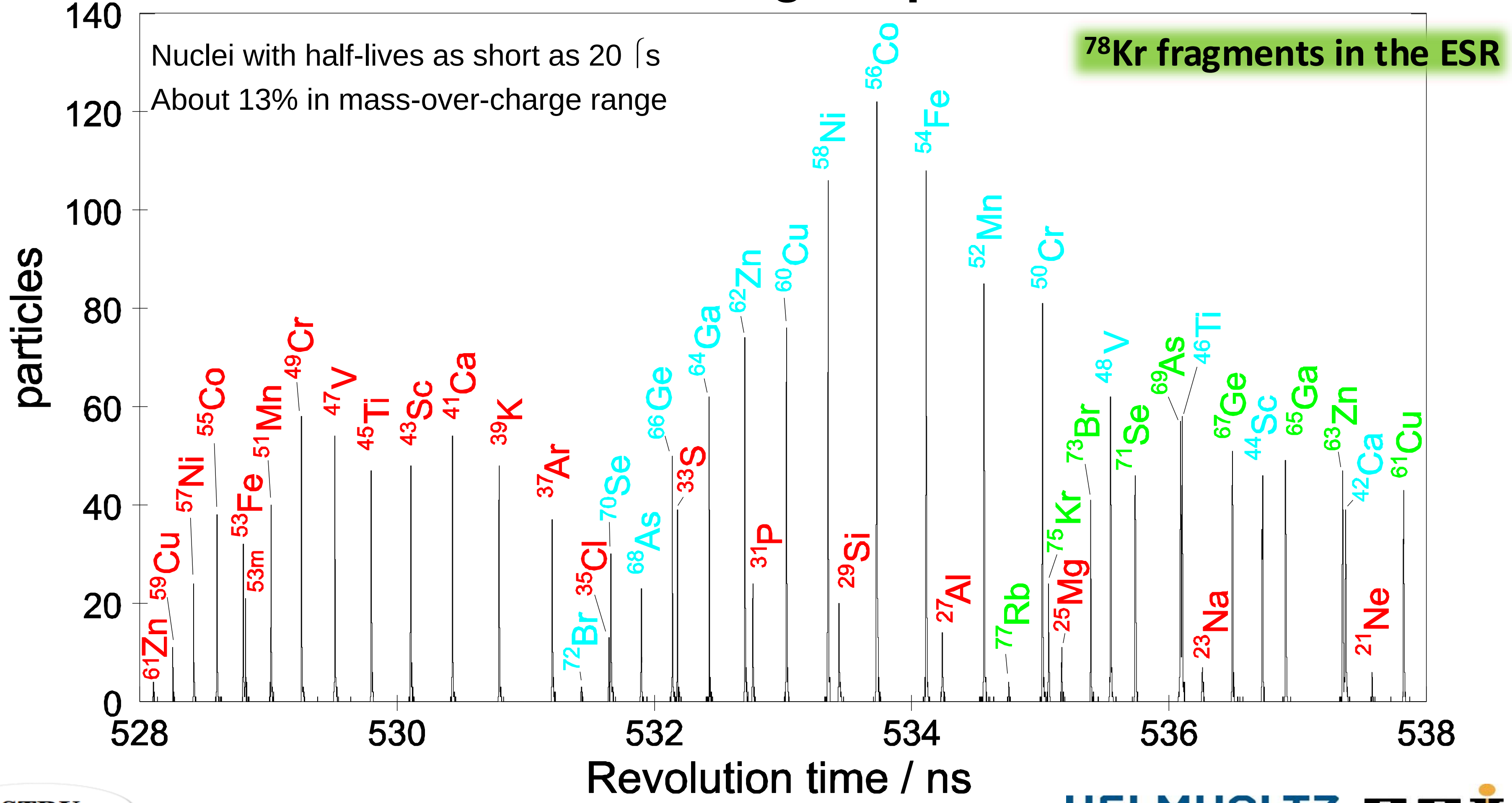
HELMHOLTZ GSI

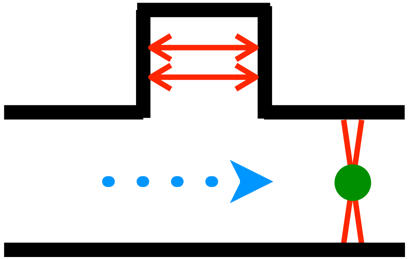
B. Franzke, H. Geissel, G. Münzenberg, Mass Spectr. Rev. 27 (2008)

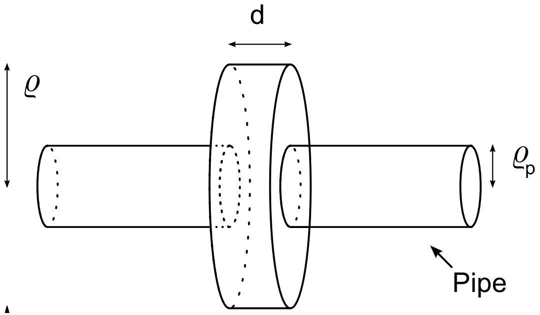
IMS: Time-of-Flight Spectra

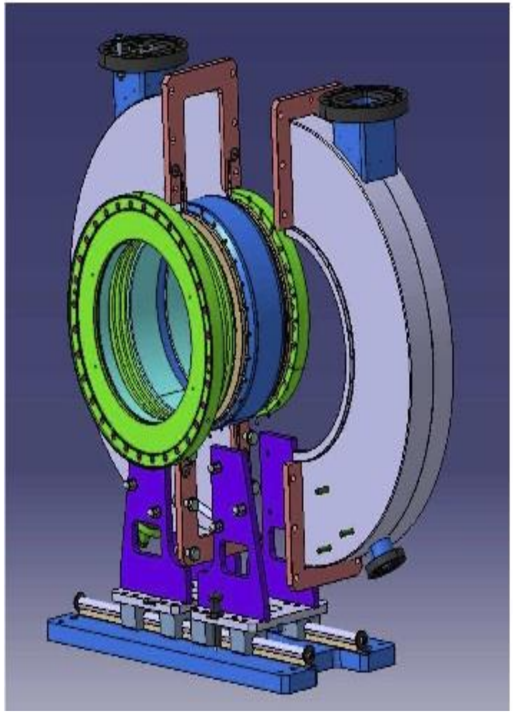


M. Hausmann et al., Hyperfine Interactions 132 (2001) 291

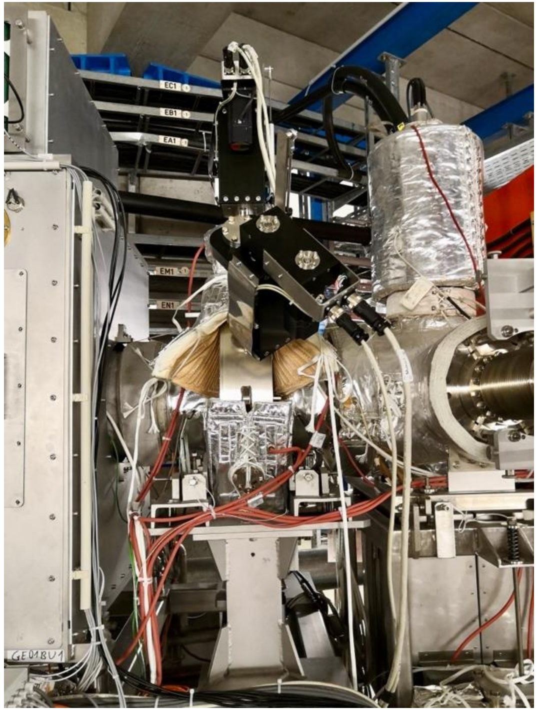
Non-Destructive Particle Detection







F. Nolden et sl., 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 miliseconds

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Courtesy F. Nolden and M. S. Sanjari

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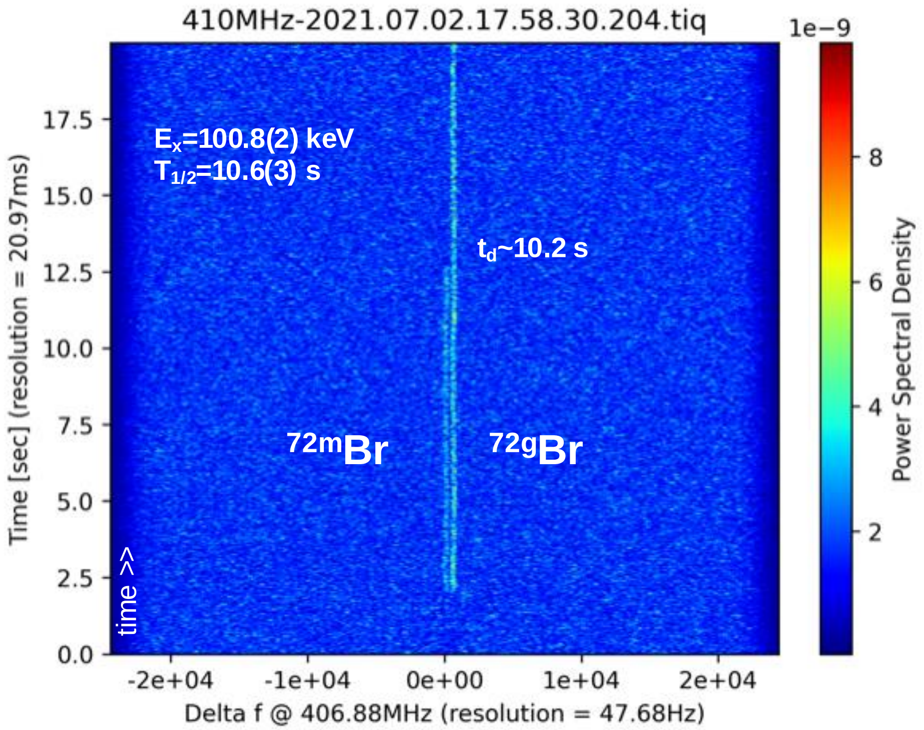
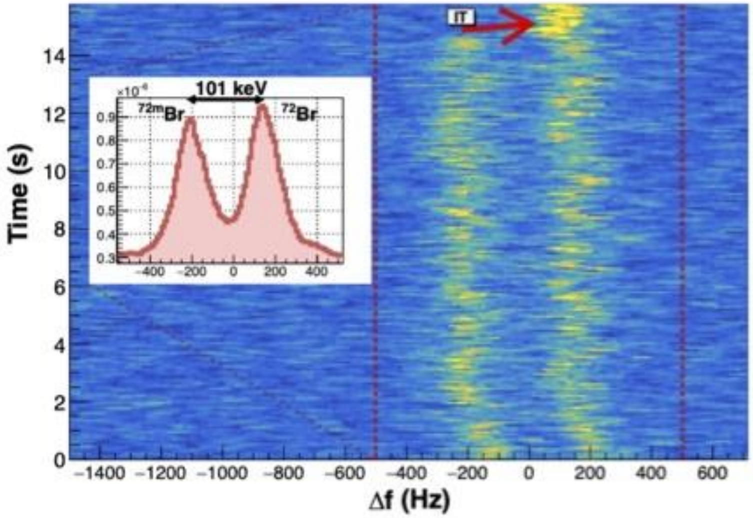
Combined Isochronous+Schottky Mass Spectrometry



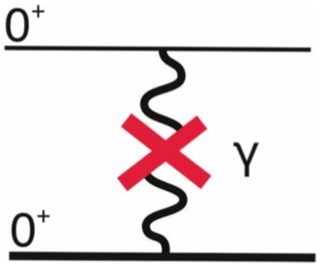
Schottky spectra of single events

Separation of the 101 keV isomer in ^{72}Br

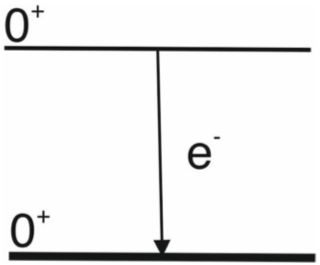


→ $\Delta m/m < 10^{-6}$

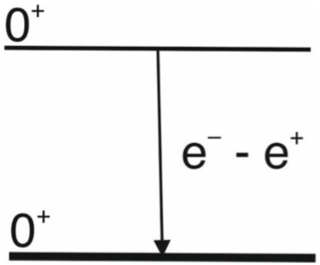
Nuclear two-photon or double-gamma decay



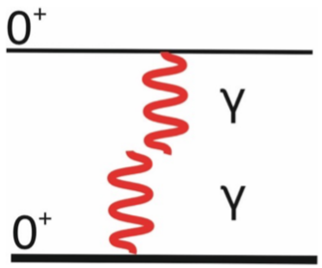
Single photon de-excitation is forbidden



conversion electron



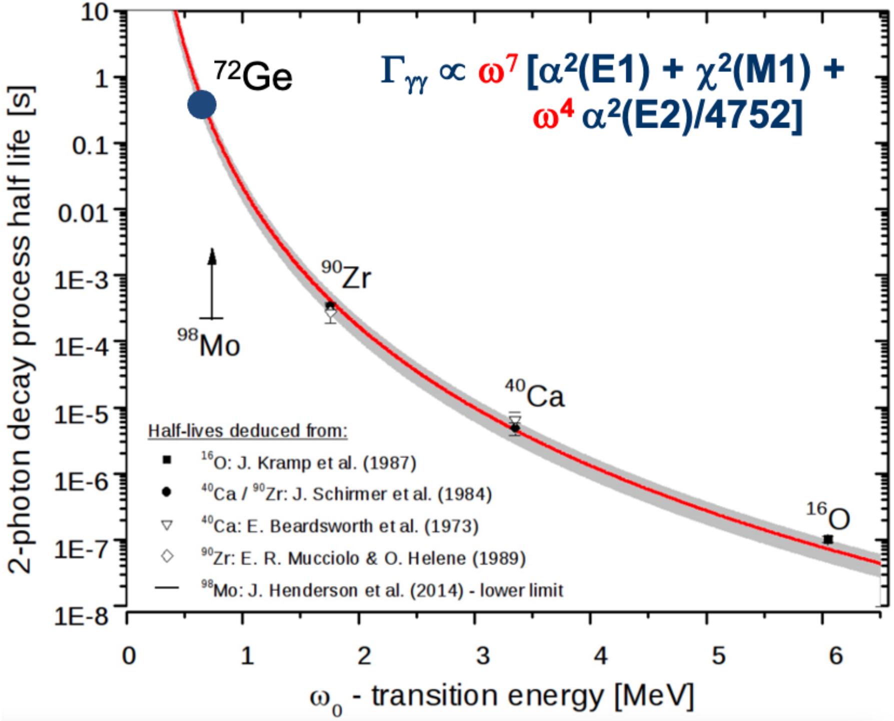
electron-positron pair (E*> 1.022 MeV)

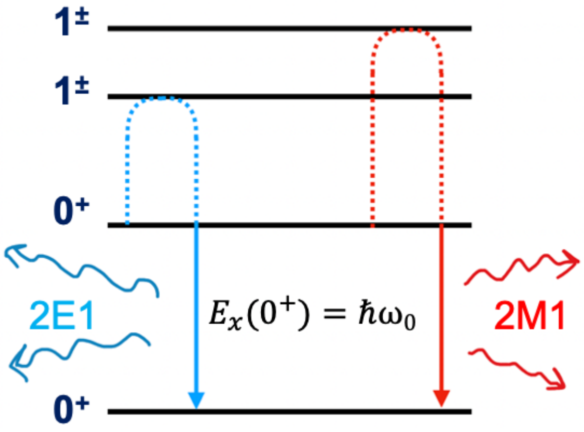


two-photon emission

First observation in 1985 with the HD-DA Crystal Ball (NaI array)

Isolated 2-photon decay in ^{72}Ge





$$\Gamma_{\gamma\gamma} = \frac{\omega_0^7}{105\pi}\left(\alpha_{E1}^2 + \chi_{M1}^2 + \frac{\omega_0^4}{4752}\alpha_{E2}^2\right)$$

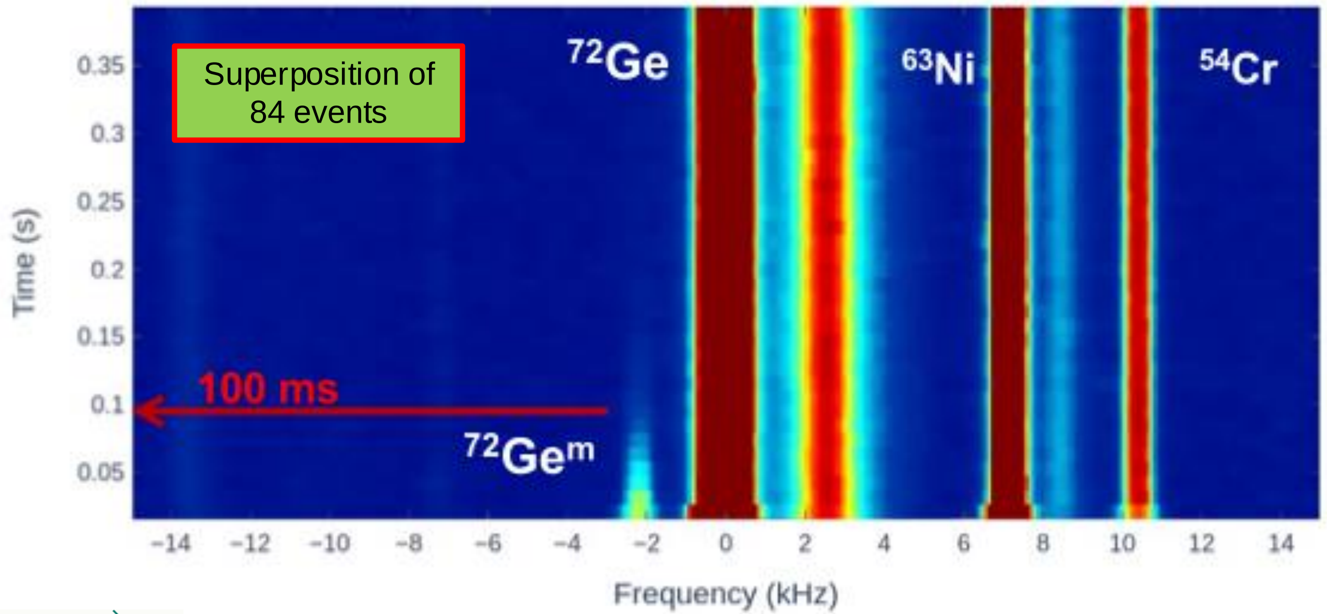
Electric dipole transition polarizability

Magnetic dipole transition susceptibility

Electric quadrupole transition polarizability

usually $\alpha_{E1} \gg \chi_{M1} \gg \alpha_{E2}$

Combined Isochronous+Schottky Mass Spectrometry



Joint PhD Position

CEA Saclay
GSI Darmstadt
MPIK Heidelberg

David
Freire Fernández

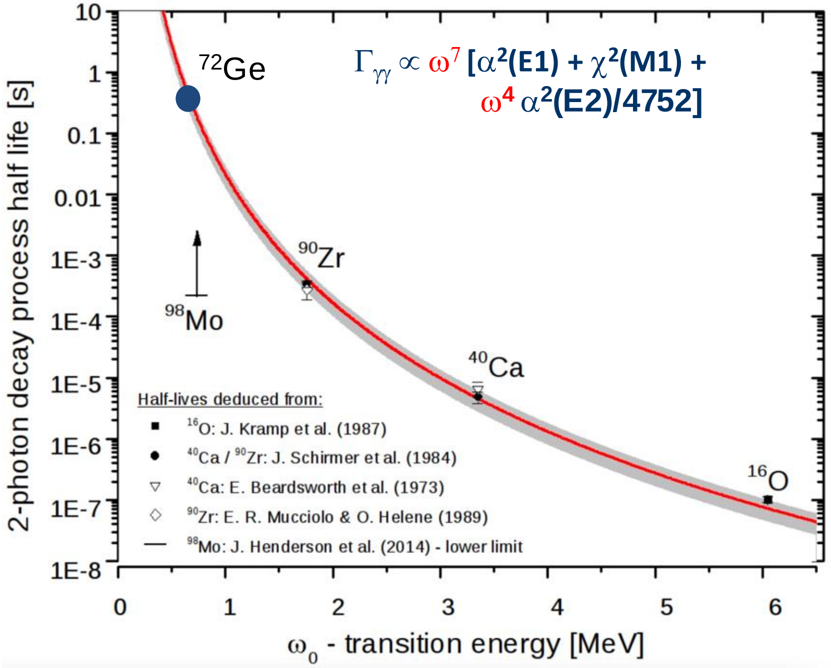
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

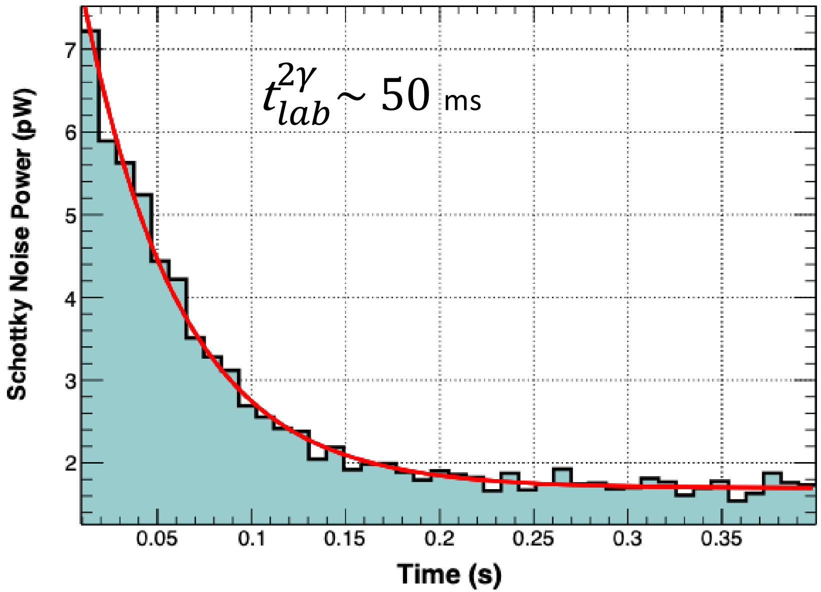
^{72}Ge^{m}: $0^{+} \rightarrow 0^{+}$ (single γ emission forbidden)

New tool to search for 0^{+} isomers in exotic nuclei

Courtesy: D. Fernandes and W. Korten

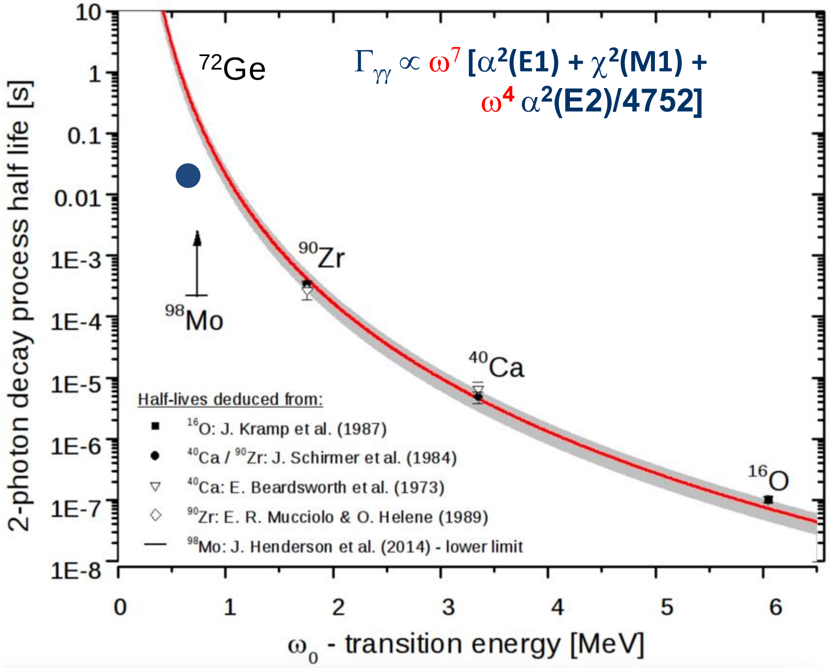
Comparison of Two-Photon Decay Half Lives

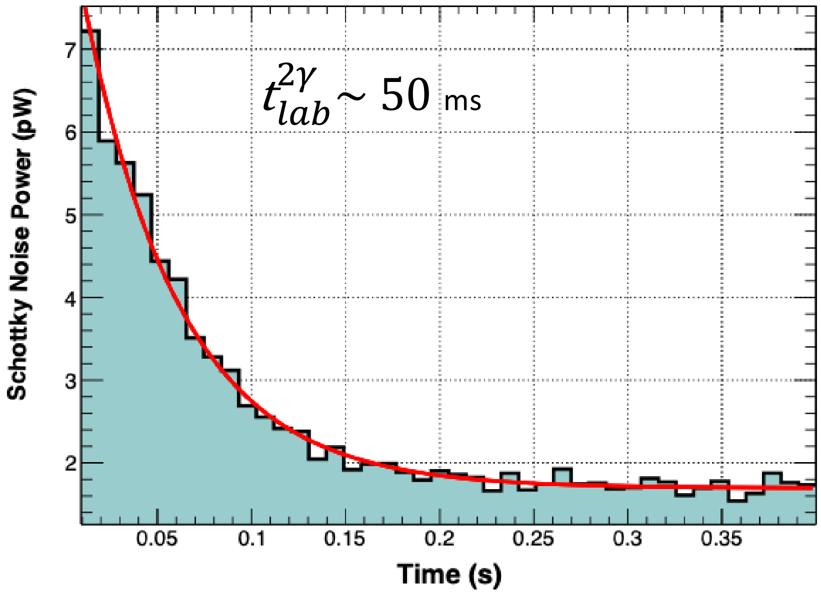




Two-photon decay in ^{72}Ge substantially faster than extrapolated from "magic" nuclei ^{16}O, ^{40}Ca, ^{90}Zr

Comparison of Two-Photon Decay Half Lives

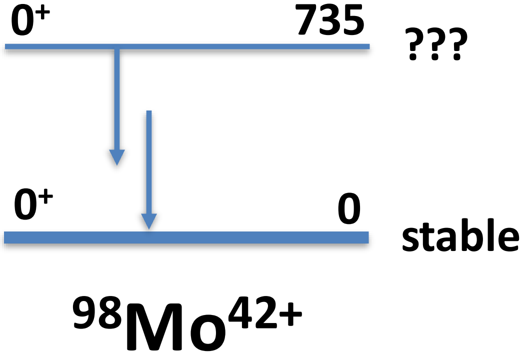


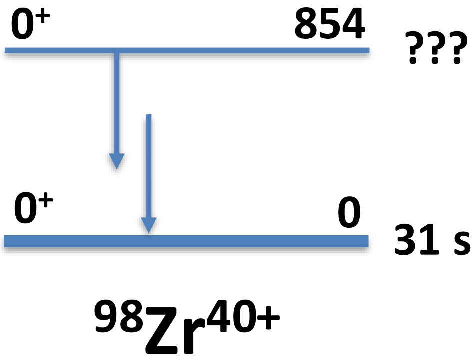


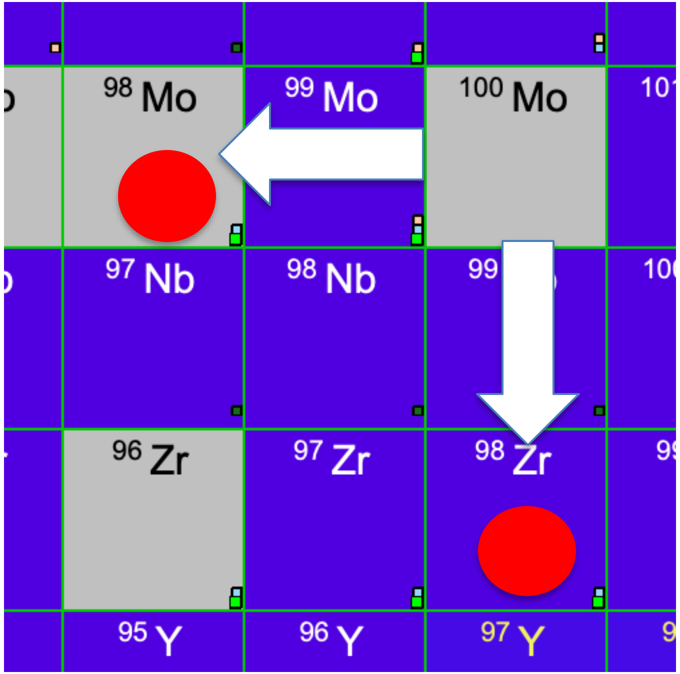
Two-photon decay in ^{72}Ge substantially faster than extrapolated from "magic" nuclei ^{16}O, ^{40}Ca, ^{90}Zr

David Freire-Fernandez et al., Phys. Rev. Lett. 133, 022502 (2024)

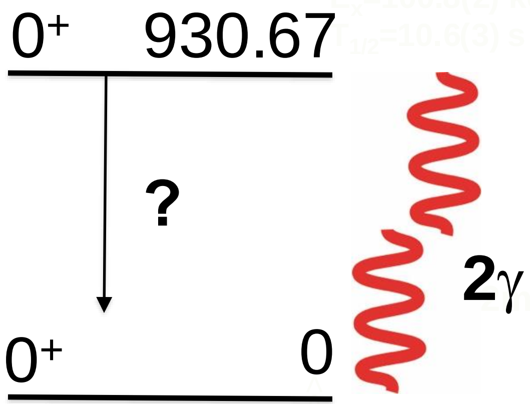
Experiment on 0^+ states in ^{98}Zr and ^{98}Mo







Bound state electron-positron pair decay in ^{194}Pb

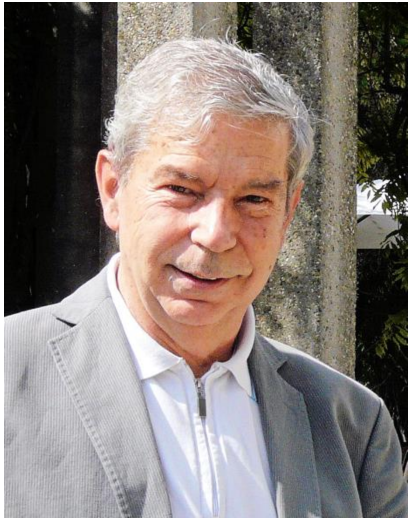


$^{196}Pb^{82+}$

B(K)=101.336 keV

$E(0^+_2)$=930.67 keV

1032 keV



Fritz Bosch
1940-2016

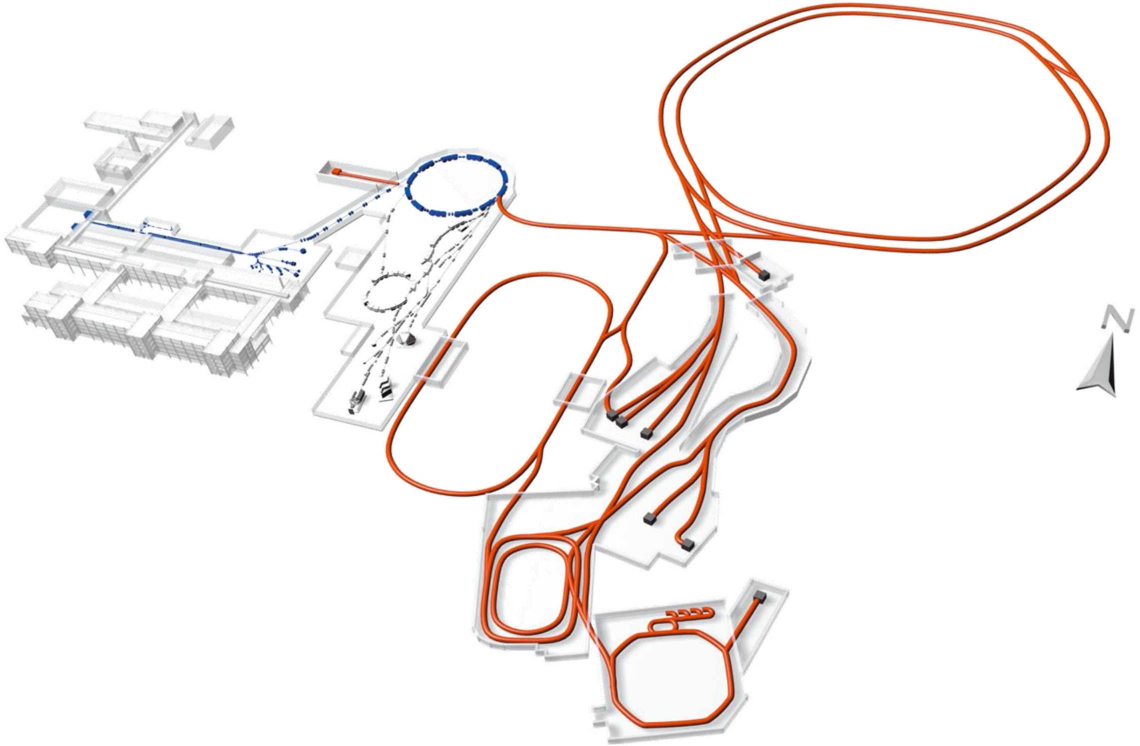
EPJ Web of Conferences **123**, 04003 (2016)
Heavy Ion Accelerator Symposium 2015

Experiment – April 2025

Heavy-ion storage rings offer rich, versatile capabilities for the research with radioactive highly charged ions

Masses of exotic nuclei
Isomeric states
Exotic decay modes
Nuclear reactions (high E)
Astrophysical reactions (low E)
Atomic reactions
Laser spectroscopy
Electron spectroscopy

ERC CoG ASTRUm Litvinov
ERC AdG NECTAR Jurado
ERC StG ELDAR Bruno
ERD AdG HITHOR Stöhlker



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

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Stored Particles Atomic Physics Research Collaboration

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RESEARCH FOR GRAND CHALLENGES

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