DE LA RECHERCHE À L'INDUSTRIE

Measurements of the isolated Nuclear Two-Photon decay

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IRFU - CEA Paris-Saclay

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Outline

- Nuclear two-photon (or double-gamma) decay
- Mass measurements of highly-charged ions in the Experimental Storage Ring (ESR) at GSI/FAIR
- First results for the two-photon decay in ^{72}Ge and further experiments

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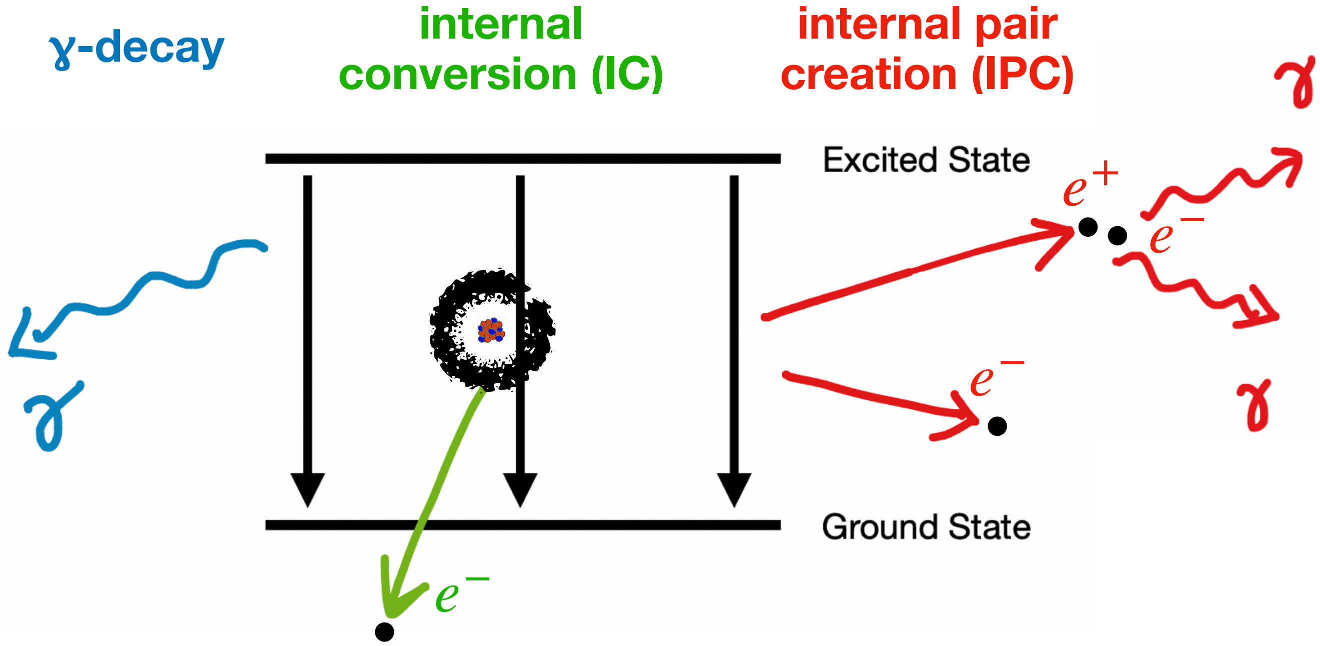
Electromagnetic decay in atomic nuclei

Electromagnetic transitions in atomic nuclei can take place as

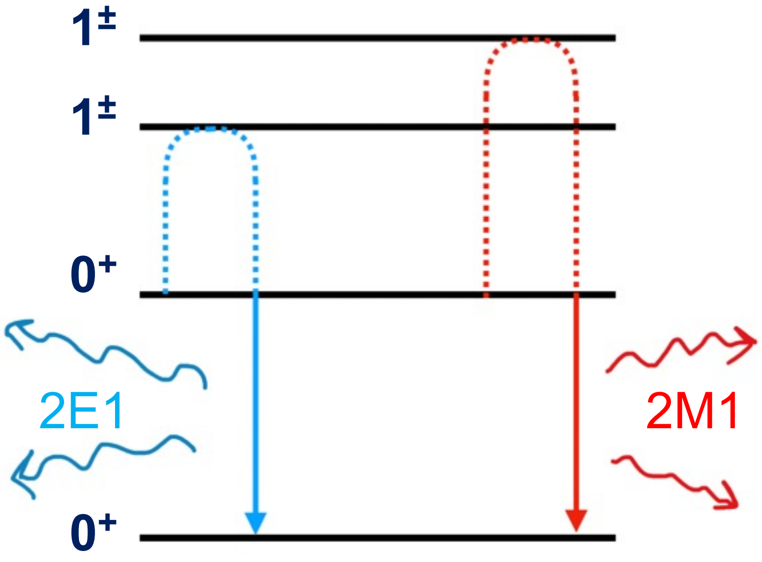
- gamma-ray emission (according to spin/parity conservation)
- electron emission from atomic shells (“internal conversion”)
- electron-positron pair creation (for ΔE > 1.022 MeV)



Nuclear two-photon or double-gamma decay

Rare decay mode whereby two gamma rays are simultaneously emitted

- Second order quantum mechanical process proceeds through virtual excitation of (high-lying) intermediate states
  Branching ratio: $\Gamma_{\gamma\gamma}/\Gamma_{\gamma}$ usually $\ll 10^{-4}$
- Observable when first order decays are (strongly) hindered
  ex. $0^+ \rightarrow 0^+$ E0 decay : single γ-ray emission is forbidden
  virtual excitation of giant dipole resonance



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

Electric dipole transition polarizability	Magnetic dipole transition susceptability	Electric quadrupole transition polarizability

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

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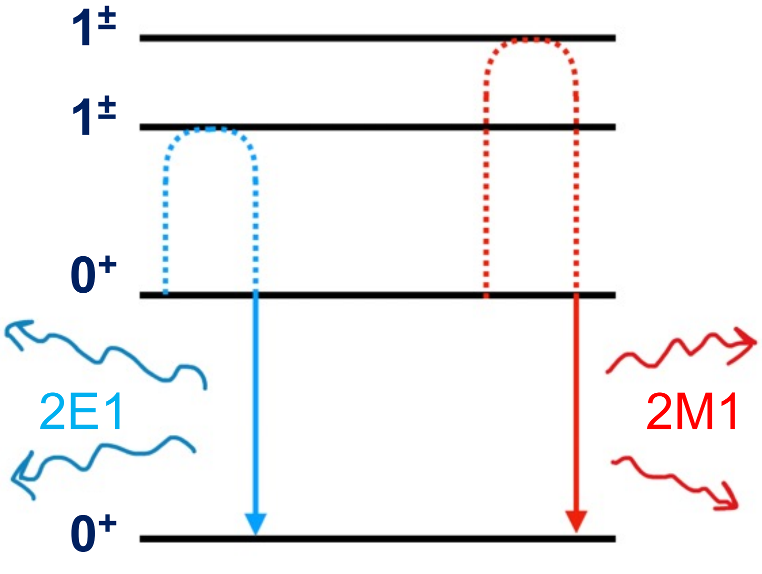


$E_{\gamma1} + E_{\gamma2} = \omega_0 = E_x(0^+)$

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

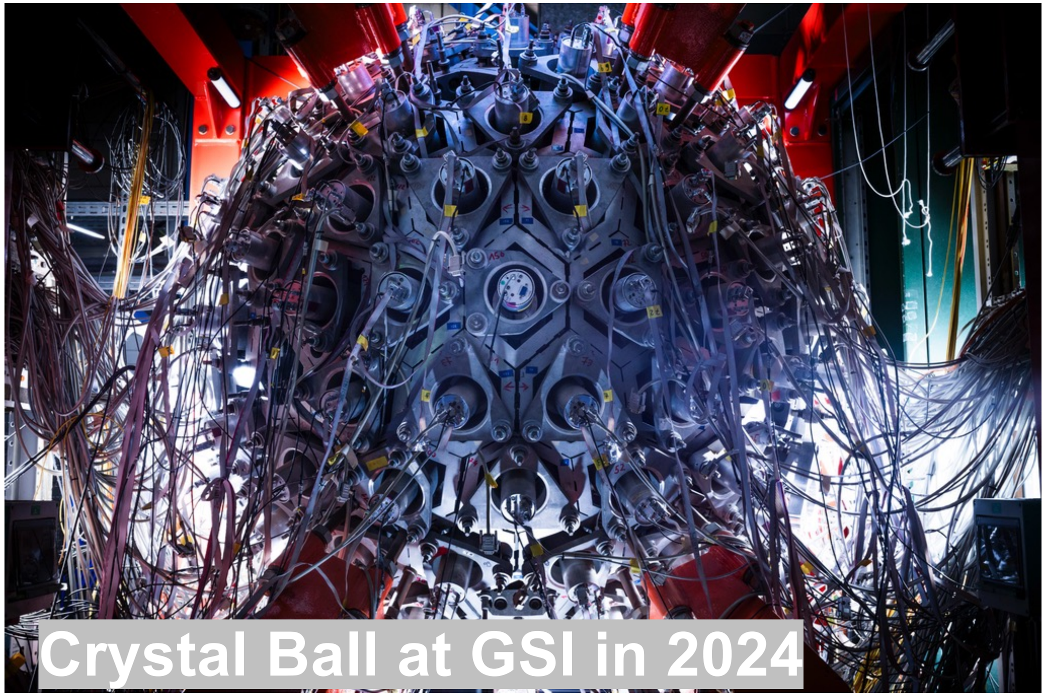
Electric dipole transition polarizability

Magnetic dipole transition susceptability

Electric quadrupole transition polarizability

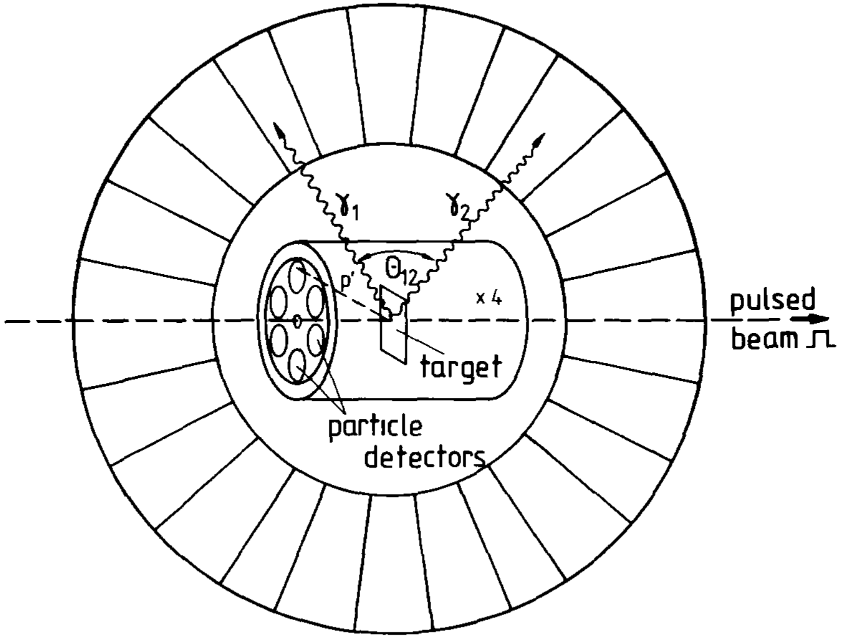
usually $\alpha_{E1} \gg \chi_{M1} \sim \alpha_{E2}$

First observation with the Heidelberg-Darmstadt Crystal Ball spectrometer in 1984



Crystal Ball at GSI in 2024

(p,p’) scattering on ^{16}O, ^{40}Ca and ^{90}Zr
Scattered proton measures E*
γ ray detection in (delayed) coincidence



Heidelberg-Darmstadt Crystal Ball
162 NaI detectors → moderate resolution
Solid angle > 98% → very high efficiency

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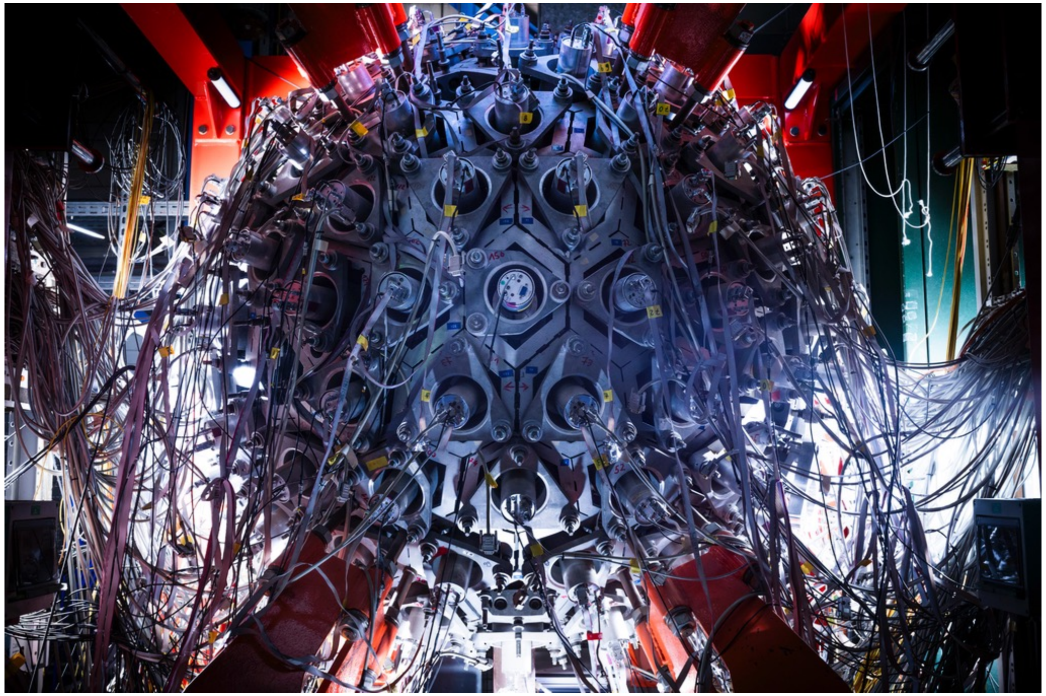
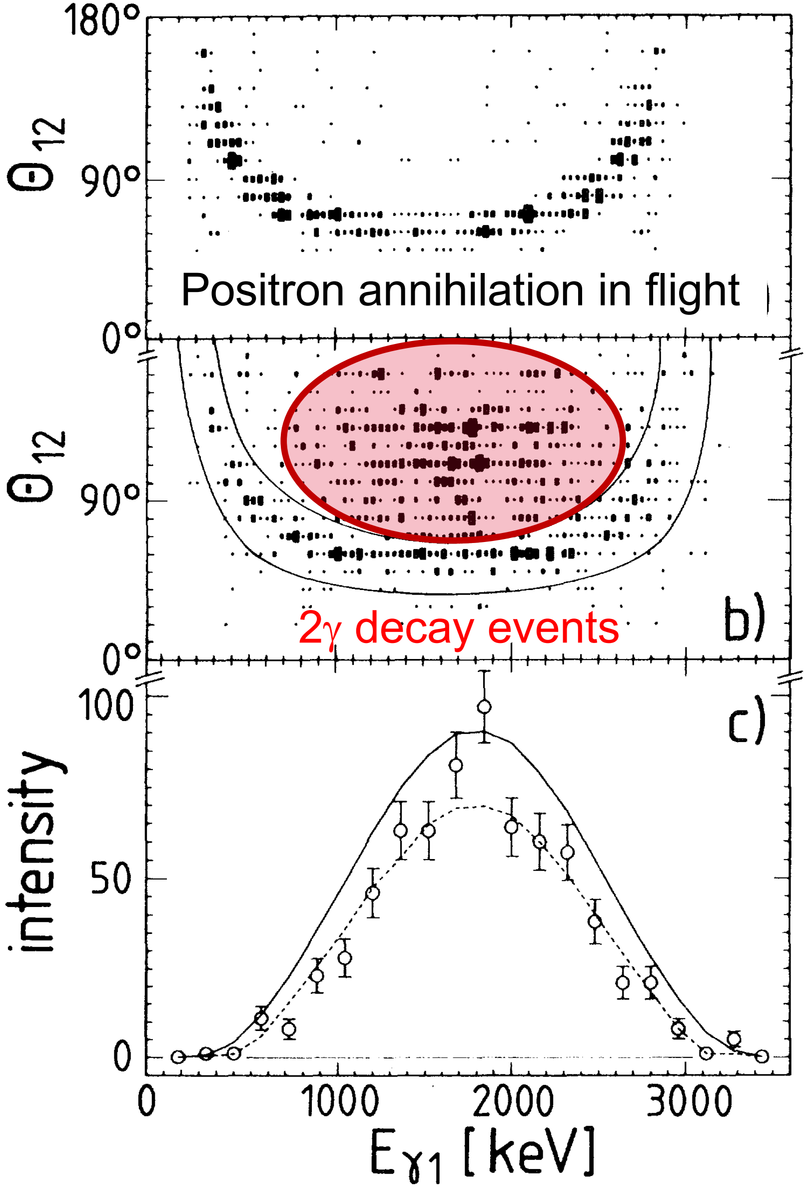


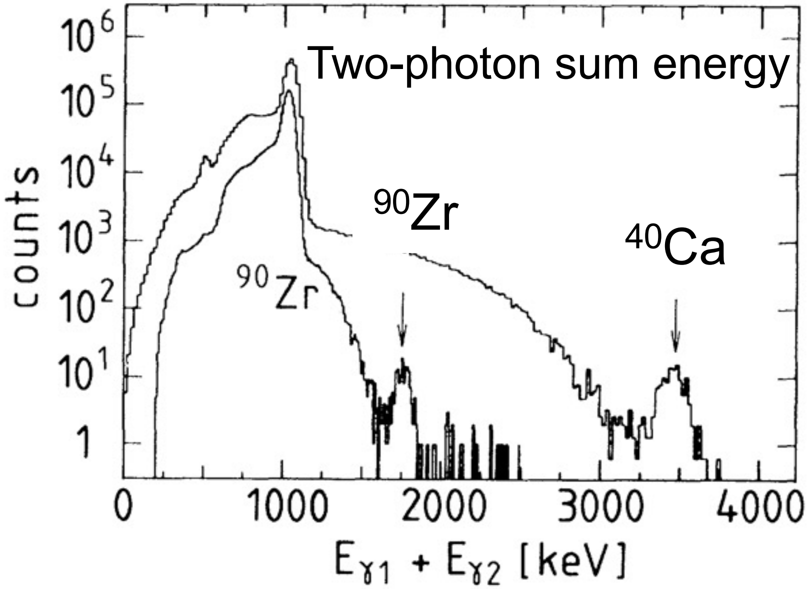
Heidelberg-Darmstadt Crystal Ball
162 NaI detectors → moderate resolution
Solid angle > 98% → very high efficiency

(p,p') scattering on ^{90}Zr: E(0_2)=1.76 MeV

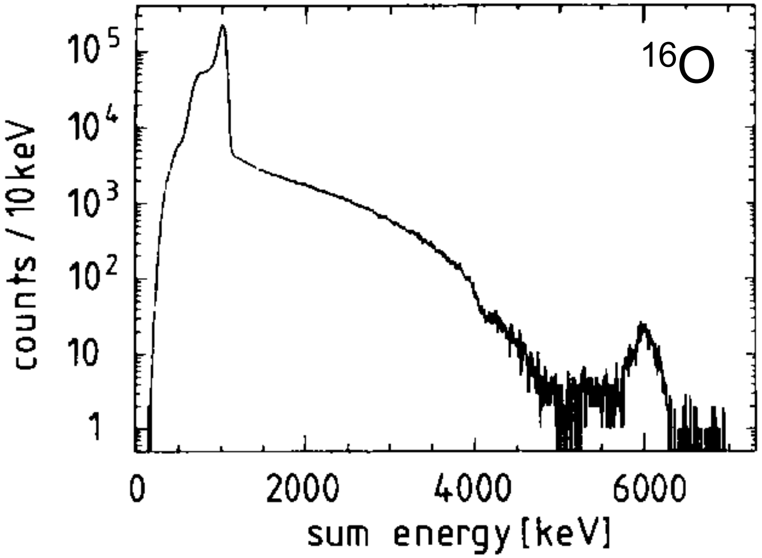


Known cases of double-gamma decay

First clear observation in 1984 at MPI-K HD-DA Crystal Ball (4π NaI array)



J. Schirmer et al., PRL 53 (1984) 1897



J. Kramp et al., Nucl. Phys. A474 (1987) 412

$E_{\gamma 1} + E_{\gamma 2} = \omega_0 = E_x(0^+)$
M1 vs. E1 from ang. corr.

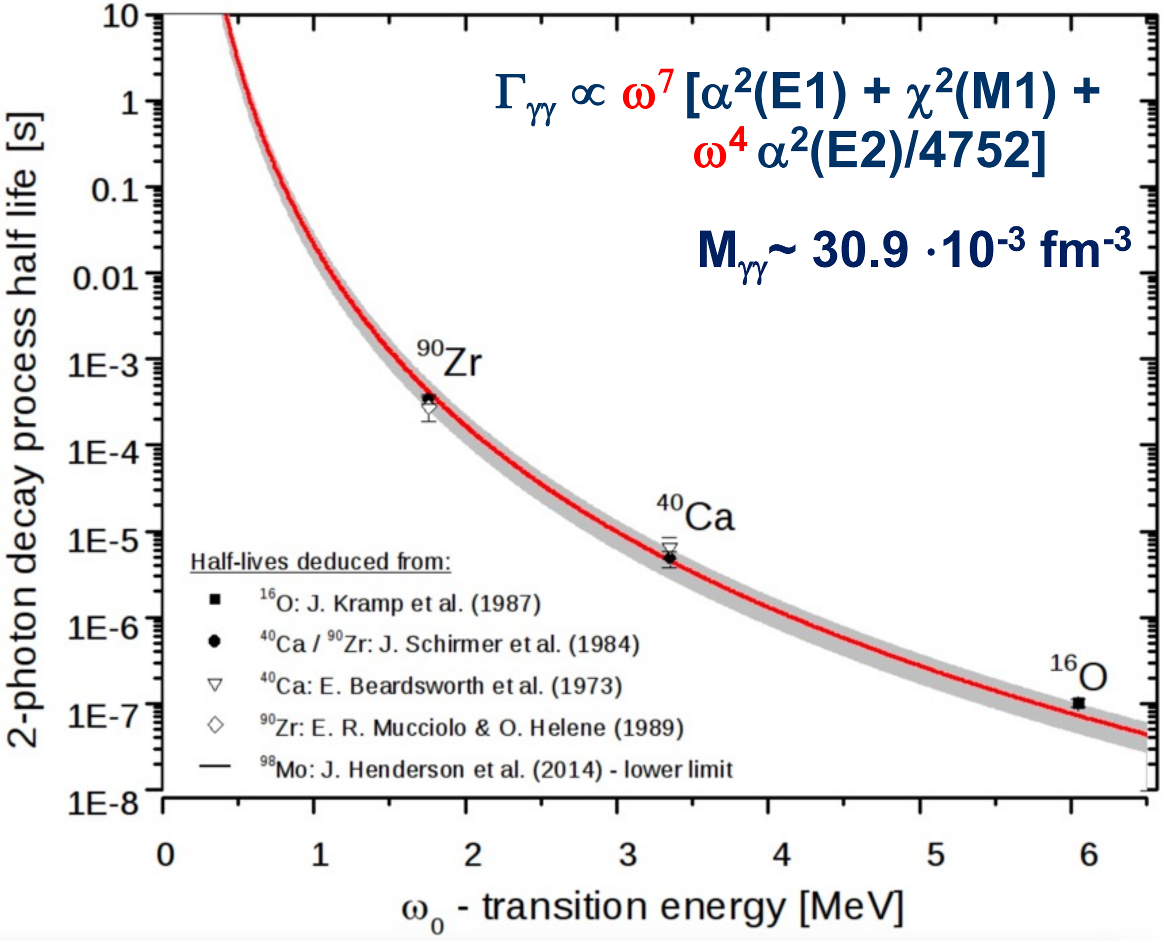
$$\Gamma_{\gamma\gamma} = \frac{\omega_0^7}{105\pi}\left(\underline{\alpha_{E1}^2} + \underline{\chi_{M1}^2} + \frac{\omega_0^4}{4752}\underline{\alpha_{E2}^2}\right)$$

Electric dipole transition polarizability

Magnetic dipole transition susceptability

Electric quadrupole transition polarizability

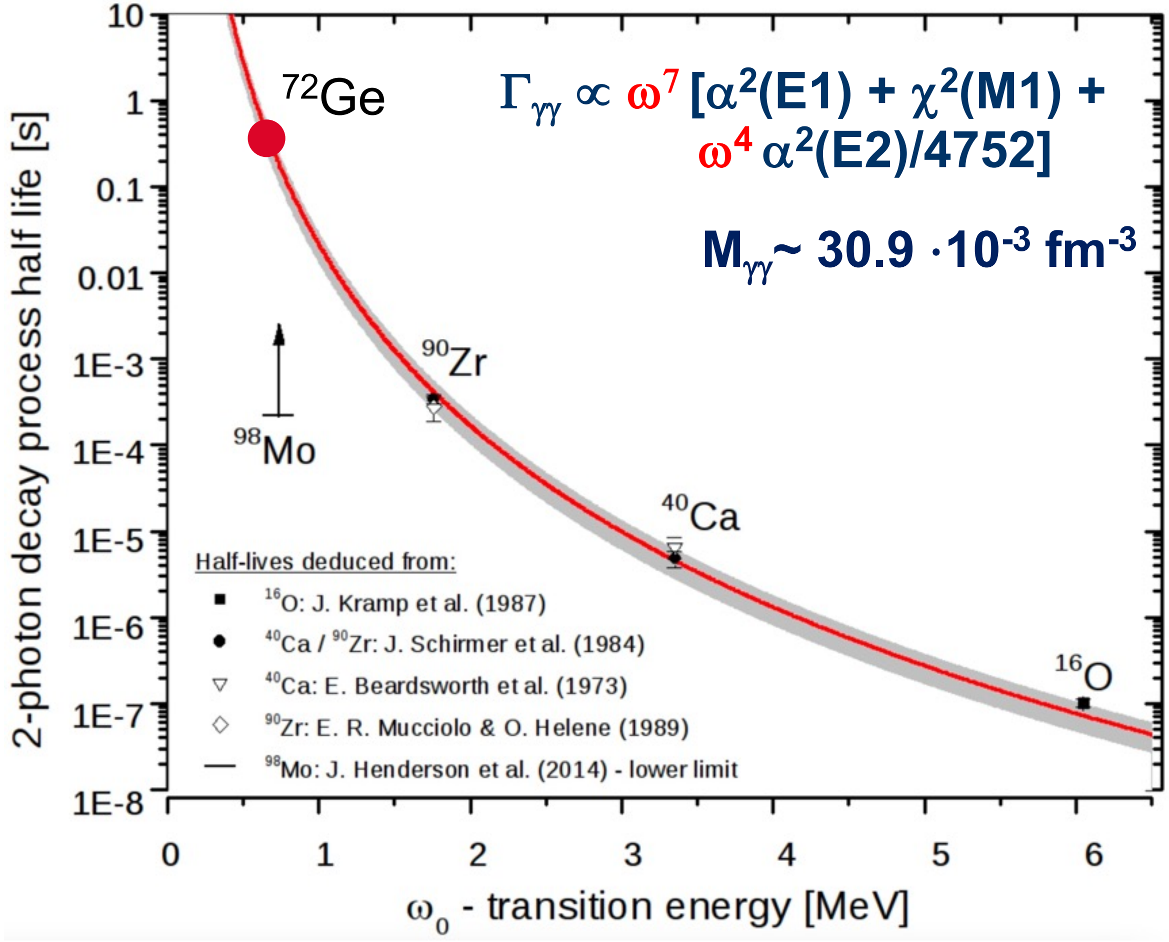
Two-Photon decay half lives in stable nuclei



$$\Gamma_{\gamma\gamma} \propto \omega^7 [\alpha^2(E1) + \chi^2(M1) + \omega^4 \alpha^2(E2)/4752]$$

$$M_{\gamma\gamma} \sim 30.9 \cdot 10^{-3}\ \mathrm{fm}^{-3}$$

Comparison of two-photon decay half lives



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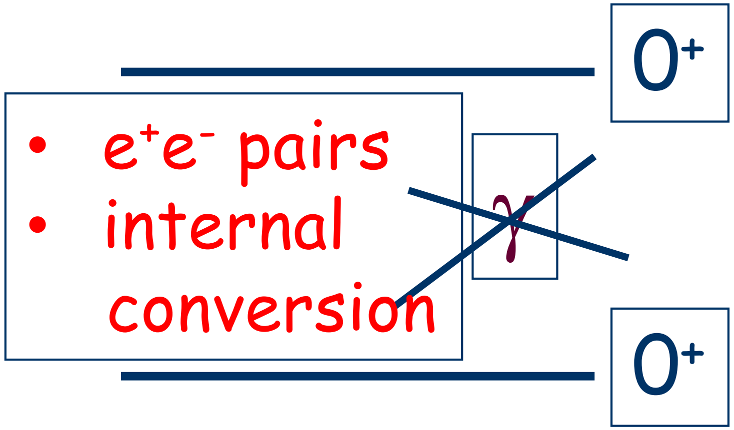
$$M_{\gamma\gamma} \sim 30.9 \cdot 10^{-3}\ \mathrm{fm}^{-3}$$

For low-energy 0^+ states the partial halflife becomes very long and therefore the branching ratio becomes very small

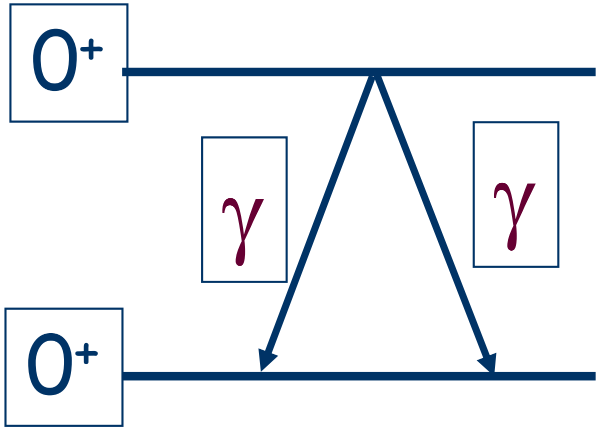
How to “isolate” the nuclear two-photon decay

Rare decay mode whereby two gamma rays are simultaneously emitted

- Second order quantum mechanical process proceeds through virtual excitation of (higher-lying) intermediate states
- Observable only when first order decays are (strongly) hindered ex. $0^+ \rightarrow 0^+$ E0 decay : single γ-ray emission is forbidden



- e^+e^- pairs
- internal conversion



- $E_x(0^+) < 2\ m_ec^2$ ➔ no e^+e^- decay
- fully stripped ions ➔ no ce decay

$E_{\gamma 1} + E_{\gamma 2} = \omega = E_x(0^+)$

Two-photon decay is the only allowed $0^+ \rightarrow 0^+$ decay in stable bare nuclei

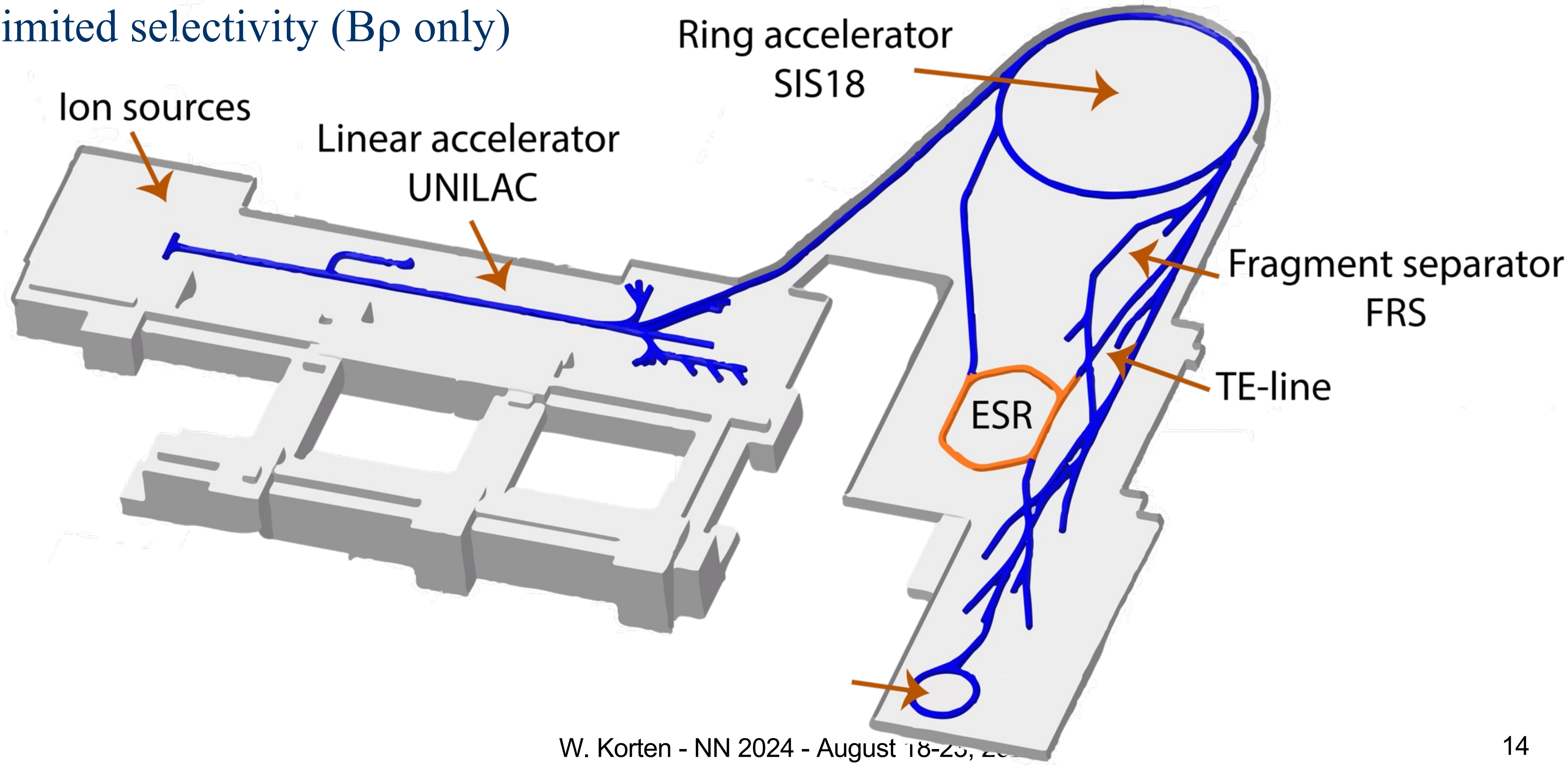
Outline

- The nuclear two-photon (or double-gamma) decay
- Mass measurements of highly-charged ions in the Experimental Storage Ring (ESR) at GSI/FAIR
- First results for the two-photon decay in ^{72}Ge and future experiments

The SIS18 + ESR experiment at GSI

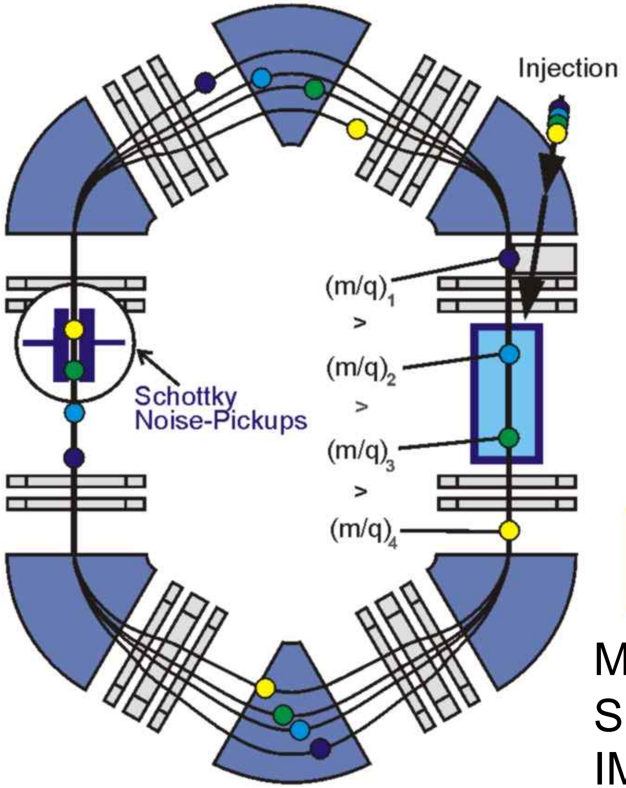
^{78}**Kr** at ~460 A.MeV, ~10^9 ions/spill (every 10s)

- ➢ Fragmentation in a Be foil (~2 g/cm^2)
- ➢ Bρ selection in the TE beam line from SIS18 to ESR
- ▪ high cross section for ^{72}Ge (~10 mb)
- ▪ good acceptance & transmission
- ▪ limited selectivity (Bρ only)



High resolution mass measurements in a storage ring

SCHOTTKY MASS SPECTROMETRY



Cooled Fragments

Very high precision
Non destructive
Slow (many seconds)

$$\frac{\Delta v}{v} \rightarrow 0$$

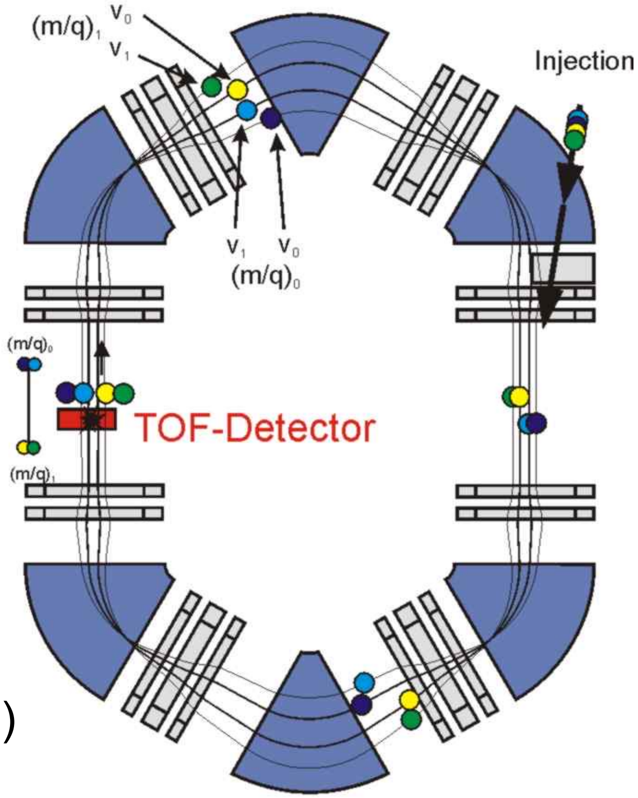
$$\gamma_t \rightarrow \gamma$$

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

Measurement
SMS: revolution frequency (~2 MHz)
IMS: revolution time (~500 ns)

Combined Schottky + Isochronous Mass Spectrometry (S+IMS)

ISOCHRONOUS MASS SPECTROMETRY

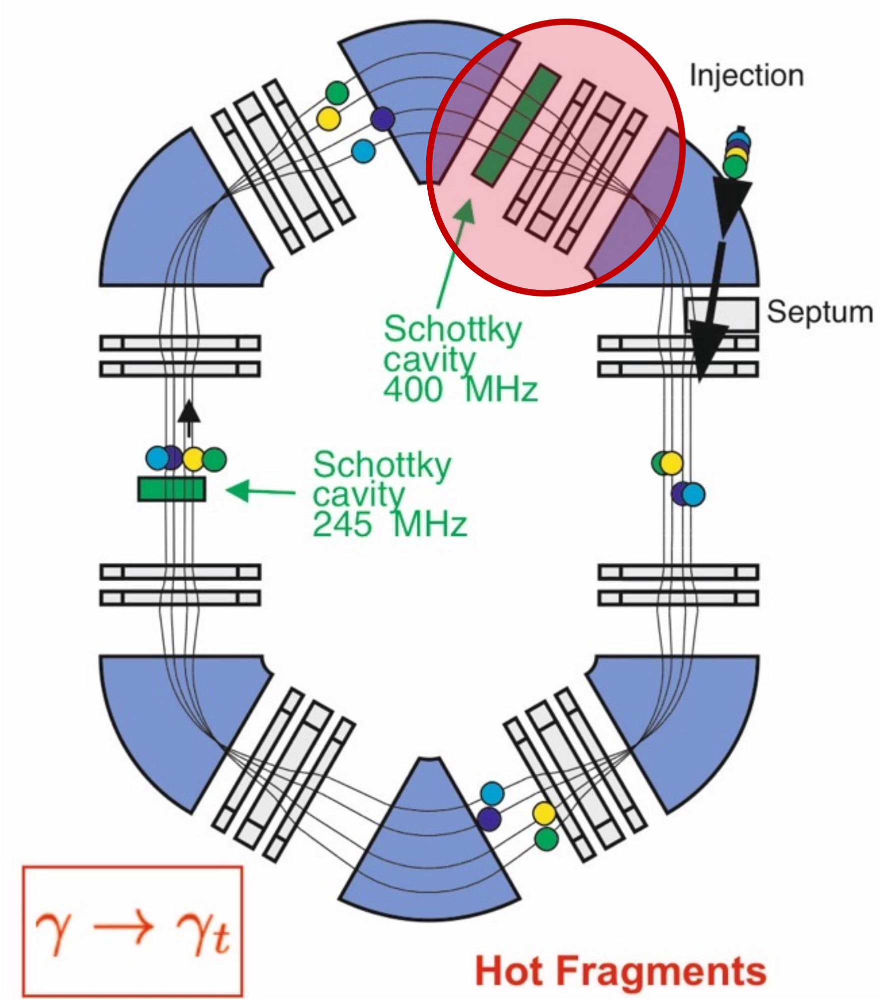


Hot Fragments

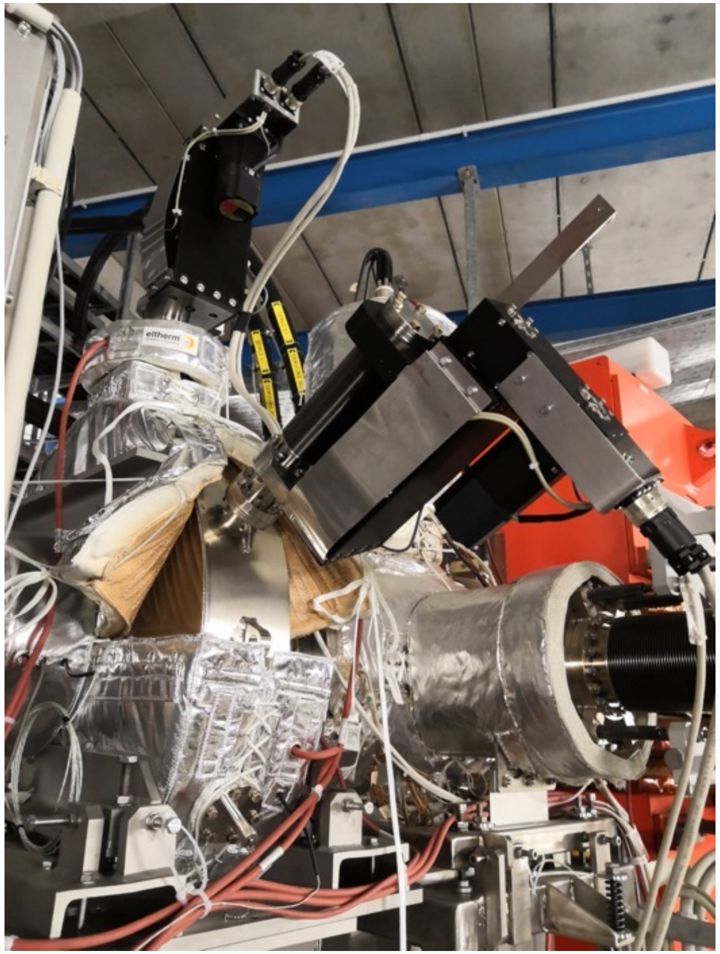
Very fast (few ms)
Good precision
Destructive method

First ever time-resolved Schottky plus Isochronous Mass Spectroscopy (S+IMS) at the ESR

Combined Schottky plus Isochronous Mass Spectroscopy (ISMS)

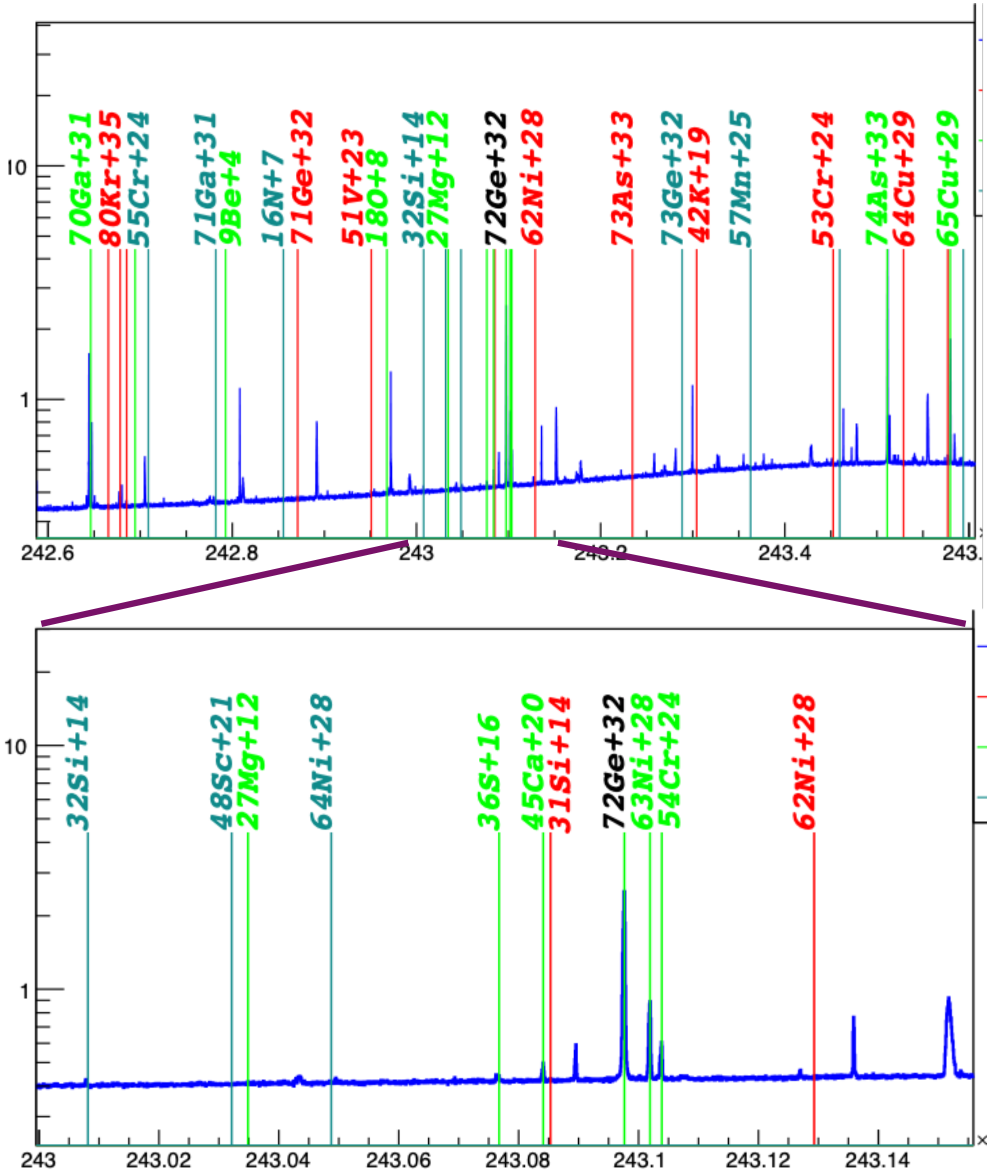


New 410 MHz Schottky cavity

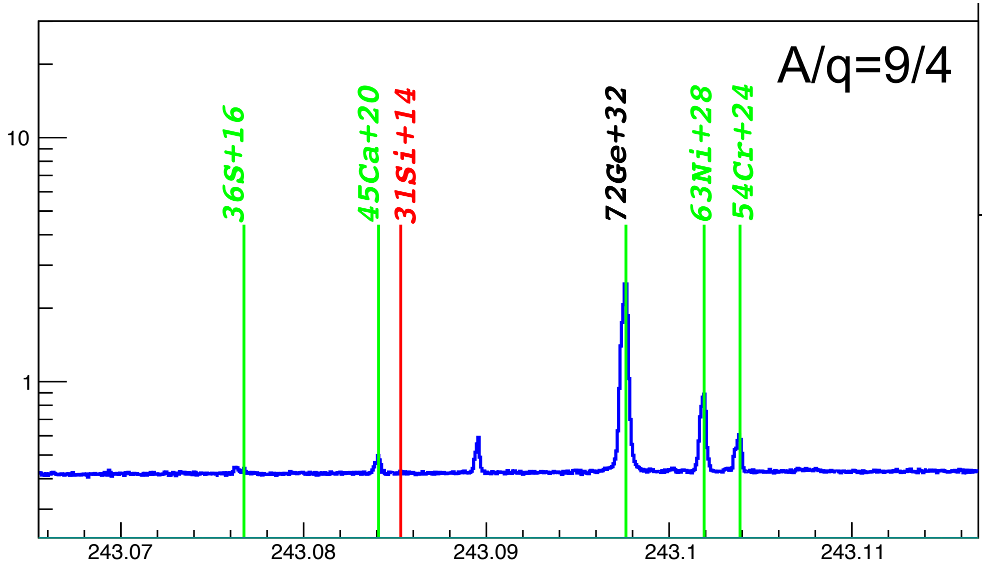


M. S. Sanjari et al.,
Rev. Sci. Instr. 91, 083303 (2020)

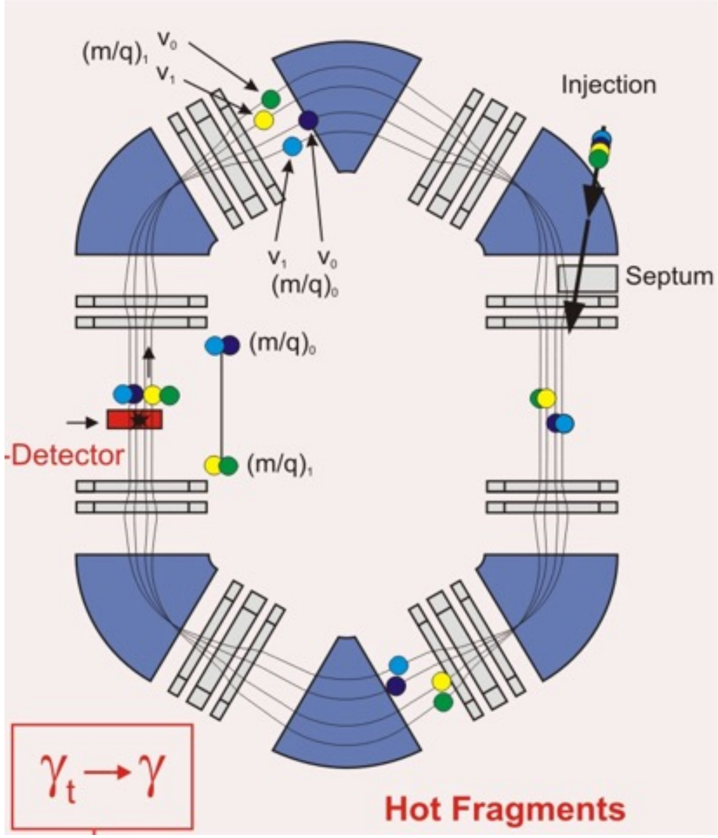
Identification of isotopes through Schottky spectra



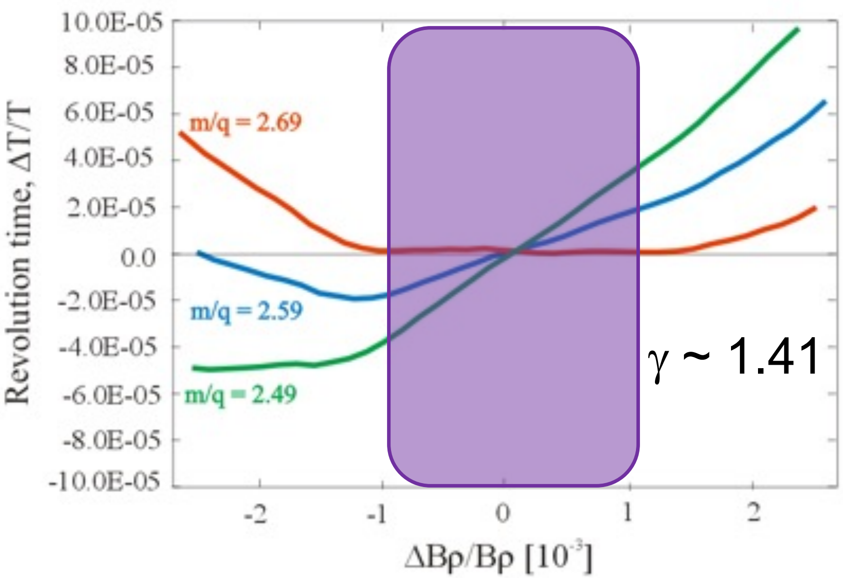
- **All stored nuclei** can be identified by their characteristic revolution frequency
- Colour code indicates different harmonics of the original revolution frequency



Challenges of Isochronous Mass Spectrometry



γ_t is not constant with Bρ,
but depends on the orbit in the ESR

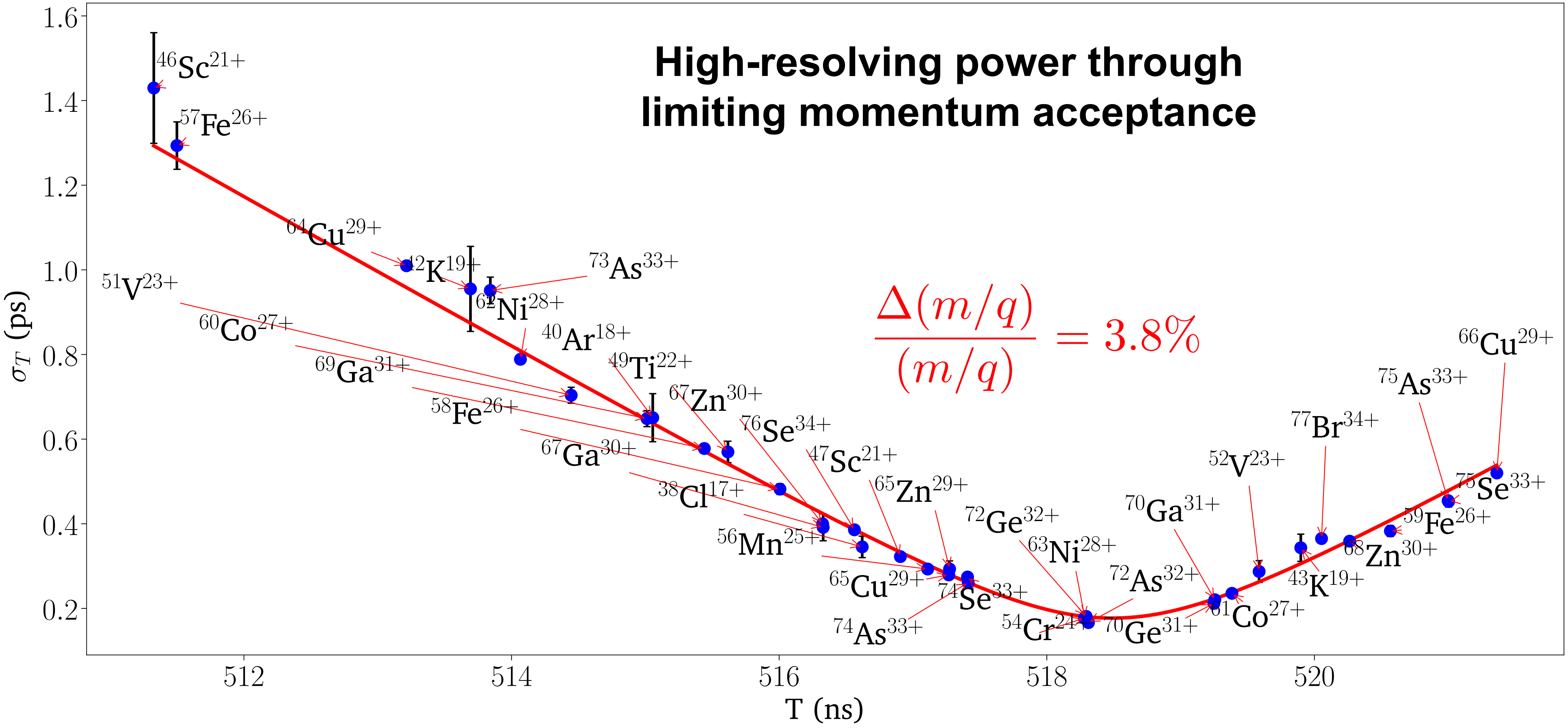


- ➢ **need to limit Bρ acceptance**
- ➢ good mass resolution for limited Bρ range

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

Mass Resolving Power in Isochronous Mode

Advantages: non-destructive detection – enables lifetime studies
no restriction of acceptance
single-ion sensitivity

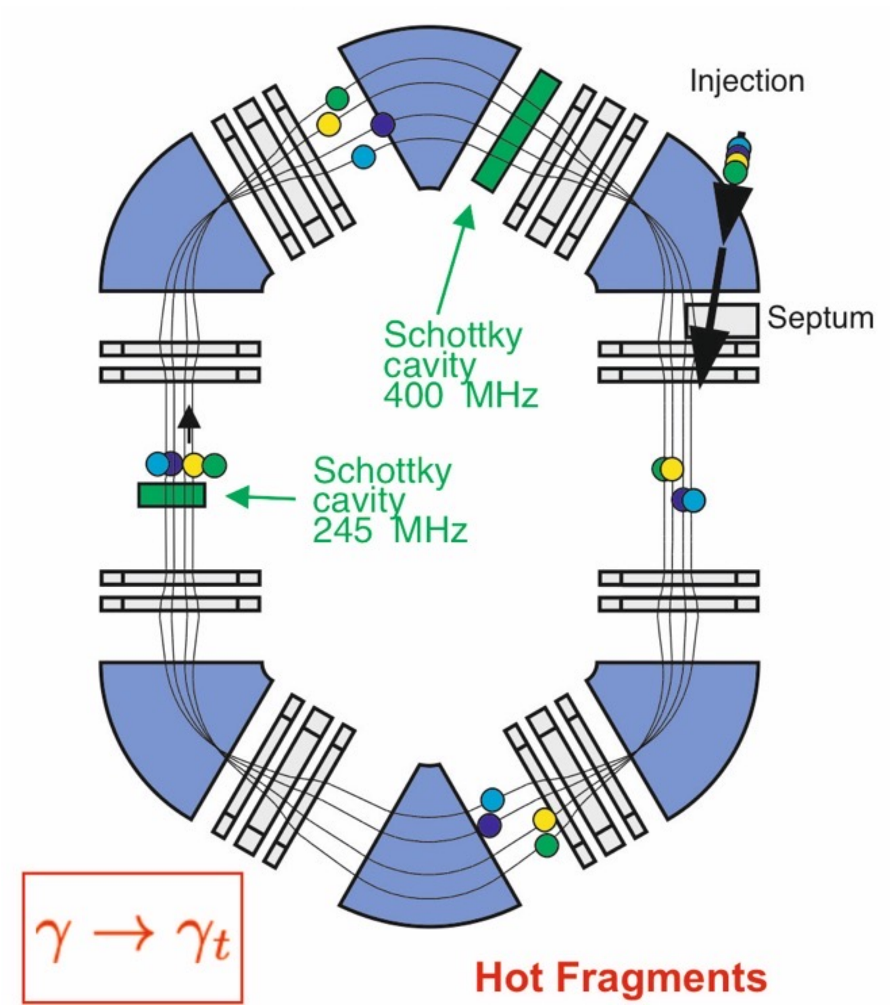


High-resolving power through limiting momentum acceptance

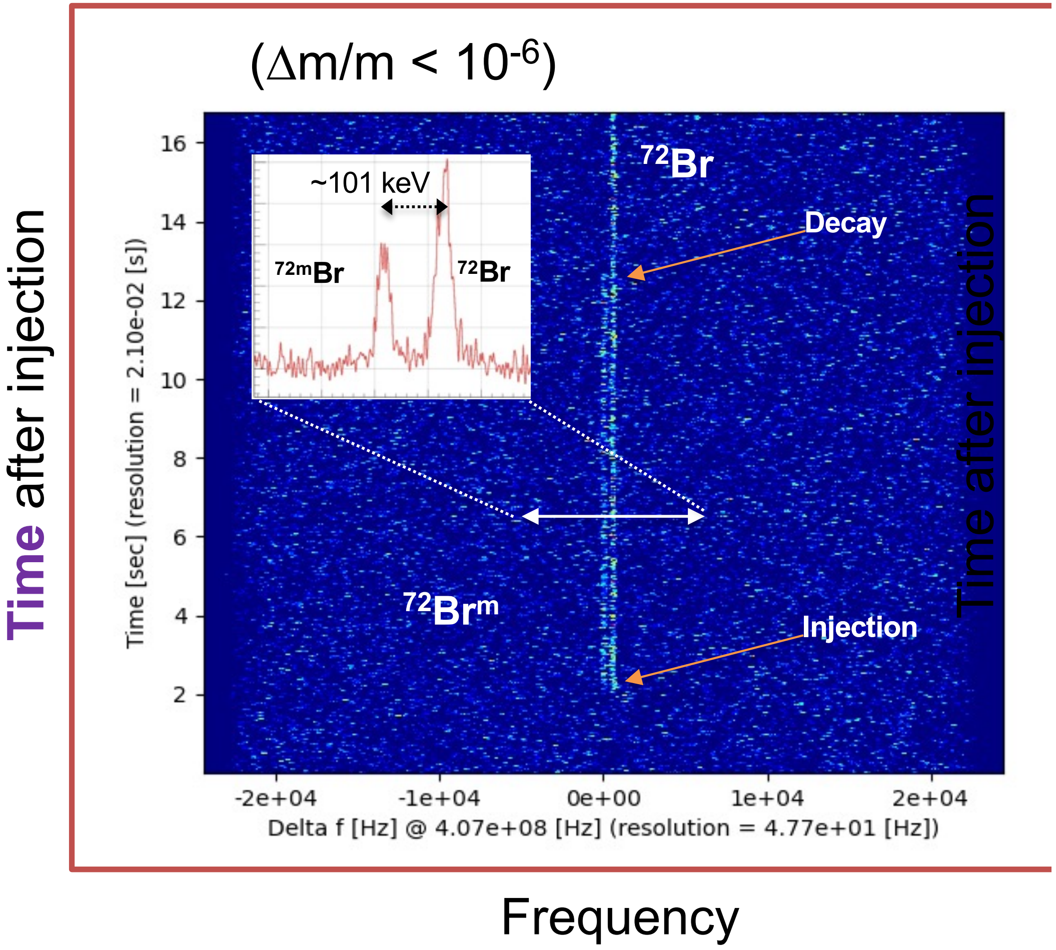
$$\frac{\Delta(m/q)}{(m/q)} = 3.8\%$$

Observation of a 101 keV isomer in ^{72}Br

Combined Schottky plus Isochronous Mass Spectroscopy (ISMS)



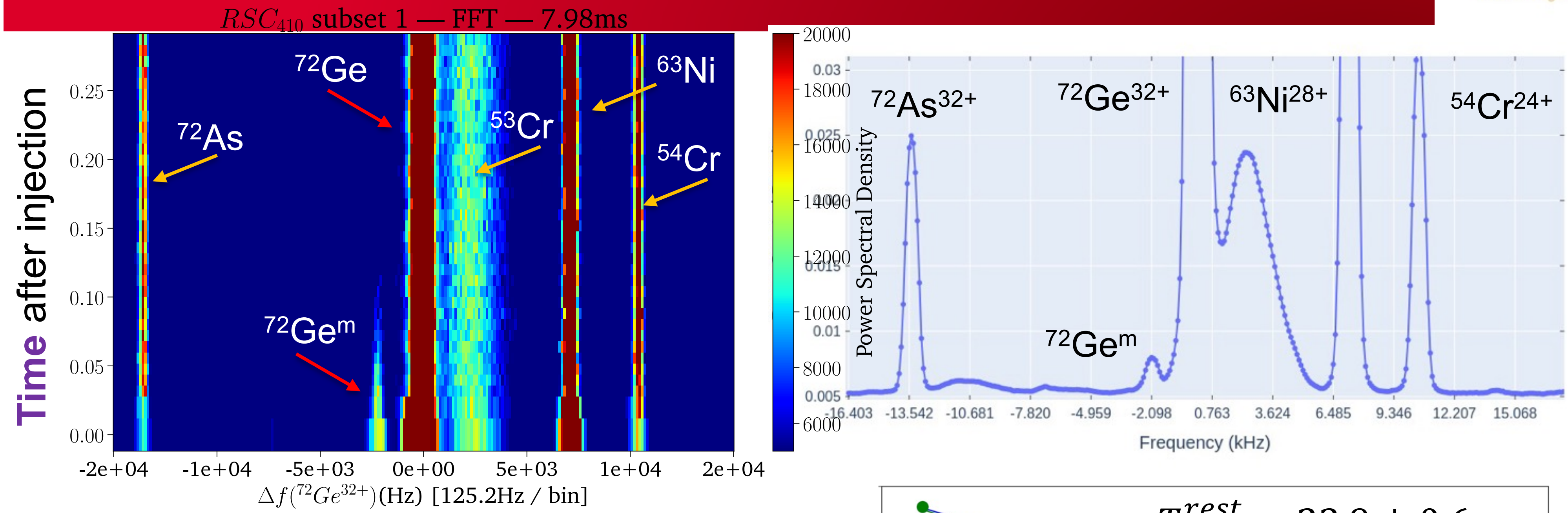
Schottky spectrum for a single event

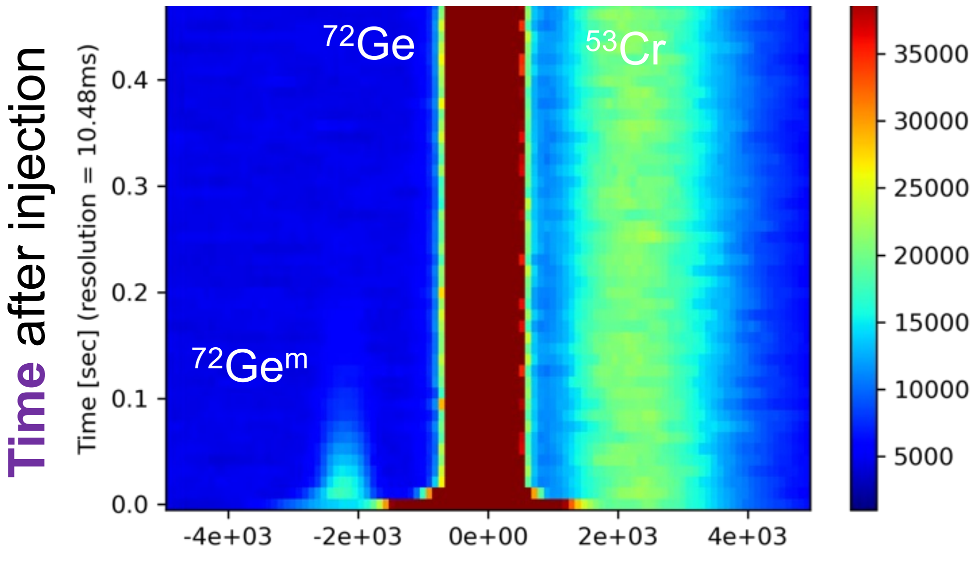


Outline

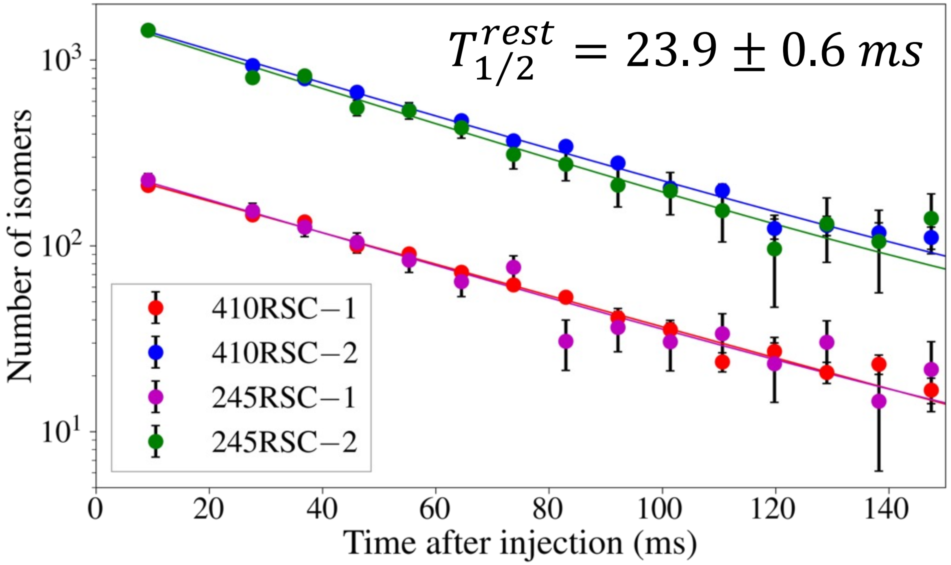
- The nuclear two-photon (or double-gamma) decay
- Mass measurements of highly-charged ions in the Experimental Storage Ring (ESR) at GSI/FAIR
- **Results for the two-photon decay in ^{72}Ge and future experiments**

Observation of a very short-lived isomer in ^{72}Ge^m





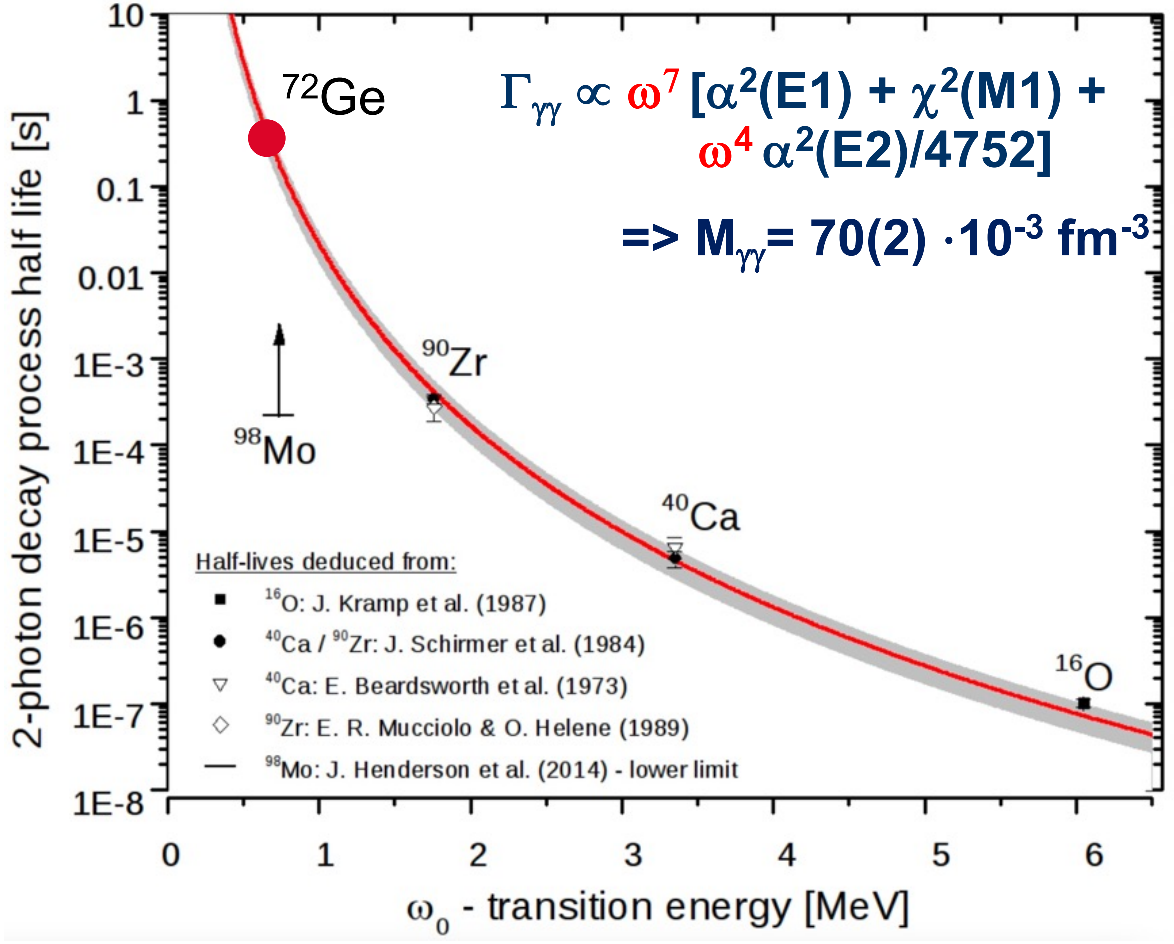
"Schottky frequency"



$$T_{1/2}^{rest} = 23.9 \pm 0.6\ ms$$

D. Freire Fernandez et al., PRL 133, 022502
https://arxiv.org/abs/2312.11313

Comparison of two-photon decay half lives



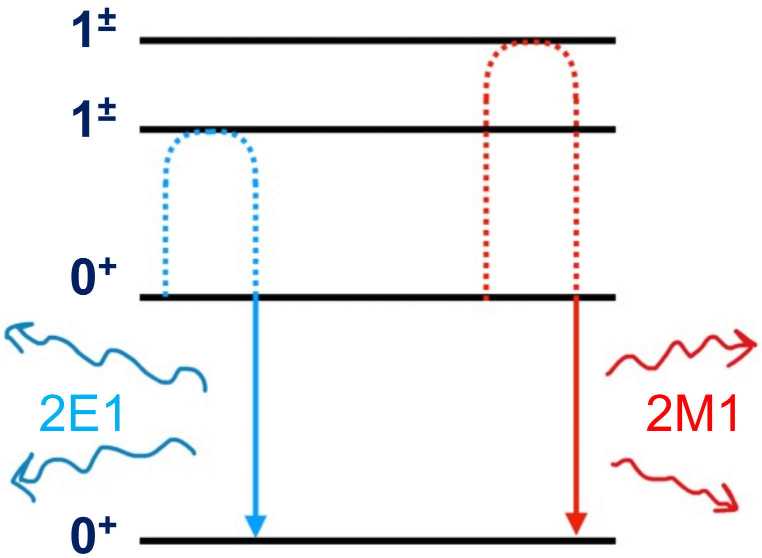
$$\Gamma_{\gamma\gamma} \propto \omega^7 [\alpha^2(E1) + \chi^2(M1) + \omega^4 \alpha^2(E2)/4752]$$

$$\Rightarrow M_{\gamma\gamma} = 70(2) \cdot 10^{-3}\ \mathrm{fm}^{-3}$$

Two-photon decay in ^{72}Ge substantially faster than expected
Need to determine electric dipole polarizabilities α^2(E1,E2,)
and magnetic dipole susceptibility χ^2(M1)

How to determine the nuclear matrix elements ?

Two-photon decay

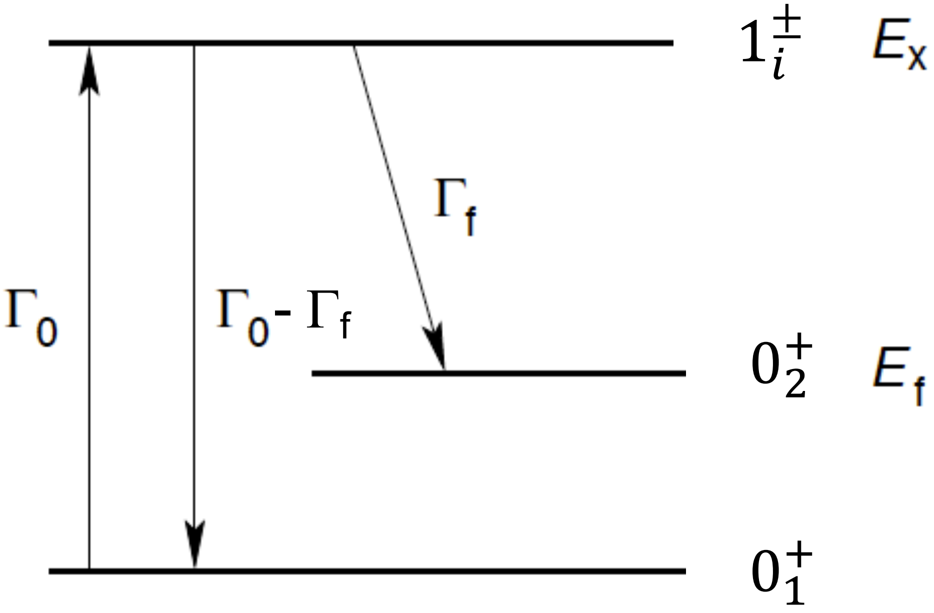


$$\sum_i \frac{\langle 0_1^+||M(\sigma L)||I_i^\pi\rangle\langle I_i^\pi||M(\sigma L)||0_2^+\rangle}{E_i - \frac{1}{2}\Delta E_{12}}$$

Nuclear Resonance Fluorescence

$\Gamma_0 \sim B(\sigma L;\, 0_1 \rightarrow 1^\pm)\quad E_x^{2L+1}$

$\Gamma_f \sim B(\sigma L;\, 1^\pm \rightarrow 0_2)\ (E_x - E_f)^{2L+1}$

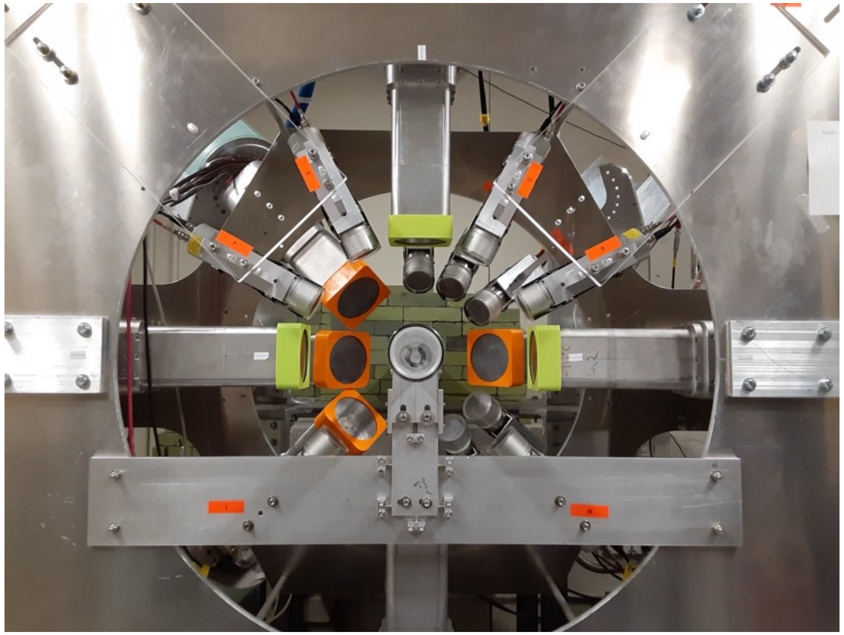


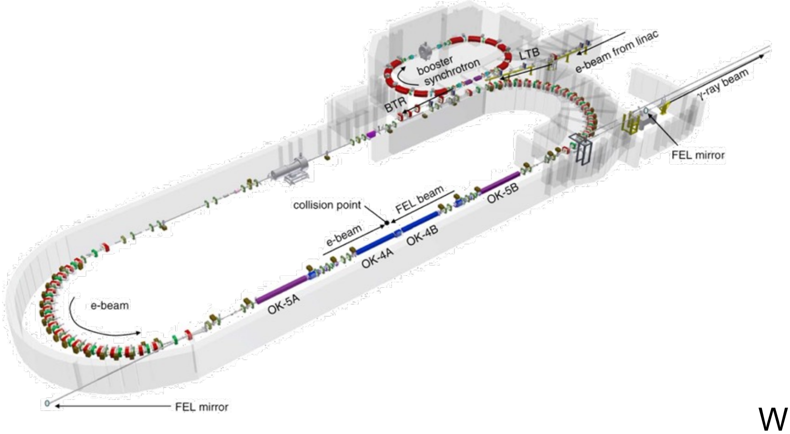
For selected 1± states (with large branching):

$$\langle 0_1^+||M(\sigma 1)||1_i^\pm\rangle\langle 1_i^\pm||M(\sigma 1)||0_2^+\rangle$$

How to determine the nuclear matrix elements ?

Experiment with the Clover Array at HIγS
B. Crider, A.D. Ayangeakaa, E. Peters et al.
April 2024

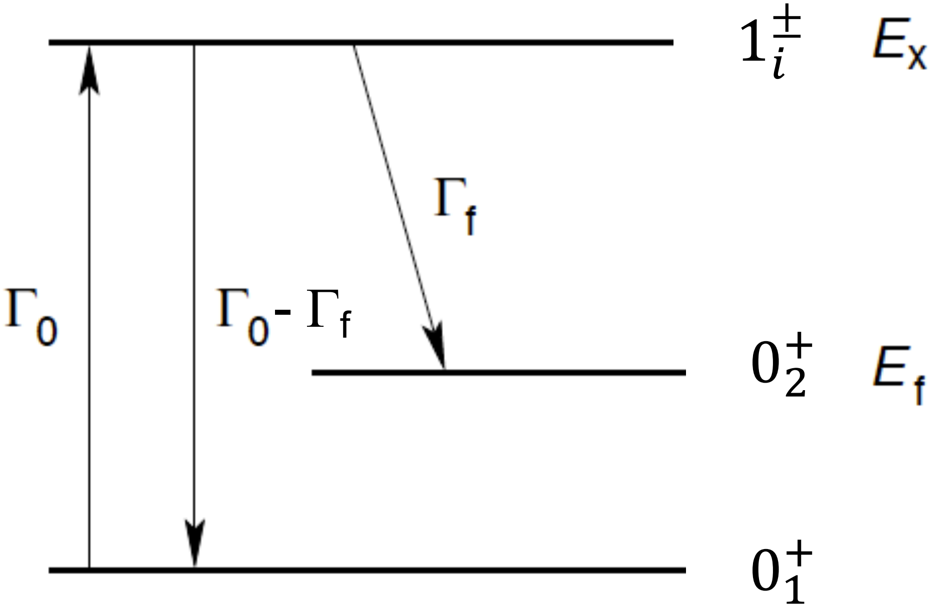




Nuclear Resonance Fluorescence

$\Gamma_0 \sim B(\sigma L;\, 0_1 \rightarrow 1^{\pm})\quad E_x^{2L+1}$

$\Gamma_f \sim B(\sigma L;\, 1^{\pm} \rightarrow 0_2)\ (E_x - E_f)^{2L+1}$



For selected 1± states (with large branching):

$$\langle 0_1^{+} || M(\sigma 1) || 1_i^{\pm} \rangle \langle 1_i^{\pm} || M(\sigma 1) || 0_2^{+} \rangle$$

How to determine the nuclear matrix elements ?

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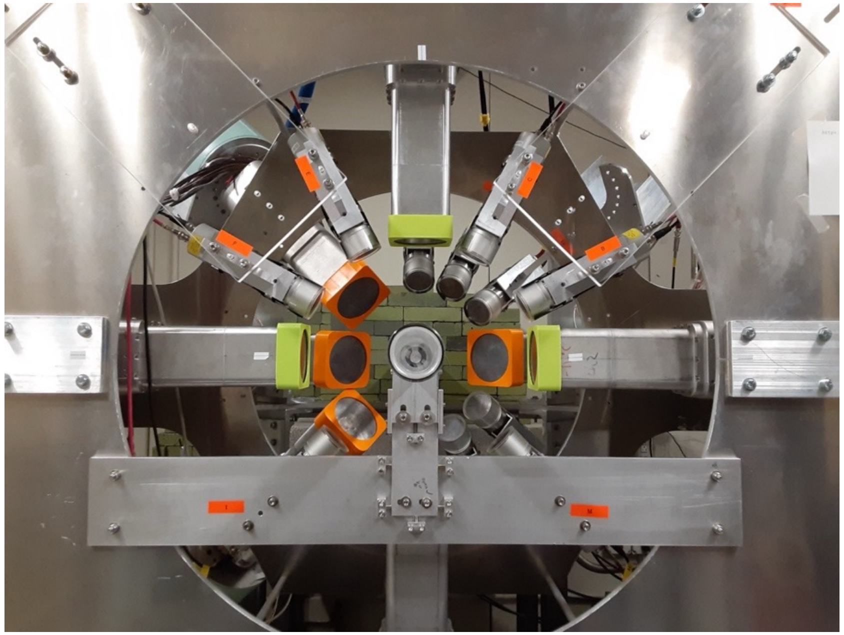
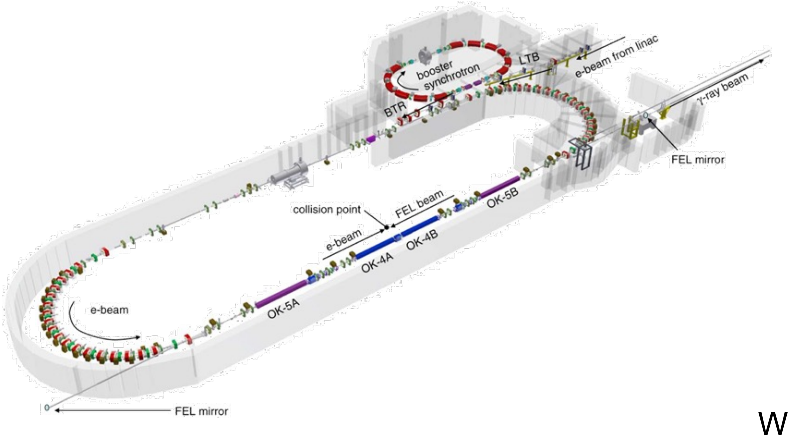
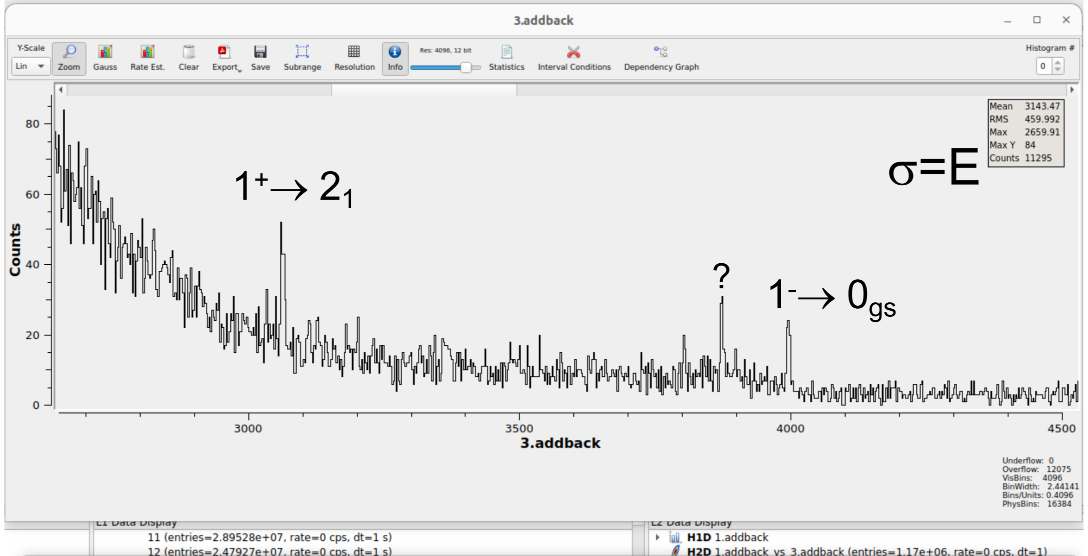




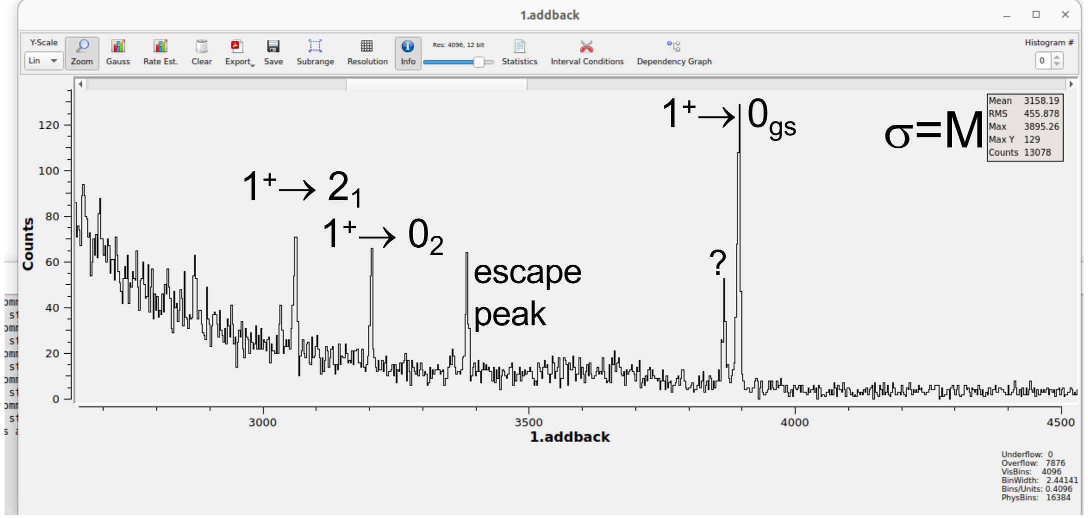
Decay of $I^\pi=1^+$ state at 3.895 MeV



```
Mean    3143.47
RMS     459.992
Max     2659.91
Max Y   84
Counts  11295
```

```
Underflow:  0
Overflow:   12075
VisBins:    4096
BinWidth:   2.44141
Bins/Units: 0.4096
PhysBins:   16384
```

```
L1 Data Display
11 (entries=2.89528e+07, rate=0 cps, dt=1 s)
12 (entries=2.47927e+07, rate=0 cps, dt=1 s)
L2 Data Display
H1D 1.addback
H2D 1.addback vs 3.addback (entries=1.17e+06, rate=0 cps, dt=1)
```

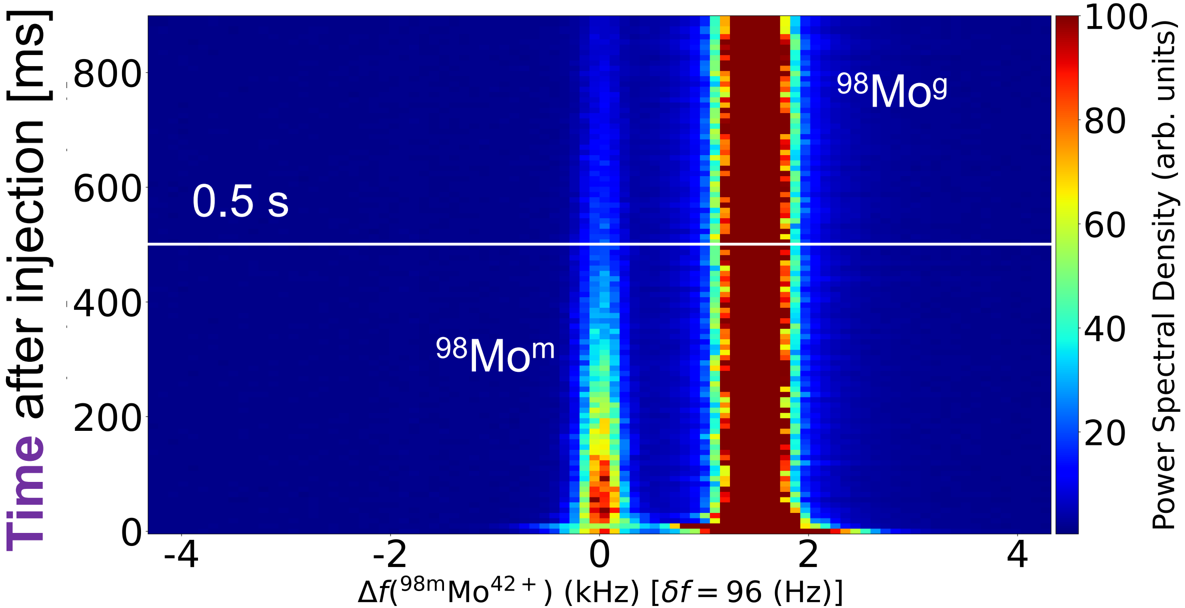


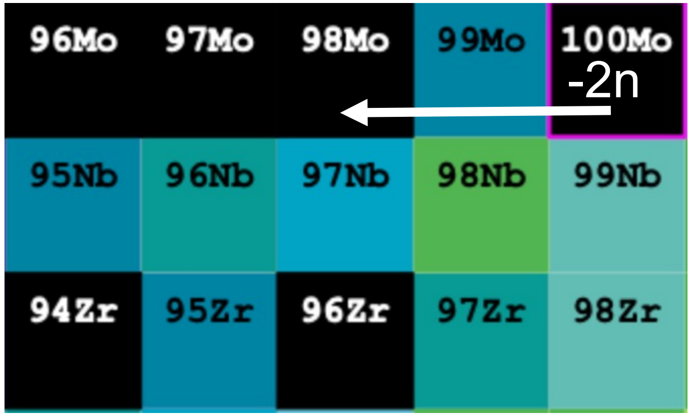
```
Mean    3158.19
RMS     455.878
Max     3895.26
Max Y   129
Counts  13078
```

```
Underflow:  0
Overflow:   7876
VisBins:    4096
BinWidth:   2.44141
Bins/Units: 0.4096
PhysBins:   16384
```

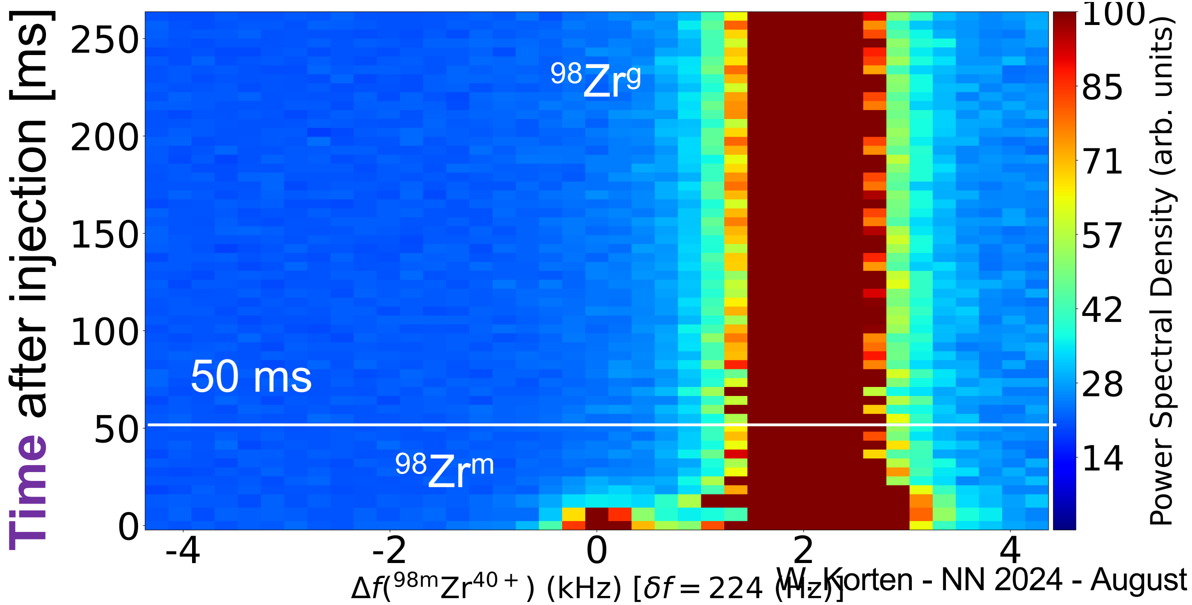
New ESR experiments on ^{98}Mo and ^{98}Zr (May 2024)

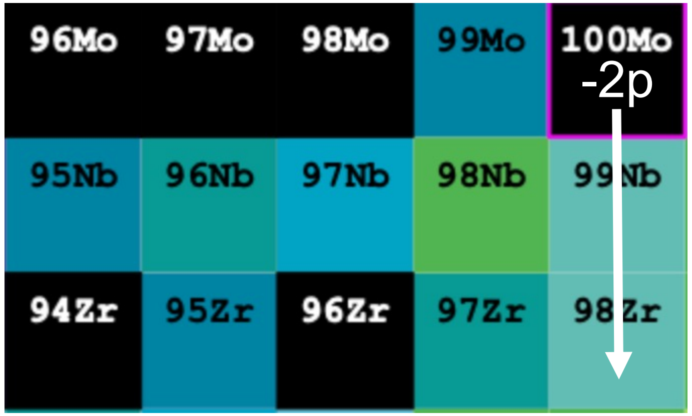
^{100}Mo at ~460 A.MeV, ~10^9 ions per spill (every 2-5s), online results





96Mo	97Mo	98Mo	99Mo	100Mo -2n
95Nb	96Nb	97Nb	98Nb	99Nb
94Zr	95Zr	96Zr	97Zr	98Zr





96Mo	97Mo	98Mo	99Mo	100Mo -2p
95Nb	96Nb	97Nb	98Nb	99Nb
94Zr	95Zr	96Zr	97Zr	98Zr

Summary

- The $0^+ \rightarrow 0^+$ E0 decay to the ground state in even-mass isotopes may proceed via nuclear two-photon decay.
- The competing first-order decays (internal electron conversion or internal pair conversion) can be be eliminated for low-energy decays (<1.022 MeV) in bare nuclei.
- Combined Schottky and Isochronous Mass Spectroscopy (ISMS) was demonstrated to measure short-lived isomers (>few ten ms) down to low energies of ~100 keV at A~70 → $\frac{\Delta M}{M} < 2\,10^{-6}$
- Partial halflife of the two-photon decay of the 0^+ isomer in ^{72}Ge $T_{1/2}$=25(2) ms → much faster than expected → Direct search for double-γ decay in ^{72}Ge using (p,p') reaction planned
- Follow-up experiment on ^{98}Mo & ^{98}Zr performed at GSI in May 2024 → Very promising new technique for 0^+ isomer searches at FAIR