Isomeric states of nuclei far from stability

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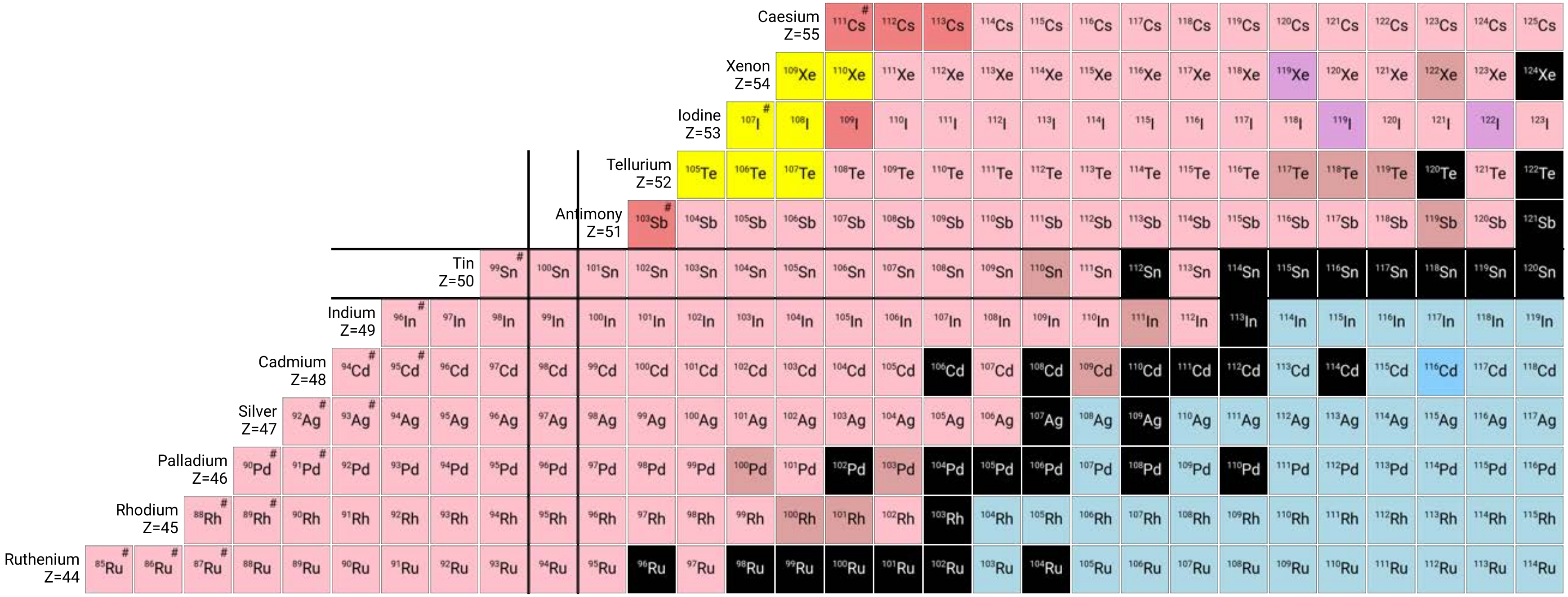
▪ Motivation for searching for isomeric states of nuclei in the region of ^{100}Sn

- ➢ ^{100}Sn is the heaviest self-conjugate doubly-magic nucleus in the chart of nuclides, and therefore, area of interest in experimental and theoretical nuclear physics
- ➢ The region of nuclei decaying with β^- -emission from the ground states, and often have a long-lived isomeric state can occur
- ➢ The properties of nuclear isomers are significant for the understanding of nuclear structure because they provide stringent tests for nuclear models
- ➢ There is a broad field of applications for nuclear isomers, ranging from new possibilities for the storage of energy to the impact on nuclear astrophysics and the synthesis of the elements in the universe
- ➢ Recently, new isotopes in this region were identified, and their half-lives, decay properties have been measured in-beam and decay spectroscopy. There is a large uncertainty still associated with the mass of ^{100}Sn (m ≈ 300 keV)
- ➢ Direct mass measurement reflect their total binding energy and allow to explore the nuclear structure and excitation in this region of the nuclear chart



Caesium Z=55																^{111}Cs #	^{112}Cs	^{113}Cs	^{114}Cs	^{115}Cs	^{116}Cs	^{117}Cs	^{118}Cs	^{119}Cs	^{120}Cs	^{121}Cs	^{122}Cs	^{123}Cs	^{124}Cs	^{125}Cs
Xenon Z=54															^{109}Xe	^{110}Xe	^{111}Xe	^{112}Xe	^{113}Xe	^{114}Xe	^{115}Xe	^{116}Xe	^{117}Xe	^{118}Xe	^{119}Xe	^{120}Xe	^{121}Xe	^{122}Xe	^{123}Xe	^{124}Xe
Iodine Z=53														^{107}I #	^{108}I	^{109}I	^{110}I	^{111}I	^{112}I	^{113}I	^{114}I	^{115}I	^{116}I	^{117}I	^{118}I	^{119}I	^{120}I	^{121}I	^{122}I	^{123}I
Tellurium Z=52													^{105}Te	^{106}Te	^{107}Te	^{108}Te	^{109}Te	^{110}Te	^{111}Te	^{112}Te	^{113}Te	^{114}Te	^{115}Te	^{116}Te	^{117}Te	^{118}Te	^{119}Te	^{120}Te	^{121}Te	^{122}Te
Antimony Z=51												^{103}Sb #	^{104}Sb	^{105}Sb	^{106}Sb	^{107}Sb	^{108}Sb	^{109}Sb	^{110}Sb	^{111}Sb	^{112}Sb	^{113}Sb	^{114}Sb	^{115}Sb	^{116}Sb	^{117}Sb	^{118}Sb	^{119}Sb	^{120}Sb	^{121}Sb
Tin Z=50									^{99}Sn #	^{100}Sn	^{101}Sn	^{102}Sn	^{103}Sn	^{104}Sn	^{105}Sn	^{106}Sn	^{107}Sn	^{108}Sn	^{109}Sn	^{110}Sn	^{111}Sn	^{112}Sn	^{113}Sn	^{114}Sn	^{115}Sn	^{116}Sn	^{117}Sn	^{118}Sn	^{119}Sn	^{120}Sn
Indium Z=49							^{96}In #	^{97}In	^{98}In	^{99}In	^{100}In	^{101}In	^{102}In	^{103}In	^{104}In	^{105}In	^{106}In	^{107}In	^{108}In	^{109}In	^{110}In	^{111}In	^{112}In	^{113}In	^{114}In	^{115}In	^{116}In	^{117}In	^{118}In	^{119}In
Cadmium Z=48						^{94}Cd #	^{95}Cd #	^{96}Cd	^{97}Cd	^{98}Cd	^{99}Cd	^{100}Cd	^{101}Cd	^{102}Cd	^{103}Cd	^{104}Cd	^{105}Cd	^{106}Cd	^{107}Cd	^{108}Cd	^{109}Cd	^{110}Cd	^{111}Cd	^{112}Cd	^{113}Cd	^{114}Cd	^{115}Cd	^{116}Cd	^{117}Cd	^{118}Cd
Silver Z=47					^{92}Ag #	^{93}Ag #	^{94}Ag	^{95}Ag	^{96}Ag	^{97}Ag	^{98}Ag	^{99}Ag	^{100}Ag	^{101}Ag	^{102}Ag	^{103}Ag	^{104}Ag	^{105}Ag	^{106}Ag	^{107}Ag	^{108}Ag	^{109}Ag	^{110}Ag	^{111}Ag	^{112}Ag	^{113}Ag	^{114}Ag	^{115}Ag	^{116}Ag	^{117}Ag
Palladium Z=46				^{90}Pd #	^{91}Pd #	^{92}Pd	^{93}Pd	^{94}Pd	^{95}Pd	^{96}Pd	^{97}Pd	^{98}Pd	^{99}Pd	^{100}Pd	^{101}Pd	^{102}Pd	^{103}Pd	^{104}Pd	^{105}Pd	^{106}Pd	^{107}Pd	^{108}Pd	^{109}Pd	^{110}Pd	^{111}Pd	^{112}Pd	^{113}Pd	^{114}Pd	^{115}Pd	^{116}Pd
Rhodium Z=45			^{88}Rh #	^{89}Rh #	^{90}Rh	^{91}Rh	^{92}Rh	^{93}Rh	^{94}Rh	^{95}Rh	^{96}Rh	^{97}Rh	^{98}Rh	^{99}Rh	^{100}Rh	^{101}Rh	^{102}Rh	^{103}Rh	^{104}Rh	^{105}Rh	^{106}Rh	^{107}Rh	^{108}Rh	^{109}Rh	^{110}Rh	^{111}Rh	^{112}Rh	^{113}Rh	^{114}Rh	^{115}Rh
Ruthenium Z=44	^{85}Ru #	^{86}Ru #	^{87}Ru #	^{88}Ru	^{89}Ru	^{90}Ru	^{91}Ru	^{92}Ru	^{93}Ru	^{94}Ru	^{95}Ru	^{96}Ru	^{97}Ru	^{98}Ru	^{99}Ru	^{100}Ru	^{101}Ru	^{102}Ru	^{103}Ru	^{104}Ru	^{105}Ru	^{106}Ru	^{107}Ru	^{108}Ru	^{109}Ru	^{110}Ru	^{111}Ru	^{112}Ru	^{113}Ru	^{114}Ru

▪ Time-of-Flight Mass Spectrometry

First step: Ions are stored in a trap and have a thermal velocity distribution

Second step: Ions with the same mass and same kinetic energy fly along a path in a characteristic time

- The m/q ratio of ions with a fixed kinetic energy can be determined:

$$E_{kin,z}=\frac{1}{2}mV_z^2=qU(z),\ \left(\frac{m}{q}\right)=2U(z)\frac{t^2}{z^2}=A(t_{means}-t_{TFS}^2)$$

were A - calibration constant, t_{means}- flight time, $t_{T\,FS}$- delay by the signal processing

- TOF of ions in comparison with a reference ion:

$$\frac{m}{m_{calib}}=\left(\frac{t}{t_{calib}}\right)^2$$

- The mass resolving power:

$$R_m=\frac{m/q}{\Delta(m/q)}=\frac{t^2}{\Delta t^2}$$

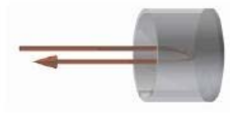
- To increase R_m => increase the flight path

Advantages:

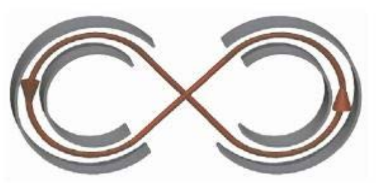
- large mass range, short half-lives nuclei
- R_m = 100.000 ÷ 200.000

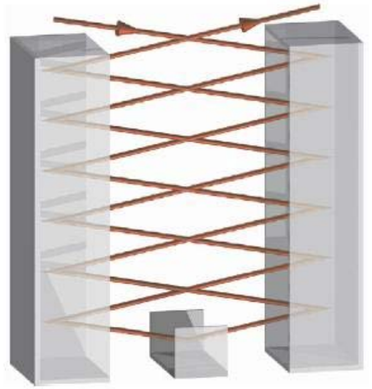
Δm= 30 keV/c^2 ÷ 200 keV/c^2

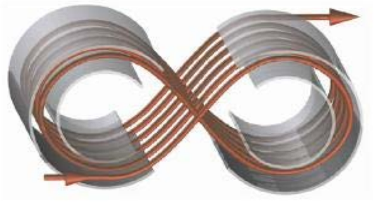

Linear TOF-MS


Reflector-TOF-MS


Multiple-Reflection TOF-MS (closed Path)


Multiple-Turn TOF-MS (closed path)


Multiple-Reflection TOF-MS (open Path)


Multiple-Turn TOF-MS (open path)

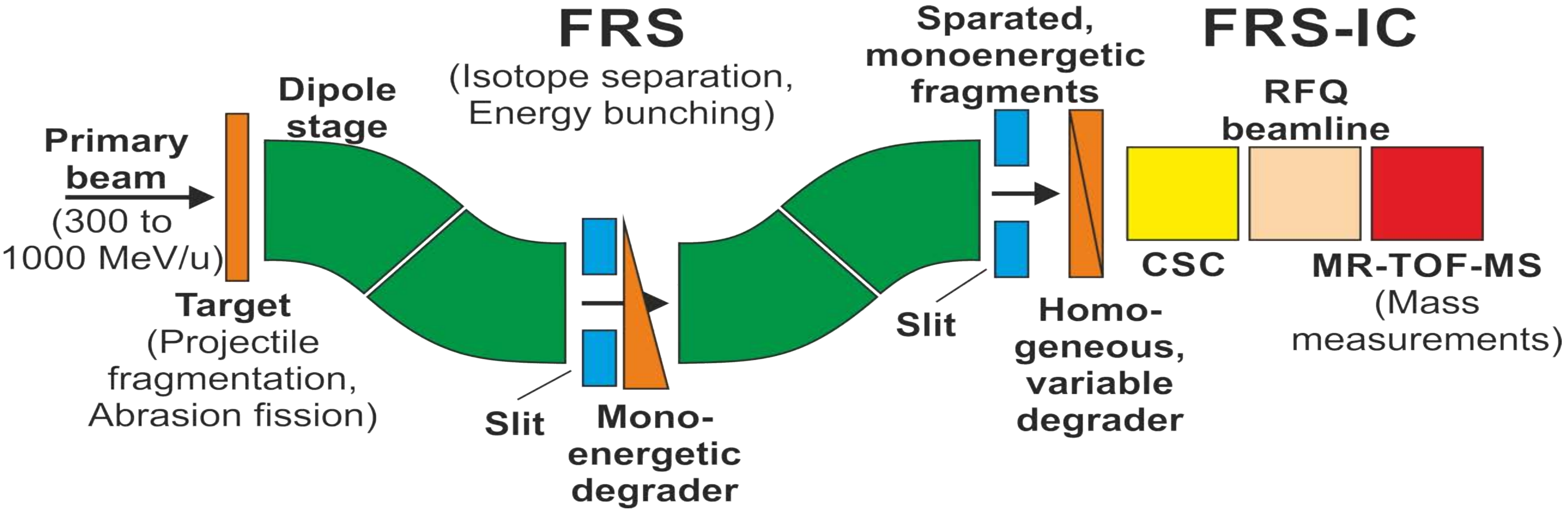
▪ Experimental Setup - FRS-IC

- Installed at the high-energy facility at GSI
- Fragment Separator - beamline of Radio Frequency Quadrupoles – ions separation
- The Cryogenic Stopping Cell (CSC) - slowing down of the exotic nuclei produced at relativistic energies
- Multiple-Reflection Time-of-Flight Mass Spectrometer (MR-TOF-MS) - direct mass
- Exotic nuclei were produced via projectile fragmentation and abrasion-fission

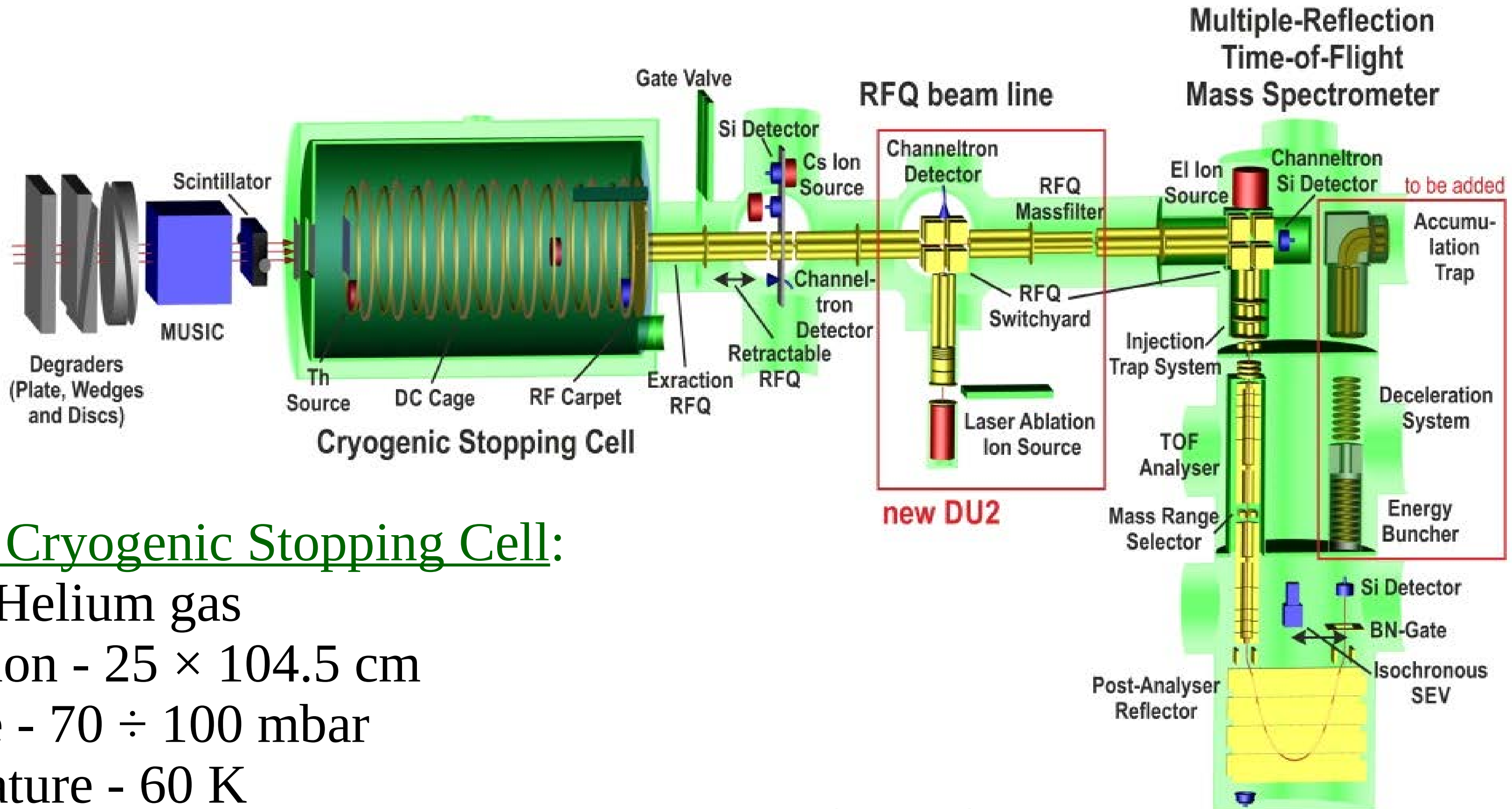
The primary beam: ^{124}Xe $E_{kin} = 600$ MeV/u

Beam:
- provided heavy-ion synchrotron SIS-18
- intensity - up to $3 \cdot 10^8$ ions per spill
- spill length - 500 ms

Target: ^{9}Be - σ = 1.622 g/cm^2



▪ Multiple-Reflection Time-of-Flight Mass Spectrometer - MR-TOF-MS



Gas-Filled Cryogenic Stopping Cell:

- ➢ Filled - Helium gas
- ➢ Dimension - 25 × 104.5 cm
- ➢ Pressure - 70 ÷ 100 mbar
- ➢ Temperature - 60 K
- ➢ Total efficiency - 20 %

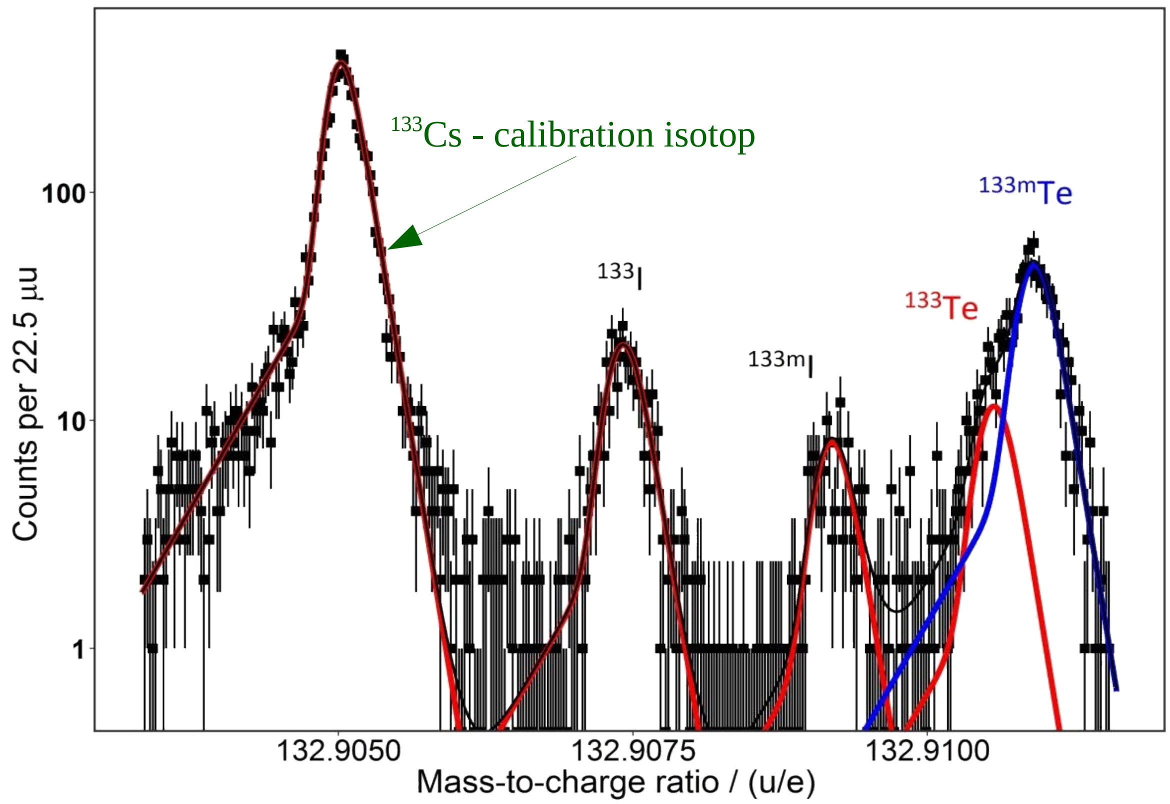
Advantages:

Additional flight path in the analyser increases the spatial separation between ions of different masses and thus the mass resolving power

MR-TOF-MS system:

- ➢ Ions E_{kin} ~ eV
- ➢ Injection rate - 50 Hz
- ➢ Control of the number in the time-of-flight analyser
- ➢ Mass Range Selector (MRS) Mass-to-charge window
- ➢ Post-Analyser Reflector - energy-time focus => the position final tuning

▪ Mass measurements - Data analysis



TOF spectrum => M-to-Ch spectrum:

$$\frac{m}{q}=\frac{c\left(t_{exp}-t_0\right)^2}{\left(1+N_{it}b\right)^2} \qquad c=\frac{2U_{eff}}{l_{tfs}}, \quad b=\frac{l_t}{l_{tfs}}$$

c, t_0 and b from calibrant ions

- ➢ Fluctuations during the measurement:
  1) changes in the potentials
  2) thermal expansion of the analyser
- ➢ Drift correction in the TOF spectrum: sum of spectra (few seconds length)

Ion Identification: based on the mass-to-charge ratio of the ions

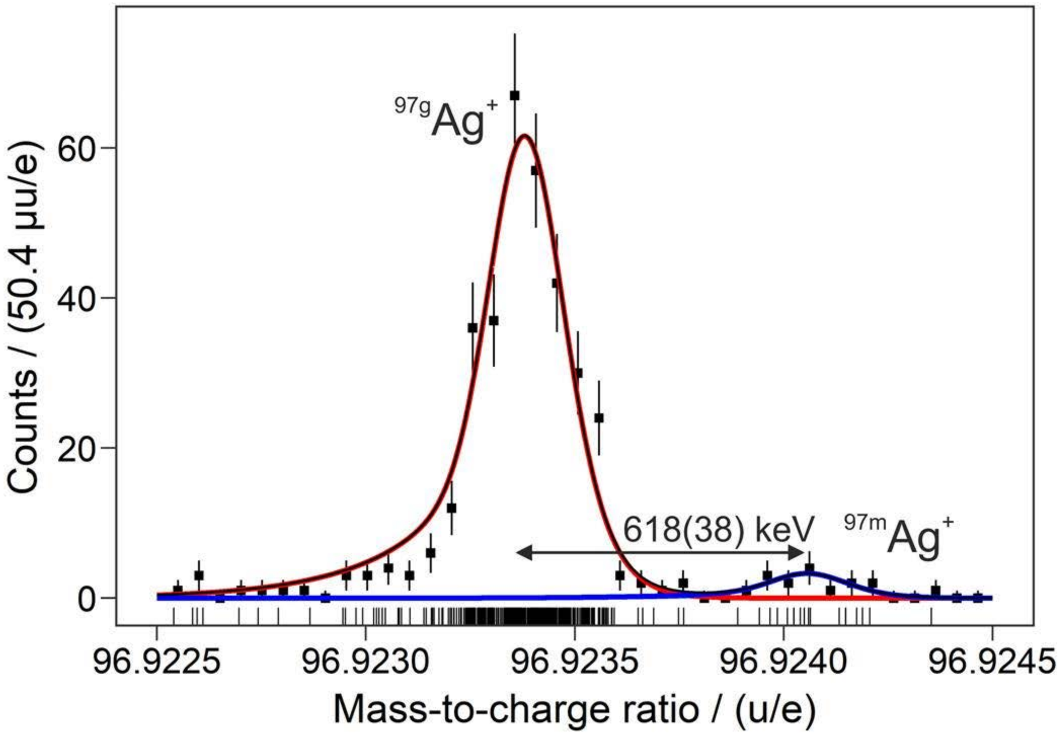
Verification:

1) Comparison with the results of simulations or independent identification methods
2) Comparison of the identifications for different turn numbers N_{it}
3) The correlation between the MR-TOF-MS and the primary beam is checked

Fitting procedure:

1) Least-squares minimization exponentially modified Gaussian (EMG)
2) μ_G of the Gaussian determines the mass-to-charge values is
3) overlapping peaks with very low number of events

▪ Isomeric State of ^{97}Ag - Experimental results



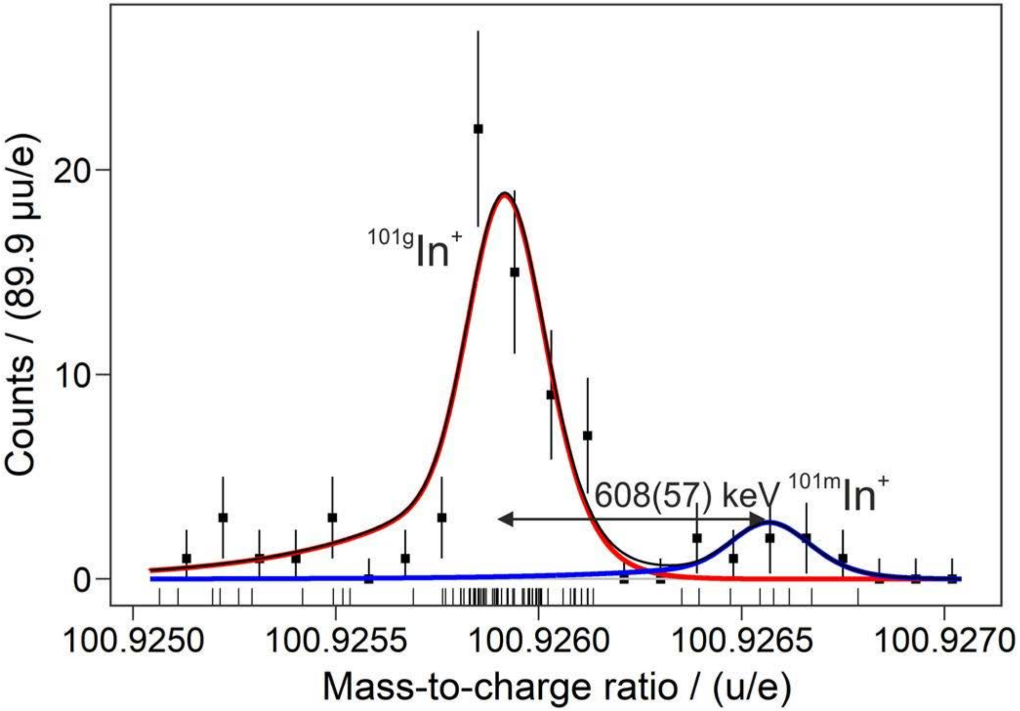
- ^{97}Ag was produced in fragmentation
  σ = 1.2 μbarn
- ^{97m}Ag 14 counts were measured
- Isomer-to-Ground state ratio
  N_{iso}/N_{gr} = 0.078 ± 0.005
  σ = 90 nbarn
- Previously, the ground state of ^{97}Ag was measured indirectly by γ -spectroscopy
- The first direct mass measurement
- The uncertainty was reduced by almost an order of magnitude

Nuclide	**Half-life**	**Momentum**	**$ME_{FRC-IC}/E_{exc,FRS-IC}$ [keV]**	**$ME_{LIT}/E_{exc,LIT}$ [keV]**
^{97}Ag	**(25.5 ± 0.3) s**	**$9/2^+$**	**– 70904 ± 12**	**– 70830 ± 110**
^{97m}Ag	**100 ms**	**$1/2^-$**	**618 ± 38**	**400 ± 200**

were:

- ME - mass excess of a nuclide is the difference between its actual mass and its mass number
  ME_{FRC-IC} - measured data, ME_{LIT} - literature values
- E_{exc} - excitation energy of isomeric state
  $E_{exc, FRS-IC}$ - measured data, $E_{exc,LIT}$ - literature values

▪ Isomeric States of $^{101\text{-}109}$In - Experimental results



- The first mass measurement for the ^{101}In
- ^{101}In was produced in fragmentation
  σ = 230 nbarn
- ^{101}In 9 counts were detected
- Isomer-to-Ground state ratio
  $N_{iso}/N_{gr} = 0.14 \pm 0.03$
  σ = 30 nbarn
- From the mass measurement of ^{97}Ag and ^{101}In
  Q_{α}=56(23) keV was directly measured
  for the first time at

Nuclide	Half-life	Momentum	$ME_{FRC\text{-}IC}/E_{exc,FRS\text{-}IC}$ [keV]	$ME_{LIT}/E_{exc,LIT}$ [keV]
^{101}In	(15.1 ± 1.1) s	$9/2^{+}$	− 68535 ± 20	− 68610 ± 200
^{101m}In	10 s	$1/2^{-}$	608 ± 57	550 ± 100
^{103}In	(60 ± 1) s	$9/2^{+}$	− 74631 ± 25	− 74633 ± 10
^{103m}In	(34 ± 2) s	$1/2^{-}$	689 ± 77	631.7 ± 0.1
^{105}In	(5.07 ± 0.07) m	$9/2^{+}$	− 79677 ± 31	− 79641 ± 10
^{105m}In	(48 ± 6) s	$1/2^{-}$	702 ± 27	674.08 ± 0.25
^{107}In	(32.4 ± 0.3) m	$9/2^{+}$	− 83583 ± 27	− 83564 ± 11
^{107m}In	(50.4 ± 0.6) s	$1/2^{-}$	663 ± 22	678.5 ± 0.3
^{109}In	(4.167 ± 0.018) h	$9/2^{+}$	− 86522 ± 34	− 86490 ± 4
^{109m}In	(1.34 ± 0.07) m	$1/2^{-}$	651 ± 27	650 . 1 ± 0.3
^{109m}In	(209 ± 6) ms	$19/2^{+}$	2098 ± 11	2101.8 ± 0.2

- Odd $^{103-109}$In also were measured

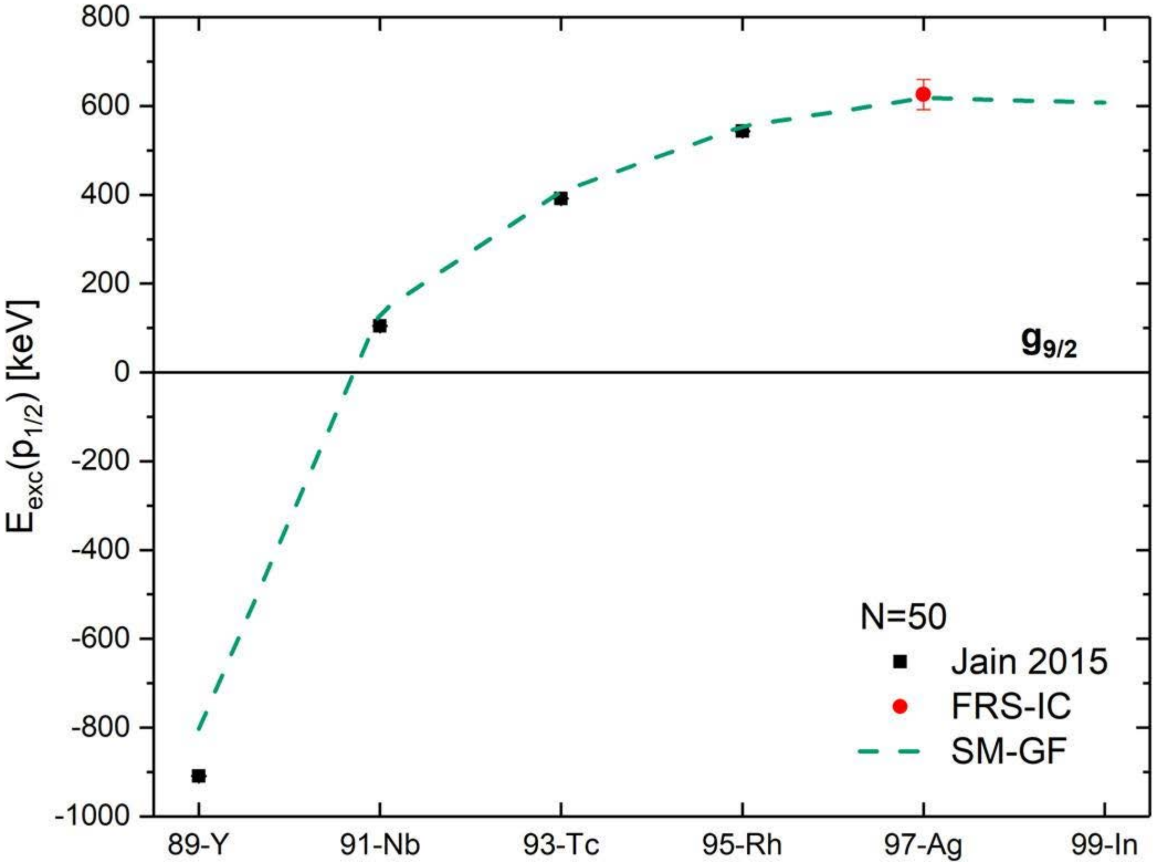
- In this isotopic chain:
  ground state $9/2^{+}$
  isomeric state $1/2^{-}$

- The mass excess values, excitation energies are in good agreement with previous experiments

▪ Isomeric States - Theoretical results

Excitation energy of the $1/2^-$ isomeric state in odd-even N=50 nuclei:

- ● measured with the MR-TOF-MS
- ■ A.K. Jain, Atlas of nuclear isomers, Nucl. Data Sheets 128 (2015) 1–130
- - - theotetical calculations



- ➢ The evolution of the proton $p_{1/2}$ and $g_{9/2}$ single-hole energies was studied using shell model (SM) approaches, and isospin-asymmetric interaction (GF) in a ($\pi\nu$ $p_{1/2}$, $g_{9/2}$) model space, outside a hypothetical ^{76}Sr core

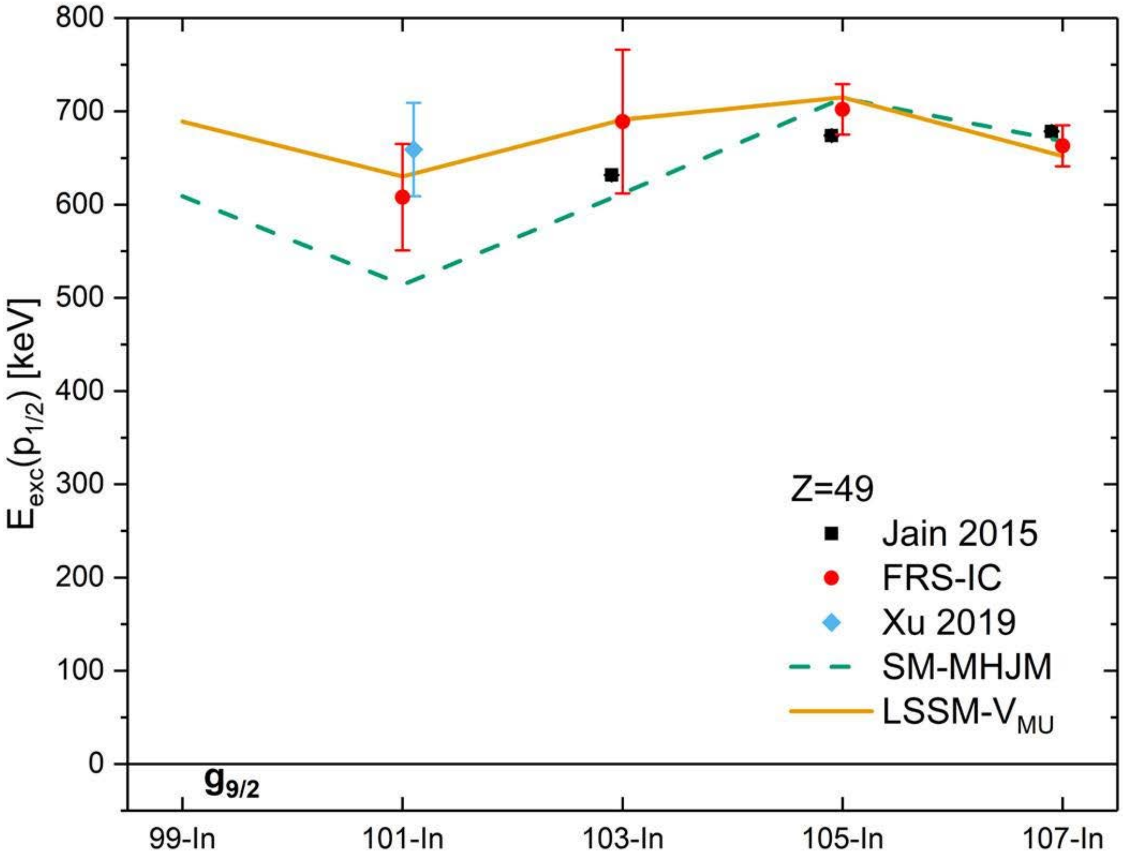
- ➢ The theory is in agreement with the measured data

- ➢ Extrapolation of the ^{99}In value was possible

▪ Isomeric States - Theoretical results

Excitation energy of the $1/2^-$ isomeric state in odd Indium nuclei:

- ● measured with the MR-TOF-MS
- ■ A.K. Jain, Atlas of nuclear isomers, Nucl. Data Sheets 128 (2015) 1–130
- - - theotetical calculations



- ➢ SM calculation with an ^{88}Sr core and $\pi(p_{1/2}, g_{9/2})$ ν $(g_{7/2}, d_{3/2}, d_{5/2}, s_{1/2}, h_{11/2})$ space
- ➢ The interaction was renormalized using many-body theory techniques (MHJM)
- ➢ LSSM approach, core Z, N = 50 closed shells and πν(p1/2, g 9/2) ν(g7/2, d3/2, d5/2, s 1/2, h11/2) model space
- ➢ Additional interaction was V_{MU} in the πν(gdsh) space
- ➢ Results show a flat trend along the indium chain
- ➢ Impact of core excitations in low-lying, dominantly single hole states

▪ Conclusions

- The high sensitivity, mass resolving power, and dynamic range make the MR-TOF-MS an ideal tool to measure and exotic nuclei in their ground and isomeric states
- The first discovery of $1/2^{-}$ isomeric state in ^{97}Ag
- The excitation energies of the $1/2^{-}$ isomeric states in the isotopes ^{97}Ag and $^{101-109}$In were determined from direct mass measurements of the ground and isomeric states of these isotopes
- The measured masses provide information on the evolution of the mass excess values in the region below the double magic nucleus ^{100}Sn
- From the mass measurement of ^{97}Ag and ^{101}In, the Q_{α} -value of ^{101}In was measured directly and reduce the error by an order of magnitude
- Q_{α} -values are necessary and important for the rp-process calculations
- The measured excitation energies of ^{97}Ag and the odd isotopes of $^{101-109}$In, along the isotonic and isotopic chains were compared to shell-model calculations
- For the nuclei in the neighborhood of the doubly-magic spherical ^{100}Sn, the leading mechanism of the decay hindrance is associated with the axial symmetry, resulting from the polarization of the core by a few particles (or holes) on top of the closed main shells at Z = 50 and/or N = 50

Thank you for your attention