Mass determination of ^{99g,m}In and ^{98m}In

INTC-P-553

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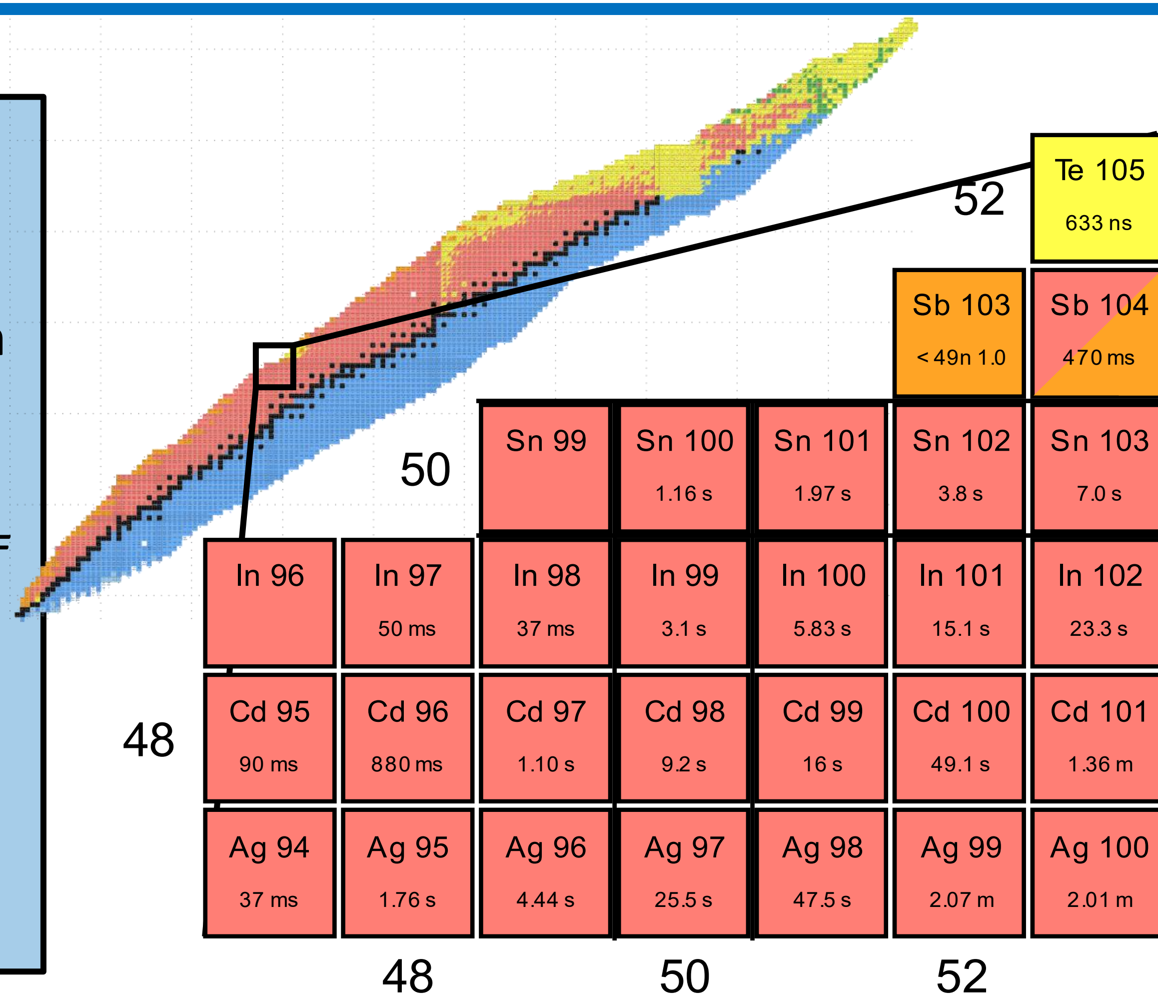
24th June 2020

64th Meeting of the INTC

Shell evolution around ^{100}Sn

- Nuclear shell model predicts shell closures (magic numbers)
- Model calculations perform well for closed shells + few nucleons in valence space
- Vicinity of doubly magic *N* = *Z* = 50 **^{100}Sn** ideal case for shell model studies
- Neutron deficient In isotopes as **^{100}Sn** core with single p-hole and n or n-holes

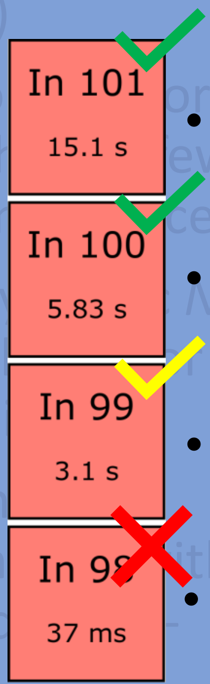


→ ***nn*- and *np*-interaction studies**

Shell evolution around ^{100}Sn

Beam development in 2018:

Measurement of three Isotopes in only three days!



- ground and isomeric states
- ground state
- ground and isomeric state mixture
- not attempted

Shell evolution around ^{100}Sn

- Nuclear sh... model predicts sh... (magic numbers)
- Model calculatio... well for closed sh... nucleons in valen...
- Vicinity of doubl... $Z = 50$ ^{100}Sn idea... shell model stud...
- Neutron deficien... isotopes as ^{100}Sn ... single p-hole and ... holes

→ *nn*- and *np*-interaction studies

Beam development in 2018:

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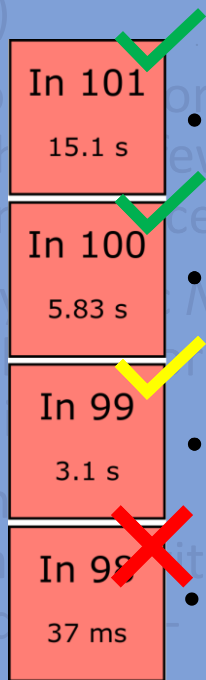
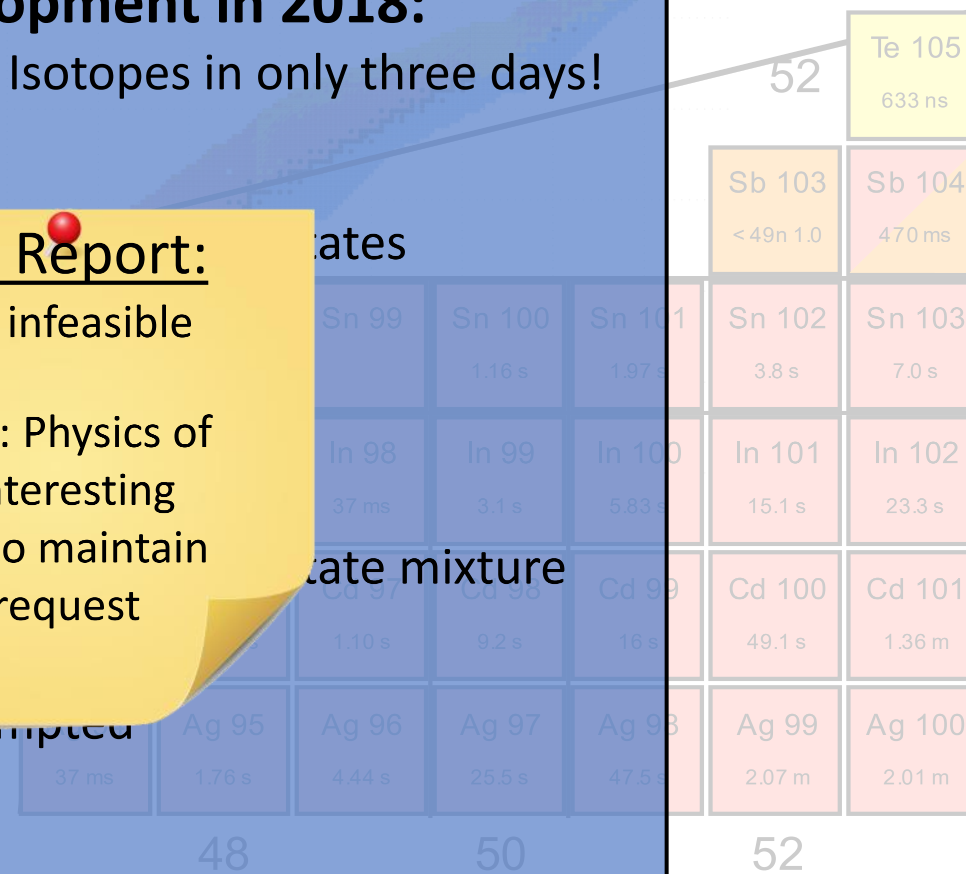


- ...tates
- ...
- ...tate mixture
- ...not attempted

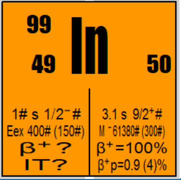
TAC Report:

^{98g}In infeasible

However: Physics of ^{98m}In interesting enough to maintain shift request



This proposal: Separate and measure ^{99g,m}In and measure ^{98m}In

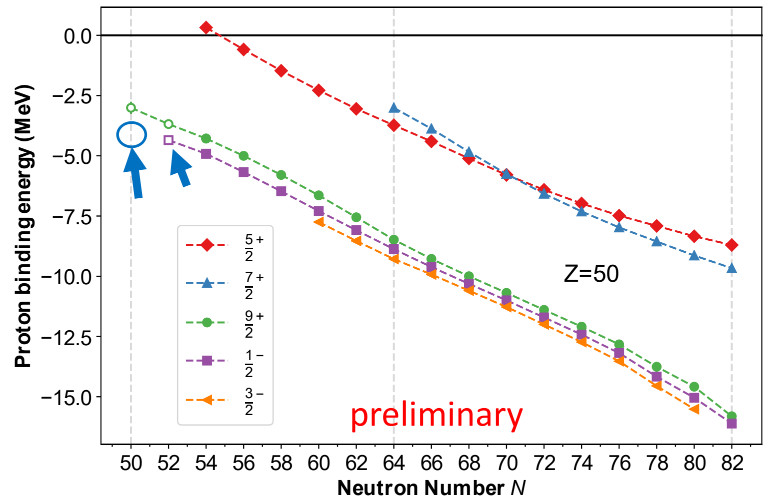


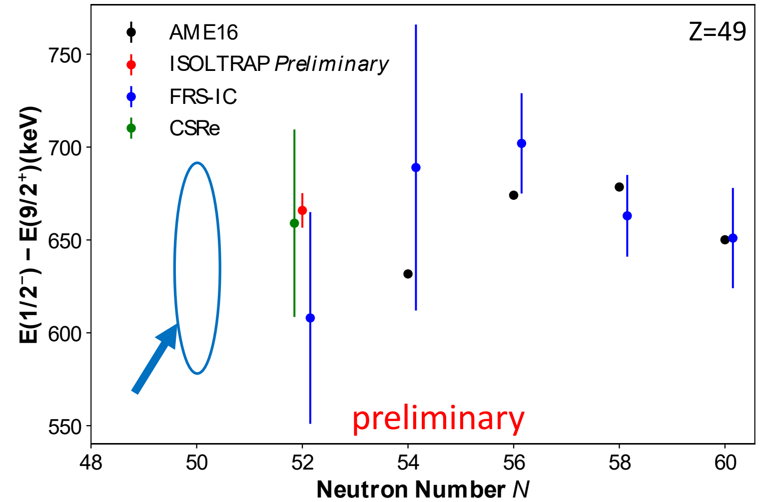
Shell evolution in odd-even ^{99}In

- Precision measurement of ^{99}In (1/2$^-$) isomeric state
  - Effective single proton separation energy along isotopic chain (type-I shell evolution)
  - Excitation energy for shell model benchmarking
- Type-II shell evolution
  - Configuration space dependendent shell evolution within same nucleus

→ Will provide essential experimental input for shell model calculations

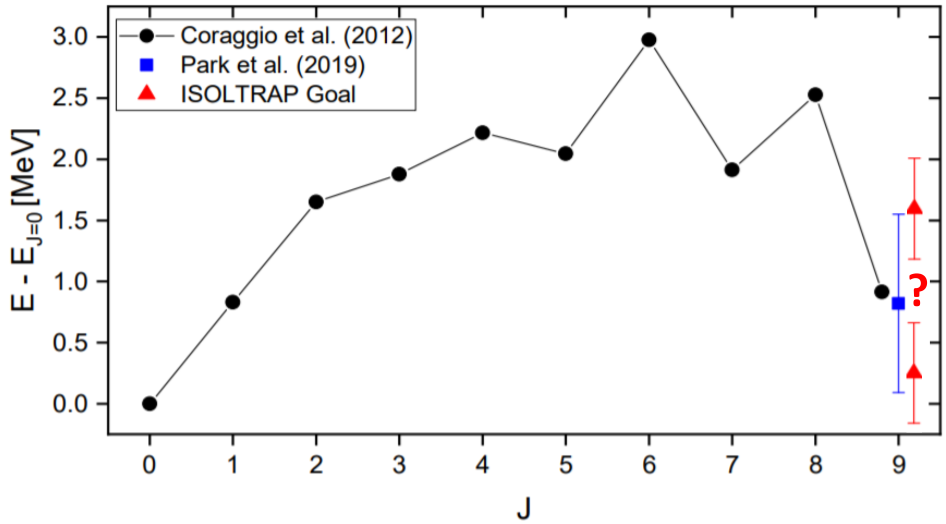
M. Mougeot *et al.*, in preparation (2020)



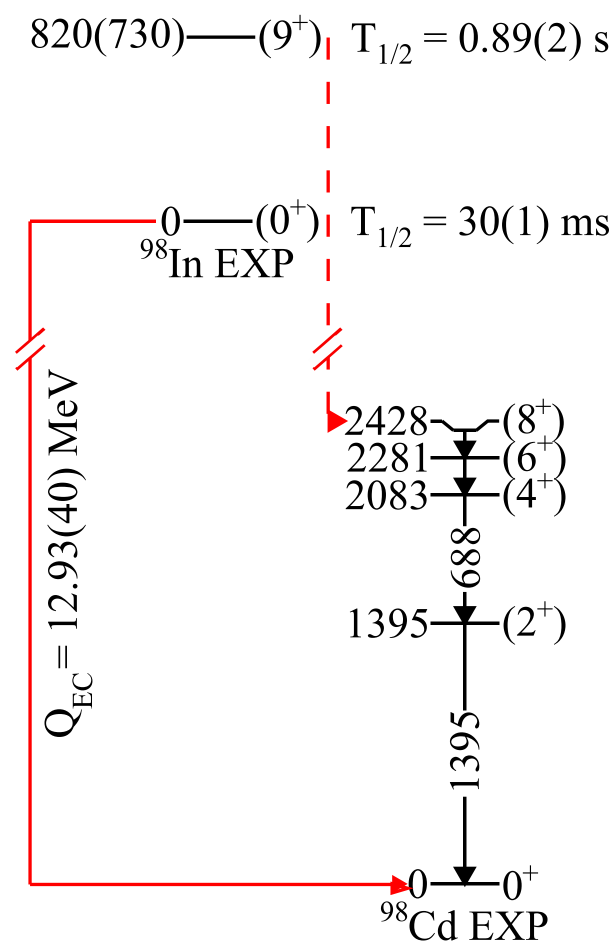


Shell evolution in odd-odd ^{98}In

Amended from L. Coraggio *et al.*, Phys. Rev. C **85**, 034335 (2012)

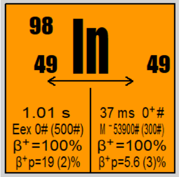


Amended from J. Park *et al.*, Phys. Rev. C **99**, 034313 (2019)



- Effective *np*-hole interaction and pairing studies in $g_{9/2}$ orbit → $J = 0$ to $J = 9$ multiplet (ordering?)
- *np* matrix element directly equivalent to excitation spectrum!
- Indirect evaluation of ground state by measuring **(9^+) excited state**

→ **Benchmarking of shell model calculations**

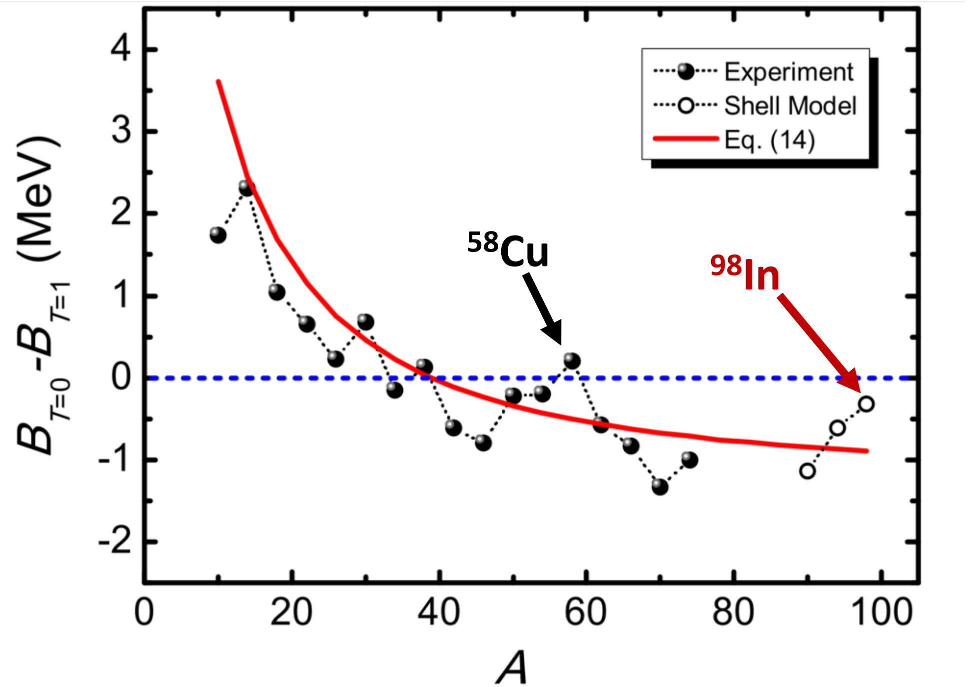


Wigner effect in self-conjugate ^{98}In

- Excess binding energy in $N = Z$ nuclei through *pn* coupling
- Accessible through lowest $T = 0$ and $T = 1$ states
  - ➢ Lowest $T = 0$ state can become ground state due to neighboring shell closure!
- Anomaly in ^{58}Cu also expected for **^{98}In**
- Binding energy difference described through interplay of Wigner + pairing + symmetry energies

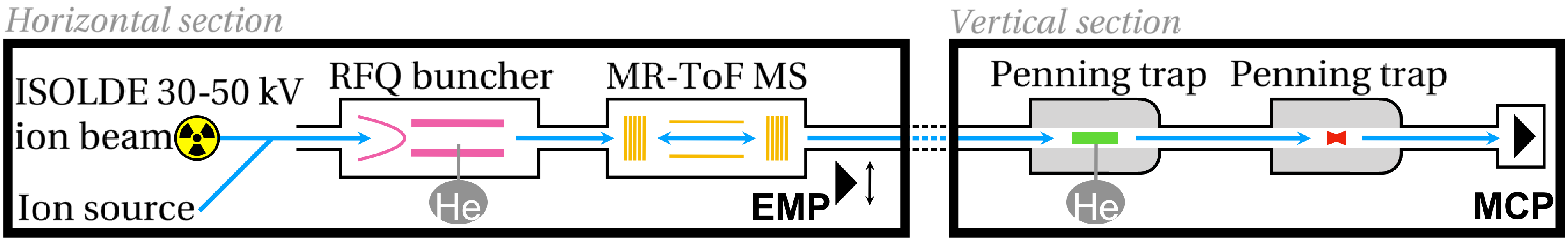
A. O. Macchiavelli, Phys. Rev. C **61**, 041303(R) (2000)

Y. Y. Cheng *et al.,* Phys. Rev. C **91**, 024313 (2015)



→ Test of this prediction by pinning down *J* = 9 excitation energy

Experimental Techniques

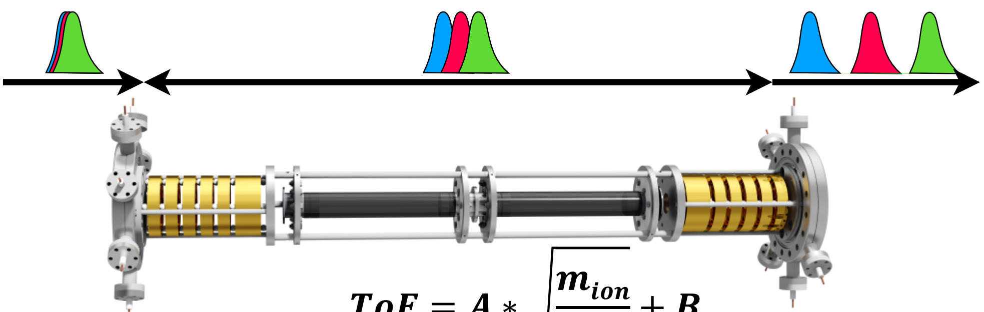


R. N. Wolff *et al.*, Int. J. of Mass Spectr. **349–350** (2013) 123–133

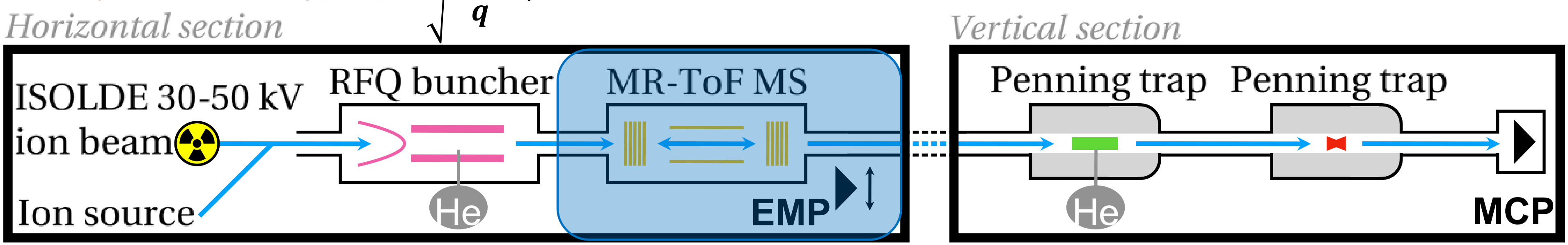
F. Wienholtz *et al.*, NIM B. **463** (2019) 348-356

Experimental Techniques

- MR-ToF: versatile and fast
  - Mass separation mode
  - Mass spectrometry mode
  - Resolving power up to 250k
- “Contaminants” can be used as calibrants



$$ToF = A * \sqrt{\frac{m_{ion}}{q}} + B$$



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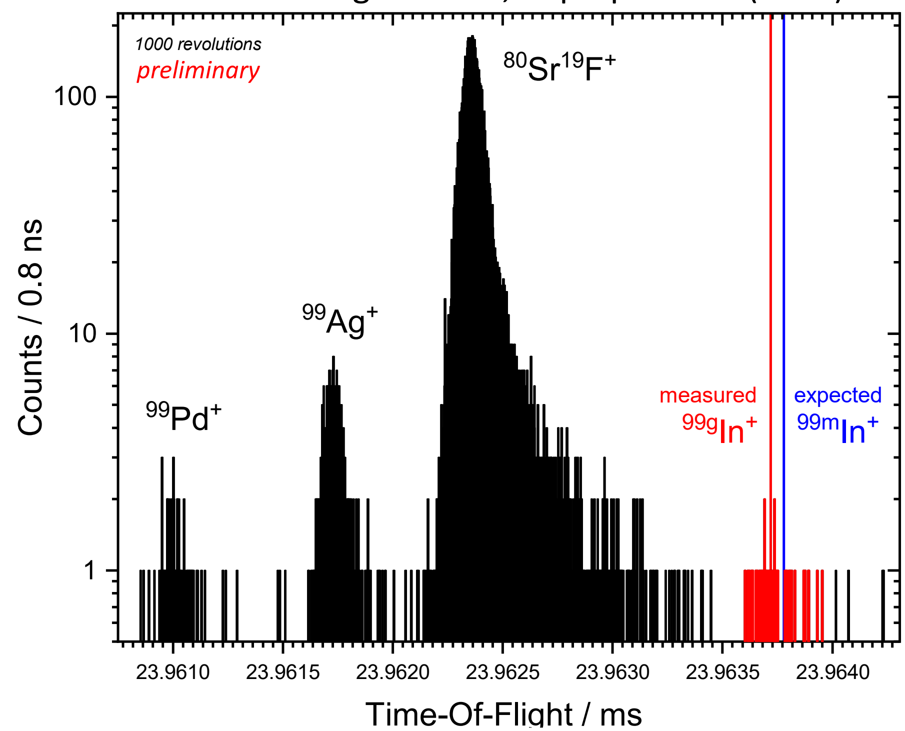

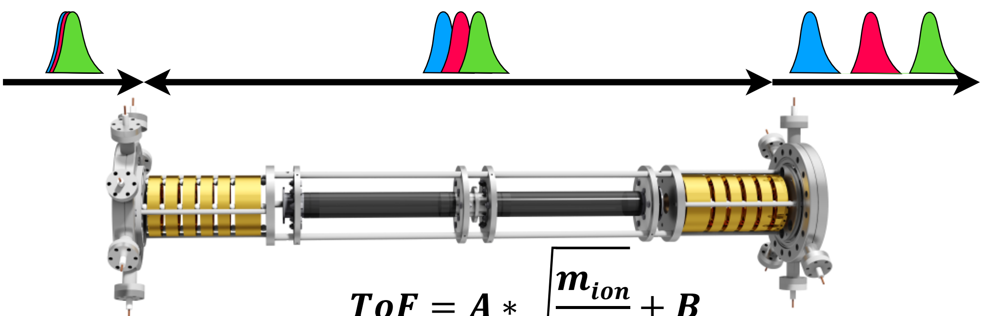

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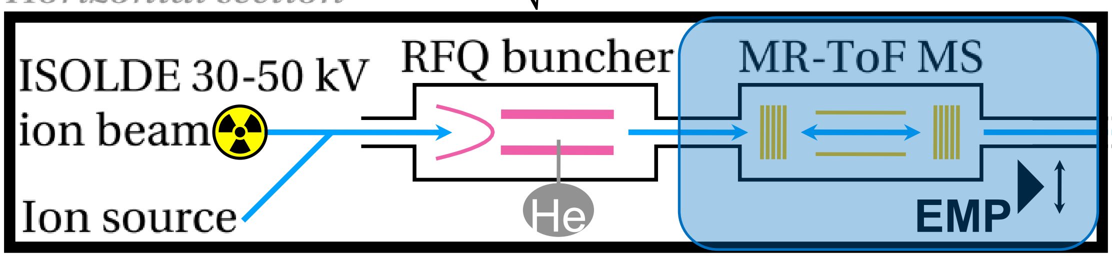
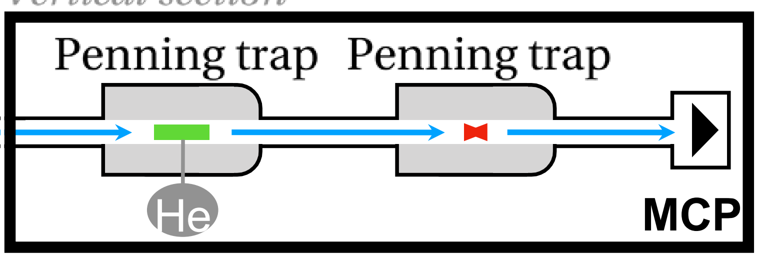
Horizontal section



Vertical section



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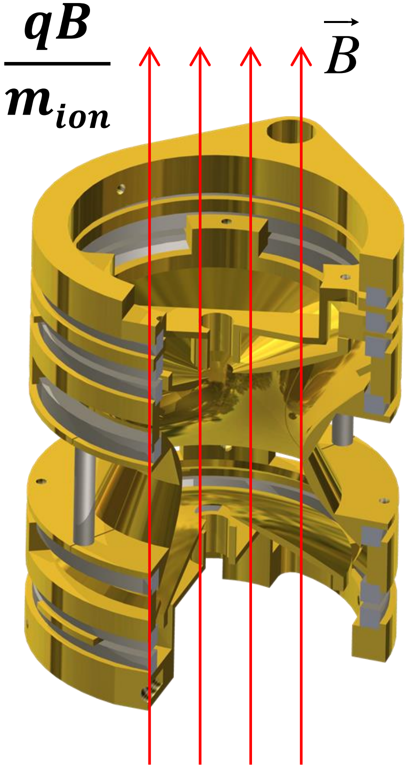
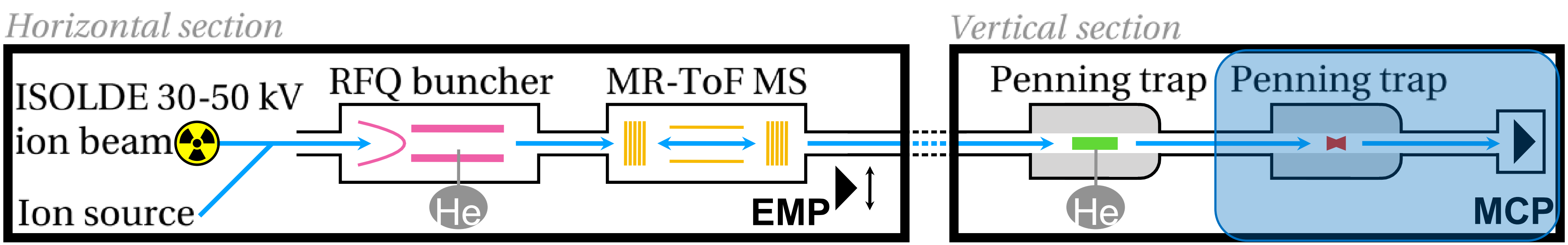
Experimental Techniques

$$\omega_c = \frac{qB}{m_{ion}}$$



- Newly commissioned **PI-ICR** technique: high precision even with low yields
- ToF between species projected on phase difference
- Shortest storage time to date: **^{101m}In** with **65ms**



S. Eliseev *et al.,* Phys. Rev. Lett. **110**, 082501 (2013)

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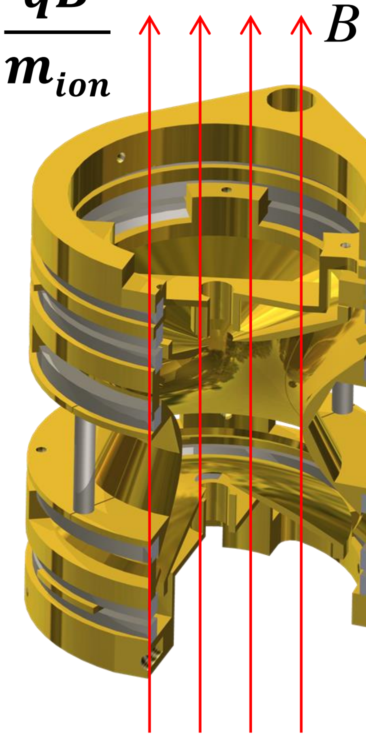

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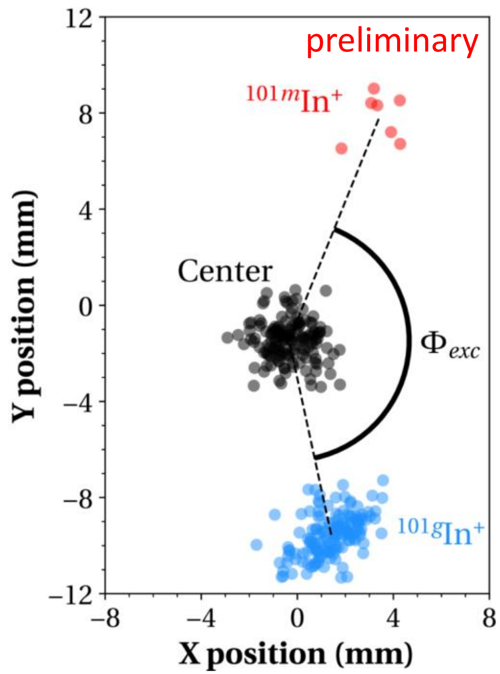
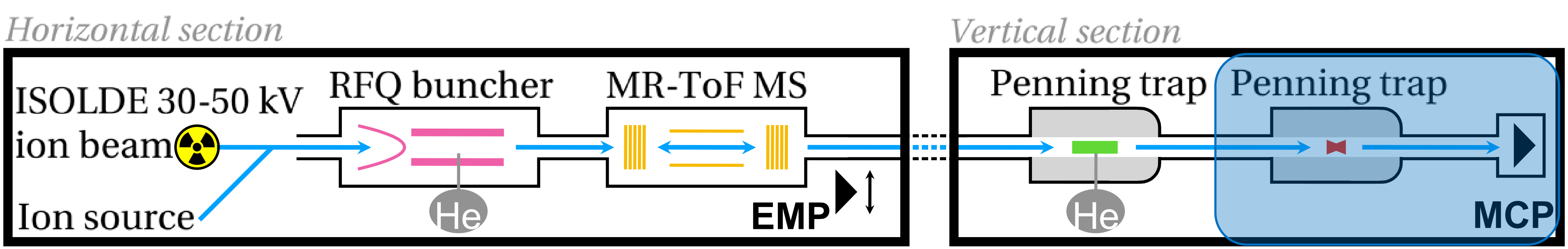




S. Eliseev *et al.*, Phys. Rev. Lett. **110**, 082501 (2013)

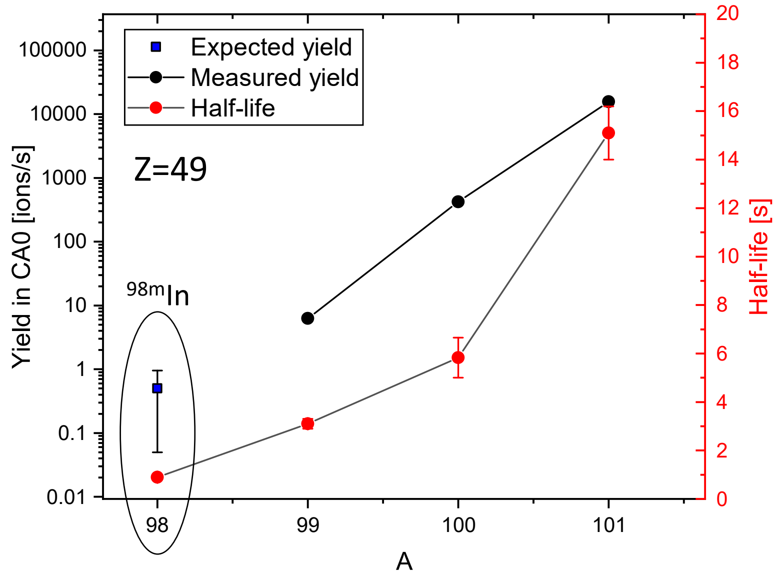
Summary

$^{99g,m}In$

- Determine single proton energy
- Test excitation energy prediction
- *Ab initio* benchmarking

~~^{98g}In~~ → ^{98m}In

- Test exp. accuracy of (9^+) state and increase precision
- Test Wigner energy prediction



Isotope	Half-life [s]	Yield in CA0 (ions/s)	Method	Target	Ion source	Shifts
^{99g}In	3.1(2)	~ 6.0	PI-ICR or MR-TOF MS	LaC_x	RILIS	**4**
^{99m}In	~ 1#					
~~^{98g}In~~	0.030(1)	~ 0.1#	PI-ICR or MR-TOF MS			**9**
^{98m}In	0.89(2)					
					Target/ion source optimization	**2**
#: extrapolated					**Total shifts**	**15**

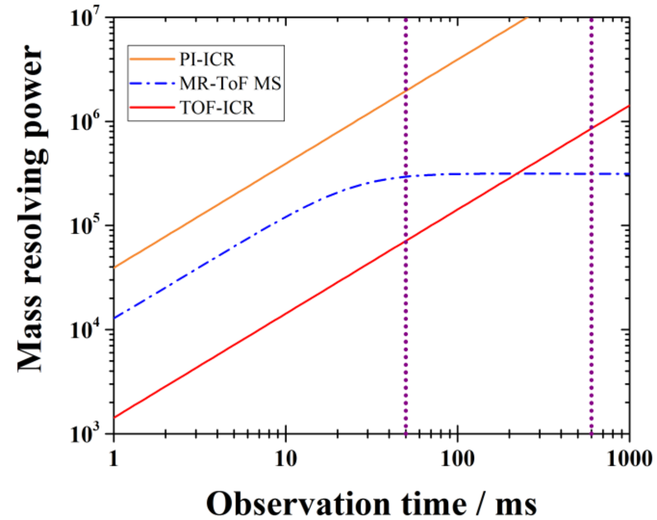
Backup: Resolving Powers

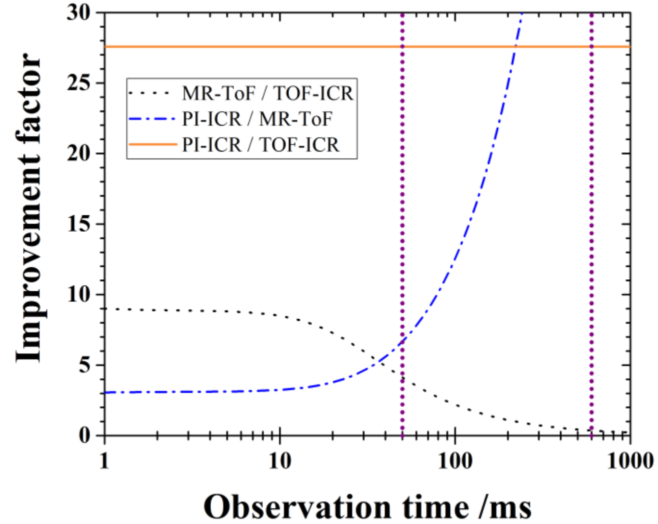
MR-ToF MS:

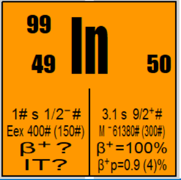
$$R = \frac{m}{\Delta m} = \frac{t_{obs}}{2\Delta t} \cong \frac{t_{\mathrm{transfer}} + nT}{2\sqrt{\Delta t_{th}^2 + (n\Delta T_A)^2 + \left(\Delta t_E - nT\left(\frac{\partial \delta_T}{\partial \delta_E}\right)\Delta\delta_E\right)^2}}$$

Penning trap PI-ICR:

$$R = \frac{m}{\Delta m} \approx \frac{\nu_+}{\Delta\nu_{+<}} \approx \pi\frac{\nu_+ t_{obs} r_+}{\Delta r_+}$$

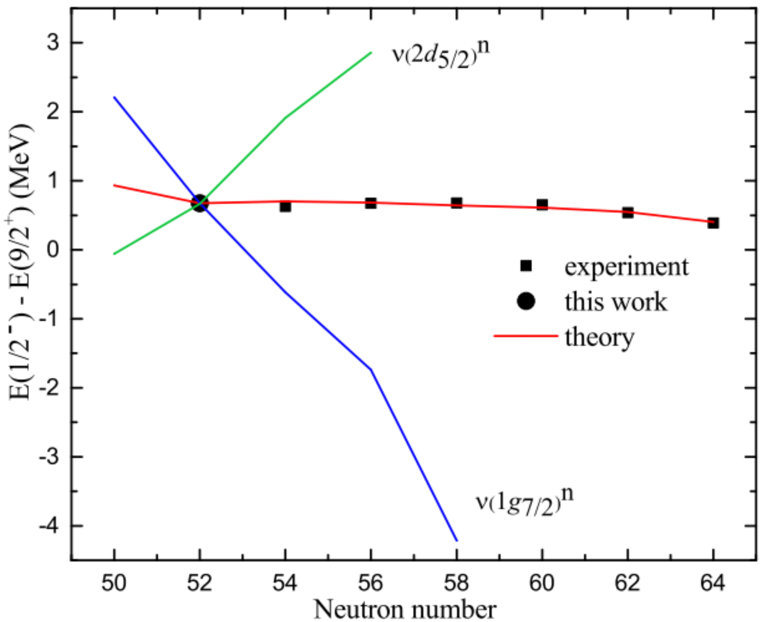




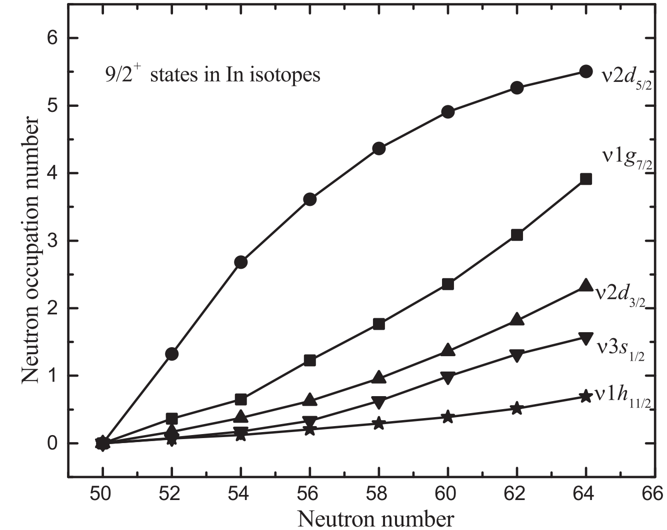


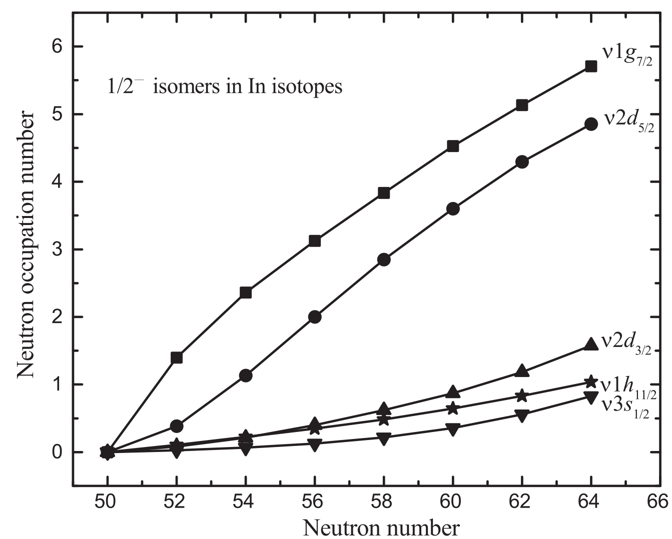
Backup: Type-II shell evolution in odd-even In

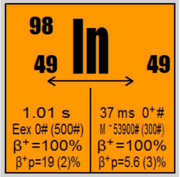
- Type-II shell evolution
  - Configuration space dependendent shell evolution within same nucleus
  - Excitation energy calculations very much depend on choice of orbital model space



X. Xu *et al.,* Phys. Rev. C **100** 051303(R) (2019)

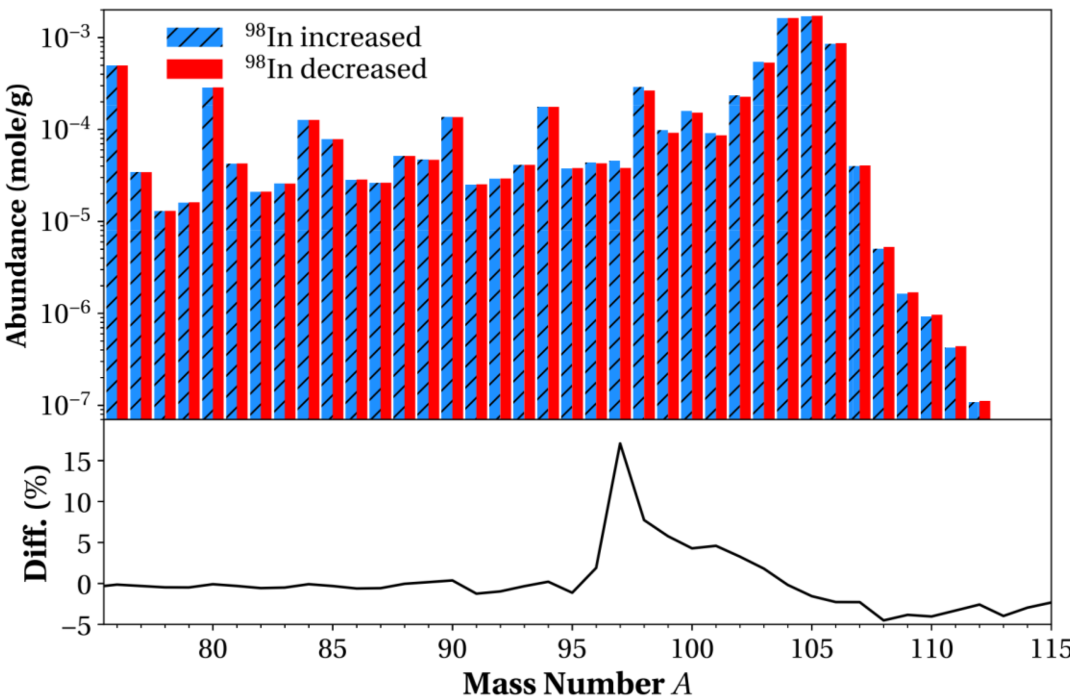


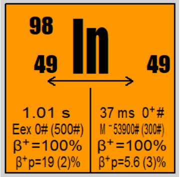




Backup: impact on rp-process

- Element creation and light curves during **Type-I X-ray bursts** along to proton trip line influenced by waiting points cause by slow beta^{+}-decay
- **Light curve**
- Remaining ashes make up crust of neutron stars above neutron core
- Models sensitive to photo-disintrigration rate which depends on the proton-capture **Q-value**
- Various key elements influence **rp-process** significantly (type 1 and 2)
- ^{99}In and ^{98}In as type 2 elements are important





Backup: weak interaction studies

- Test of CVC hypothesis and through this determination of $\mathbf{V_{ud}}$ and test of unity of first row of **CKM-matrix**
- $\mathbf{Q_{ec}}$**-value** of superallowed beta decay of ^{98g}**In** contributes to the calculation of the global Ft-value
- Very challenging measurement of **R** and $\mathbf{T_{1/2}}$ needed, alongside $\mathbf{Q_{ec}}$**-value**. Measurement might be one of the first steps
- Will stimulate new theoretical approaches like *ab initio* calculations to determine theoretical corrections