II. Physikalisches Institut

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

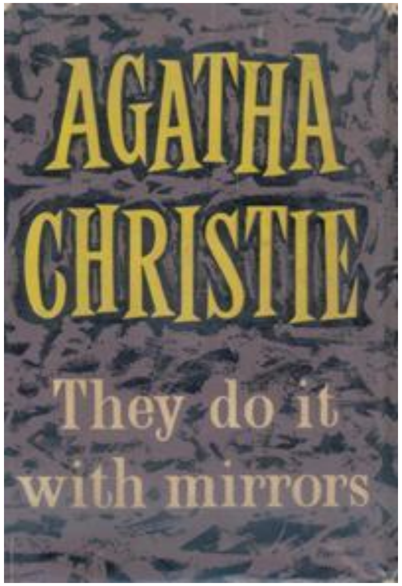
HFHF Helmholtz Forschungsakademie Hessen für FAIR

THE UNIVERSITY of EDINBURGH

Addressing open riddles in heavy N=Z nuclei with the FRS Ion Catcher and plans for the first experiments at the Super-FRS Ion Catcher at FAIR

Super-FRS EC

FAIR Phase 0 Research Program FRS



Gabriella Kripkó-Koncz
for the Super-FRS Experiment Collaboration

II. Physikalisches Institut, JLU Gießen, Germany

School of Physics and Astronomy, University of Edinburgh, United Kingdom

Motivation: the vicinity of ^{100}Sn

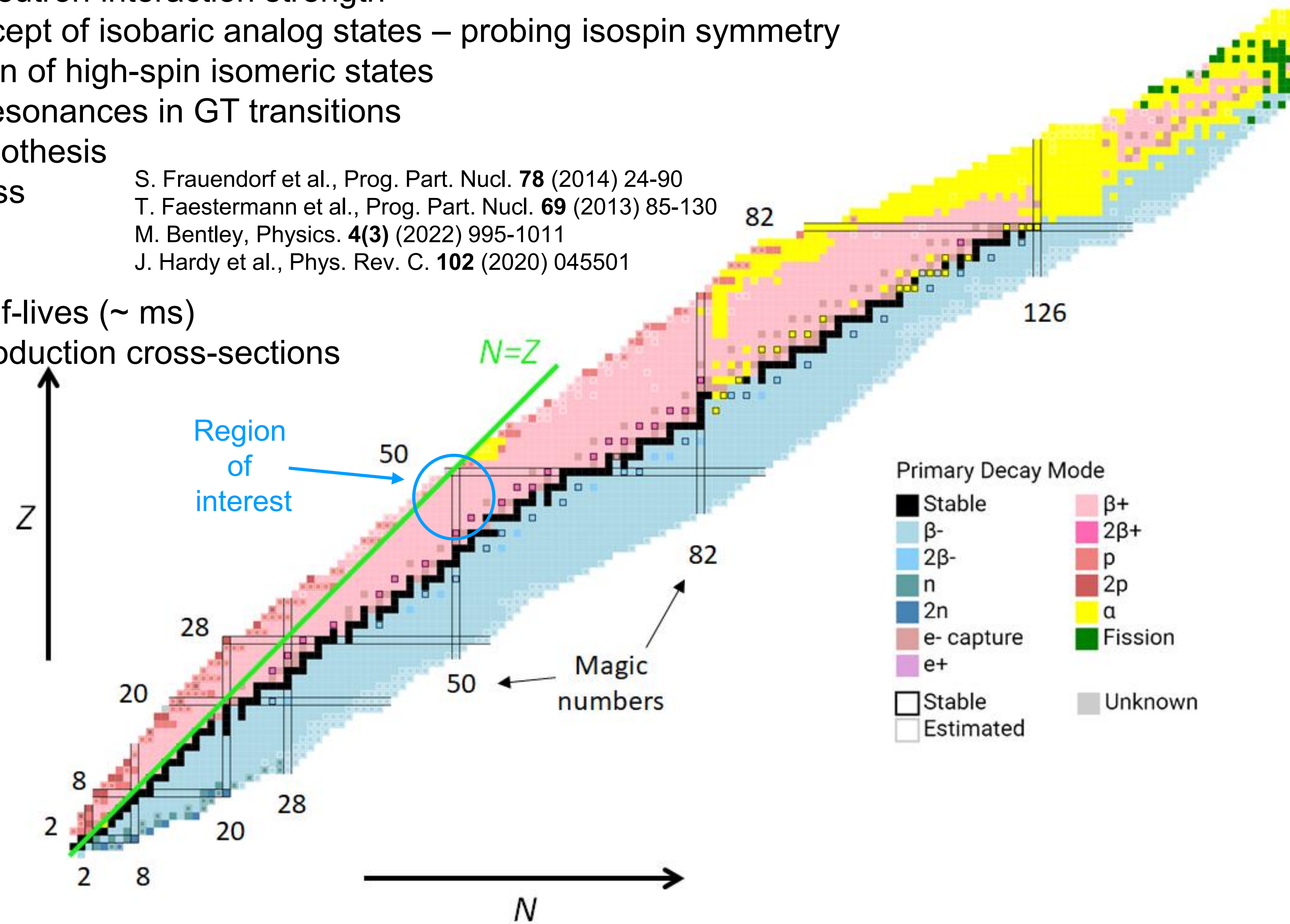
Study of heavy N≈Z nuclei, e.g.:

- Proton-neutron interaction strength
- The concept of isobaric analog states – probing isospin symmetry
- Formation of high-spin isomeric states
- Strong resonances in GT transitions
- CVC hypothesis
- rp-process

S. Frauendorf et al., Prog. Part. Nucl. **78** (2014) 24-90
T. Faestermann et al., Prog. Part. Nucl. **69** (2013) 85-130
M. Bentley, Physics. **4(3)** (2022) 995-1011
J. Hardy et al., Phys. Rev. C. **102** (2020) 045501

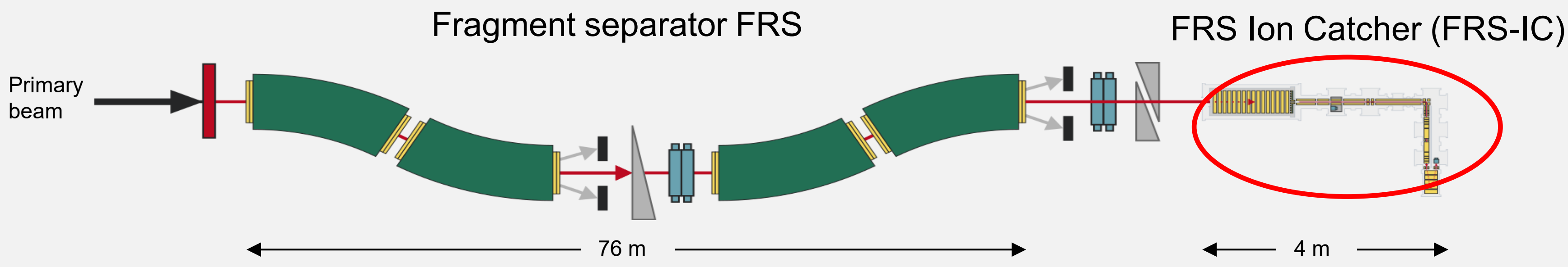
Challenges:

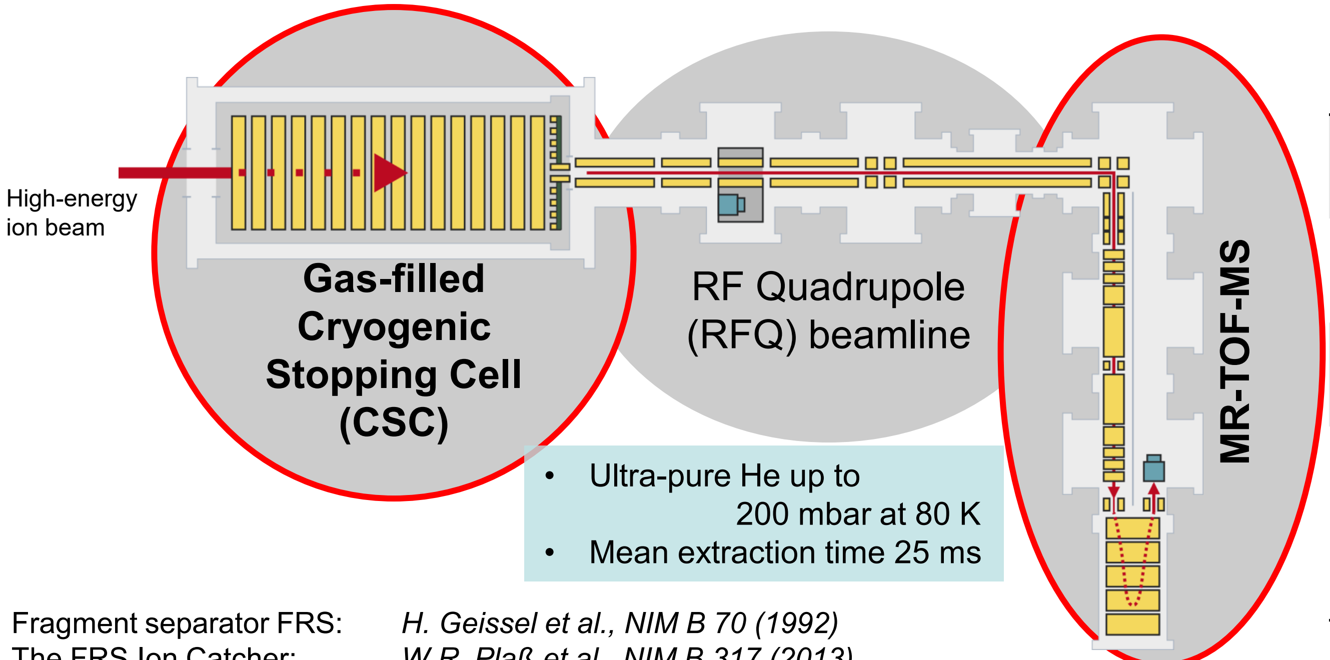
- Short half-lives (~ ms)
- Small production cross-sections



The FRS Ion Catcher at GSI

- **FRS: In-flight** isotope production and separation
- High-resolution **mass spectrometer/separator** for the projectile fragmentation/fission products
- **FRS Ion Catcher:** High-precision studies on thermalized ions



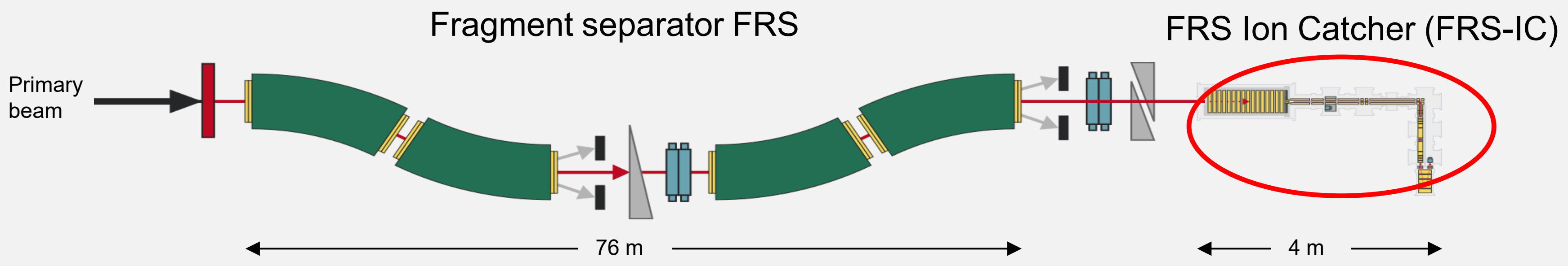


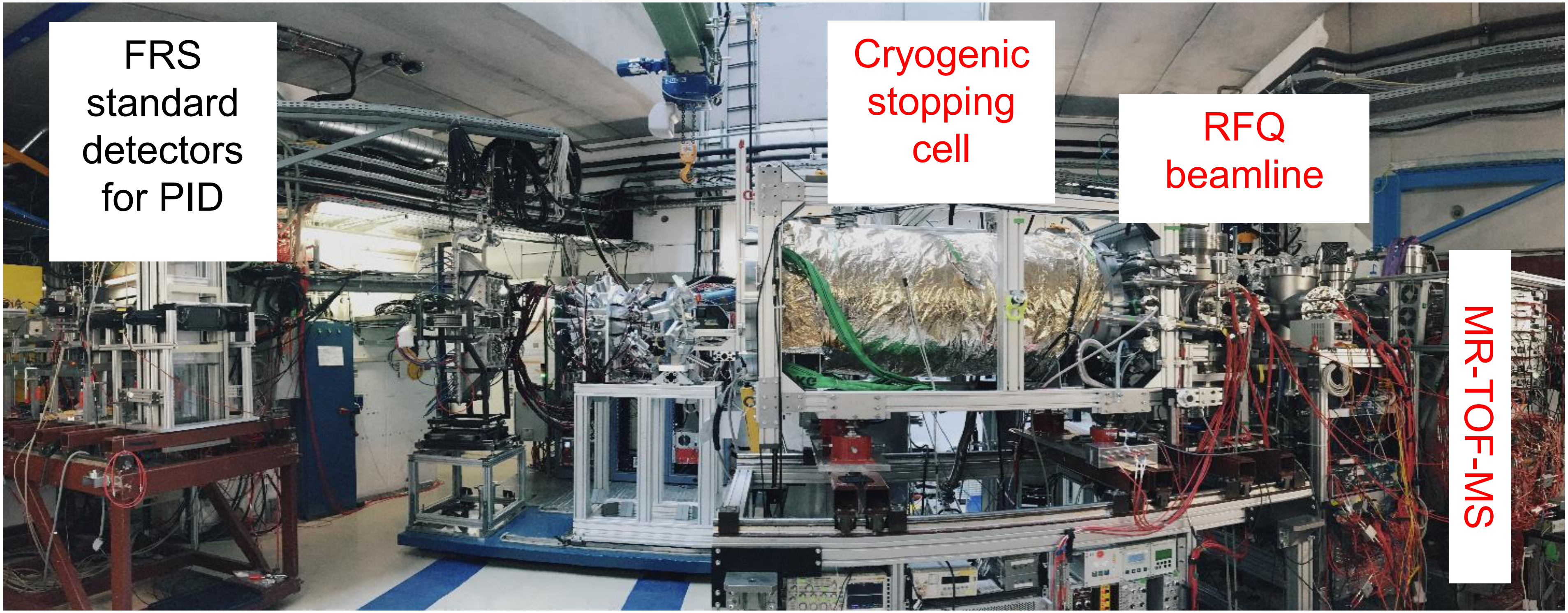
Thick CSC	Stopping of relativistic nuclei
Clean and sensitive	low production cross section
Fast	short-lived ions with $T_{1/2}$ ~ms
Broadband & non-scanning MR-TOF-MS	Efficient way of collecting data

Fragment separator FRS: *H. Geissel et al., NIM B 70 (1992)*
The FRS Ion Catcher: *W.R. Plaß et al., NIM B 317 (2013)*
Coupling of FRS and FRS IC: *T. Dickel et al., Atoms (2024), 12, 52*

The FRS Ion Catcher at GSI

- **FRS: In-flight** isotope production and separation
- High-resolution **mass spectrometer/separator** for the projectile fragmentation/fission products
- **FRS Ion Catcher:** High-precision studies on thermalized ions



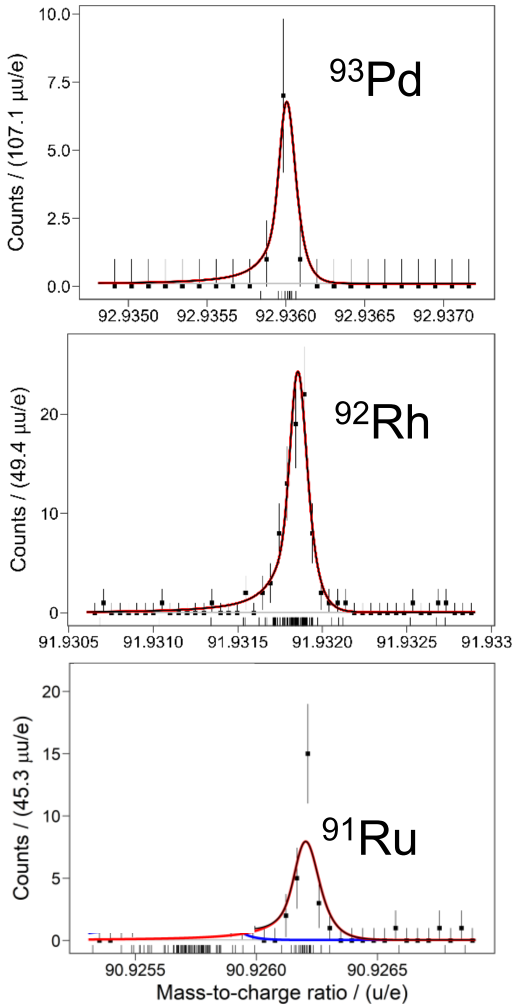


Optimal stopping in an ultra thin stopper

+ optimize beam energy

max. stopping efficiency for single isotopes

N=47 isotones



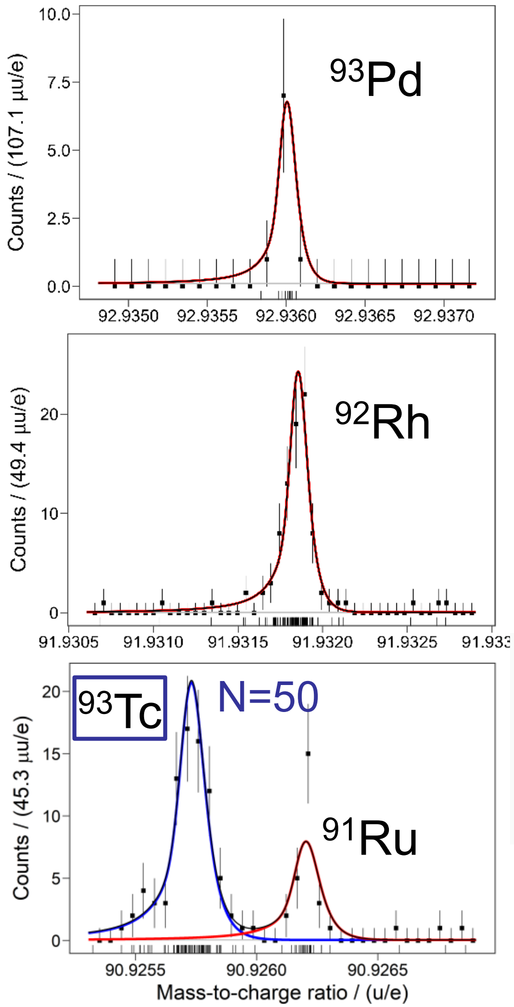
Efficient measurement scheme and riddle #1

Optimal stopping in an ultra thin stopper

+ optimize beam energy

max. stopping efficiency for single isotopes

N=47 isotones



„Unexpected“ isotopes were observed.

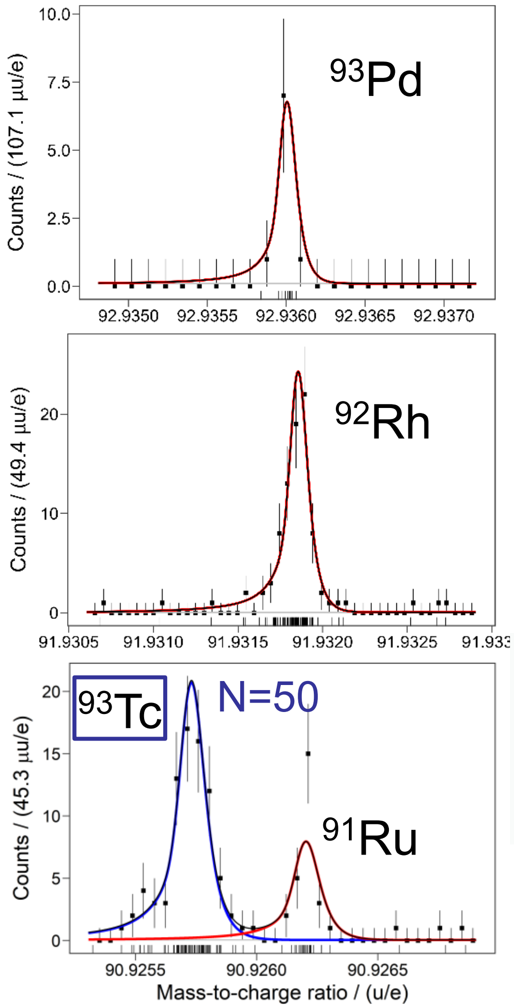
Efficient measurement scheme and riddle #1

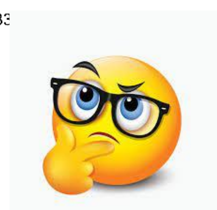
Optimal stopping in an ultra thin stopper

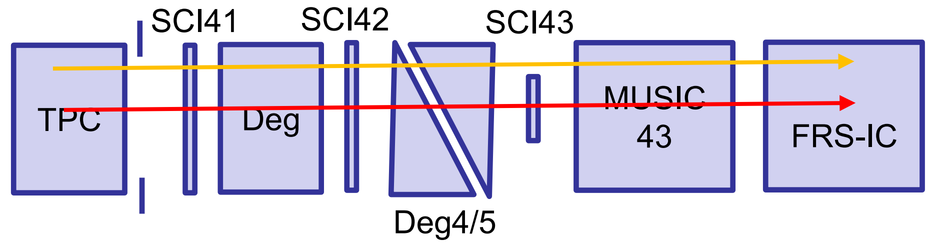
+ optimize beam energy

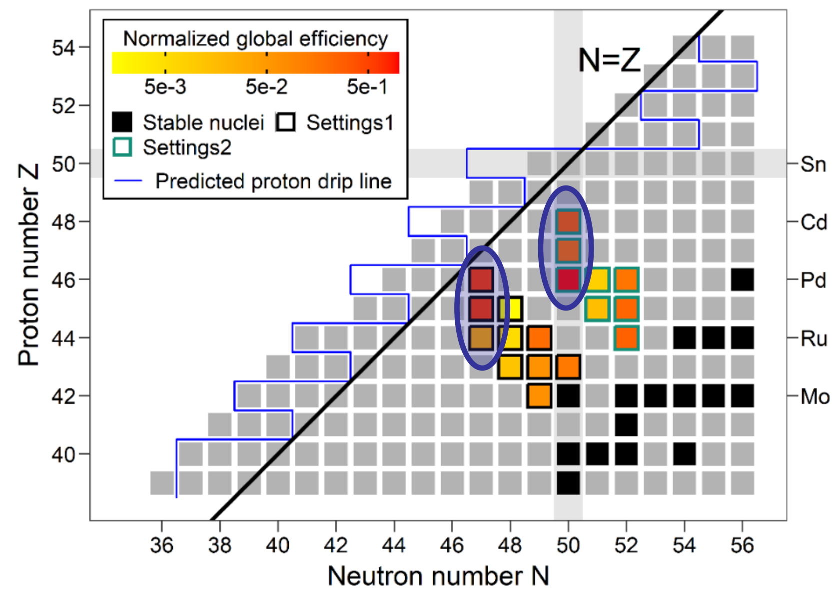
max. stopping efficiency for single isotopes

N=47 isotones







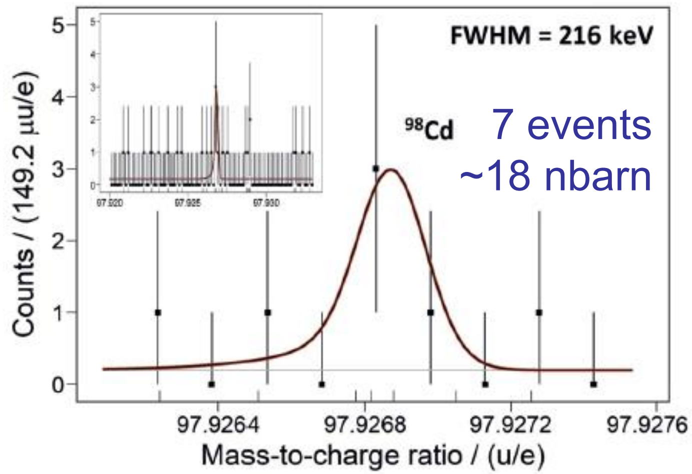


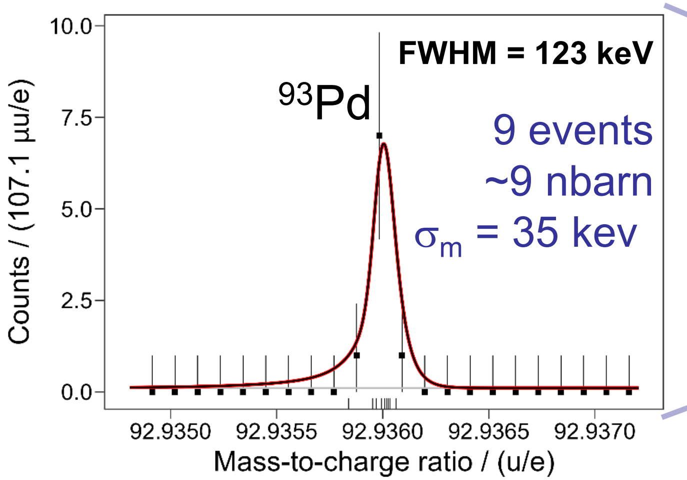
„Unexpected“ isotopes were observed.

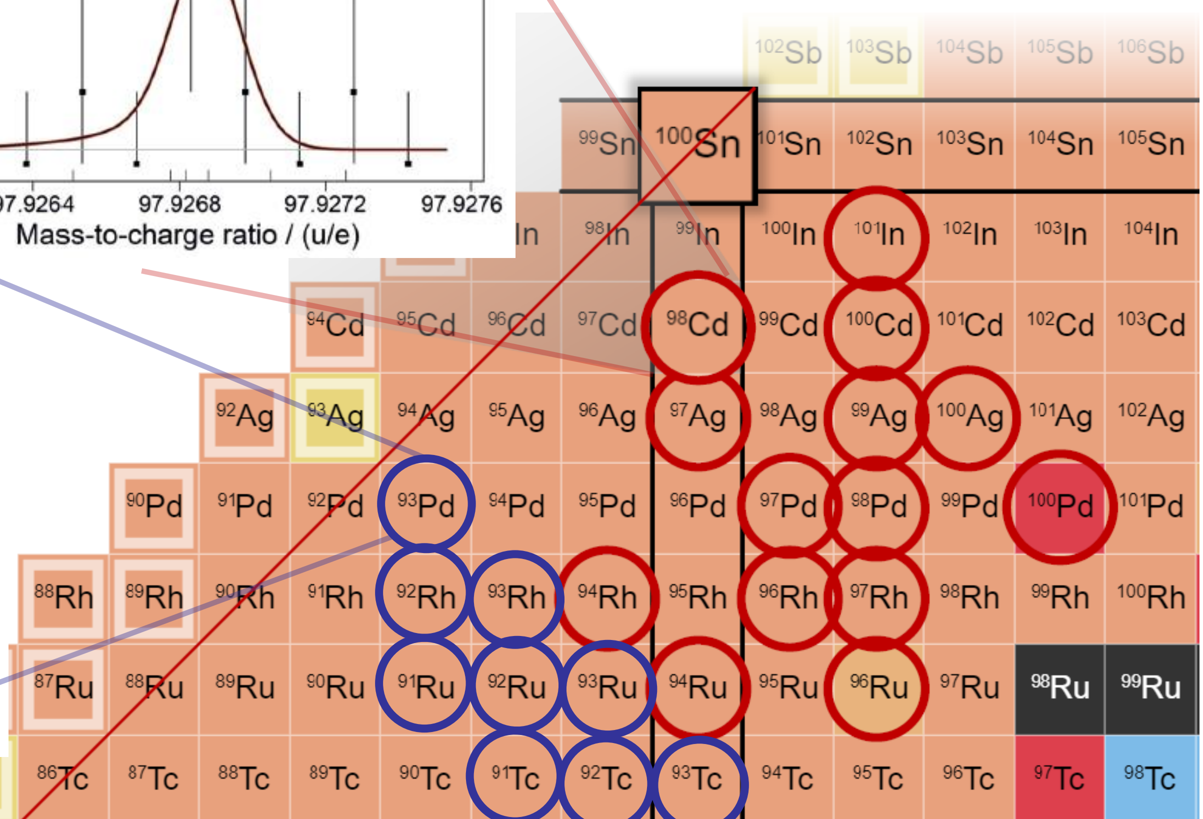
Measured masses in the vicinity of ^{100}Sn

- Direct mass measurements of 24 ground states and 2 isomers
- First direct mass measurements of ^{98}Cd and ^{93}Pd

A. Mollaebrahimi et al., Phys. Lett. B 839 (2023) 137833





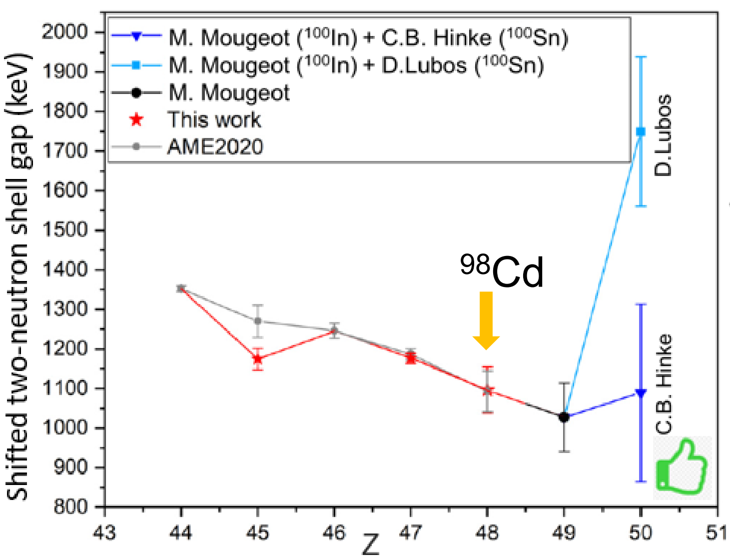


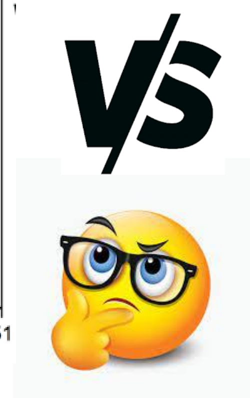
Riddle #2: Controversy around the mass of ^{100}Sn

- The "^{100}Sn mass riddle": measured mass of ^{100}In [M. Mougeot et al.] + two different Q_{EC} values

D. Lubos et al., Phys. Rev. Lett. 122 (2019) 222502

C.B. Hinke et al., Nature 486 (2012) 341

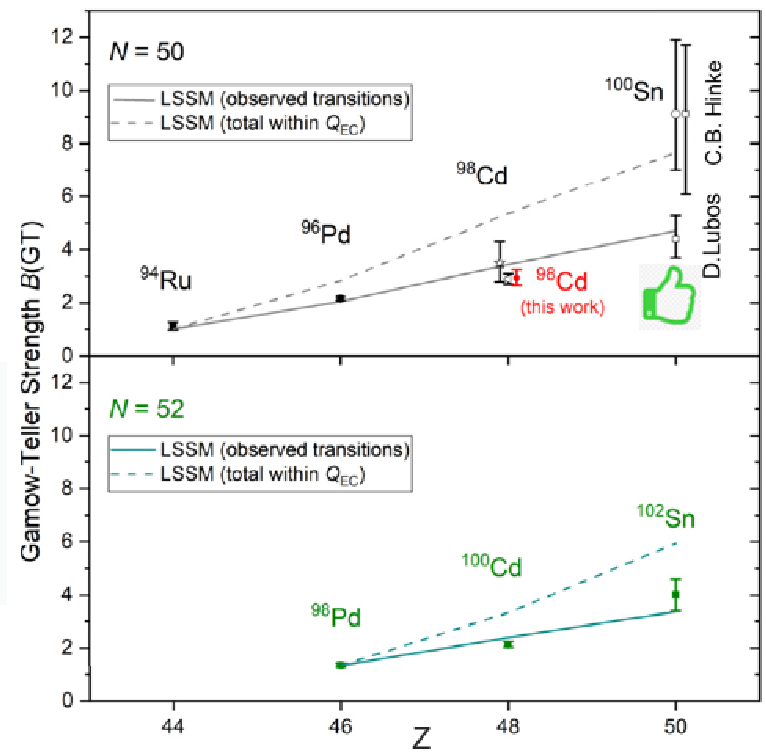




[C.B. Hinke et al.] was favored in comparison to ab-initio calculation done in [M. Mougeot et al.]

M. Mougeot et al., Nat. Phys. 17 (2021) 1099

See also recent LEBIT results: C. Ireland et al., arxiv: 2510.11815v1



The evolution of B(GT) for N=50 and N=52 isotones in comparison to LSSM **favors [D. Lubos et al.].**

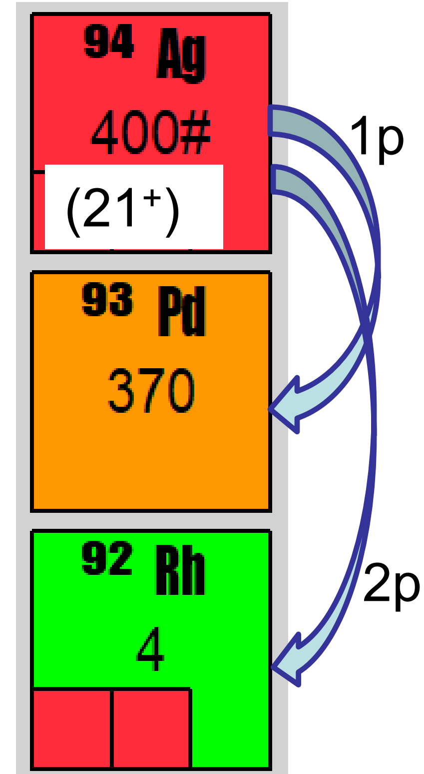
New/improved experiments are needed!

A. Mollaebrahimi et al., Phys. Lett. B 839 (2023) 137833

Riddle #3: ^{94}Ag (21^{+}) isomer

A (21^{+}) isomer in ^{94}Ag has been reported to have unique properties:

- β-decay C. Plettner et al., Nucl. Phys. A 733, 20 (2004)
- β-delayed proton emission I. Mukha et al., Phys. Rev. C 70, 044311 (2004)
- direct 1p-decay I. Mukha et al., Phys. Rev. Lett. 95 (2005) 022501
- direct 2p-decay I. Mukha et al., Nature 439 (2006) 298



- It has a measured β-decay half-life of 400(40) ms.
- It has an excitation energy of more than 6 MeV.

Intense scientific discussions

- O. L. Pechenaya et al., Phys. Rev. C 76, 011304 (2007)
- K. Kaneko et al., Phys. Rev. C 77, 064304 (2008)
- D. G. Jenkins et al., Phys. Rev. C 80, 054303 (2009)
- J. Cerny et al., Phys. Rev. Lett. 103, 152502 (2009)
- A. Kankainen et al., Phys. Rev. Lett. 101 (2008) 142503
- . . . **And many more . . .**

Riddle #3

1p and 2p-decay of ^{94}Ag are unique and puzzling

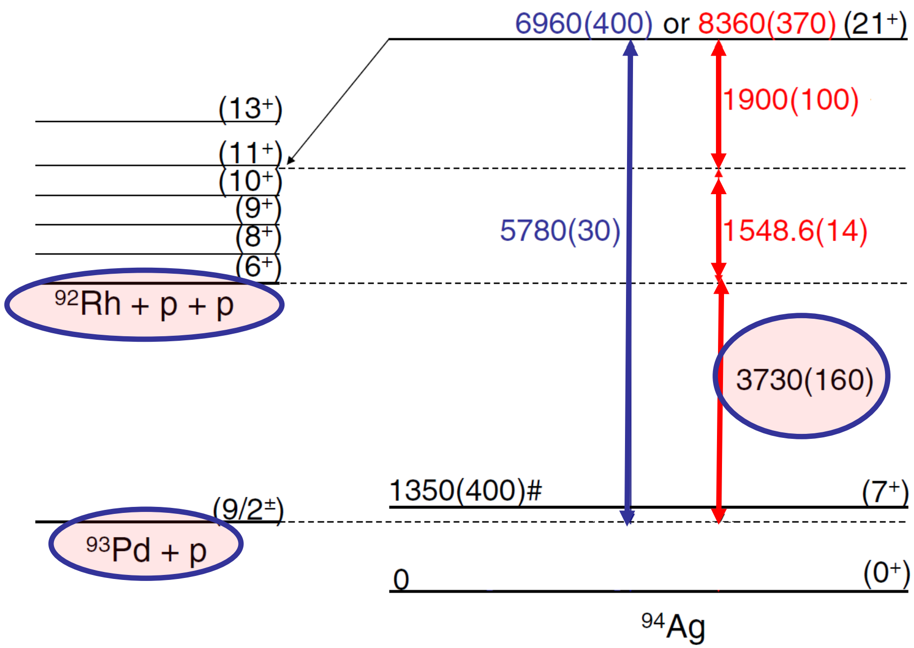
Riddle #3.1: 2p emission could not be confirmed in Berkeley?!

J. Cerny et al., Phys. Rev. Lett. 103, 152502 (2009)

Riddle #3.2: Why simultaneous 2p emission, why not sequential 2p?!

I. Mukha et al., Nature 439 (2006) 298

Riddle #3.4: Energy mismatch?!



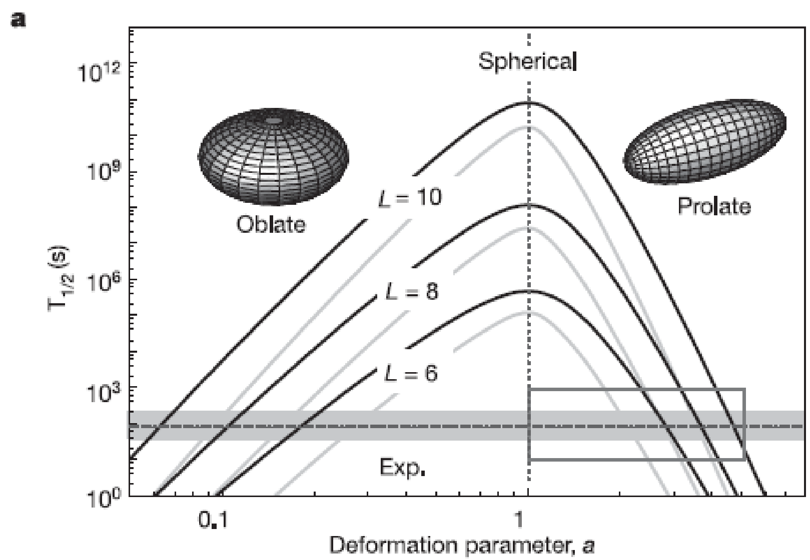
Based on extrapolation

A. Kankainen et al., Phys. Rev. Lett. 101 (2008) 142503

Riddle #3.3: Strongly deformed?!

K. Kaneko et al., Phys. Rev. C 77, 064304 (2008)

I. Mukha et al., Nature 439 (2006) 298



UNIVERSITY OF JYVÄSKYLÄ

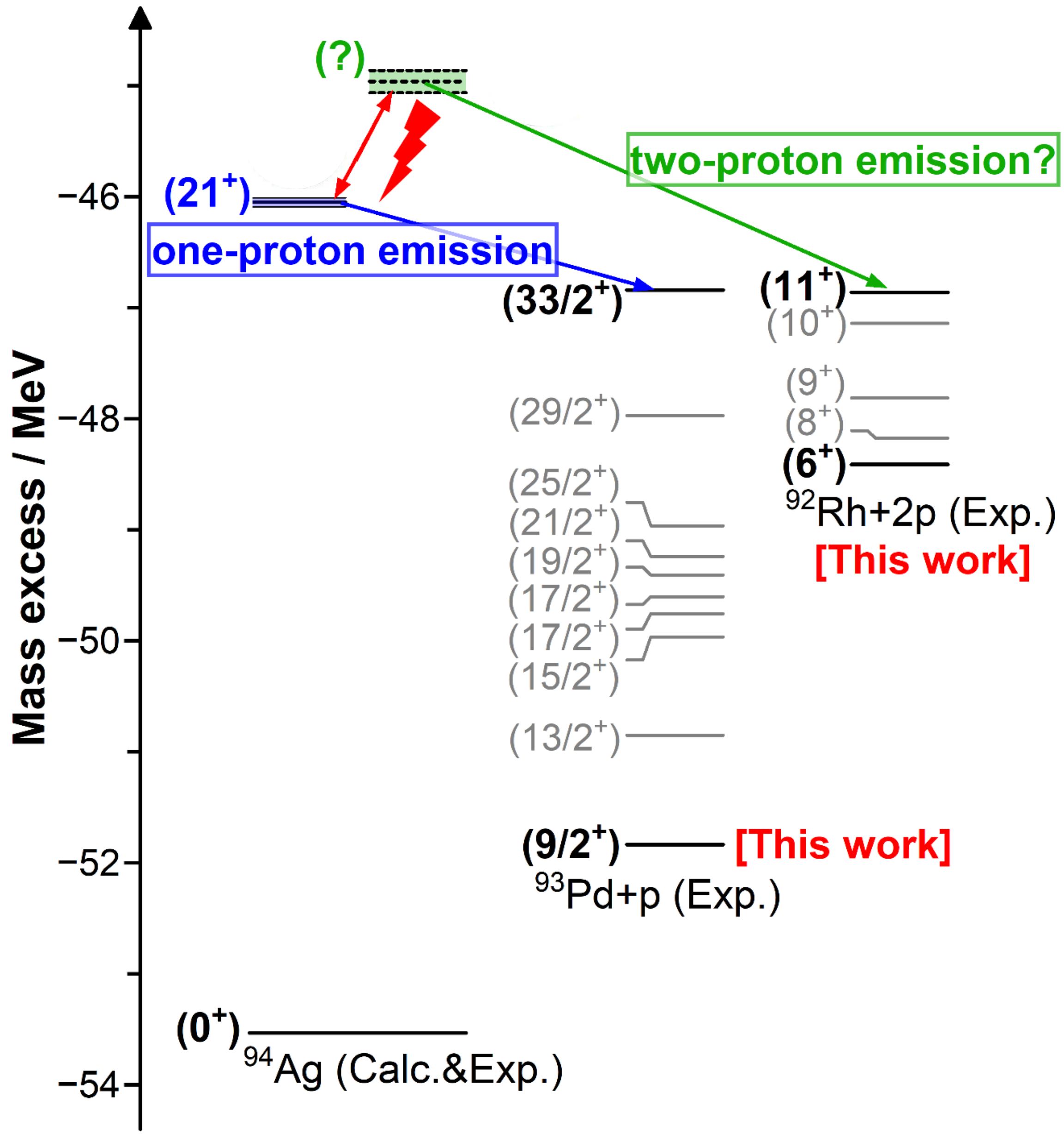
Dedicated hot cavity catcher for measuring ^{94}Ag

M. Reponen et al., Rev. Sci. Instrum. 123501 (2015)

Riddle #3: the 1p/2p-decay of ^{94}Ag (21$^+$) isomer

Measurement yields a ~10σ mismatch between ME of 21+, when obtaining it from 1p/2p-decay branches.

G. Kripkó-Koncz *et al.*,
Phys. Rev. Research, in print
https://doi.org/10.1103/mhhn-kmgx



FAIR Phase 0 Research Program FRS

Super-FRS EC

Estimating the mass of the ^{94}Ag ground state (0+, T=1)

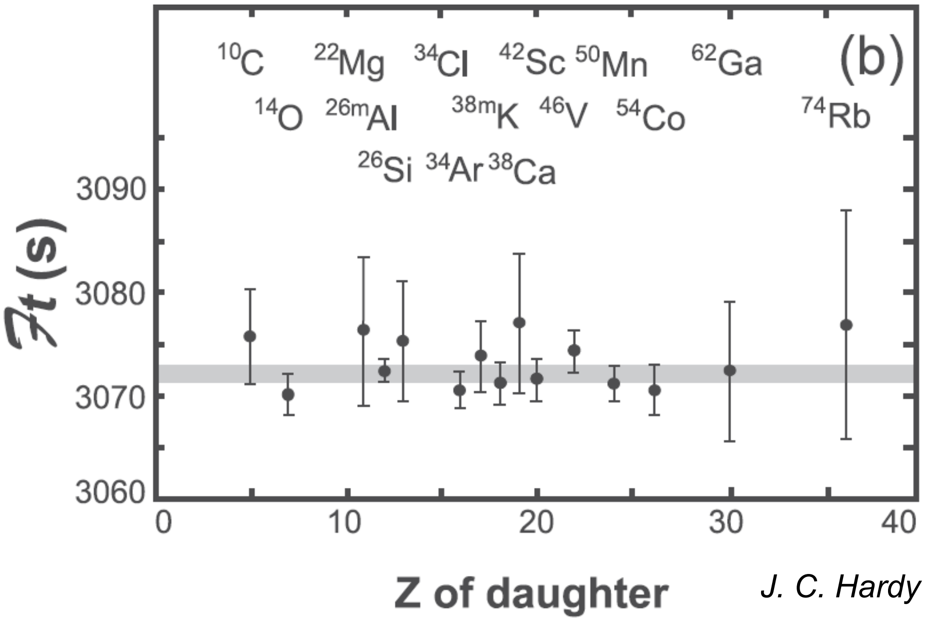
Measured the Q_{EC} value of ^{94}Ag (large uncertainties): J. Park et al., PRC 99 (2019) 034313
Extrapolation based on Coulomb-displacement energy systematics:

A. Kankainen et al., PRL 101 (2008) 142503

	Park2019	AME2020	Kankainen2008	Global Ft calc.
$Q_{EC}(^{94}Ag)$ [keV]	$13350\,^{+690}_{-610}$	13700(400)	12760(360)	12570(190)
$ME(^{94}Ag)$ [keV]	$-52750\,^{+690}_{-610}$	−52400(400)	−53340(360)	−53530(190)

J. Äystö, X. Mougeot (priv. comm.)

$$\mathcal{F}t \equiv ft(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$



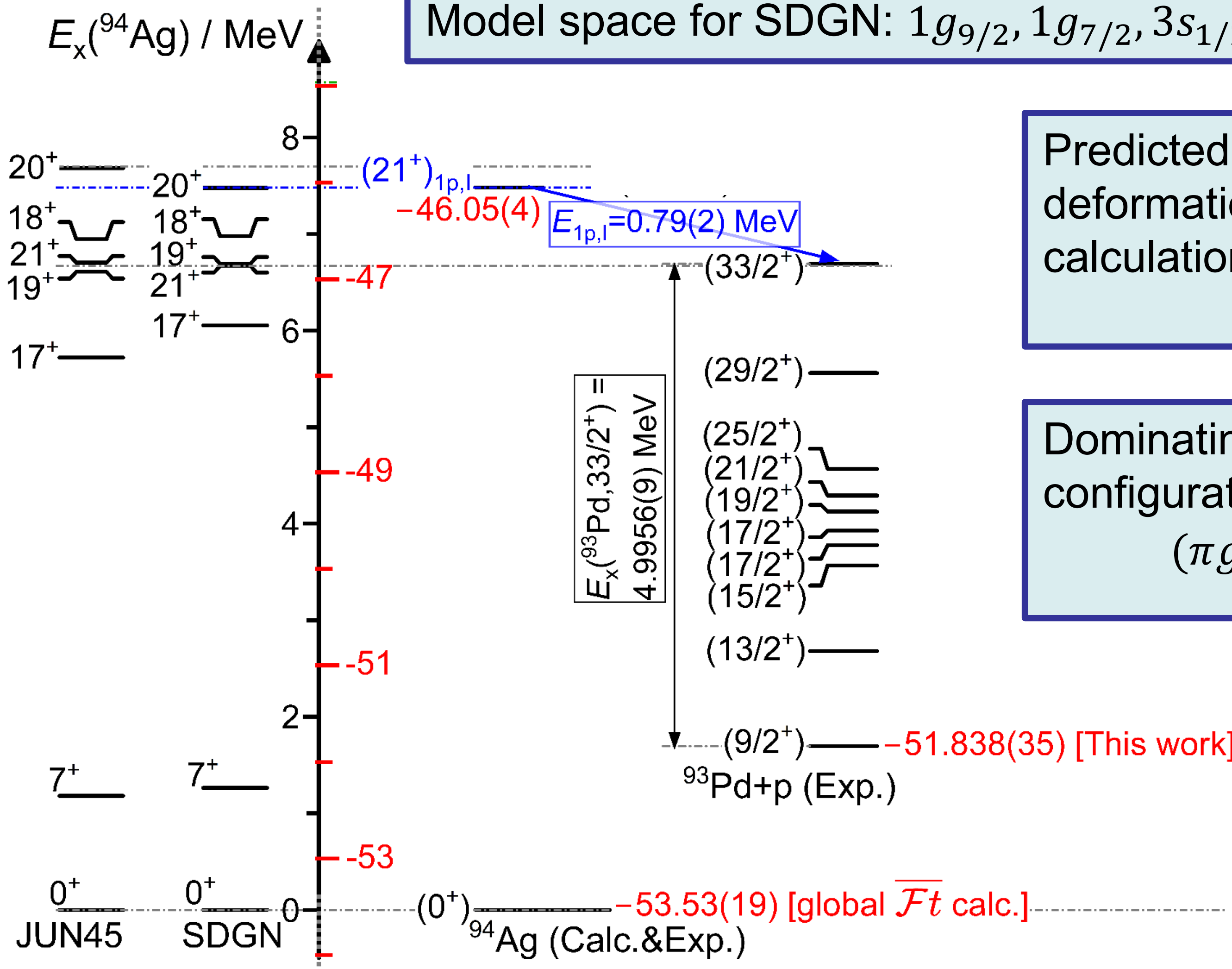
J. C. Hardy and I. S. Towner, PRC **102**, 045501 (2020)

Superallowed β-decay half-life of ^{94}Ag, $0^+ \rightarrow$ ^{94}Pd, 0^+ has been measured: **27(2) ms**

J. Park et al., PRC 99 (2019) 034313

→ The $Q_{EC}(^{94}Ag)$ can be "reverse-engineered".

Model space for JUN45: $2p_{3/2}, 1f_{5/2}, 2p_{1/2}, 1g_{9/2}$
Model space for SDGN: $1g_{9/2}, 1g_{7/2}, 3s_{1/2}, 2d_{5/2}, 2d_{3/2}$



Predicted small prolate deformation using DNO-SM calculations:

$$\alpha_{20} < 0.1$$

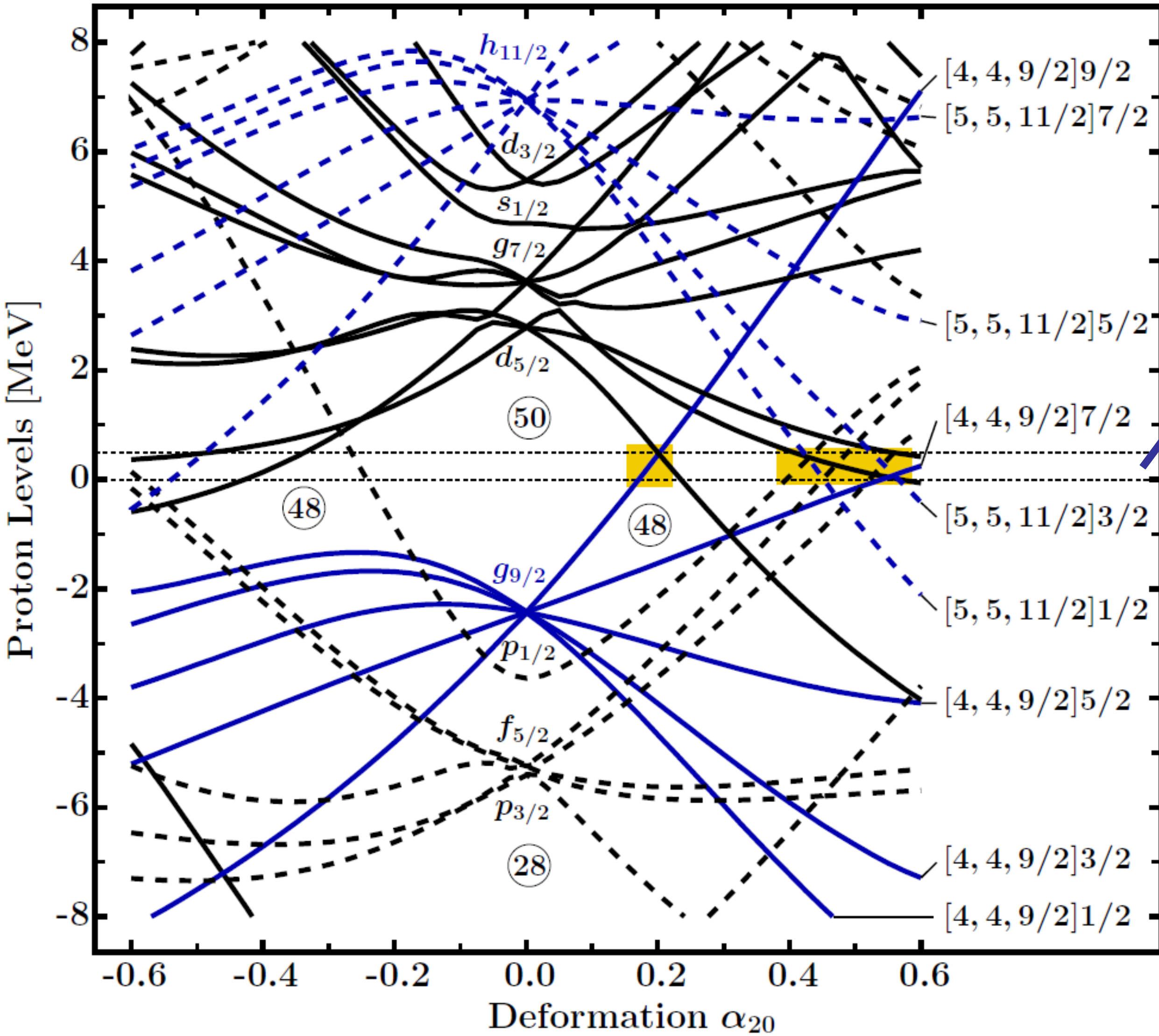
Dominating single-particle configuration for 21_1^+:

$$(\pi g_{\frac{9}{2}}^{-3}\ \nu g_{\frac{9}{2}}^{-3})_{21}$$

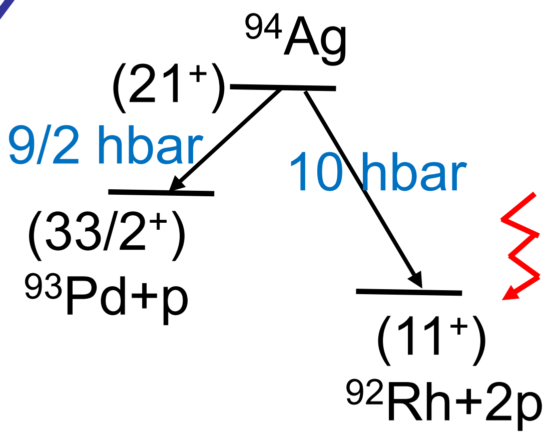
D. D. Dao, F. Nowacki, A. Blazhev, M. Górska (priv. comm.)

G. Kripkó-Koncz et al., Phys. Rev. Research, in print (https://doi.org/10.1103/mhhn-kmgx)

Mean-field calculations



Proton-emitting orbital with $T_{1/2}$ > 30 ms

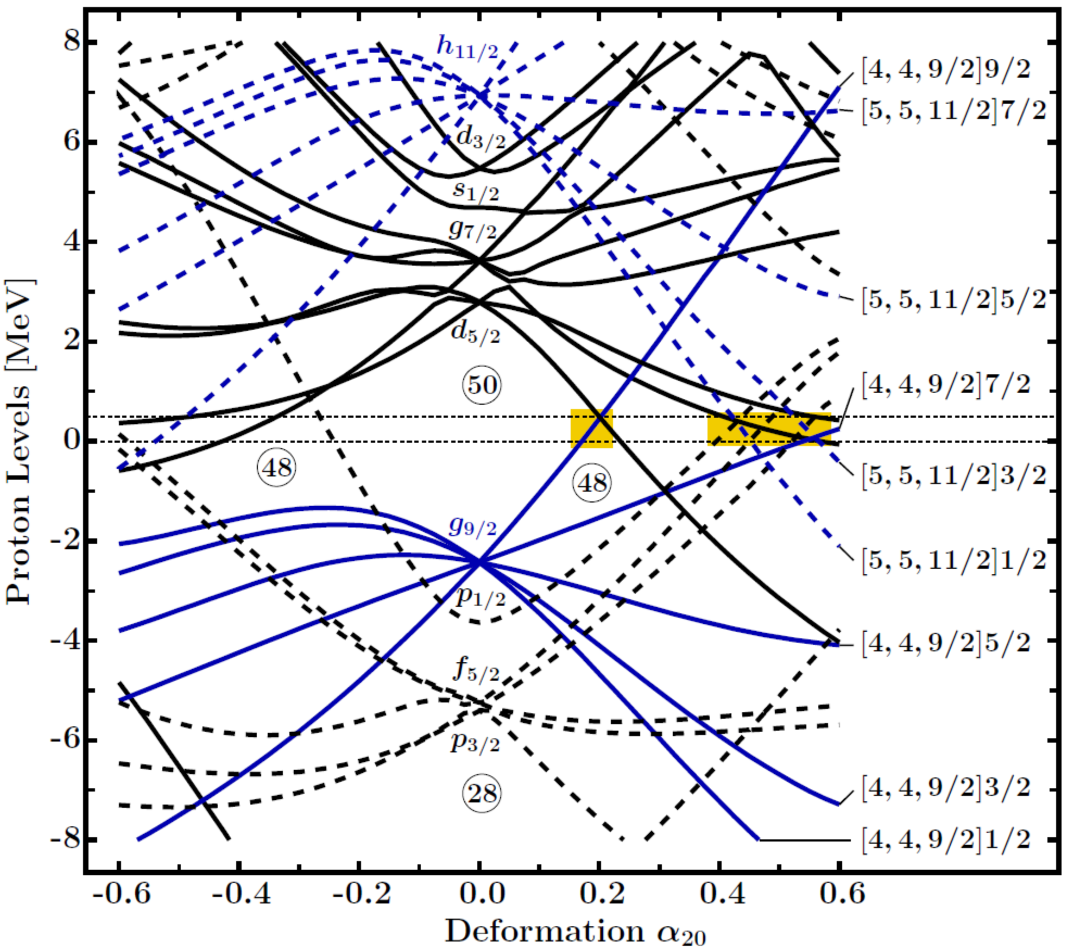


I. Dedes, J. Dudek, A. Baran, J. Yang (priv. comm.)

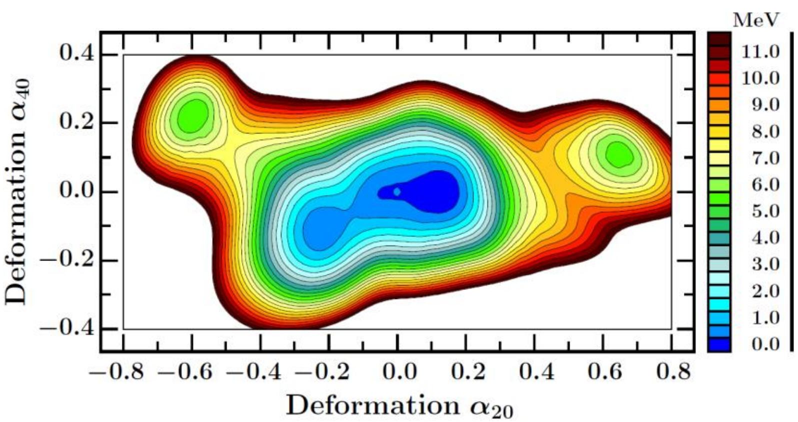
Mean-field calculations indicate that 1p and 2p decay should occur from two different isomers

G. Kripkó-Koncz et al., Phys. Rev. Research, in print (https://doi.org/10.1103/mhhn-kmgx)

Mean-field calculations



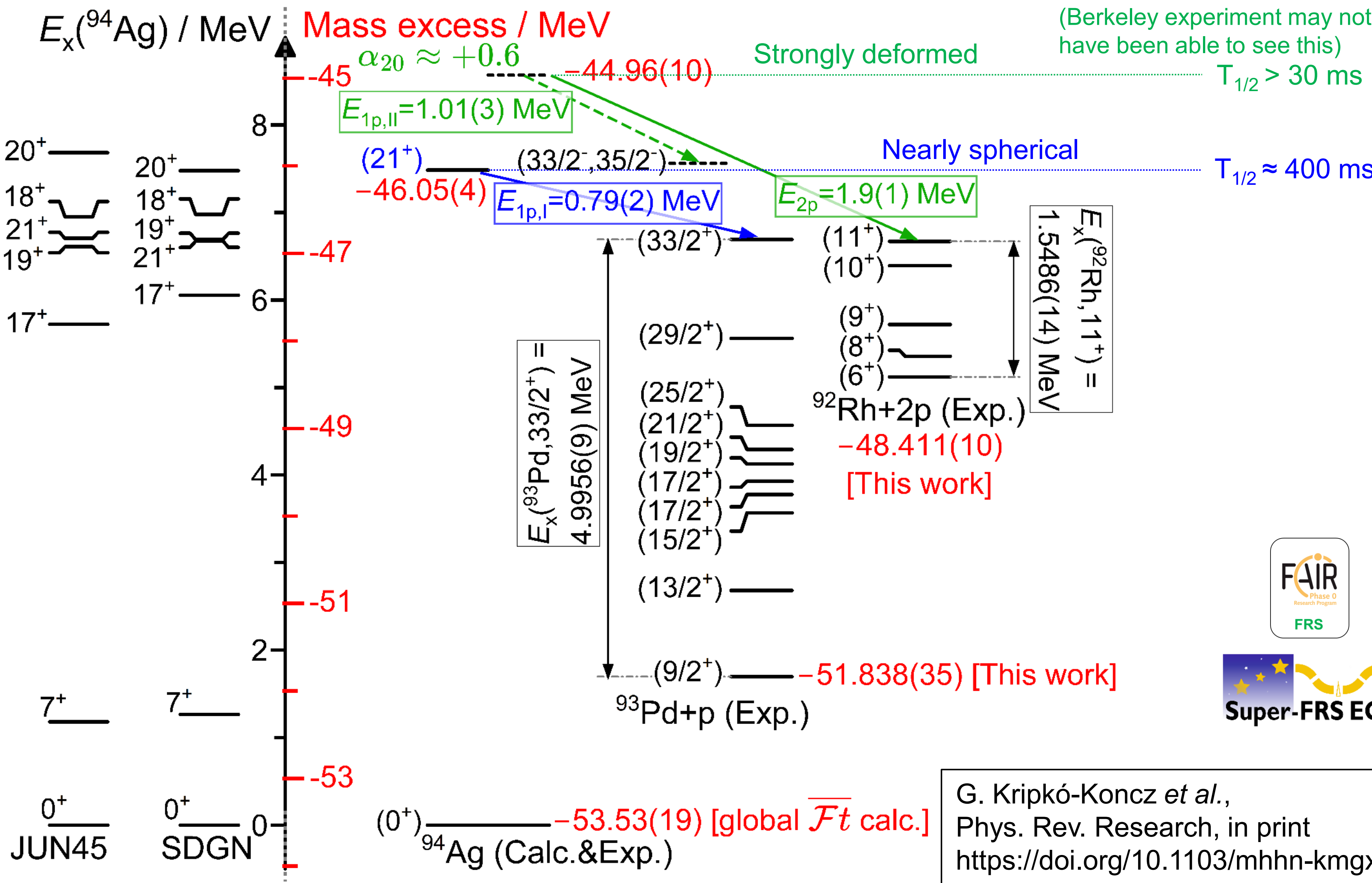
Concerning the normal-deformed states: a 21^+ state is predicted as a spin-trap isomer with dominating single-particle configuration of $(\pi g_{\frac{9}{2}}^{-3}\ \nu g_{\frac{9}{2}}^{-3})_{21}$



Mean-field calculations indicate that 1p and 2p decay should occur from two different isomers

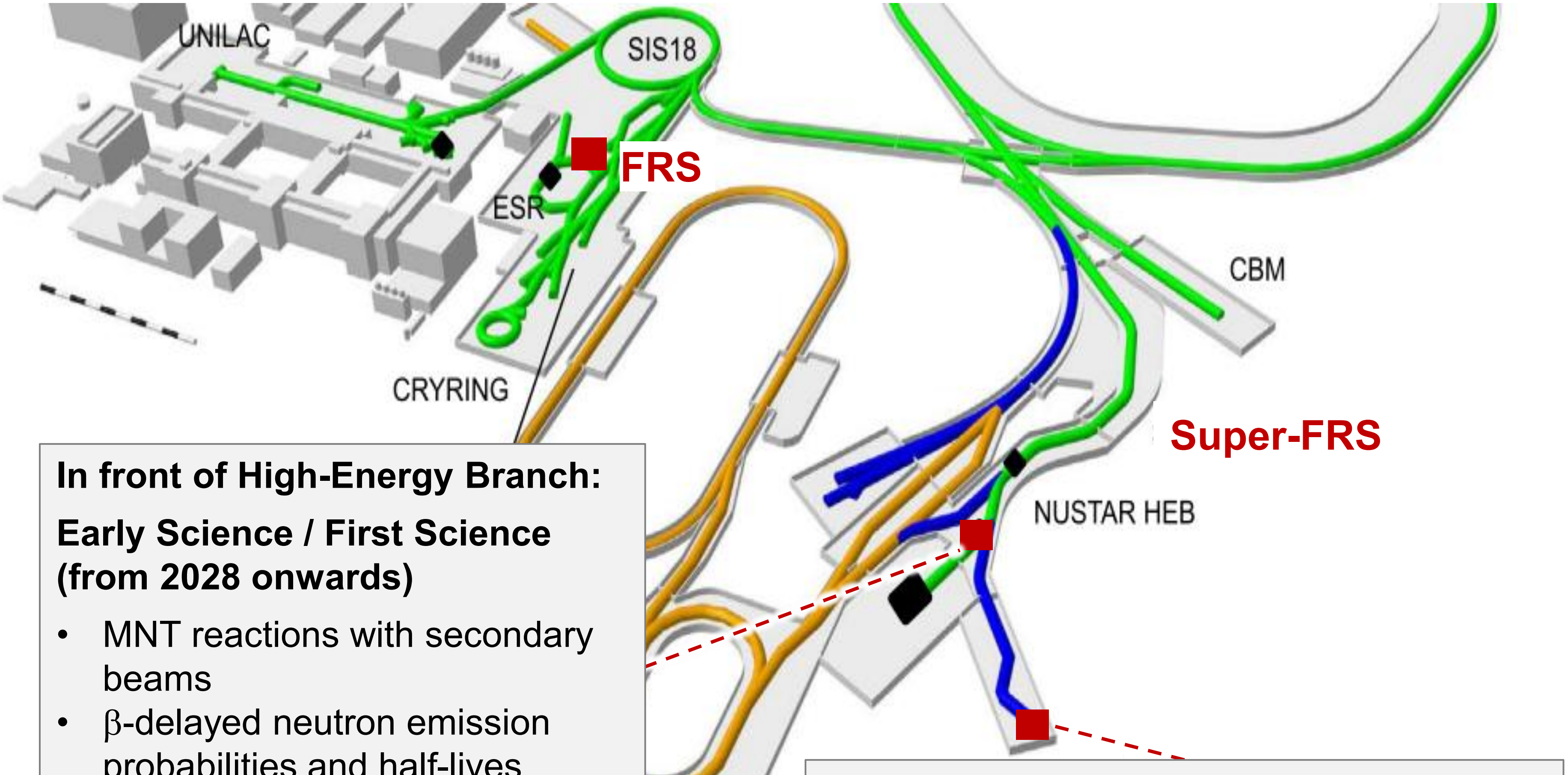
G. Kripkó-Koncz et al., Phys. Rev. Research, in print (https://doi.org/10.1103/mhhn-kmgx)

One possible scenario, which is “consistent with all”



G. Kripkó-Koncz *et al.*,
Phys. Rev. Research, in print
https://doi.org/10.1103/mhhn-kmgx

The FRS and Super-FRS Ion Catcher at GSI/FAIR



In front of High-Energy Branch:

Early Science / First Science (from 2028 onwards)

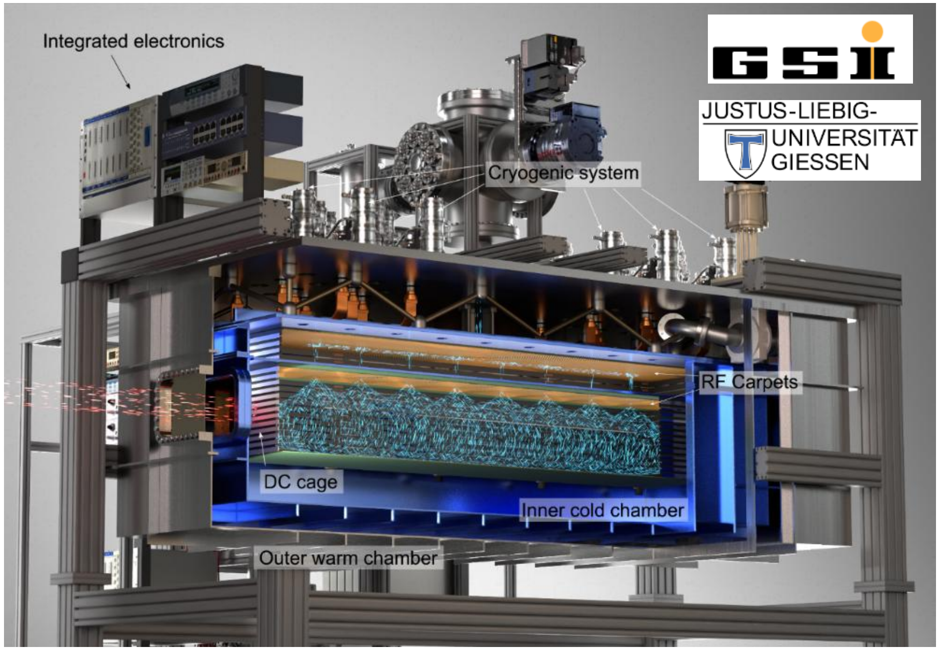
- MNT reactions with secondary beams
- β-delayed neutron emission probabilities and half-lives
- Mass measurements of more exotic species
- and more…

Low-Energy Branch: First Science++

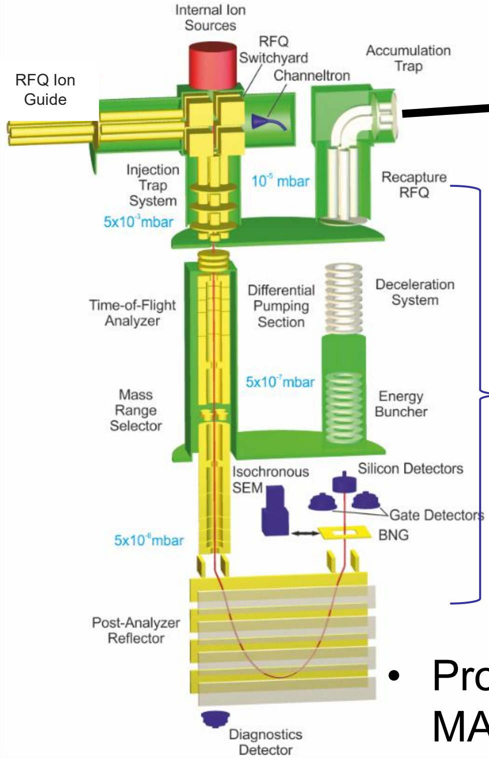
- Mass measurements
- Laser spectroscopy experiments
- In-cell decays, …

Almost all that is needed for r-process

Expected performance of Super-FRS Ion Catcher



D. Amanbayev, et al, EPJ. ST (2025) 234: 861-917



Isobarically or isomerically pure beam

MR-TOF-MS for MATS/LaSPEC extension will be added

TECHNISCHE UNIVERSITÄT DRESDEN

eli nuclear physics

THE UNIVERSITY of EDINBURGH

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

- Providing pure beams for MATS/LaSpec experiments
- Mass-selected decay spectroscopy experiments

	Present CSC	Super-FRS CSC
Areal density (He)	9 mg/cm^2	28…40 mg/cm^2
Extraction time	25 ms	5…15 ms
Rate capability	10^4 ions/s	>10^7 ions/s

x 4 higher stopping efficiency

x 2 faster ion extraction

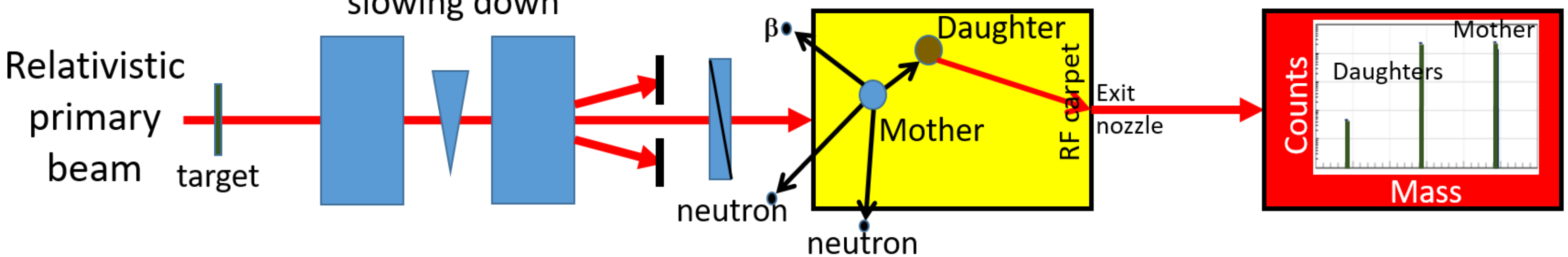
x 10^3 more intense beams

Future example #1: Beta-delayed neutron emission

Super-FRS
In-flight isotope production and separation, energy bunching, slowing down

CSC
Mother of interest stopped, contained and decays

MR-TOF-MS
Mother and daughters identification and counting

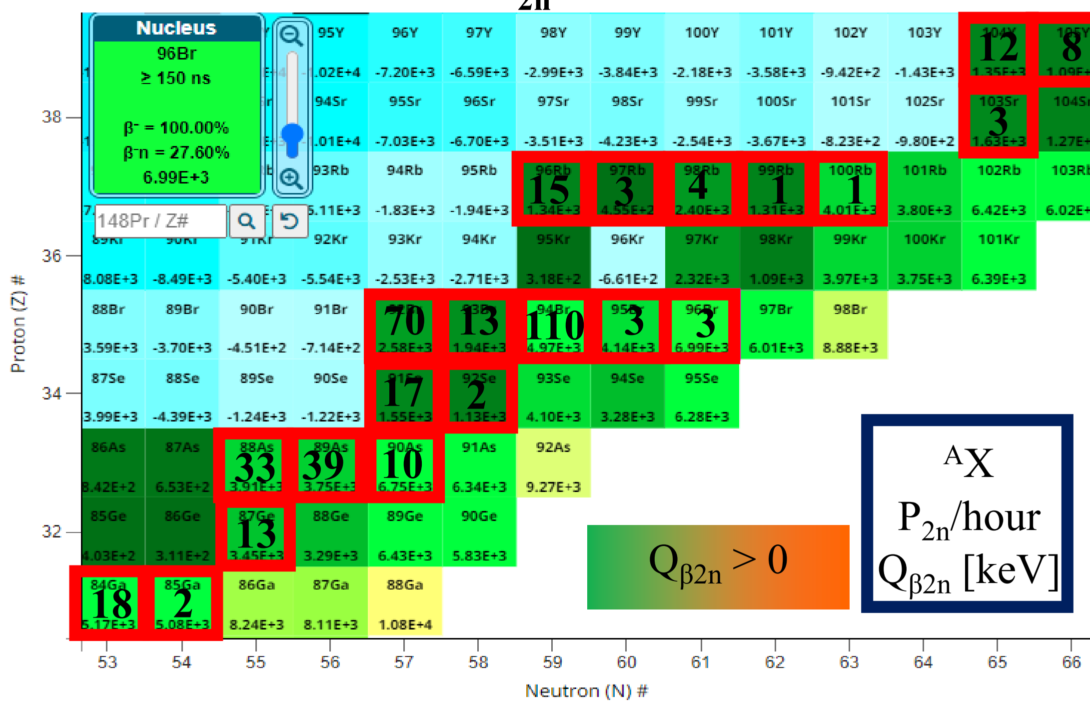


End of June 2025 test experiment with ^{135}Sb

Parameter	Factor
^{238}U @ production target	~3
Super-FRS transmission	~8
Super-FRS Ion Catcher	~5
Total	**~120**

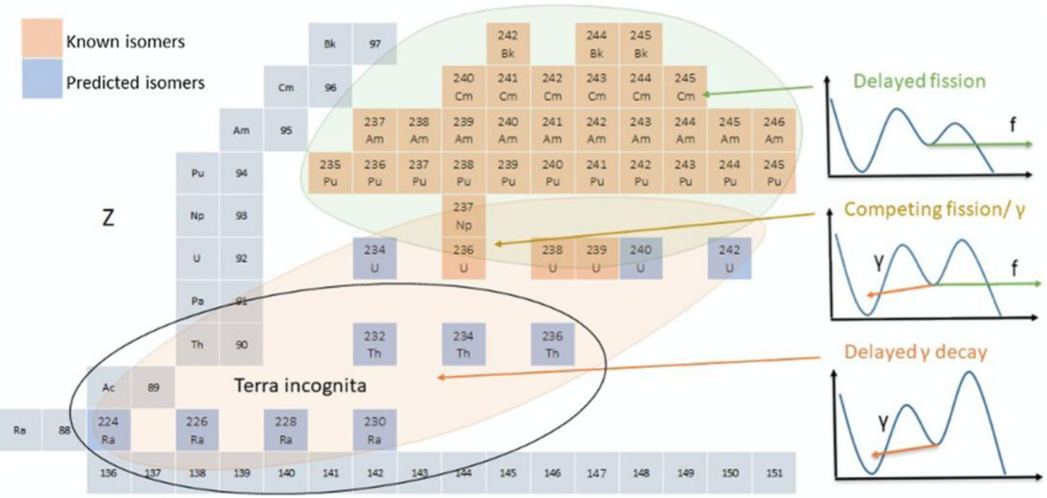
Improved S-FRS separation reduces background by order(s) of magnitude

~18 P_{2n} in ~15 shifts

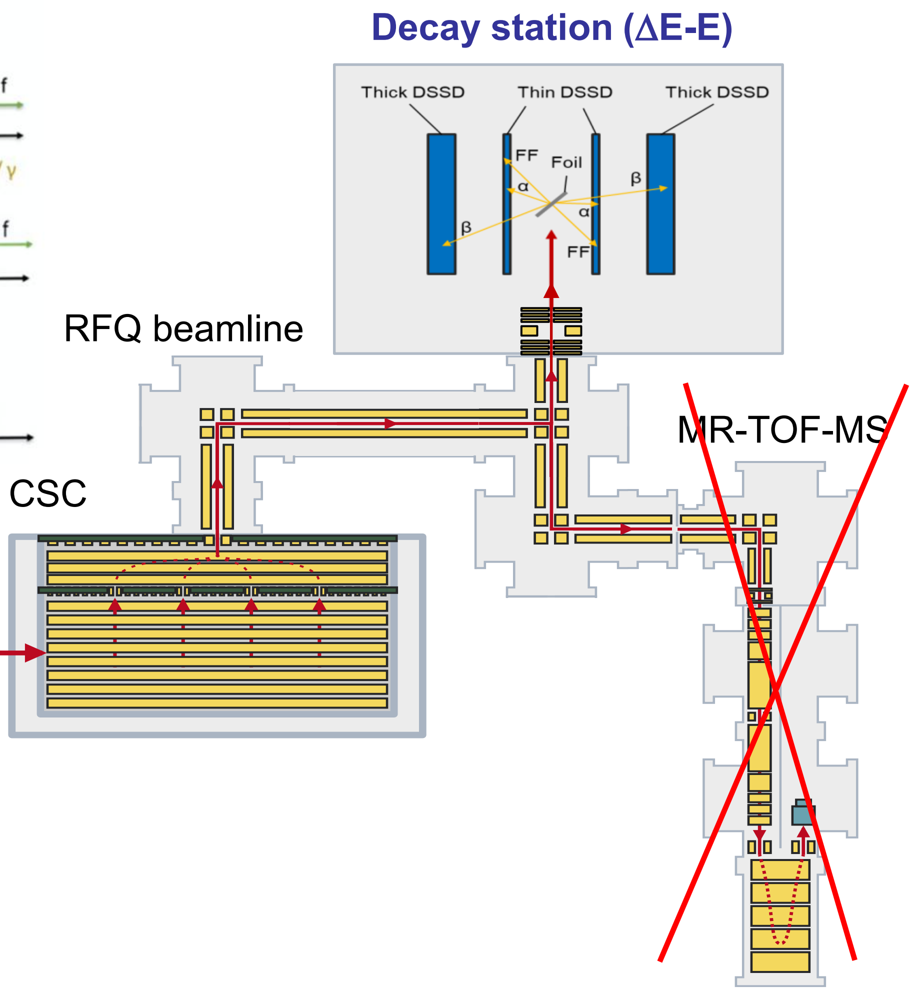


Future example #2: Fission isomers

Fission isomers: excited metastable nuclear states decay by spontaneous fission.



S. Leoni et al., Eur. Phys. J. Spec. Top. (2024) 233:1061–1074



Ion Catcher + DSSSD → $T_{1/2}$ > 5 ms

- high efficiency, low background
- allow full rate from the Super-FRS
- efficient fission isomer searching
- $T_{1/2}$ only limited by the extraction from CSC

Summary and Outlook

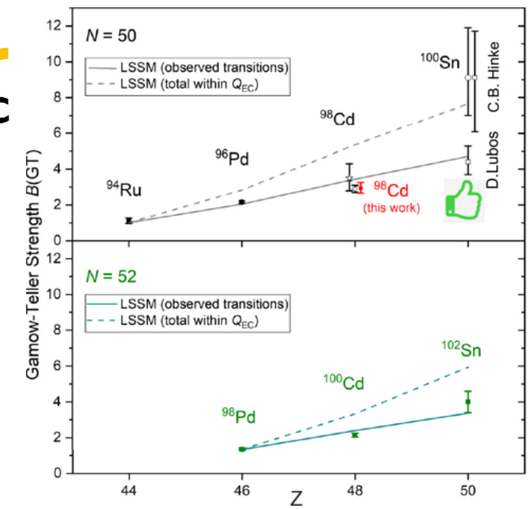
Three riddles studied at FRS Ion Catcher:

- The riddle of unexpected isotopes solved
- Implications for the “^{100}Sn mass riddle”
- Riddles surrounding the 1p/2p decay in ^{94}Ag:

If the 2p decay exists, it cannot come from the same isomer as the 1p decay.

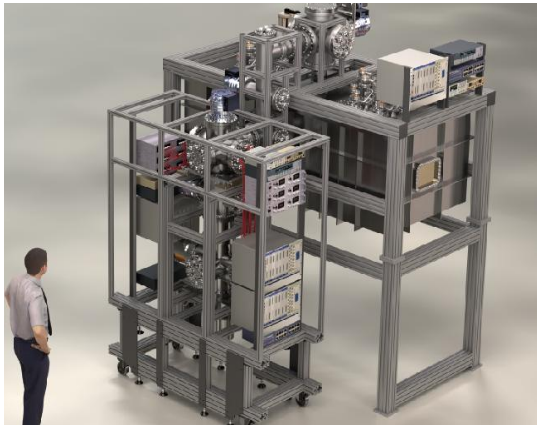
Super-FRS EC

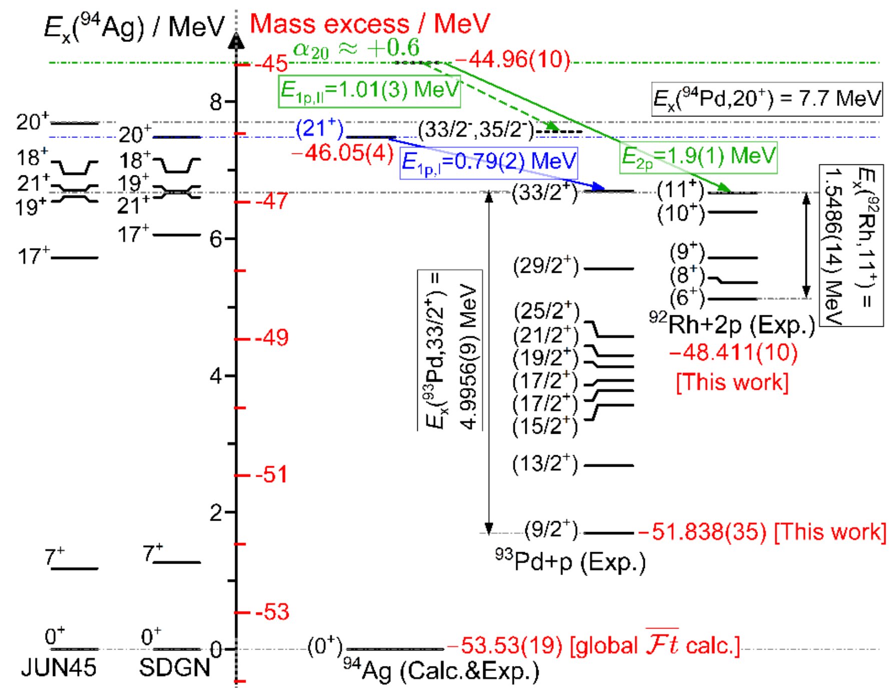
FAIR Phase 0 Research Program FRS



(Super-)FRS Ion Catcher:

- Three approved experiments in 2026/27
- 2028 and beyond: Higher intensities and cleaner conditions at the Super-FRS will allow to study the most exotic cases





Acknowledgements

Super-FRS Experiment Collaboration

FRS Ion Catcher

D. Amanbayev, O. Aviv, S. Ayet San Andrés, J. Äystö, S. Bagchi, D.L. Balabanski, S. Beck, O. Beliuskina, J. Bergmann, A. Blazhev, K. Botsiou, Z. Brencic, S. Cannarozzo, V. Charviakova, P. Constantin, D. Curien, I. Dedes, T. Dickel, F. Didierjean, G. Duchene, J. Dudek, T. Eronen, T. Fowler-Davis, M. Friedman, Z. Ge, H. Geissel, S. Glöckner, M. Górska, T. Grahn, F. Greiner, L. Gröf, M. Gupta, E. Haettner, M. Harakeh, J. Harkin, C. Hornung, W. Huang, Y. Ito, A. Jaries, A. Jokinen, N. Kalantar-Nayestanaki, A. Kankainen, D. Kar, A. Karpov, N. Keeppalli, Y. Kehat, K. Khokhar, D. Kostyleva, G. Kripkó-Koncz, D. Kumar, B. Lehnert, K. Mahajan, I. Mardor, A.A. Mehmandoost-Khajeh-Dad, N. Minkov, A. Mollaebrahimi, D. Morrissey, I. Mukha, M. Narang, Z. Patyk, H. Penttilä, A. Perry, S. Pietri, A. Pikhtelev, W.R. Plaß, I. Pohjalainen, S. Pomp, R.K.Prajapat, S. Purushothaman, M.P. Reiter, M. Reponen, H. Rösch, A. Rotaru, J. Ruotsalainen, C. Scheidenberger, P. Schury, A. Shrayer, M. Simonov, S.K. Singh, A. Solders, A. Spataru, A. State, N. Steinbrenner, Y. Tanaka, P. Thirolf, Y. Tian, N. Tortorelli, F. Uhlemann, L. Varga, M. Vencelj, V. Virtanen, M. Wada, H. Weick, L. Welde, M. Will, H. Wilsenach, M.I. Yavor, J. Yu, A. Zadvornaya, J. Zhao, K. Zuber

FAIR Phase 0 Research Program

FRS

The results presented here are based on the experiment S474, which was performed at the FRS at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt (Germany) in the context of FAIR Phase-0

Funding: German Federal Ministry of Research, Technology and Space (05P19RGFN1, 05P21RGFN1, 05P24RG4), **JLU Giessen and GSI** (JLU-GSI strategic Helmholtz partnership agreement), **Helmholtz Research Academy Hesse for FAIR (HFHF)**, **HGS-HIRe**, **German Research Foundation** (422761894, AY 155/2-1), **DAAD** (57610603), **Israel Ministry of Energy** (220-11-052), **Israel Science Foundation** (2575/21), **Romanian Ministry of Research, Innovation and Digitalization** (PN 23 21 01 06), **Polish Minister of Science and Higher Education** (5237/GSI-FAIR/ 2022/0), **French-Polish collaboration COPIN** (04-113 and 435 23-157), **Research Council of Finland** (354589), **IAEA** (CRP F42007, 24000), **European Union's Horizon Europe Research and Innovation program** (101057511 EURO-LABS, 771036 ERC CoG MAIDEN)