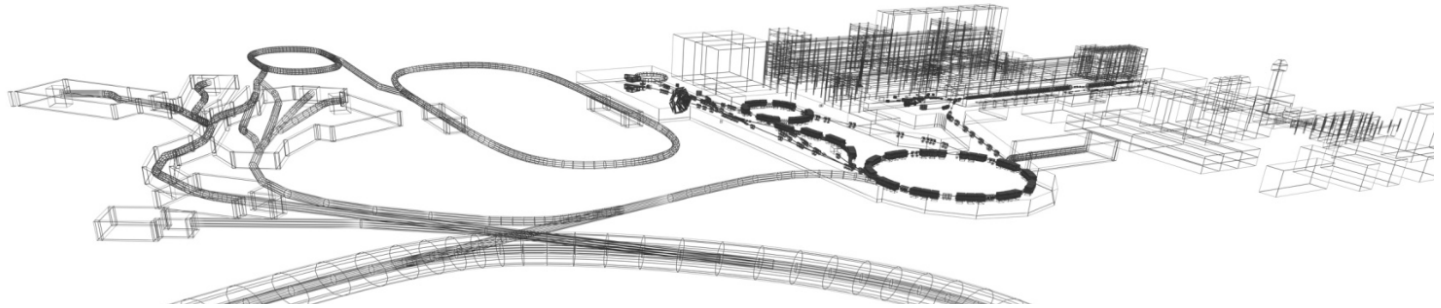
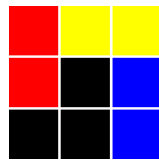


Decay studies of exotic nuclei at the Super-FRS



Plans and dreams of the Warsaw group

Marek Pfützner



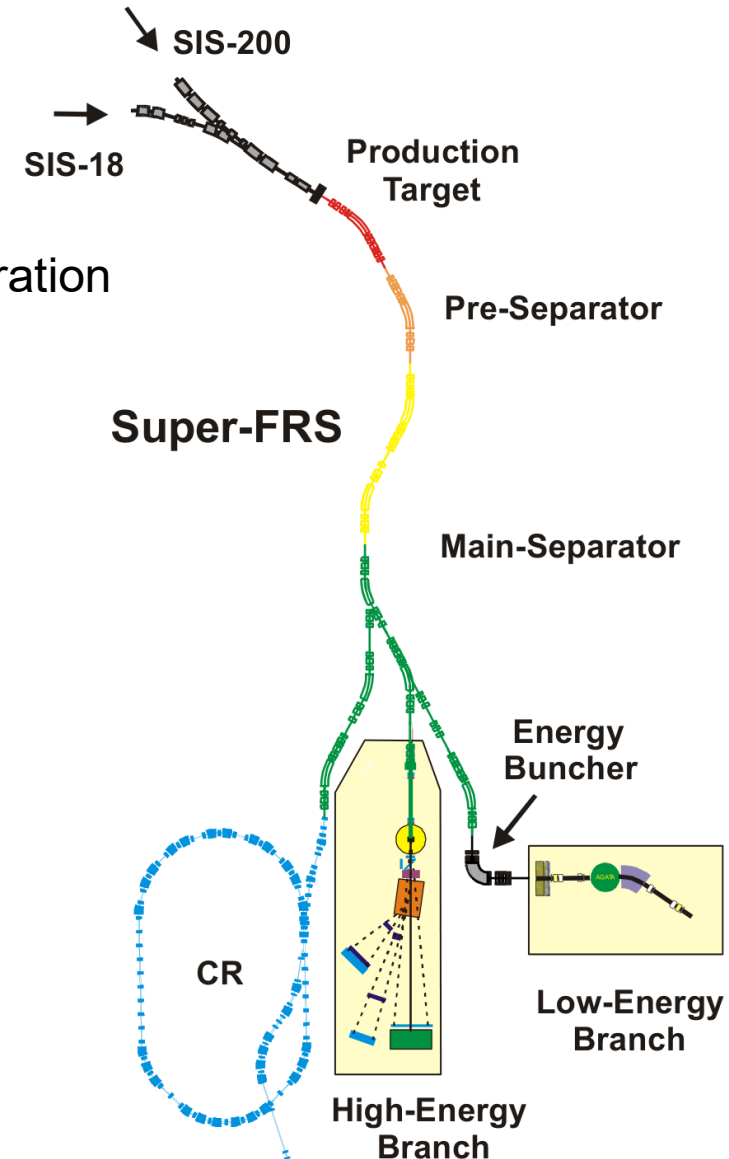
NUCLEAR PHYSICS DIVISION
UNIVERSITY OF WARSAW





Plan

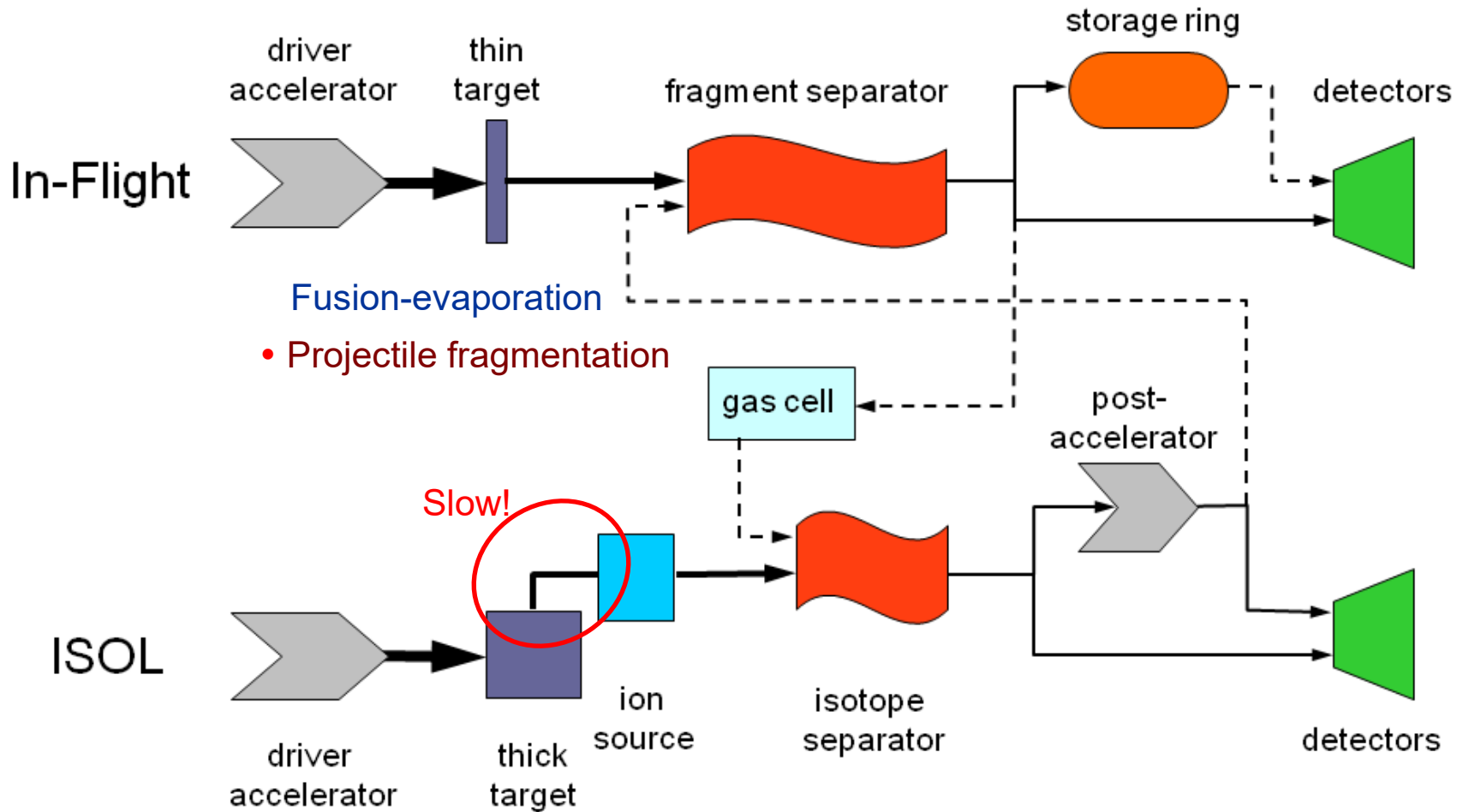
- ✦ Brief introduction to fragment separation
- ✦ Super-FRS and its advantages
- ✦ Spectroscopy of isomers
- ✦ Two-proton radioactivity
- ✦ Beta-delayed particles
- ✦ In-flight decay spectroscopy
- ✦ Probing the nuclear sandbank

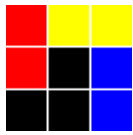




Radioactive beams

Two general schemes





Projectile Fragmentation

Pioneered at Bevalac (LBNL, Berkeley)

VOLUME 42, NUMBER 1

PHYSICAL REVIEW LETTERS

1 JANUARY 1979

Observation of New Neutron-Rich Isotopes by Fragmentation of 205-MeV/Nucleon ^{40}Ar Ions

T. J. M. Symons, Y. P. Viyogi,^(a) G. D. Westfall, P. Doll,^(b) D. E. Greiner, H. Faraggi,^(c)
P. J. Lindstrom, and D. K. Scott

Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

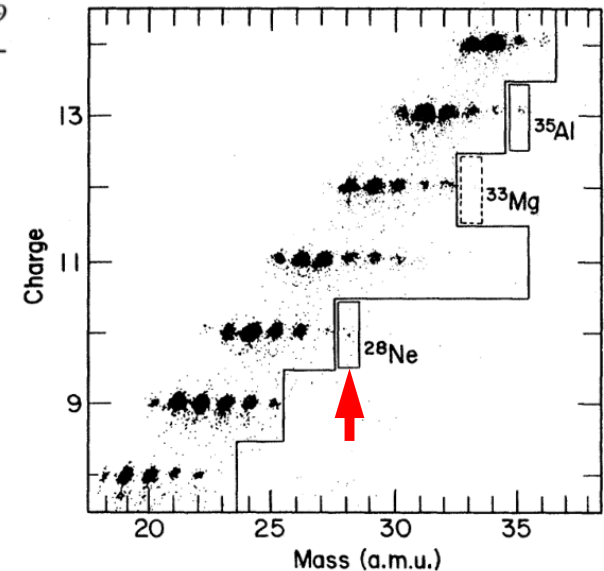
and

H. J. Crawford and C. McParland

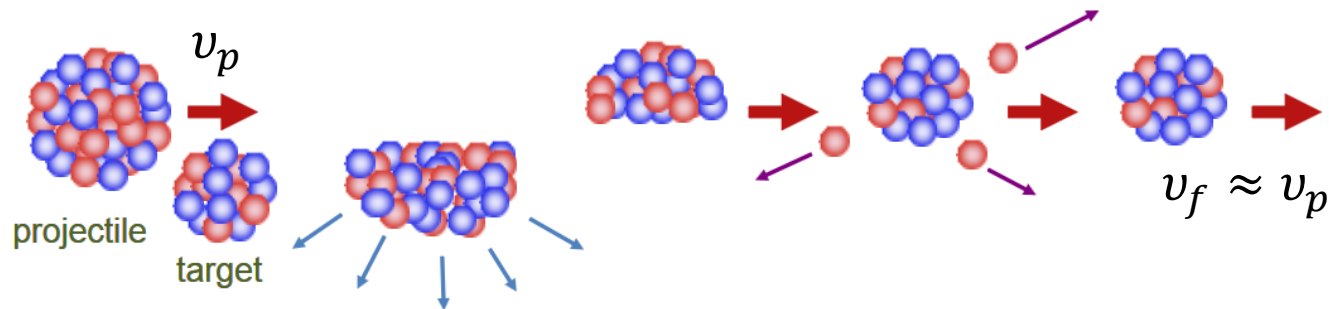
Space Sciences Laboratory, University of California, Berkeley, California 94720

(Received 1 November 1978)

Yields of projectile fragments have been measured at 0° for the reaction of 205-MeV/nucleon ^{40}Ar ions on an 860-mg-cm^{-2} carbon target. Mass resolution was achieved using a combination of magnetic analysis and energy-loss measurements. The isotopes ^{28}Ne and ^{35}Al have been observed for the first time.

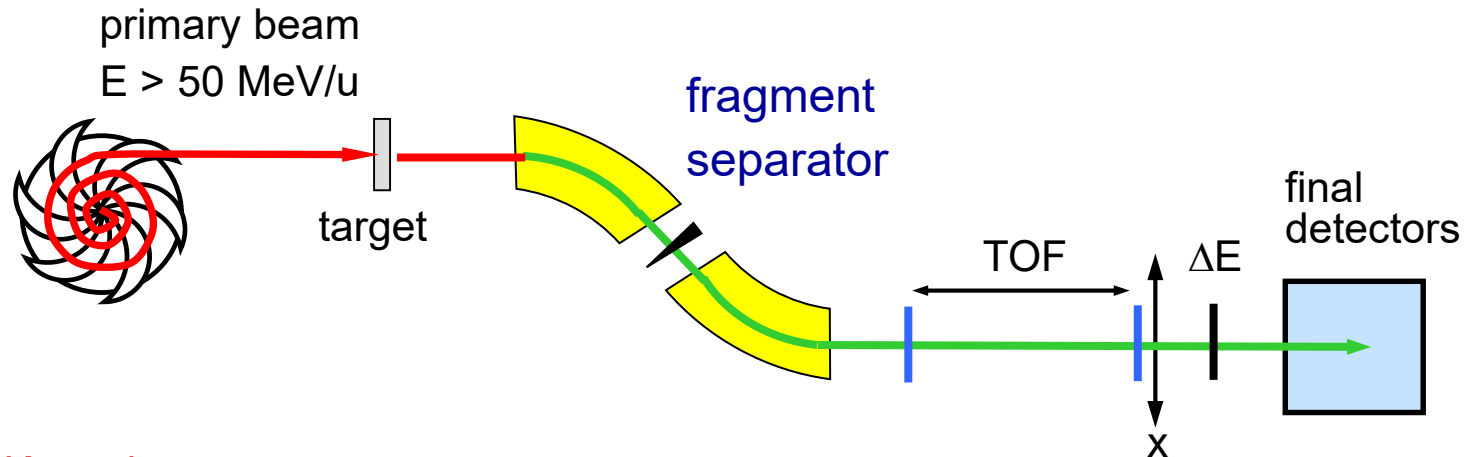


Projectile energy/nucleon larger than Fermi energy ($> 50 \text{ MeV/u}$)





Projectile Fragmentation



Key advantages

- thick targets (large yields)
- chemical independence
- full identification of single ions in-flight
- fast transport (μs)
- implantation into thick detectors
- ready for secondary reactions
- cocktail beams

However

- large and expensive facility
- low intensity of heavy projectiles
- large range straggling
- bad ion-optical properties of secondary beams
- products are lighter than projectiles



Fragment Separators

➤ First generation

- LISE at GANIL (1985) 30 - 100 MeV/u
- RIPS at RIKEN (1990) 135 MeV/u
- A1200 at NSCL/MSU (1991) 50-200 MeV/u
- FRS at GSI (1991) 0.5 - 2 GeV/u
- Acculinn at FLNR (1996) 50 MeV/u
- RIBLL at HIRFL (1998) 60 MeV/u
- Fribs at LNS (2001) 50 MeV/u

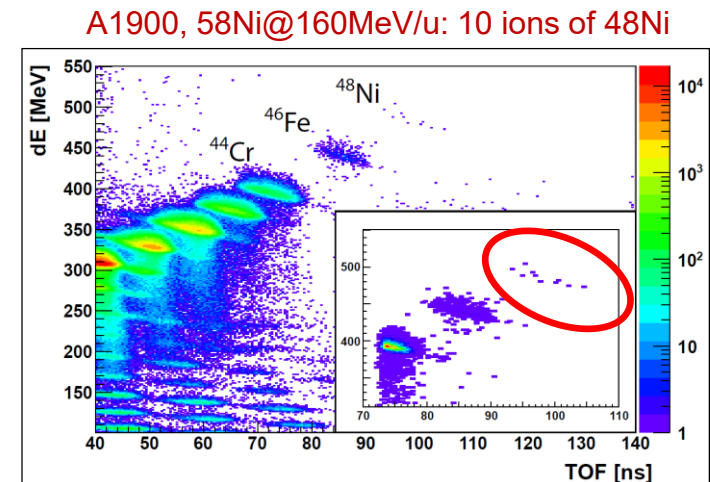
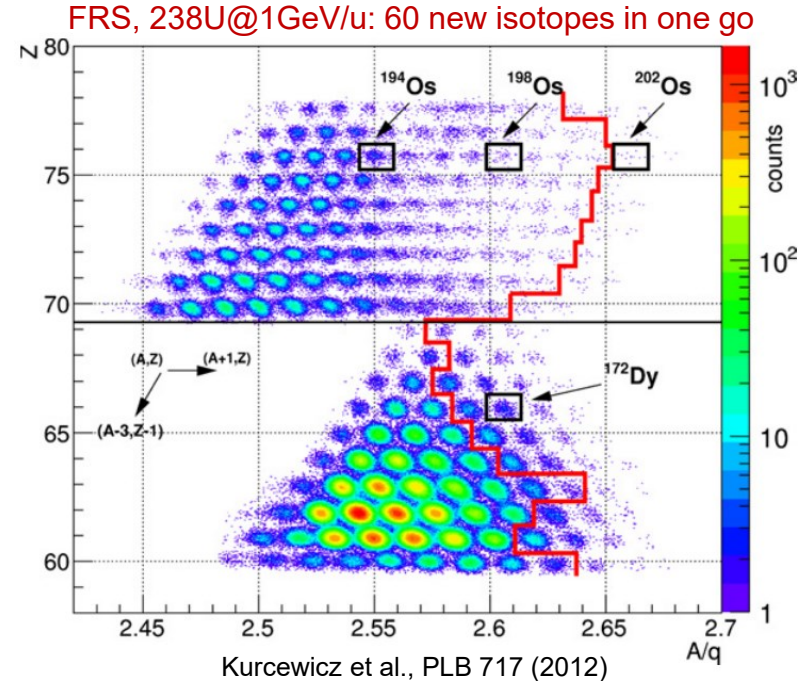
➤ Second generation

- A1900 at NSCL/MSU (2003) 50-200 MeV/u
- BigRIPS at RIKEN (2007) 350 MeV/u

➤ Third generation

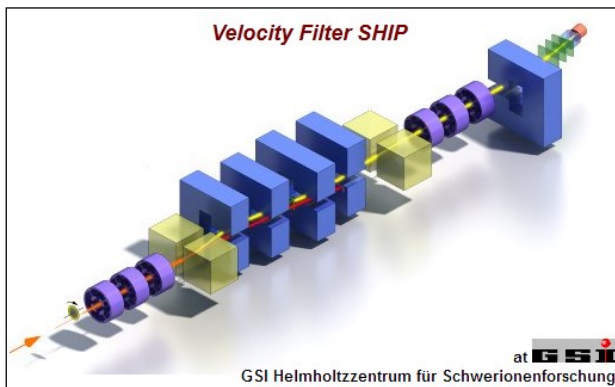
- ARIS at FRIB (2022) 280 → 400 MeV/u
- SuperFRS at FAIR 1.5 GeV/u

....





Sensitivity



• Hunt for element 120 at SHIP



Cross section:

$\approx 90 \text{ fb}$

Beam intensity:

750 pA

Running time (1 event):

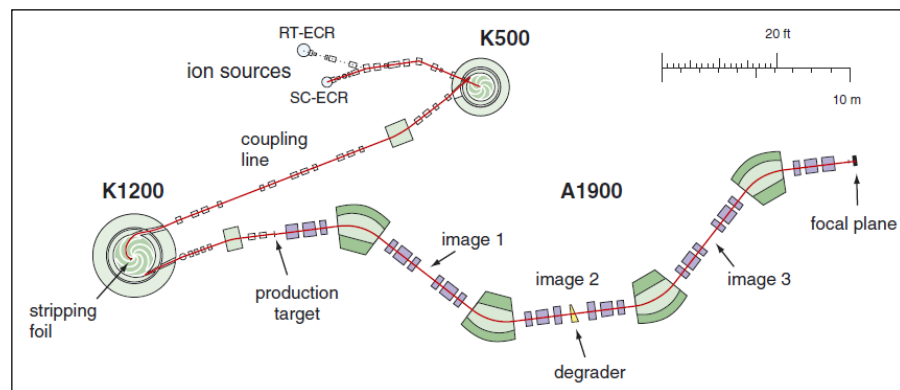
$\approx 100 \text{ days}$

Total dose:

$\approx 4 \cdot 10^{19} \text{ part.}$

Target thickness:

0.5 mg/cm²



• Production of ^{48}Ni at NSCL



$\approx 100 \text{ fb}$

20 pA

$\approx 1 \text{ day}$

$\approx 1 \cdot 10^{16} \text{ part.}$

580 mg/cm²

38 times weaker

100 times shorter

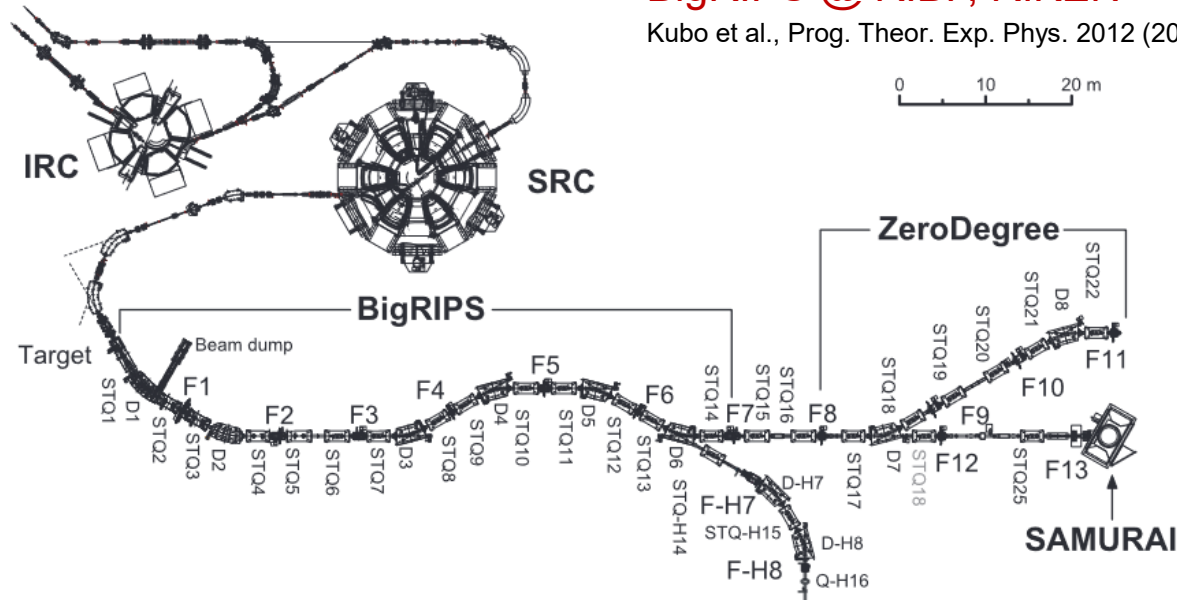
4000 times smaller



State of the art

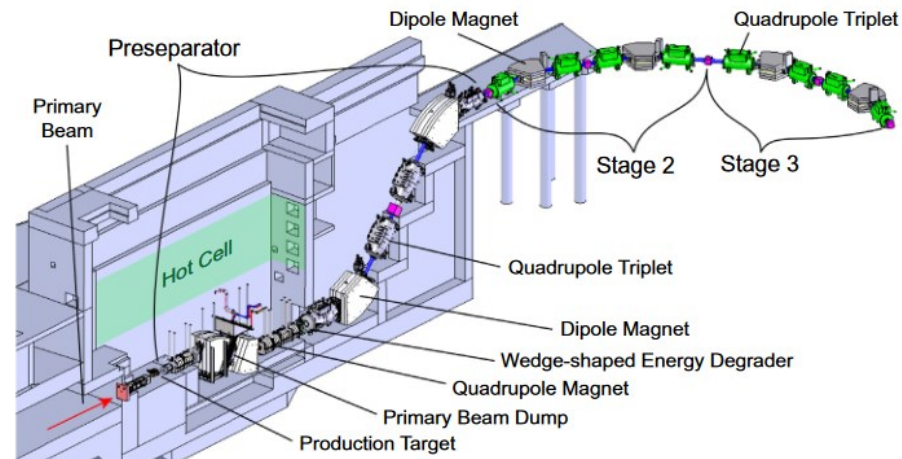
BigRIPS @ RIBF, RIKEN

Kubo et al., Prog. Theor. Exp. Phys. 2012 (2012)



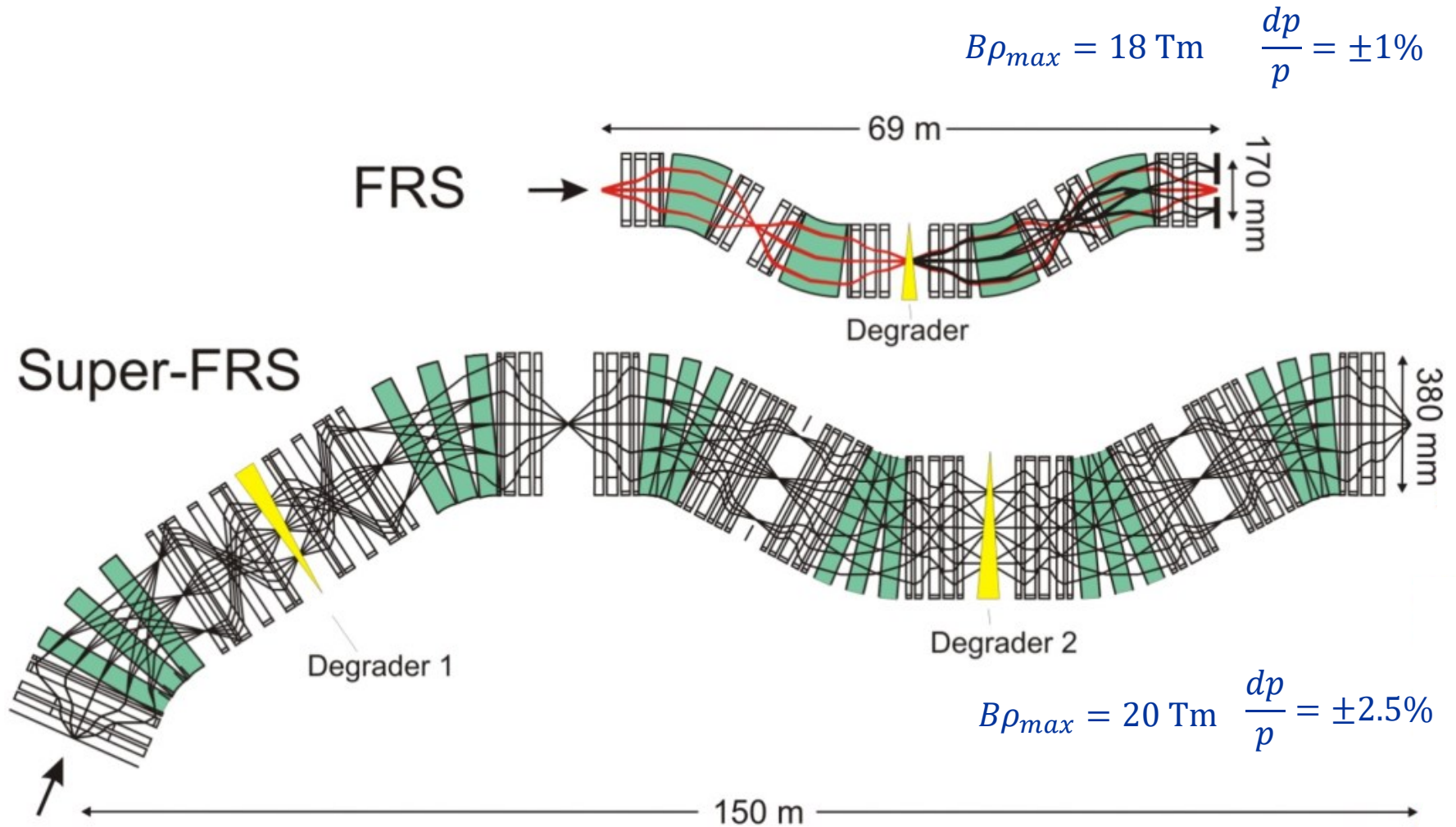
Advanced Rare Isotope Separator (ARIS) @ FRIB, MSU

Portillo et al., NIM B 540 (2023)





FRS vs. Super-FRS

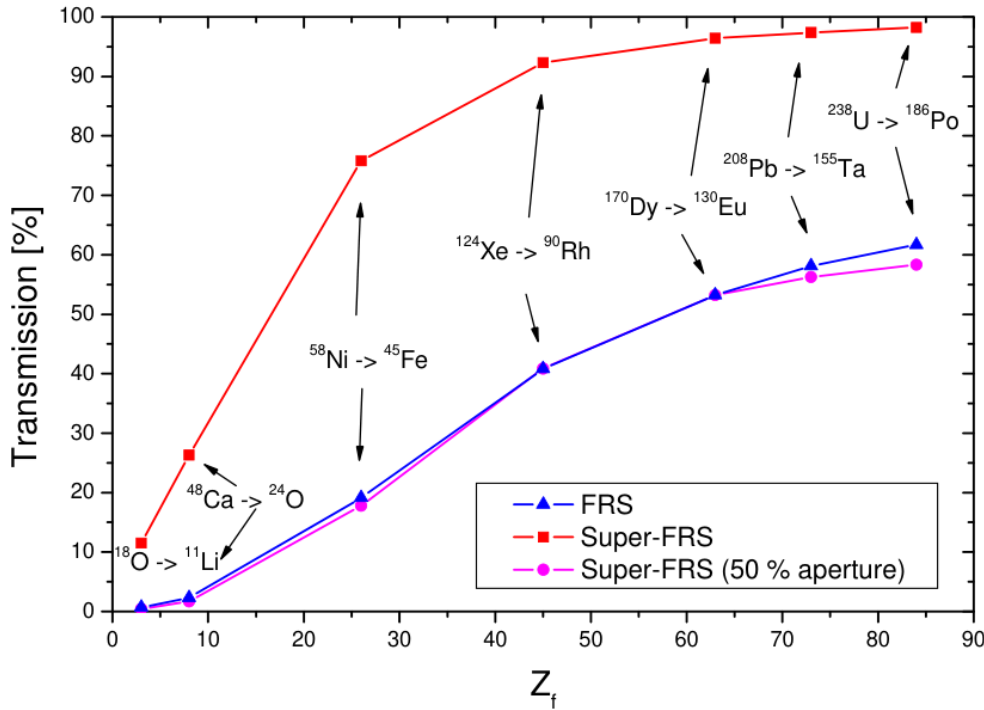


H. Geissel, 2012

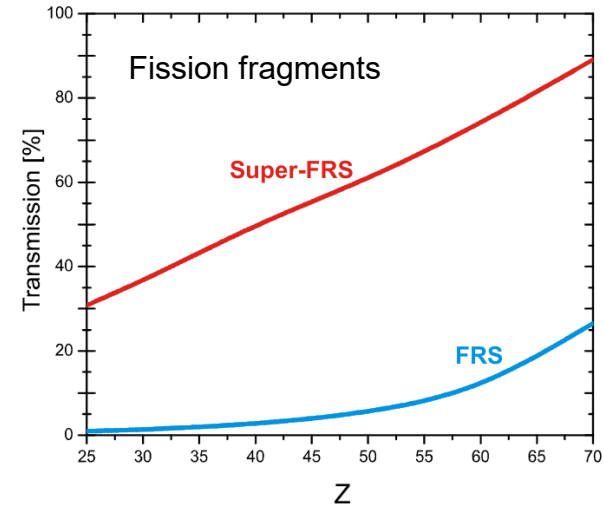


Super-FRS advantage

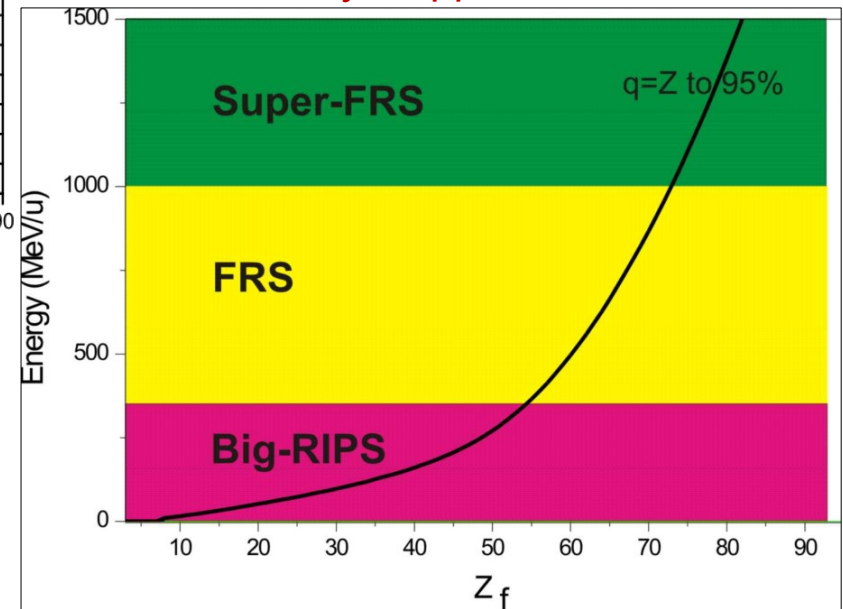
Ion-optical transmission



H. Geissel, 2012

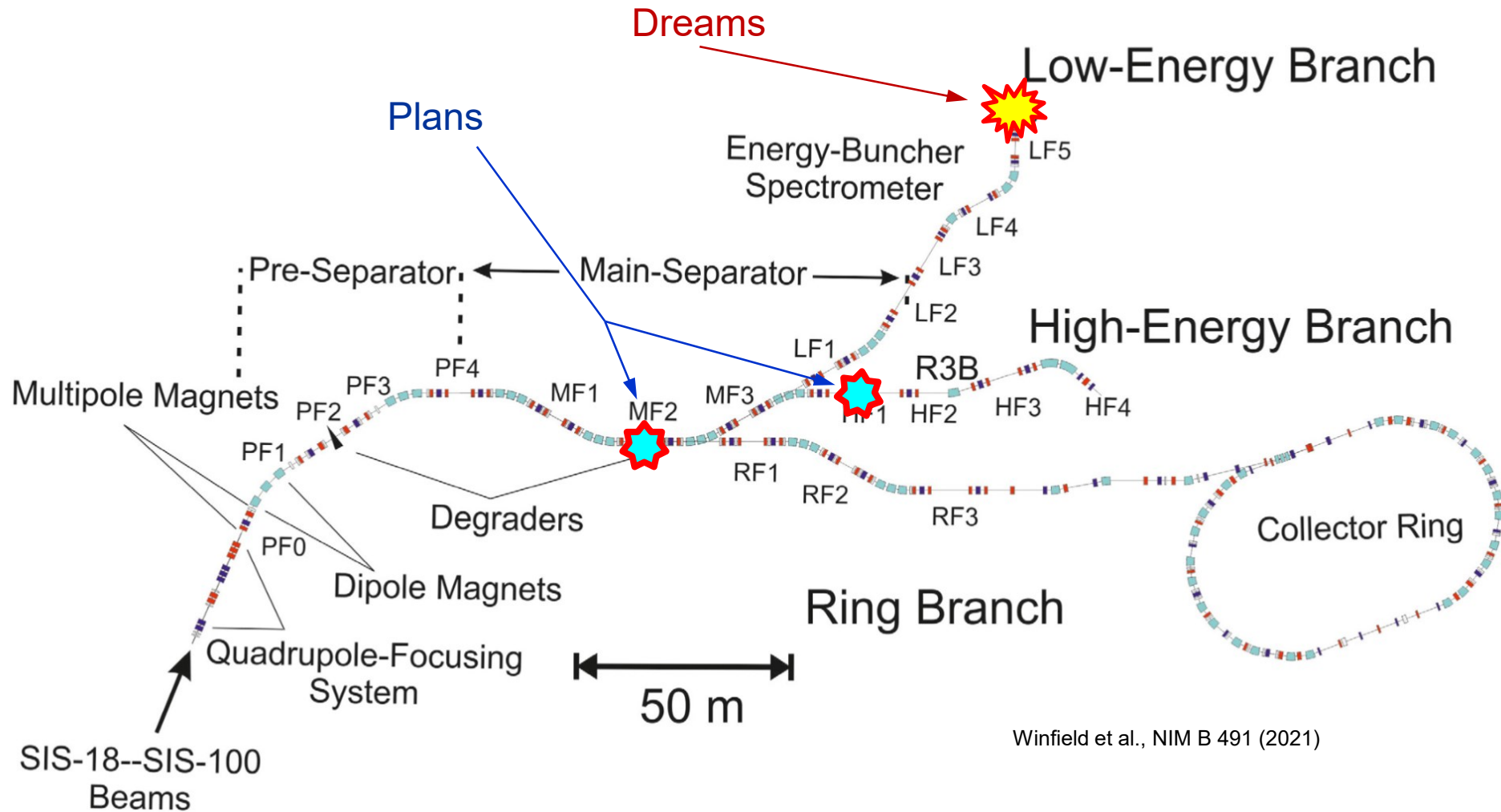


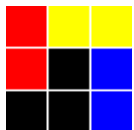
Fully stripped ions





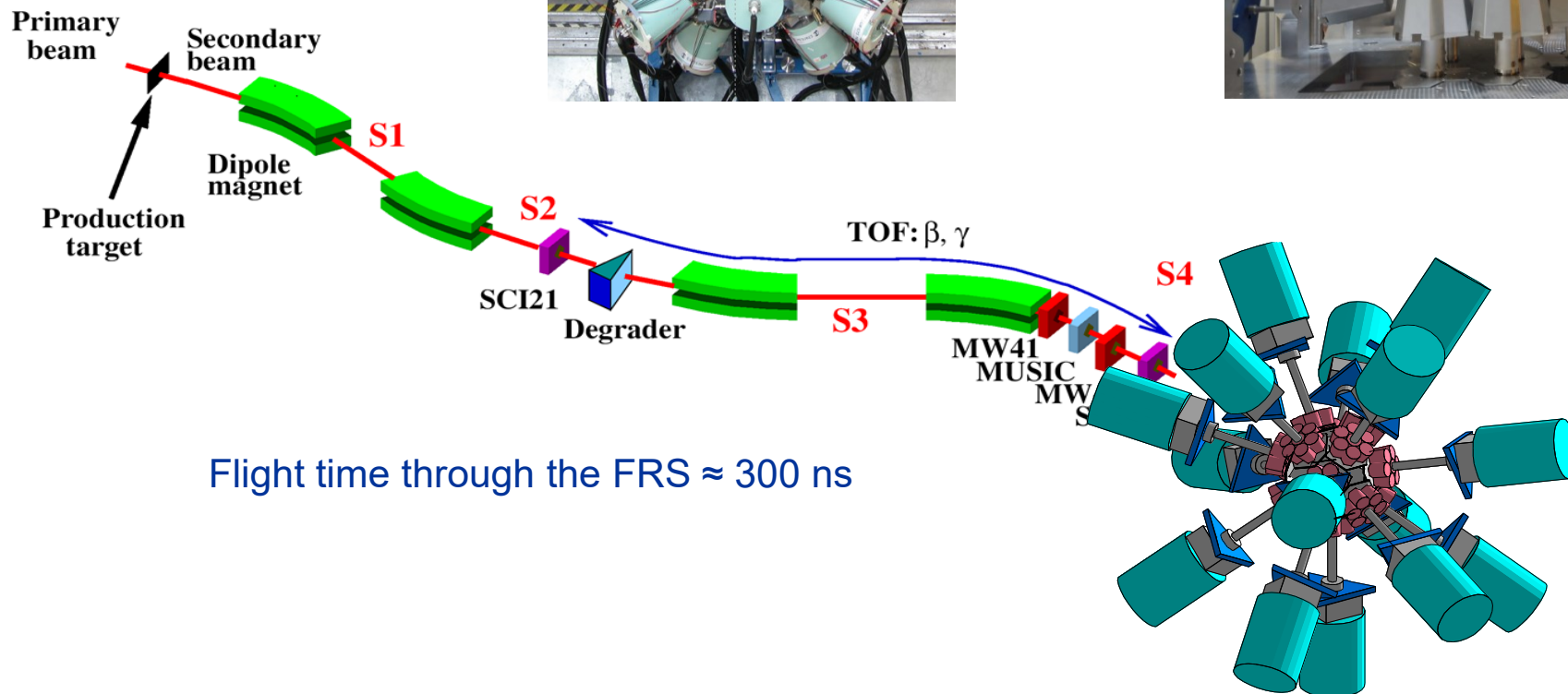
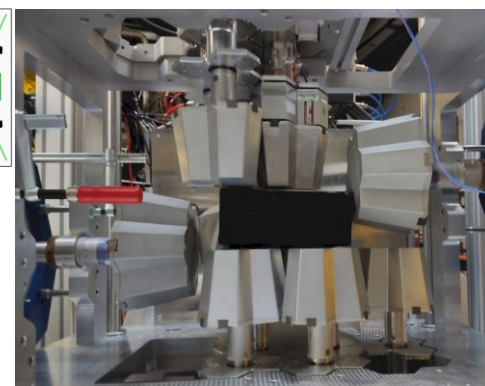
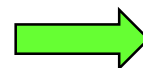
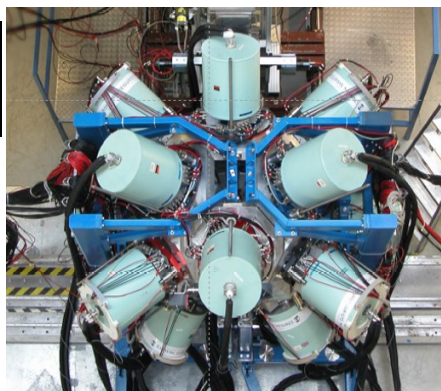
Super-FRS in full





Isomer spectroscopy

Microseconds isomers are efficiently produced in the projectile fragmentation!



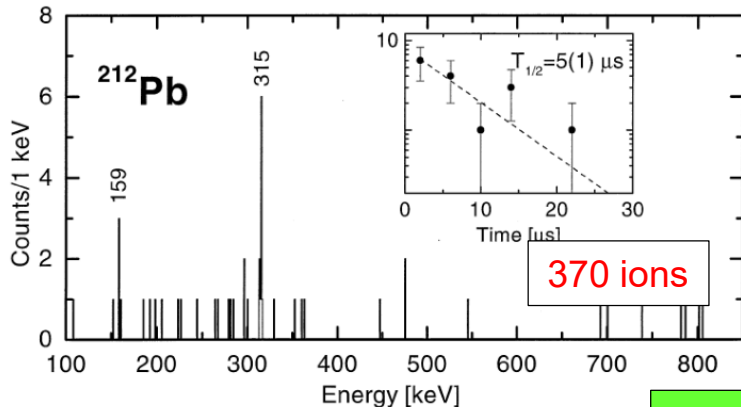


Isomers

Test of seniority scheme

GSI: ^{238}U @1 GeV/u + Be

MP et al., Phys. Lett B 444 (1998)



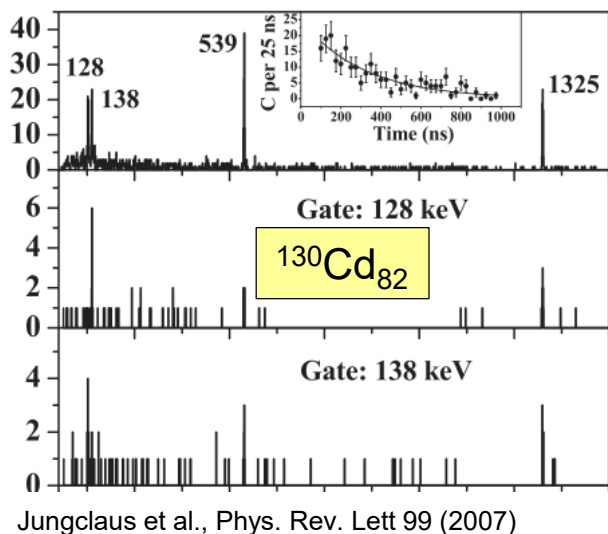
$$v(2g_{9/2})^2$$

Who will make

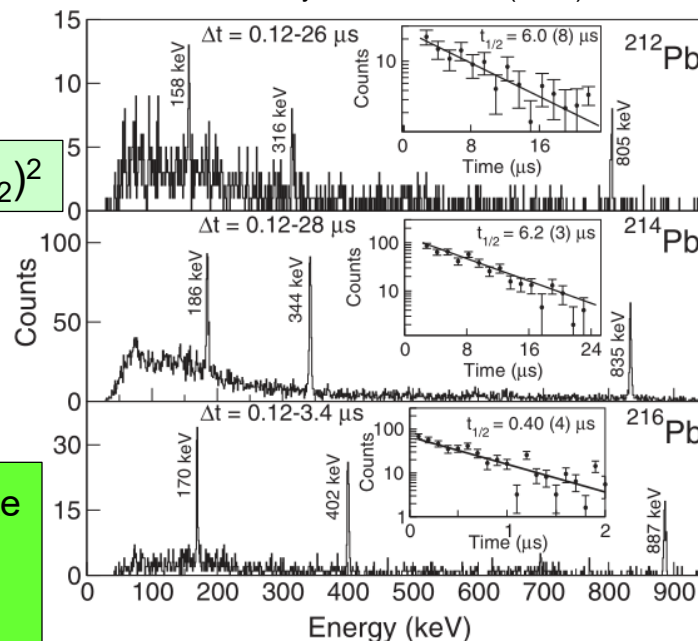
$^{126}\text{Ru}_{82}$?

$^{124}\text{Mo}_{82}$?

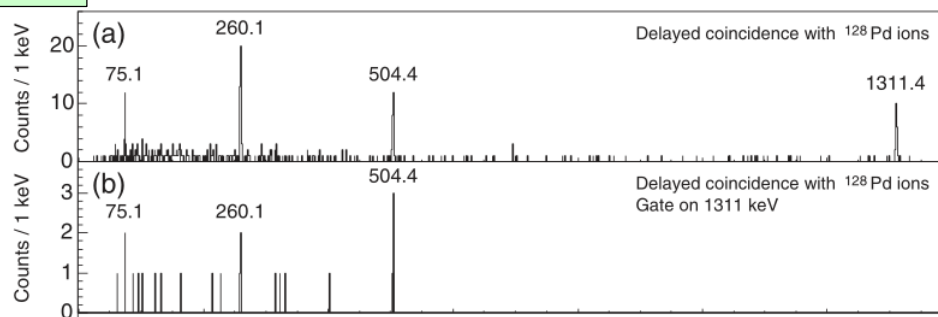
$$\pi(1g_{9/2})^2$$



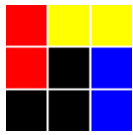
Gottardo et al., Phys. Rev. Lett 109 (2012)



RIKEN: ^{238}U @345 MeV/u + Be $\rightarrow$ $^{128}\text{Pd}_{82}$



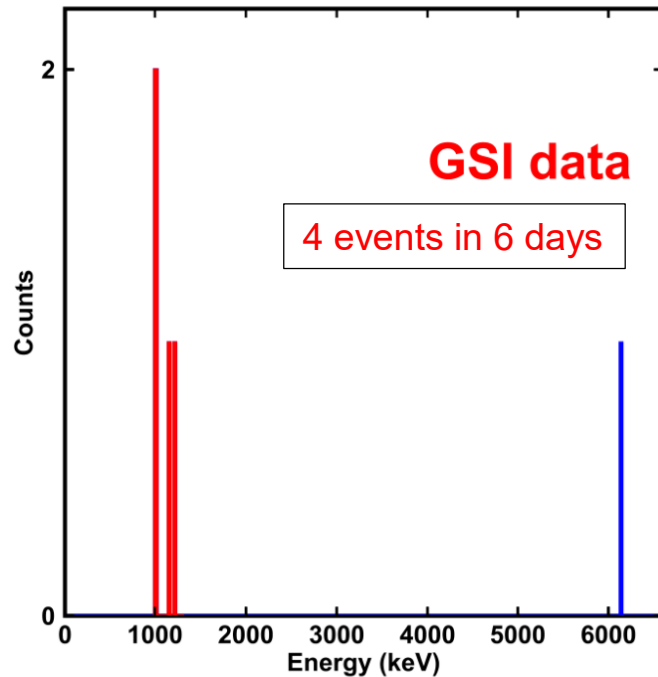
Watanabe et al., Phys. Rev. Lett 111 (2013)



2p radioactivity

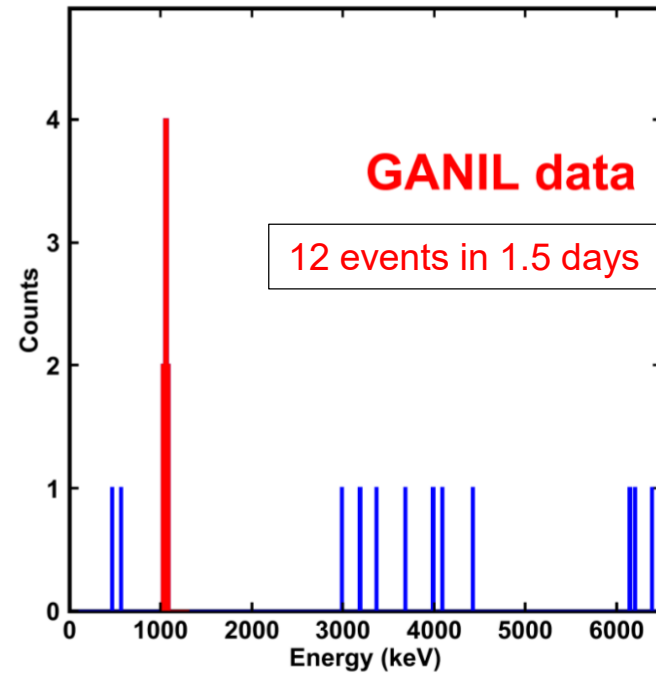
Two-proton emission discovered in ^{45}Fe

GSI: ^{58}Ni @ 650 MeV/A + Be $\rightarrow$ ^{45}Fe



MP et al., EPJ A 14 (2002)

GANIL: ^{58}Ni @ 75 MeV/A + Ni $\rightarrow$ ^{45}Fe



Giovinazzo et al., PRL 89 (2002)

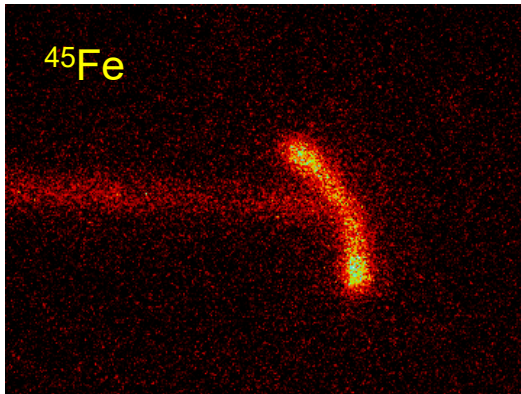
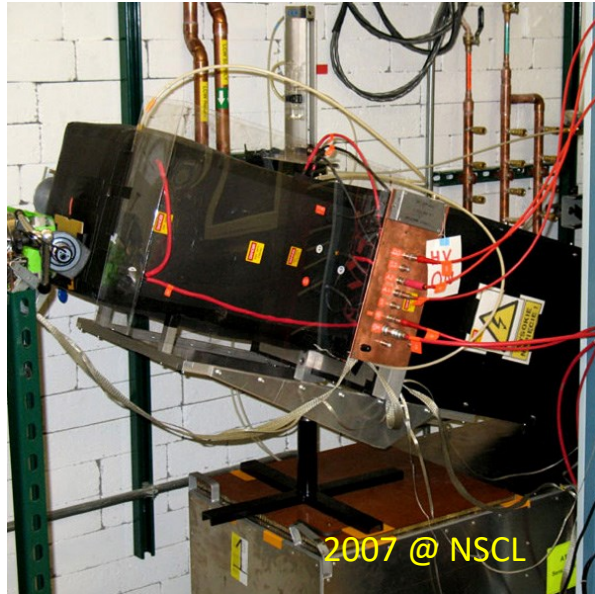
$T_{1/2} = 2.6$ ms

Decay inside Si detector

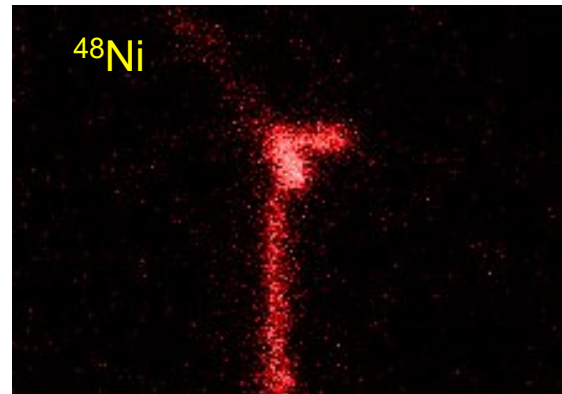
$\rightarrow$ only total energy and time measured



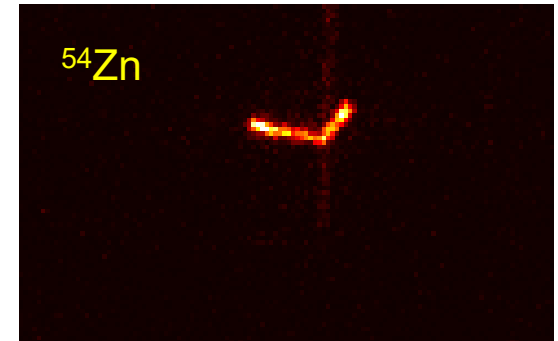
2p decay with the Warsaw OTPC



Miernik et al., PRL 99 (07)



Pomorski et al., PRC 83 (2011)



Kubiela et al., to be published (2024)



p - p correlations around $Z=28$

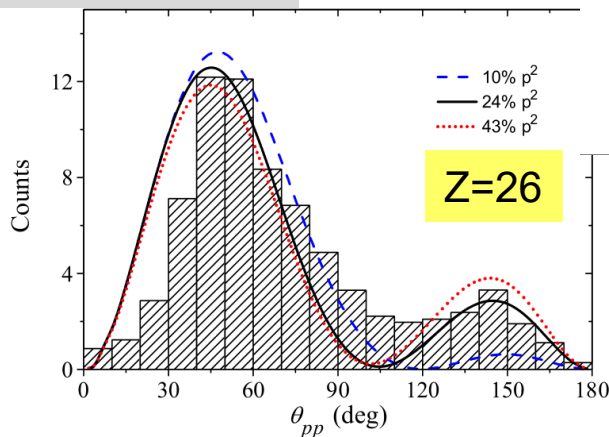
$$R_{>90} = \frac{N(\theta > 90^\circ)}{N_{tot}}$$

^{54}Zn : $R_{>90} = 0.5(2)$

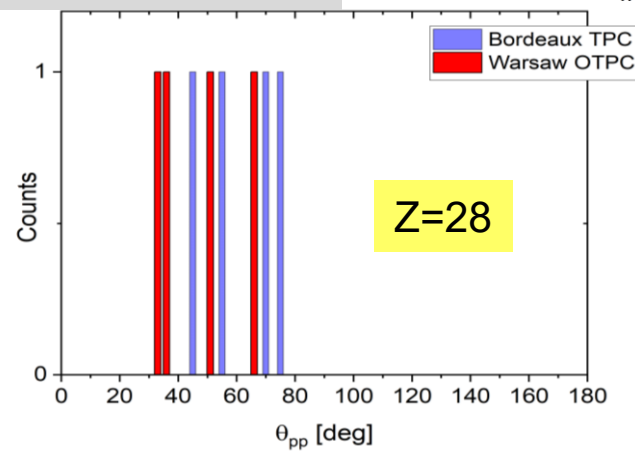
^{48}Ni : $R_{>90} = 0.0(1)$

^{45}Fe : $R_{>90} = 0.20(5)$

^{45}Fe : 75 events

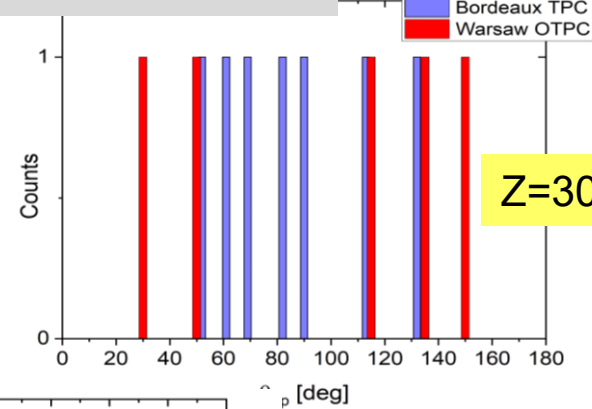


^{48}Ni : 4 + 4 events



Miernik et al.
PRL 99 (2007)

^{54}Zn : 5 + 7 events



Ascher et al.
PRL 107 (2011)

Kubiela et al.,
to be published

Ortega-Moral et al., to
be published

Pomorski et al.
PRC 90 (2014)

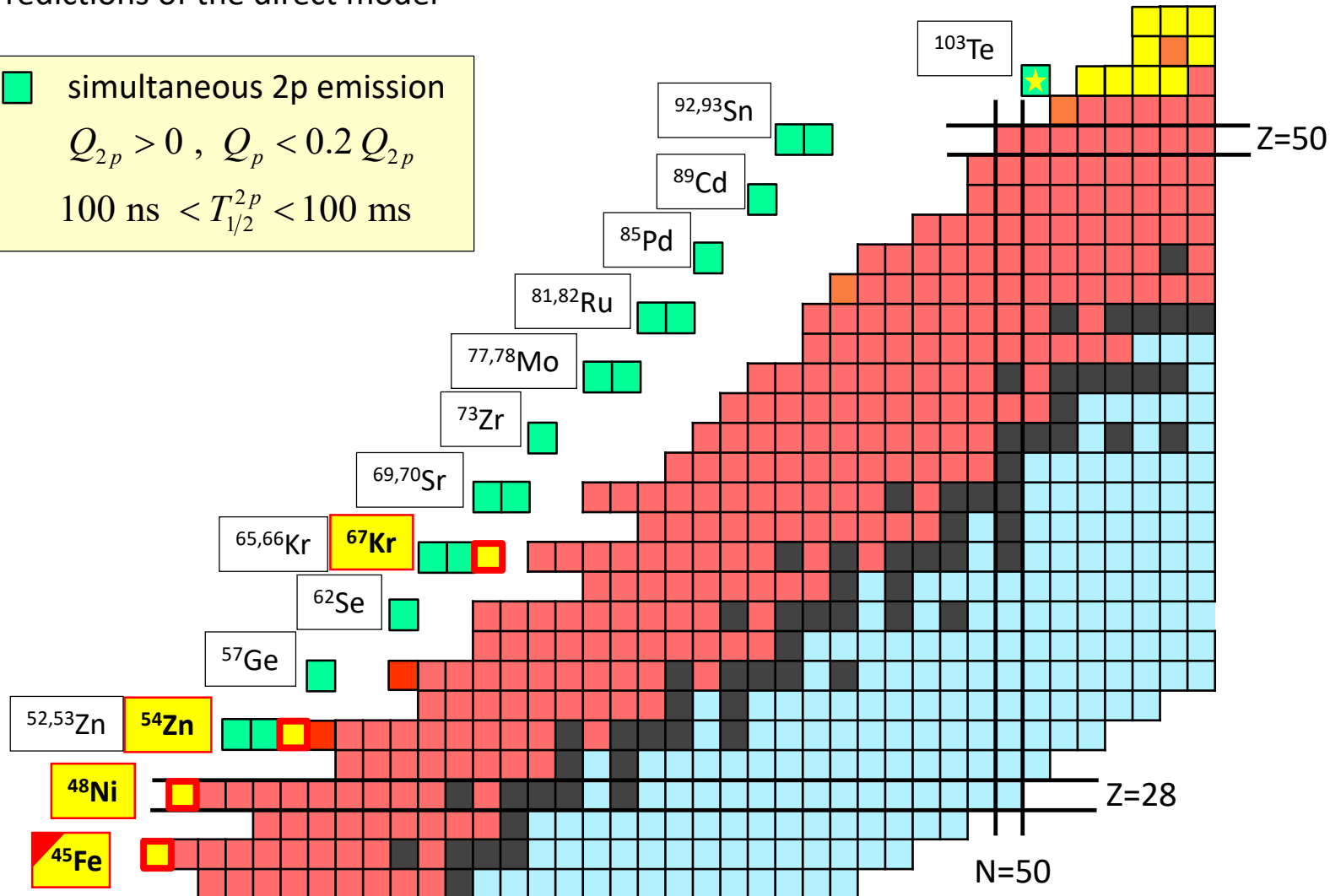
Much more statistics is needed!
Experiment at FRIB in 2025



Global 2p predictions (I)

► Predictions of the direct model

 simultaneous 2p emission
 $Q_{2p} > 0$, $Q_p < 0.2 Q_{2p}$
 $100 \text{ ns} < T_{1/2}^{2p} < 100 \text{ ms}$





Global 2p predictions (II)

► Predictions of the direct model

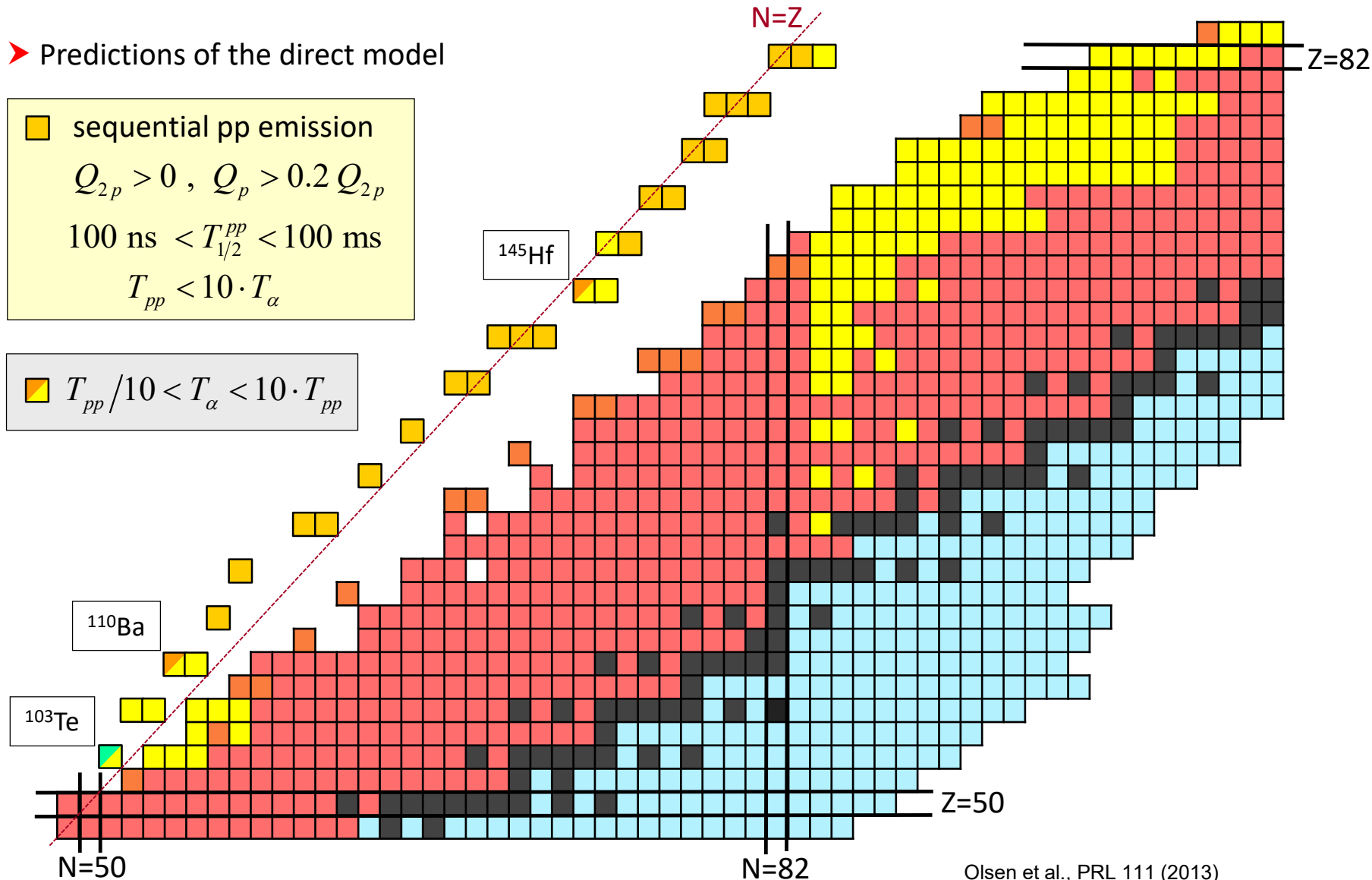
■ sequential pp emission

$$Q_{2p} > 0, Q_p > 0.2 Q_{2p}$$

$$100 \text{ ns} < T_{1/2}^{pp} < 100 \text{ ms}$$

$$T_{pp} < 10 \cdot T_{\alpha}$$

■ $T_{pp}/10 < T_{\alpha} < 10 \cdot T_{pp}$



Olsen et al., PRL 111 (2013)



β -delayed particles

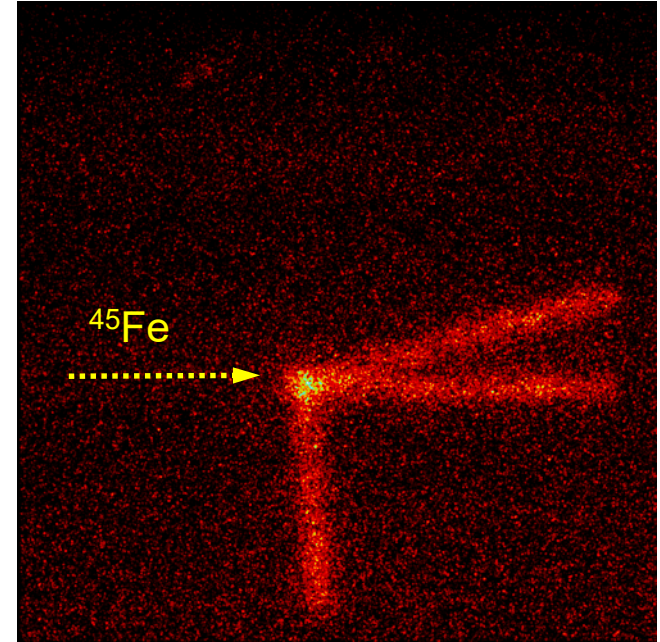
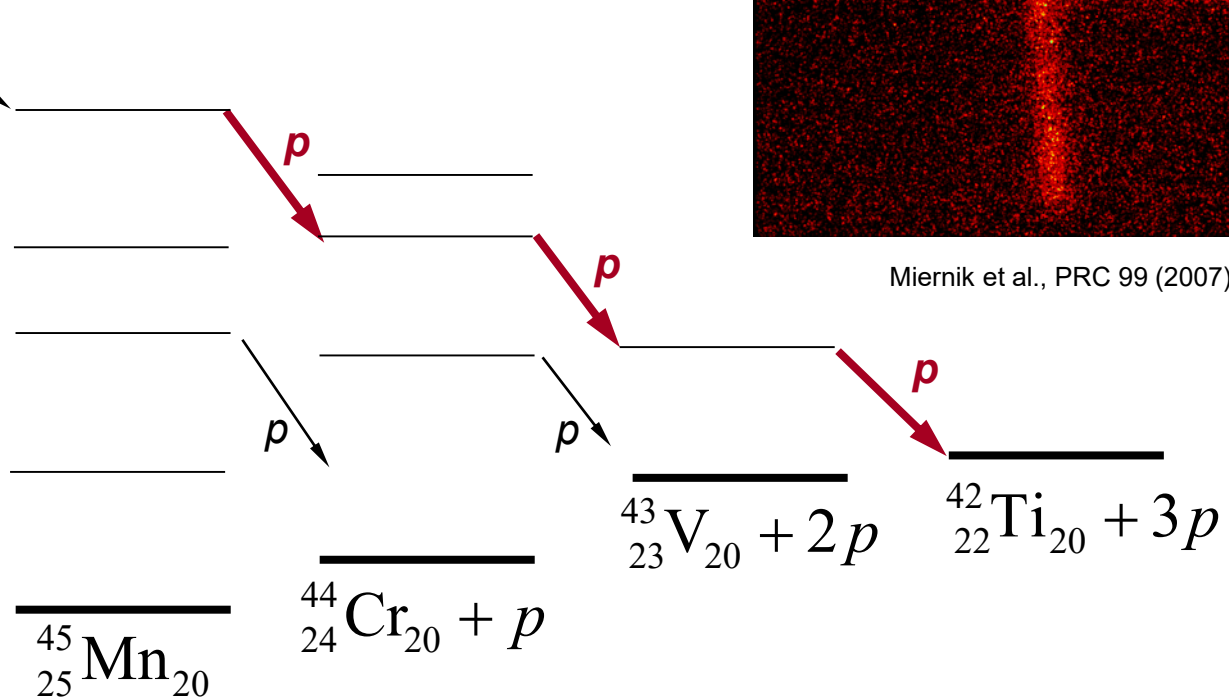
Discovery of β -delayed three-proton emission

NSCL: ^{58}Ni @ 161 MeV/u + Ni $\rightarrow$ ^{45}Fe

$T_{1/2} = 2.6(2)$ ms

$^{45}_{26}\text{Fe}_{19}$

30% β^+/WE



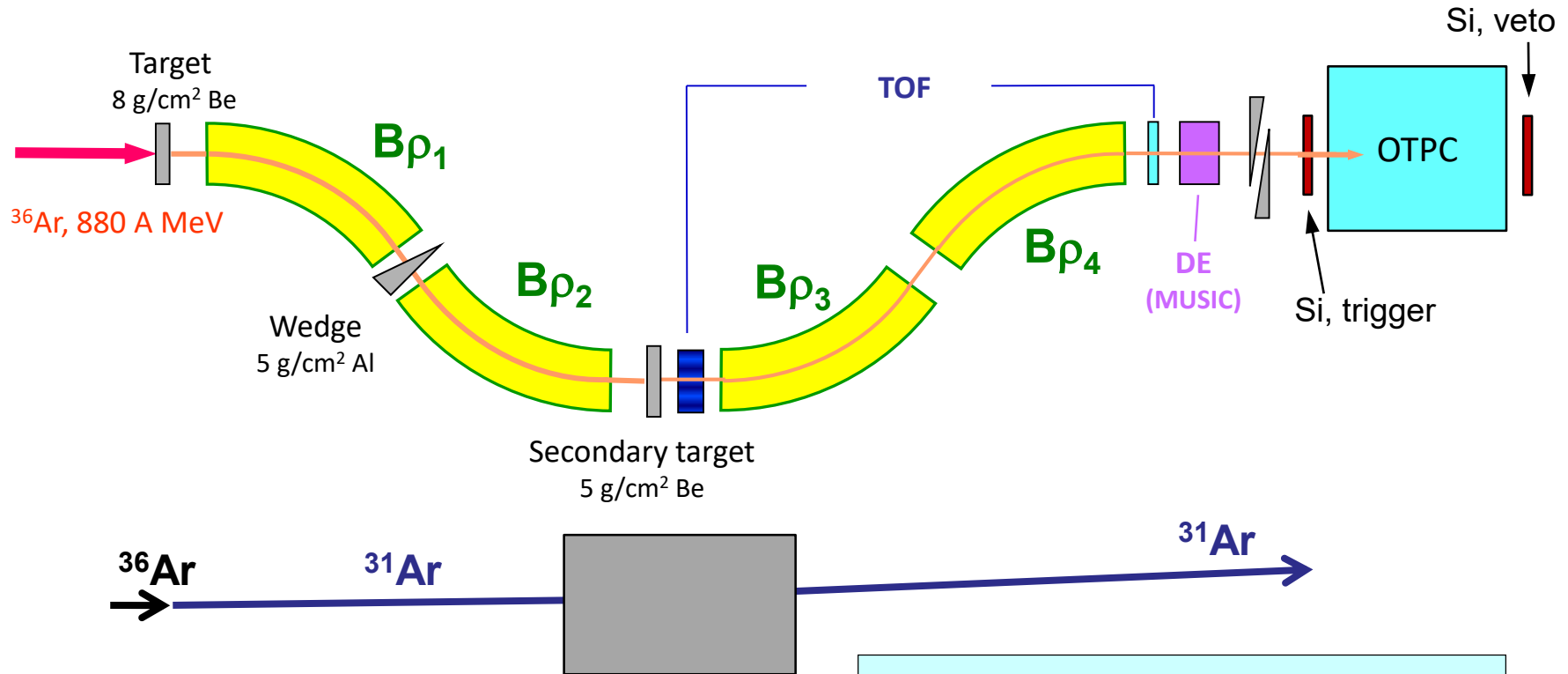
Miernik et al., PRC 99 (2007)



^{31}Ar at the FRS

➤ Experiment at GSI-FRS, August 2012

Secondary reactions at S2

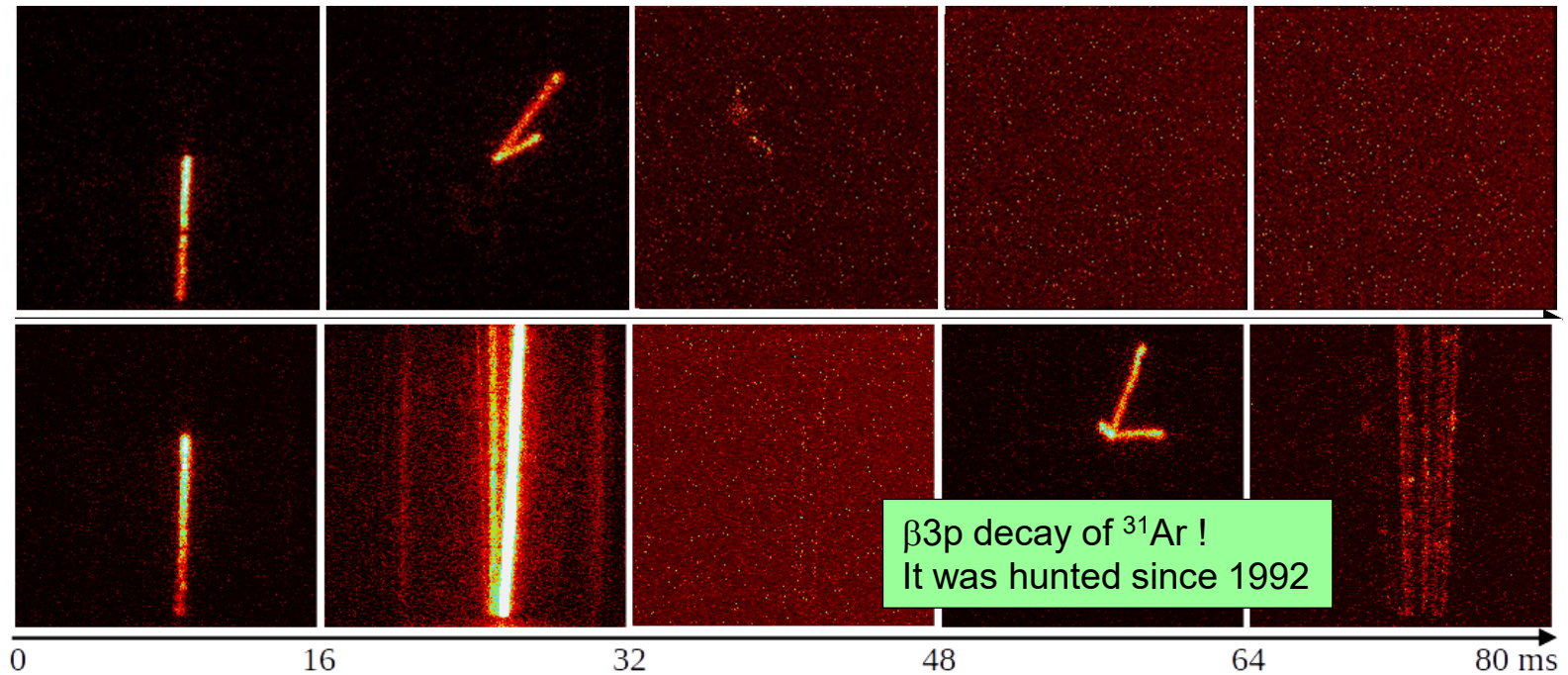


➤ Many ^{31}Ar ions pass to the S4
We stopped some of them in the OTPC
and looked for βxp channels of ^{31}Ar



Decay of ^{31}Ar

- GSI-FRS, August 2012, beam from the synchrotron – we cannot stop it upon trigger ☹
- ➔ A new acquisition mode – a series of shorter expositions („movie”)



- 21 000 „interesting movies” inspected individually
- ➔ 13 events of $\beta 3p$ decay of ^{31}Ar found

Lis et al., PRC 91 (2015)

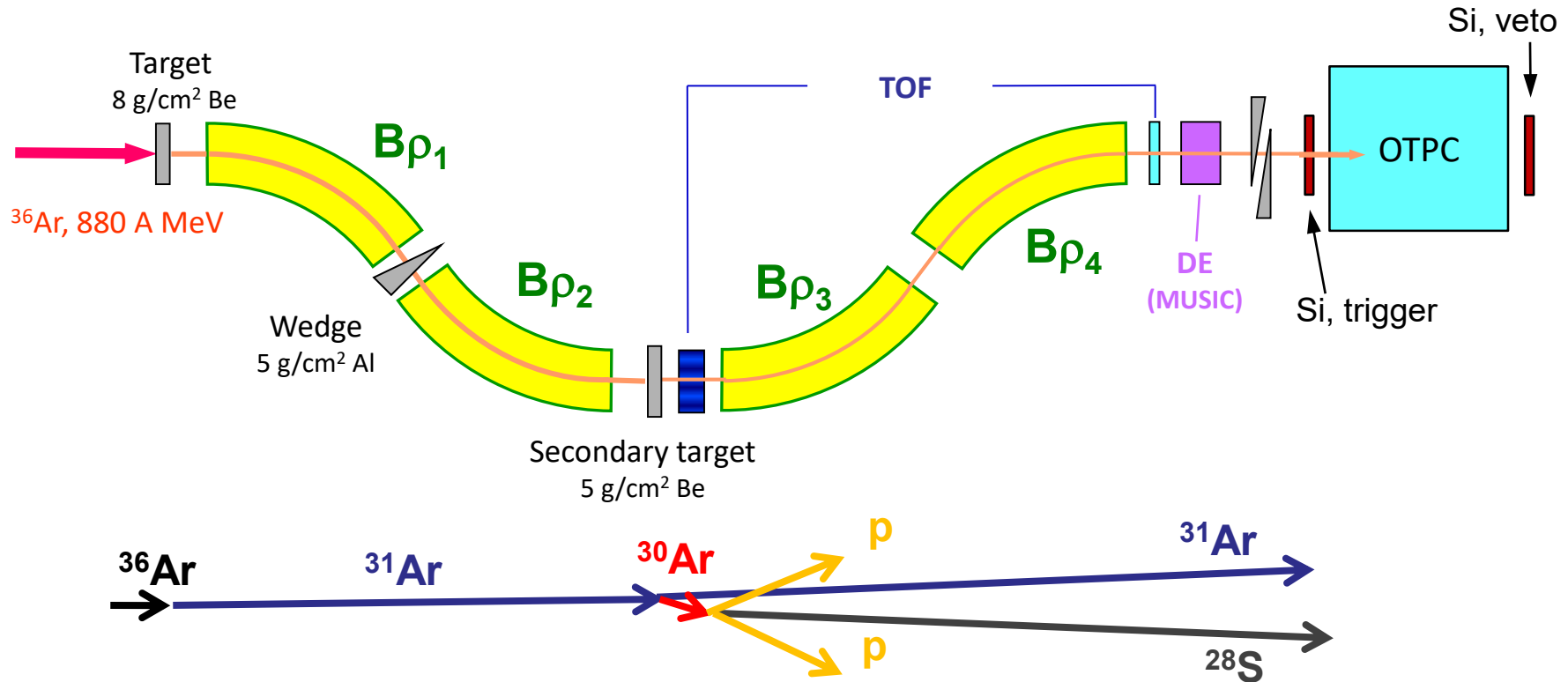
Channel	Events	Branching [%]
$\beta 0p$	5984	22.6(3) ^a
$\beta 1p$	13157	68.3(3)
$\beta 2p$	1729	9.0(2)
$\beta 3p$	13	0.07(2)



In-flight decays at FRS

➤ Experiment at GSI-FRS, August 2012

"Search for two-proton decay of ^{30}Ar in flight by the tracking technique" by I. Mukha



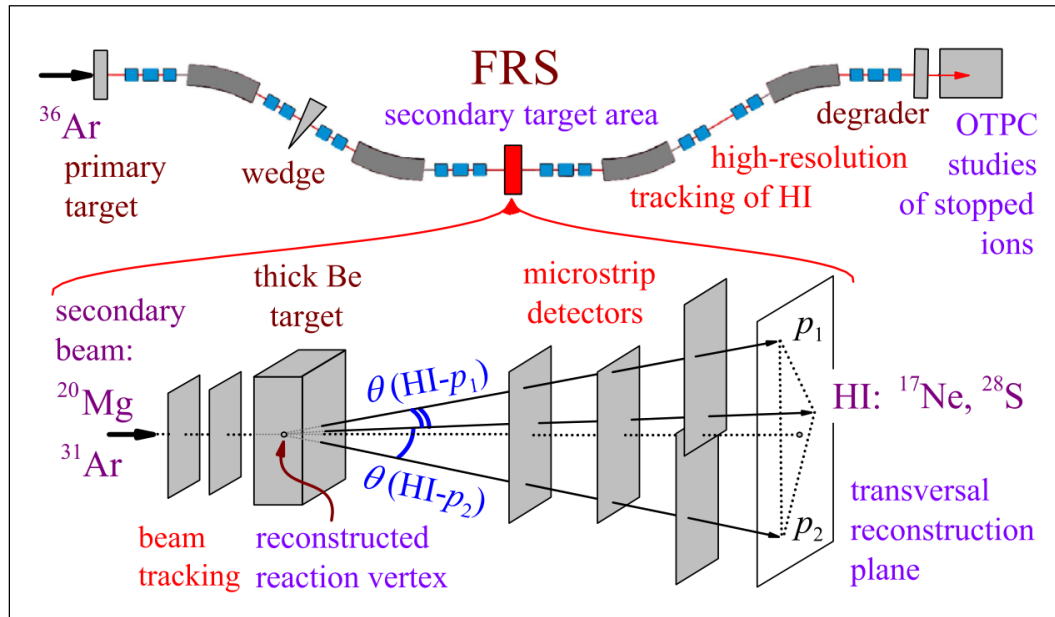
➤ Some ^{31}Ar ions react at S2 and decay products are tracked



In-flight decays at FRS

Study of in-flight 2p emission

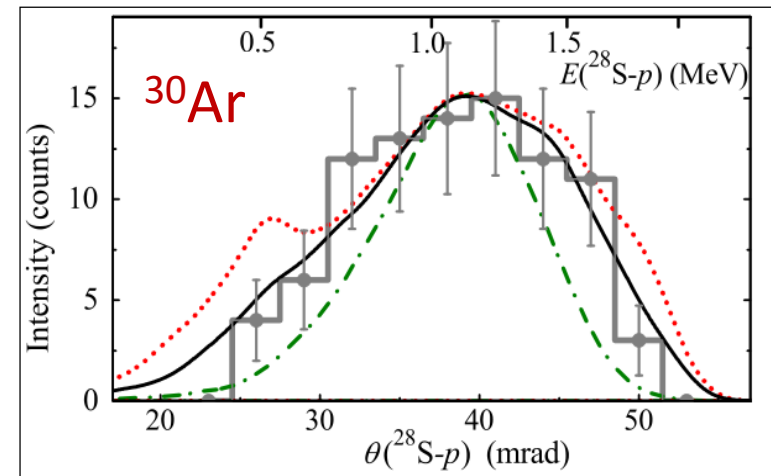
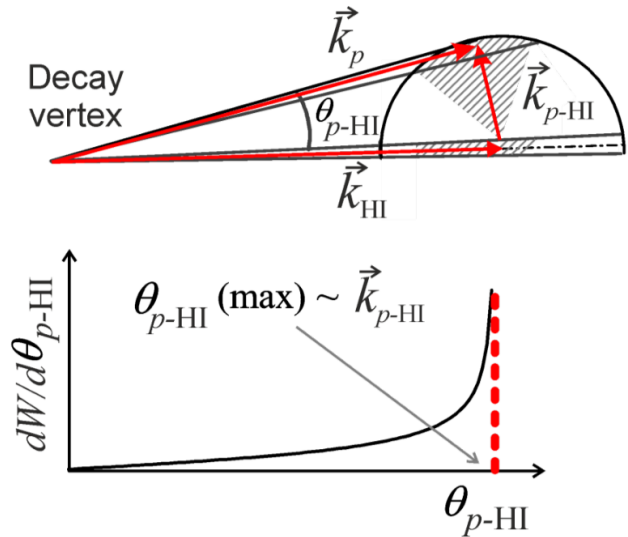
GSI: ^{36}Ar @ 885 MeV/A + Be $\rightarrow$ ^{31}Ar



Mukha et al., PRL 115 (2015)

In-flight approach applied @ GSI
to study decays of ^{16}Ne , ^{19}Mg , ^{30}Ar

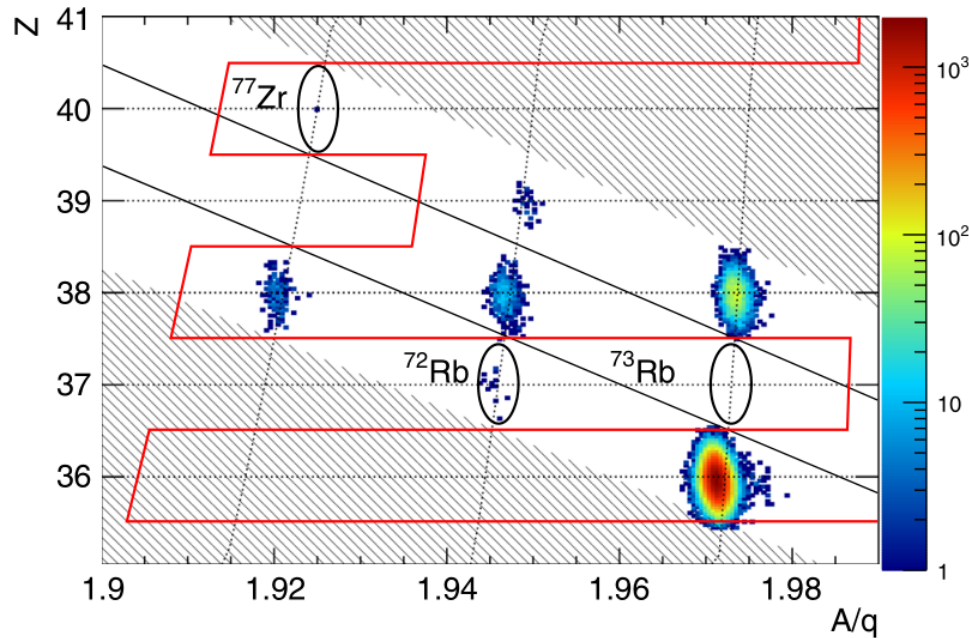
Ivan Mukha, Daria Kostyleva



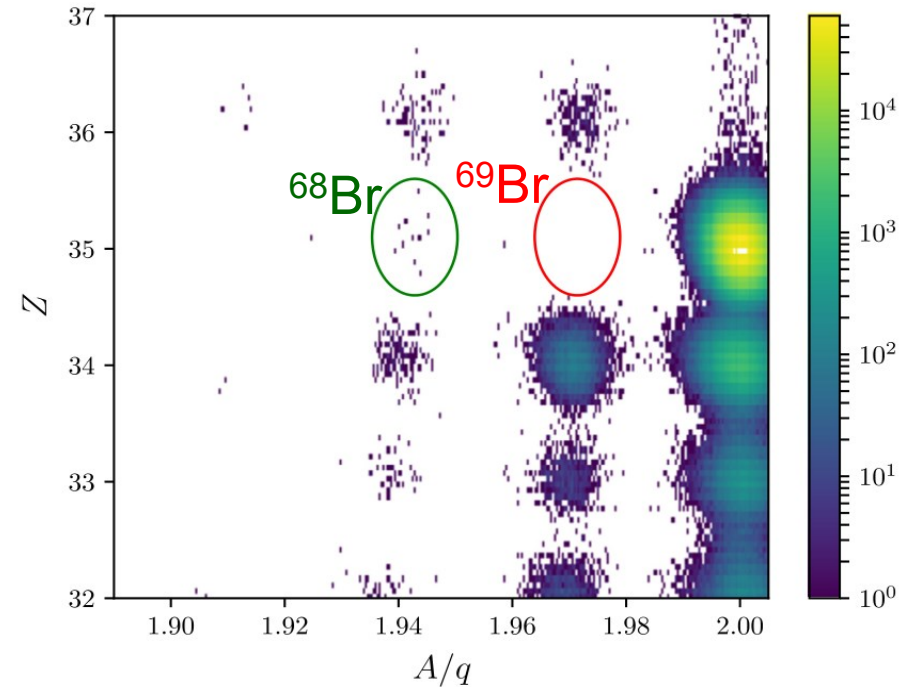


Nuclear sandbank?

Accepted FRS experiment (G-22-00115), to be run in 2025



Suzuki, PRL 119 (2017)



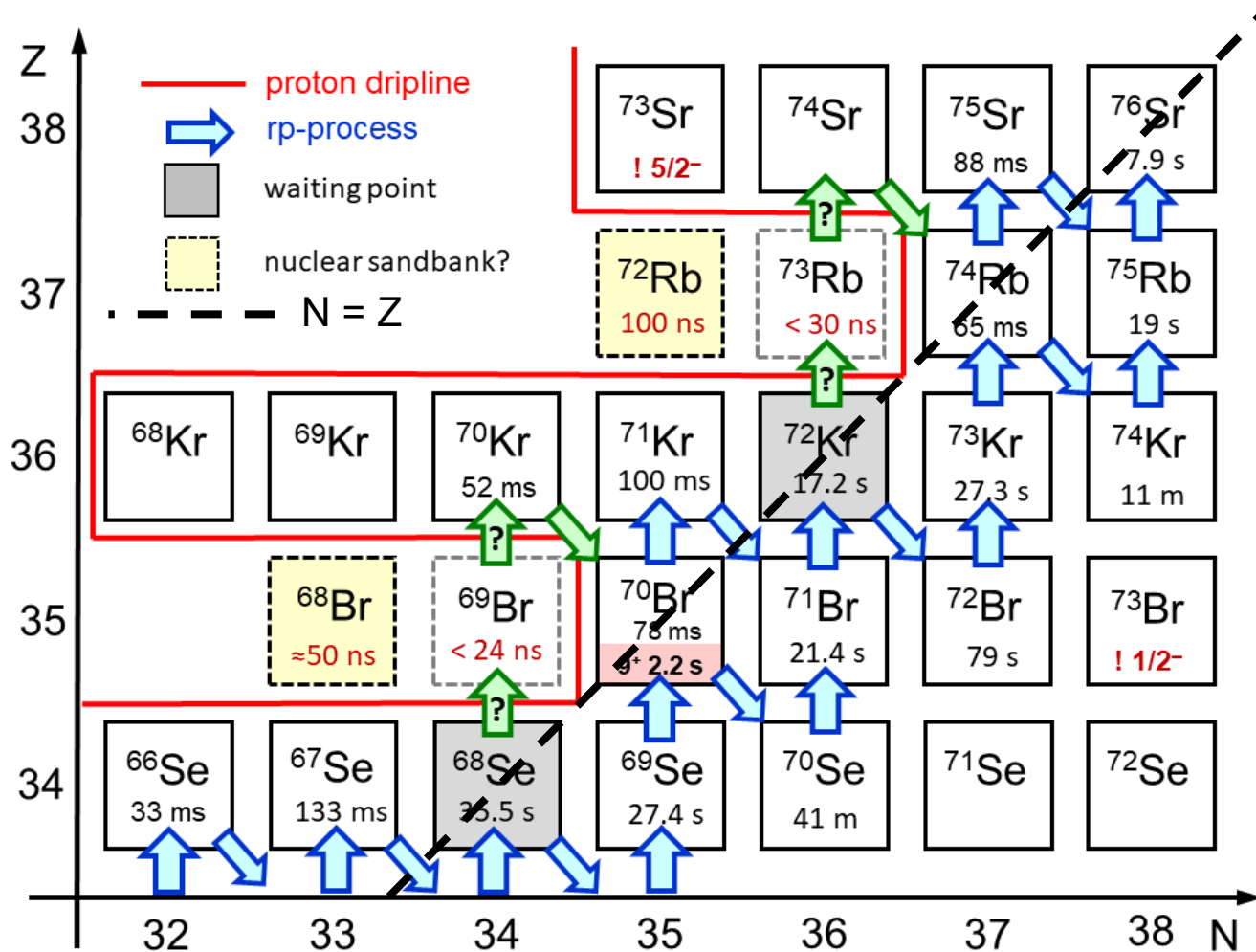
Wimmer, PLB 795 (2019)

➤ More exotic odd-odd isotope lives longer than even-odd closer to stability ?!



Nuclear sandbank?

► Particularly interesting spot on the chart!





Nuclear sandbank?

→ $^{78}\text{Kr} + \text{Be} \rightarrow ^{70\text{m}}\text{Br}$, 345 MeV/u at BigRIPS:

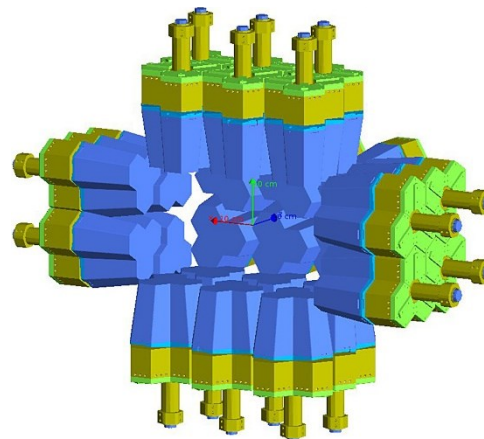
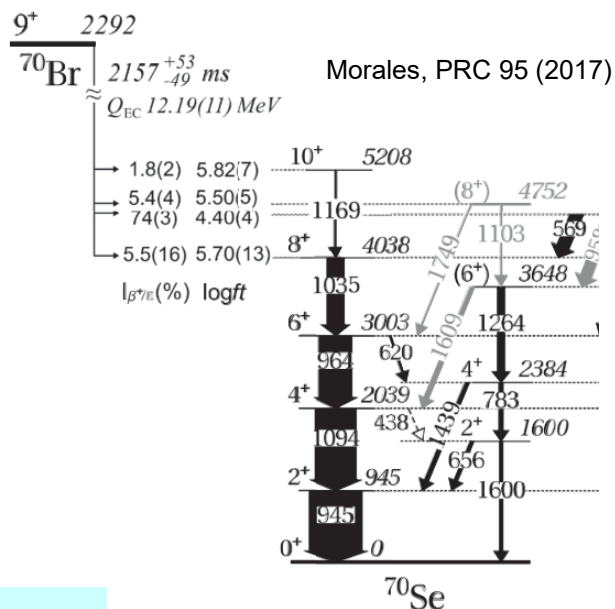
Morales et al. PRC 95 (2017) → 42%

Wimmer et al. PRL 126 (2021) → not seen
but both observations indirect

➤ Measure the isomeric ratio of $^{70\text{m}}\text{Br}(9^+)$
with detectors from the **DEGAS** array
 γ detection between the short spills

➤ Decay of ^{69}Br : production from ^{70}Br (-1n)
• proton angles → energies of p-resonances
• vertex distribution → $T_{1/2}(^{69}\text{Br})$ if in ps range

➤ Decay of ^{68}Br : analogous to ^{69}Br (-2n)
• proton angles → energies of p-resonances
• counting F2/F4 → $T_{1/2}(^{68}\text{Br})$ if ≥ 50 ns



DEGAS array, courtesy of DESPEC



Summary

We plan to:

- ✦ Study the drip line region at $Z=35$ with the in-flight tracking and isomeric spectroscopy
- ✦ Search for the fast $2p$ emission by the in-flight tracking; good candidates: $^{57,58}\text{Ge}$ and ^{62}Se
- ✦ Explore the *terra incognita* beyond the p drip-line

We dream about:

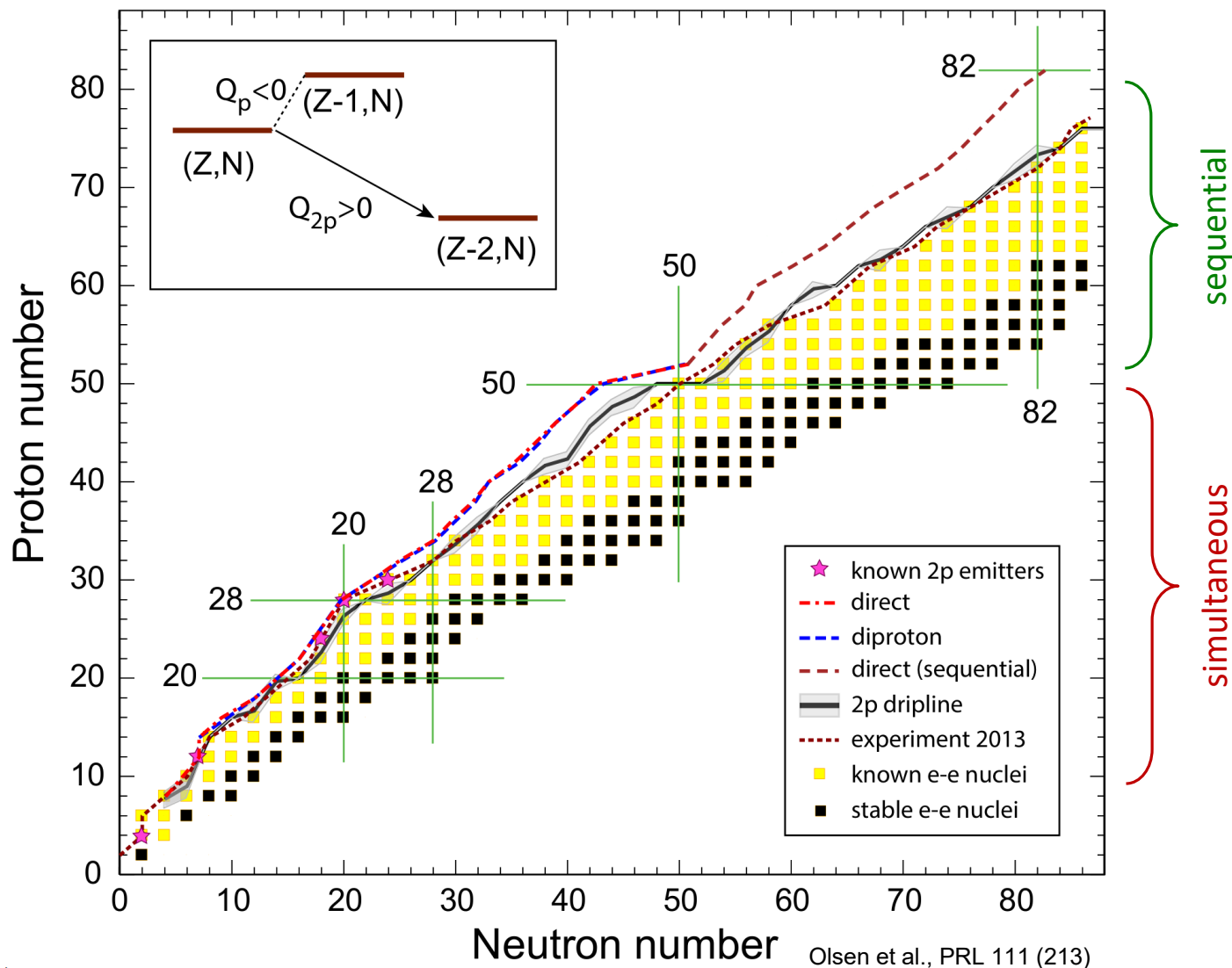
- ✦ Observing the 8^+ isomer in ^{124}Mo
- ✦ Producing ^{103}Te and ^{110}Ba , and investigating their decays
- ✦ Mounting a TPC detector after the Energy Buncher to search for (and study of) next cases of $2p$ radioactivity between Kr and Sn
- ✦ Verifying if indeed, the $2p$ emission above Ba is only sequential
- ✦ Finding a lot of surprises and fun on the way...



Thank you
for attention!

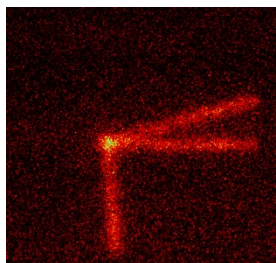


Global 2p predictions



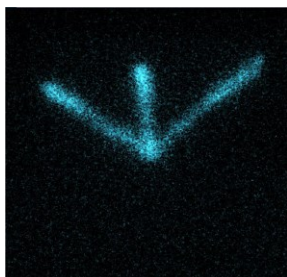


All known cases of $\beta 3p$



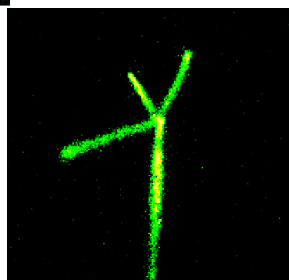
^{45}Fe
NSCL 2007

Miernik et al., PRC 76 (2007) 041304(R)



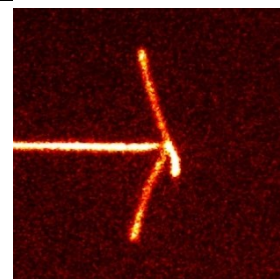
^{43}Cr
NSCL 2007

Pomorski et al., PRC 83 (2011) 014306



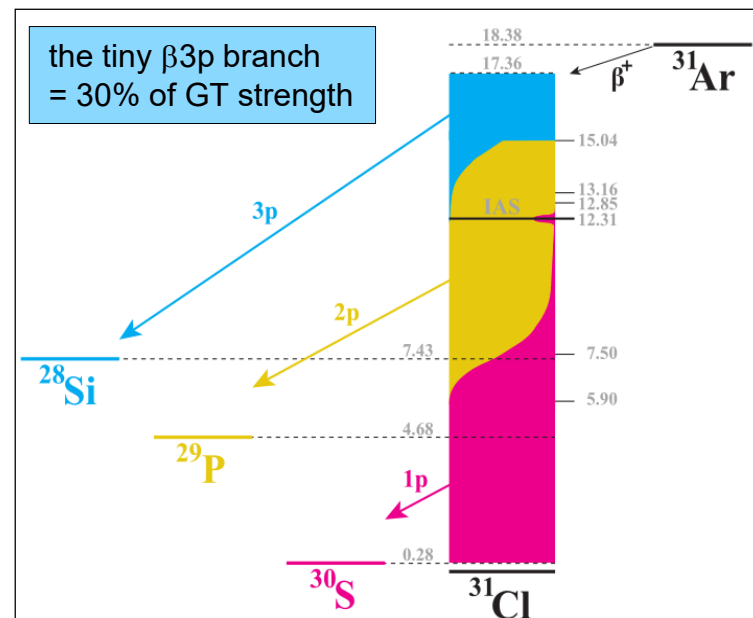
^{31}Ar
GSI 2012

Lis et al., PRC 91 (2015) 064309



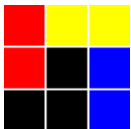
^{23}Si
Texas A&M 2017

Ciemny et al., PRC 106 (2022) 014317



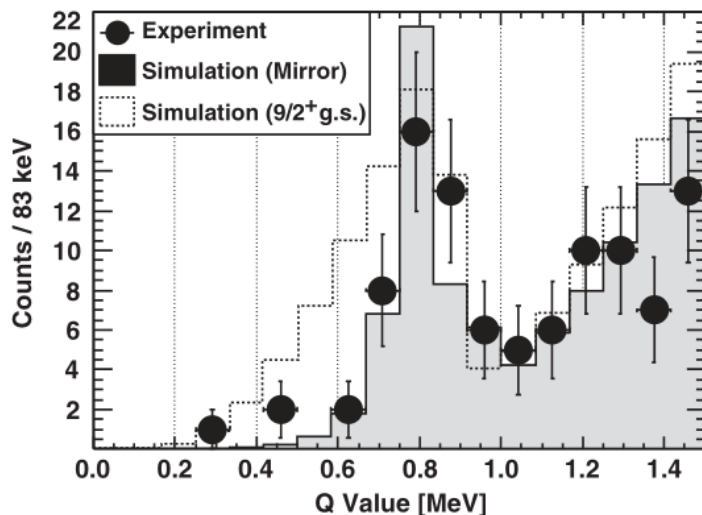
Koldste et al., PRC 89 (2014) 064315

We need much more statistics
to study decay schemes in detail



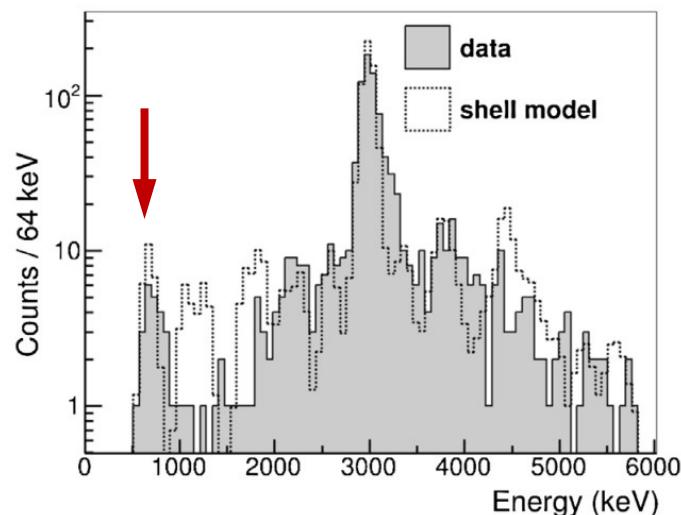
How much unbound is ^{69}Br ?

Rogers, PRL 106 (2011)

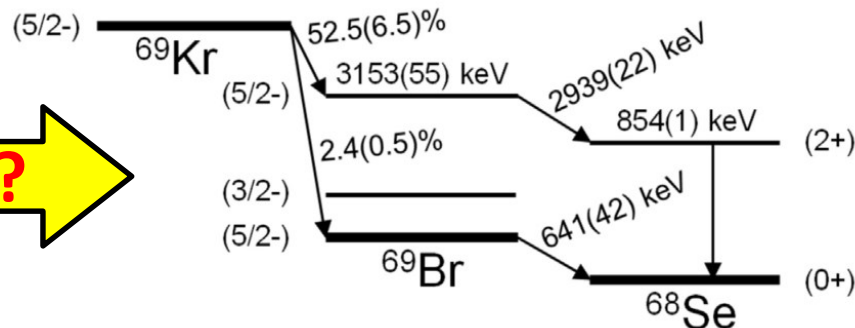
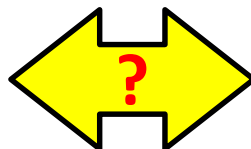
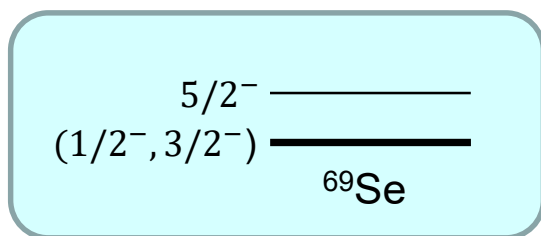


$$S_p = -785^{+34}_{-40} \text{ keV} \quad \text{gs. } J^\pi = 3/2^-$$

Del Santo, PL B 738 (2014)



$$S_p = -641 \pm 42 \text{ keV} \quad \text{gs. } J^\pi = 5/2^-$$



► Ground-state mirror asymmetry, like in the ^{73}Br ($1/2^-$) and ^{73}Sr ($5/2^-$) pair ?