AHEAD OF ITS TIME
FOR 150 YEARS

The study of nuclear structure at the IGISOL-4 facility

Iain Moore

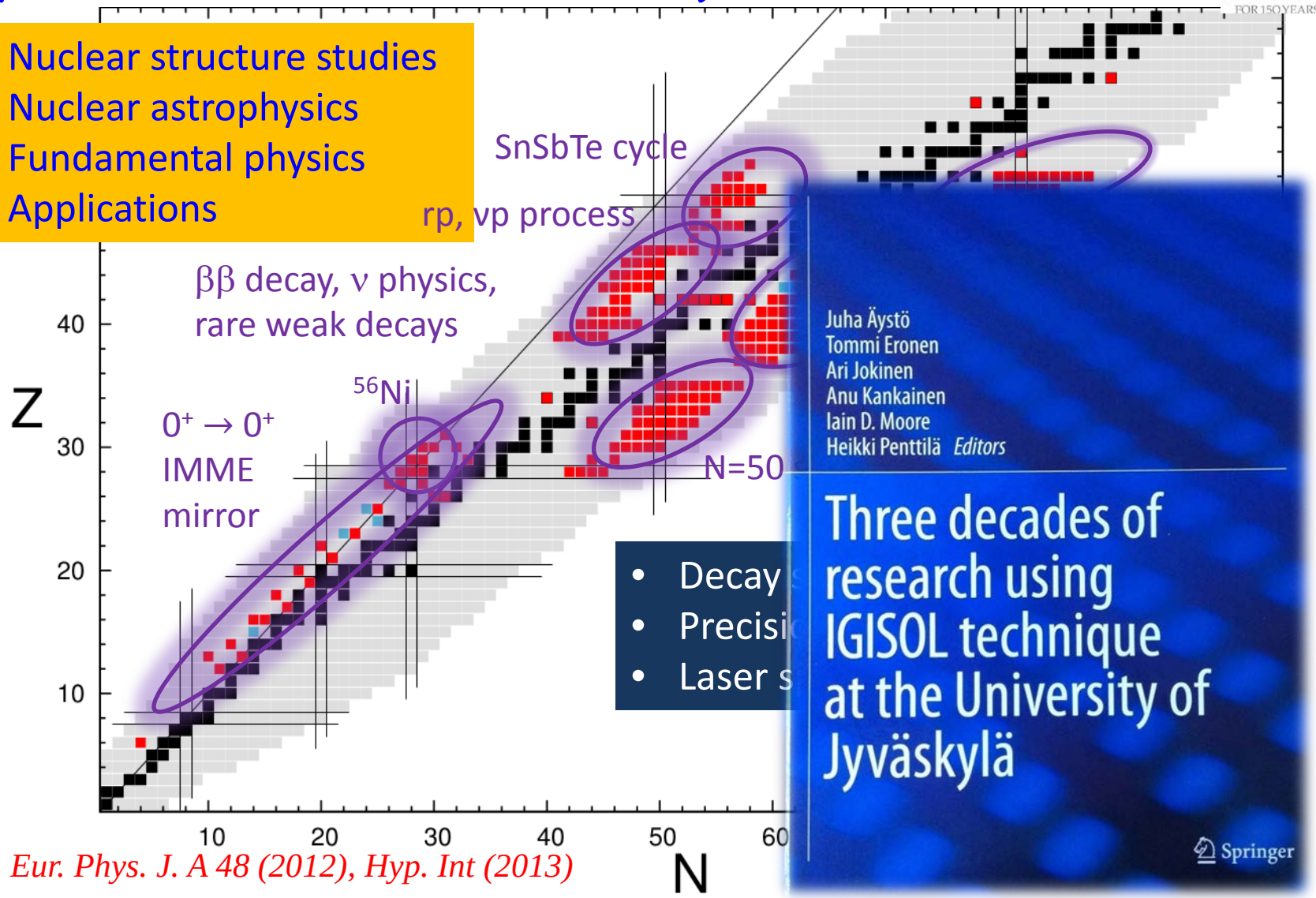
JYFL, Finland

Outline

- General introduction to IGISOL-4
- Recent experiments 2014-2015
  - Laser spectroscopy
  - Post-trap spectroscopy
- Pushing towards more neutron-rich nuclei
  - neutron-induced fission
- New projects
  - Bose-Einstein Condensate

Rare isotope beam science at IGISOL (status at EURORIB 2012)

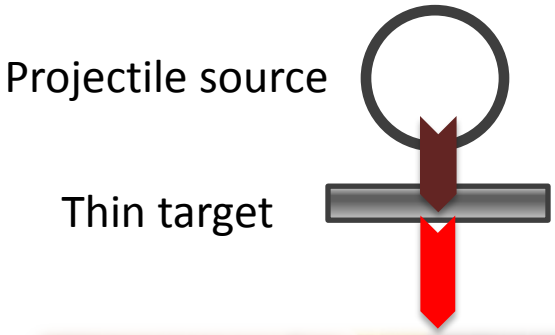
- Nuclear structure studies
- Nuclear astrophysics
- Fundamental physics
- Applications



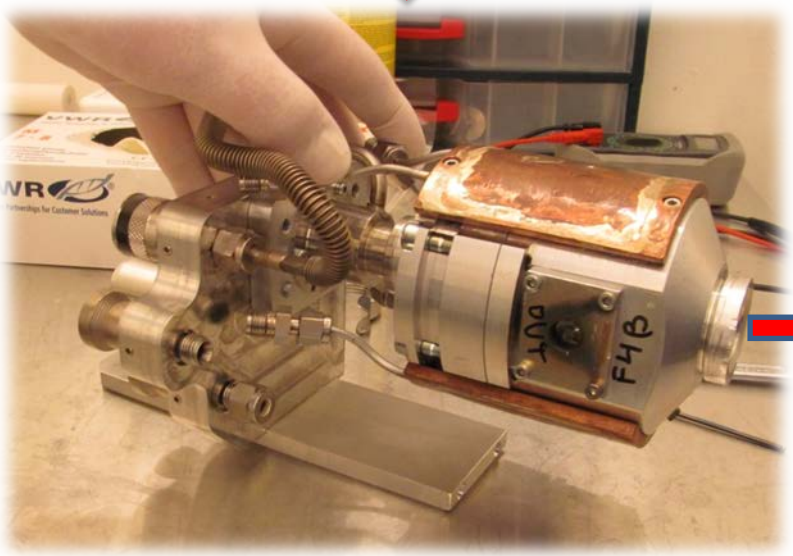
- Decay
- Precisi
- Laser s

Eur. Phys. J. A 48 (2012), Hyp. Int (2013)

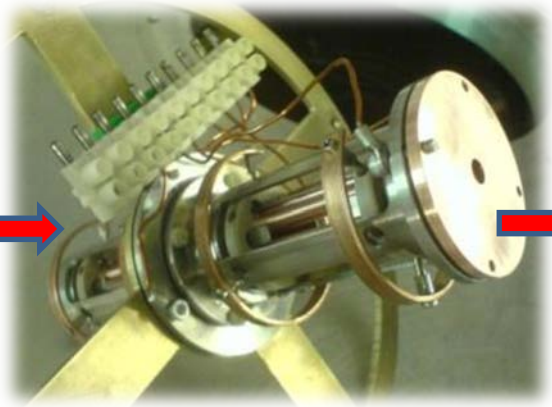
The (IG)ISOL method of RIB production

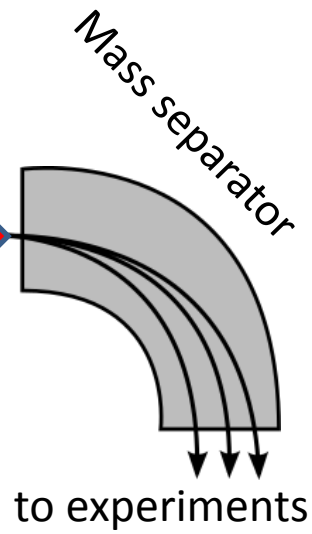


- An ISOL system for ALL elements
- Fast extraction (~ms)
- Relatively low efficiency
- Poor selectivity



Ion guidance through rf sextupole





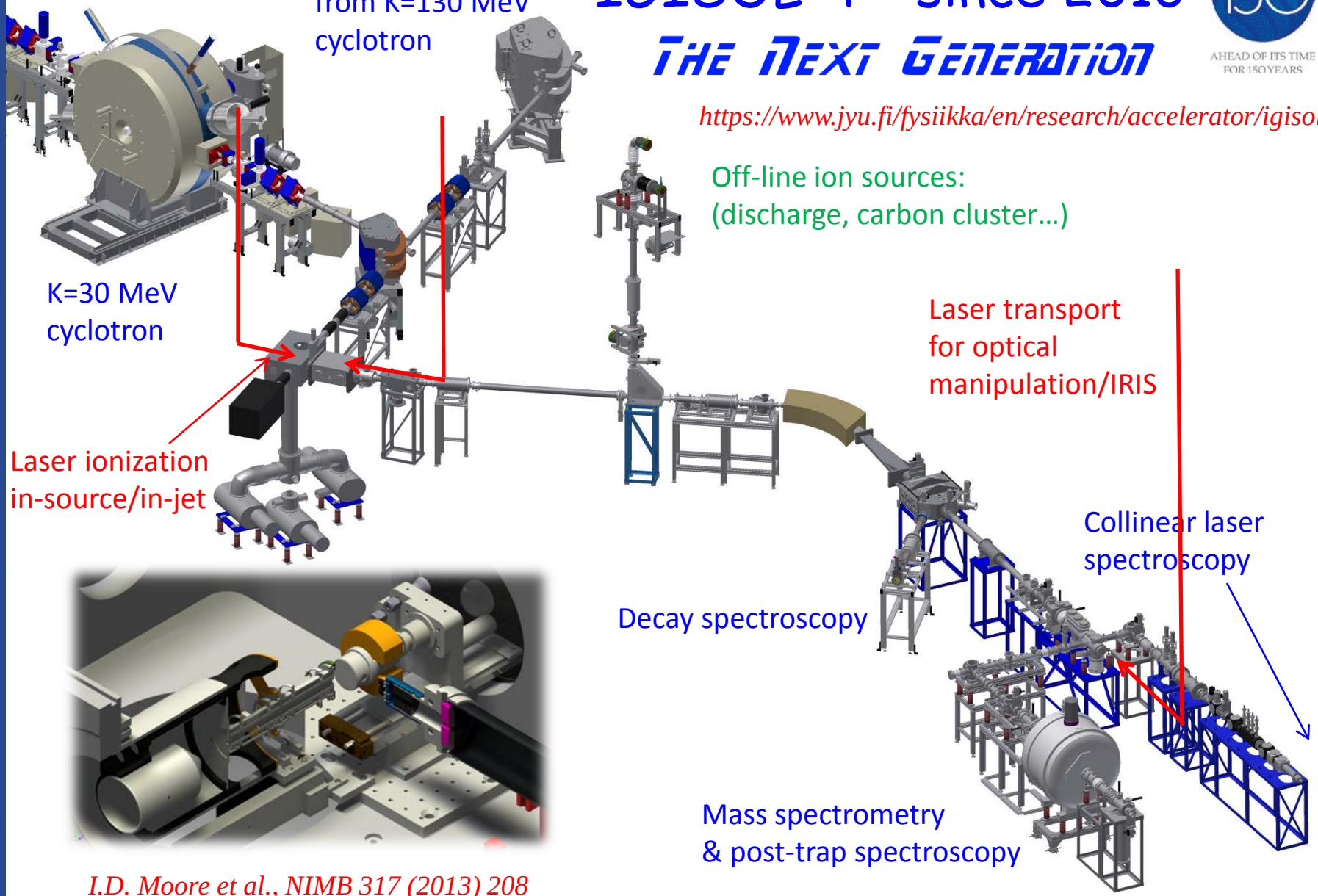
- Ion survival → ion guide method (non-selective)
- Neutralization → laser re-ionization (*Z* selectivity)

I.D. Moore et al., Hyp. Int. 223 (2014) 17

IGISOL-4 – since 2013

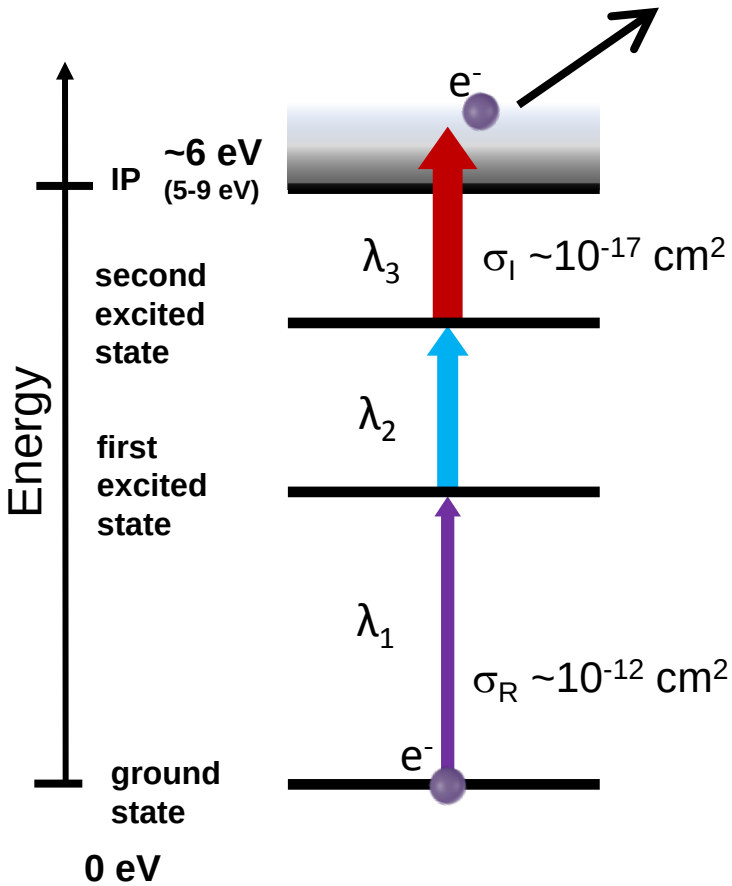
The Next Generation

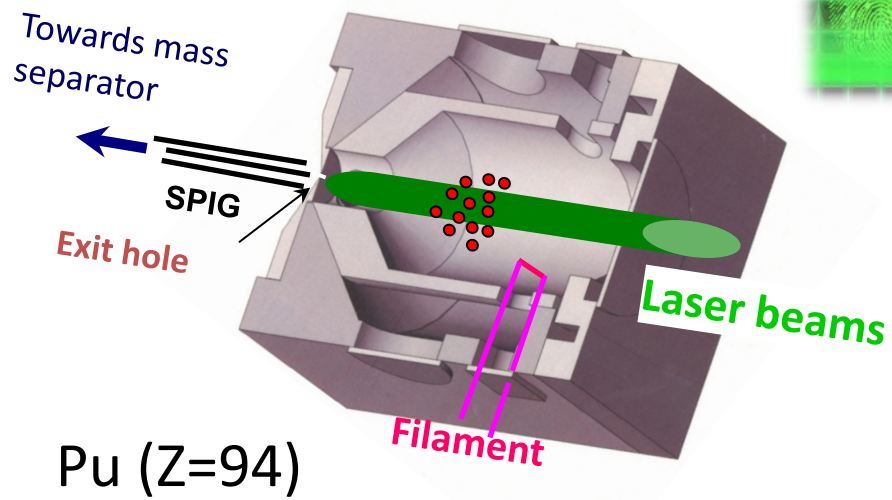
https://www.jyu.fi/fysiikka/en/research/accelerator/igisol



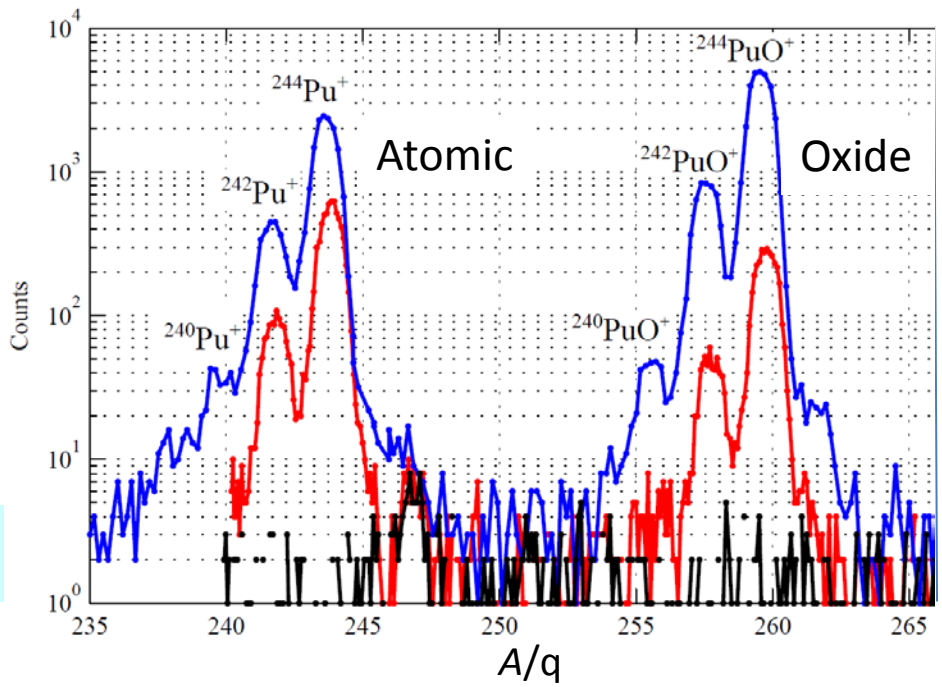
I.D. Moore et al., NIMB 317 (2013) 208

Element selectivity: an atomic fingerprint





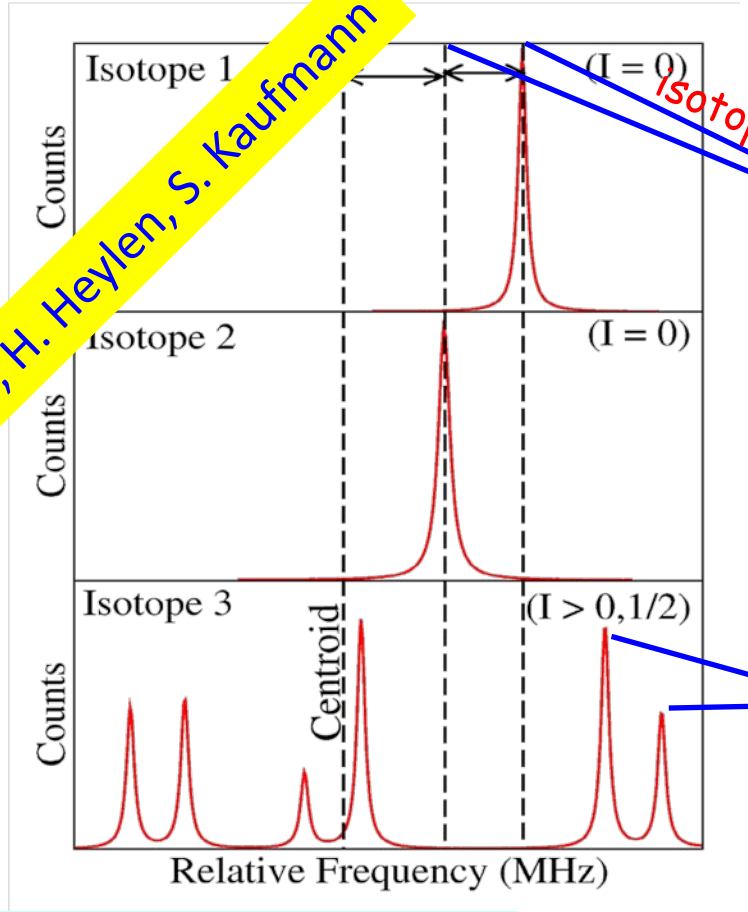
Pu (Z=94)



SELECTIVITY & EFFICIENCY

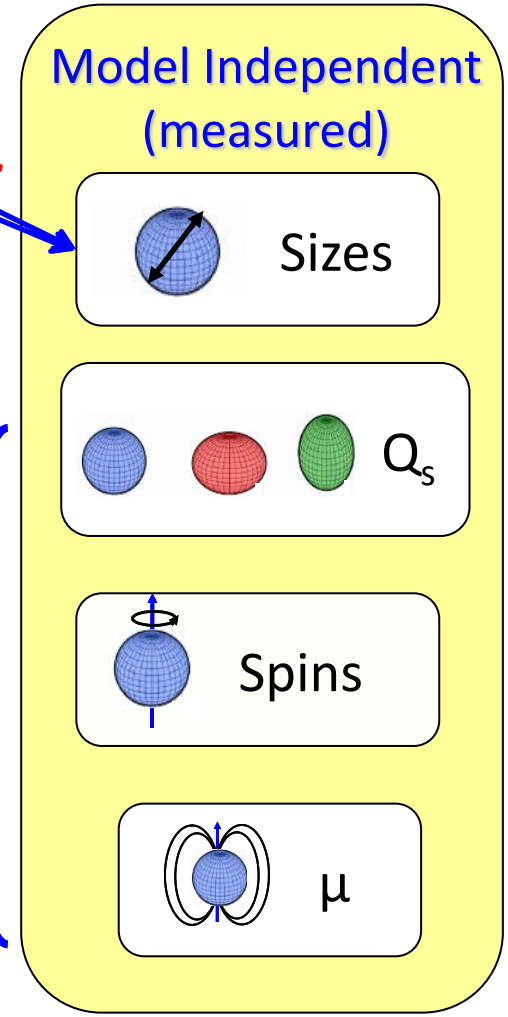
Probing nuclear structure via atomic level perturbations – laser spectroscopy

D. Yordanov, H. Heylen, S. Kaufmann



Isotope shifts

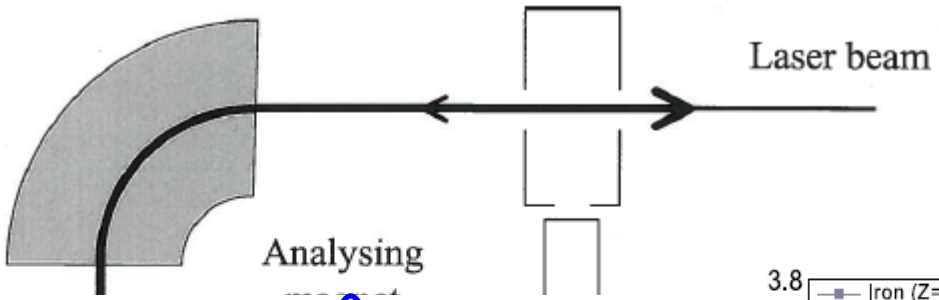
HFS

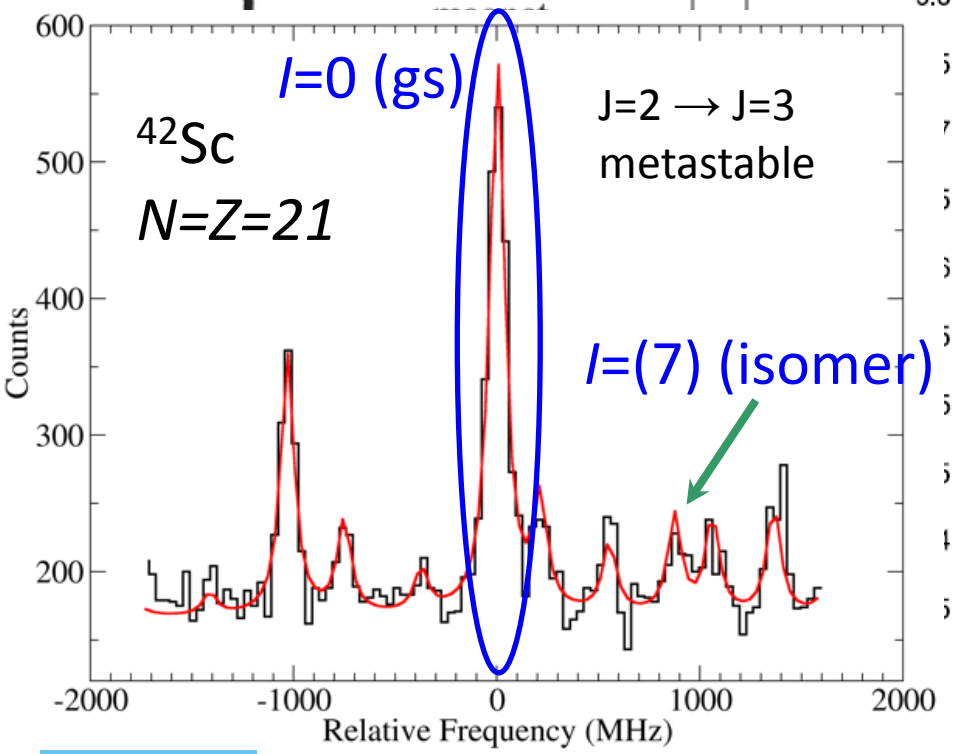


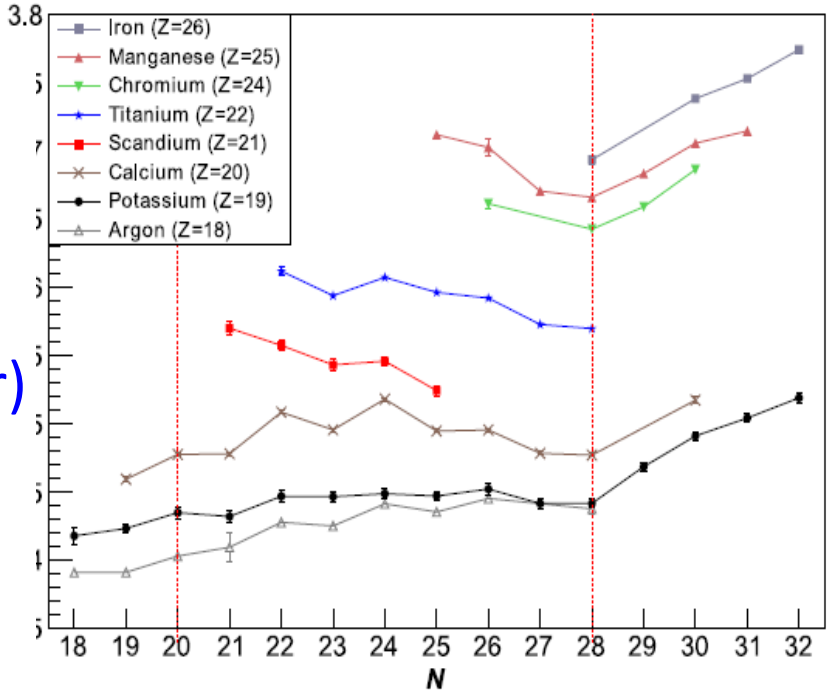
$$\langle r^2 \rangle = \langle r^2 \rangle_0 \left(1 + \frac{5}{4\pi} \sum_{i=2}^{\infty} \langle \beta_i^2 \rangle \right)$$

$$\langle \beta_2^2 \rangle \Leftrightarrow \langle \beta_2 \rangle$$

Collinear laser spectroscopy





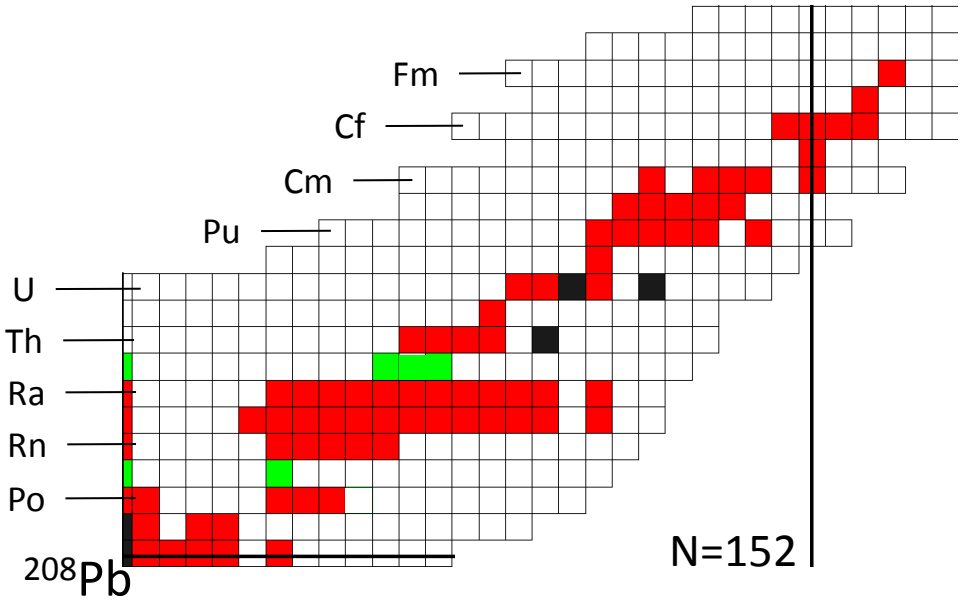


*K. Kreim et al., PLB **731** (2014) 97*

*M. Avgoulea et al., J. Phys. G **38** (2011) 025104*

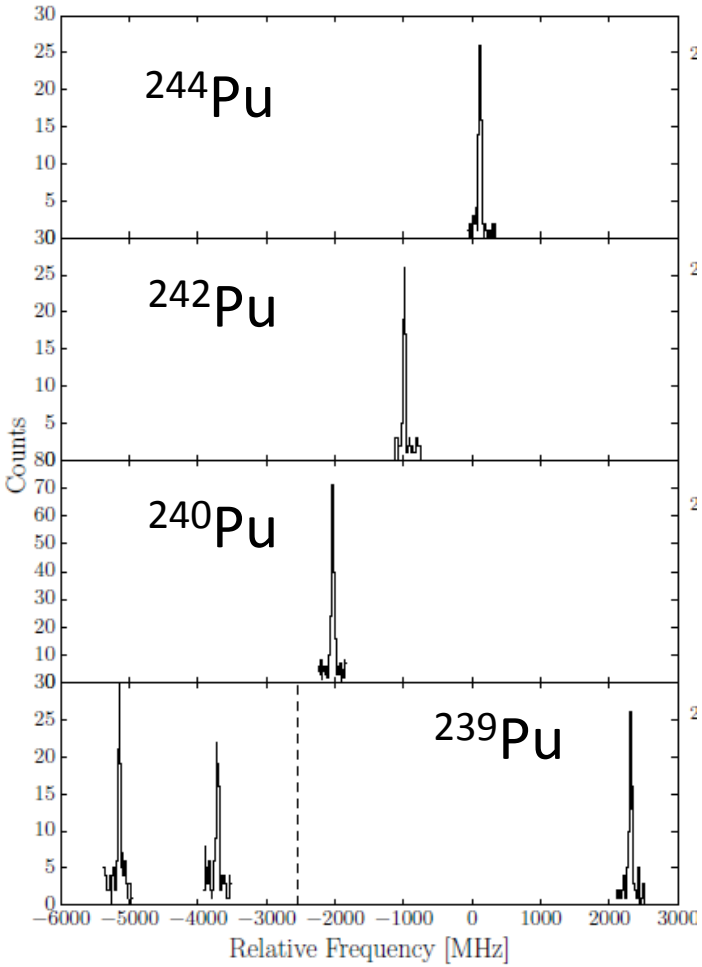
KU LEUVEN

Moving towards heavy elements



JOHANNES GUTENBERG UNIVERSITÄT MAINZ

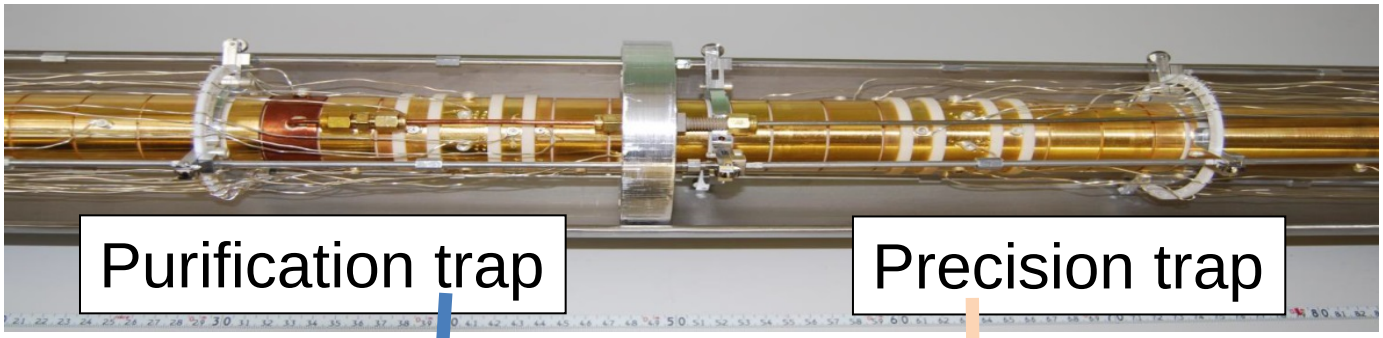
M. Block, C. Granados, K. Lynch, D. Fink



- Uranium is heaviest ISOL target
- Lack of stable isotopes – lack of optical transitions
- Laser ionization of Pu samples (ng)
- Collinear spectroscopy on ^{244,242,240,239}Pu

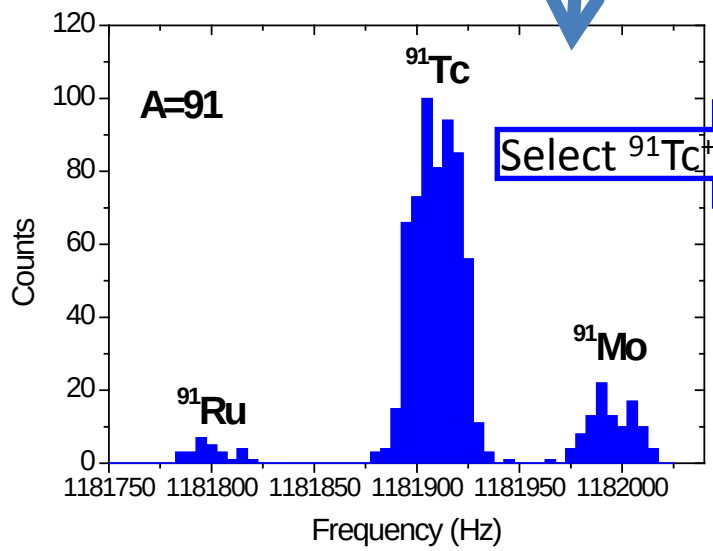
JYFLTRAP – purification & measurement

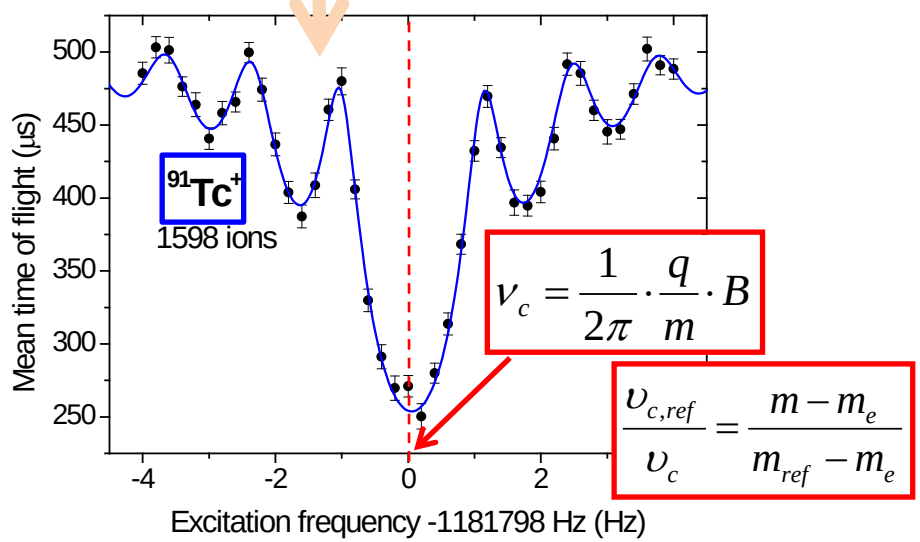
JYFLTRAP review: T. Eronen et al., Eur. Phys. J. A 48 (2012) 46



Mass-selective buffer gas cooling ($M/\Delta M \sim 10^5$)

TOF-ICR method



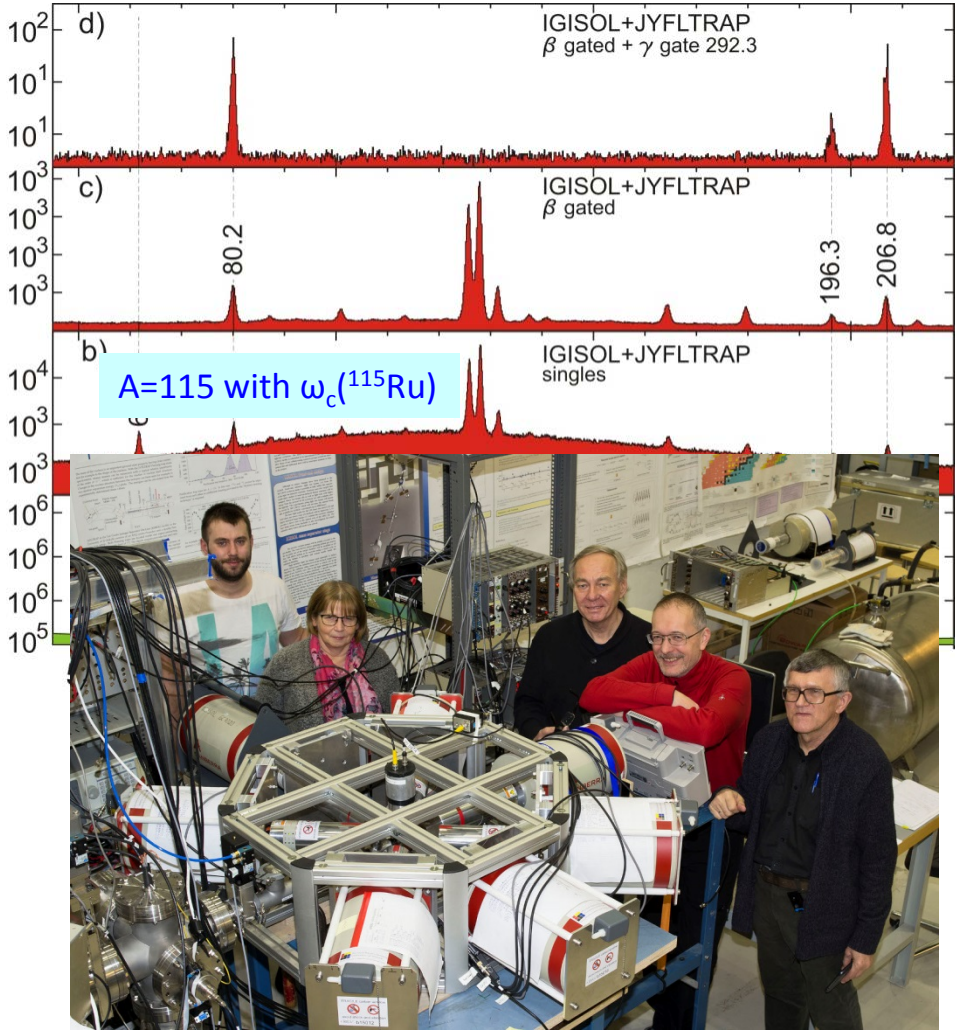


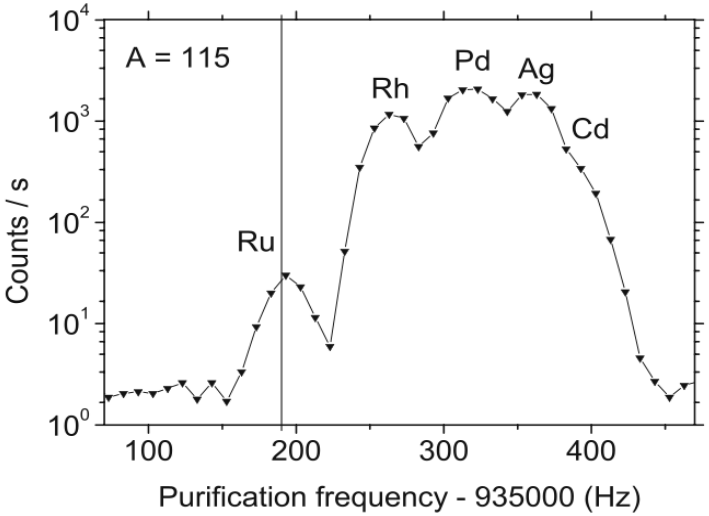
$$\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

$$\frac{\upsilon_{c,ref}}{\upsilon_c} = \frac{m - m_e}{m_{ref} - m_e}$$

M. Block, S. Eliseev, S. Kaufmann

Post-trap spectroscopy: IGISOL-3

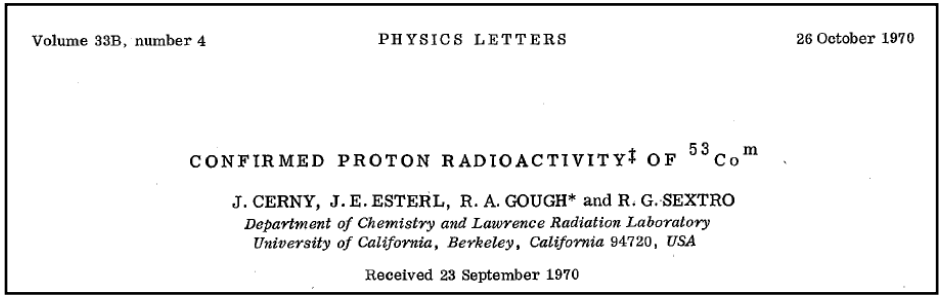




J. Kurpeta, University of Warsaw (2015)

TASISPEC @IGISOL-4: ^{53m}Co

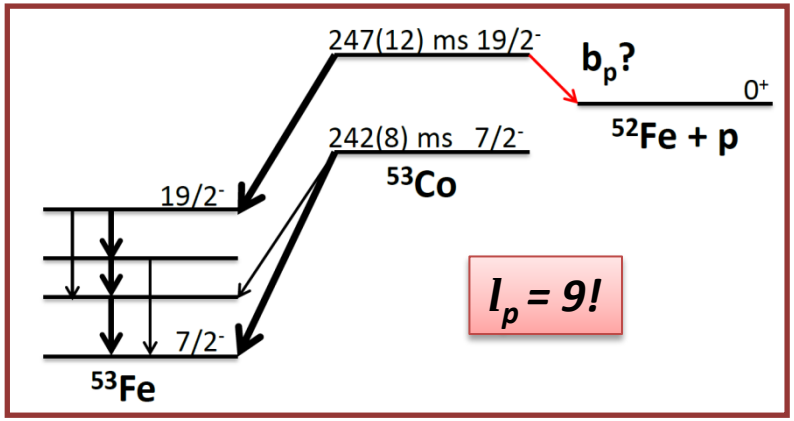
Proton radioactivity discovered 45 years ago!

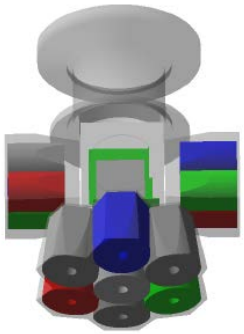

Volume 33B, number 4 PHYSICS LETTERS 26 October 1970

CONFIRMED PROTON RADIOACTIVITY‡ OF ^{53}Co^{m}

J. CERNY, J. E. ESTERL, R. A. GOUGH* and R. G. SEXTRO
Department of Chemistry and Lawrence Radiation Laboratory
University of California, Berkeley, California 94720, USA

Received 23 September 1970





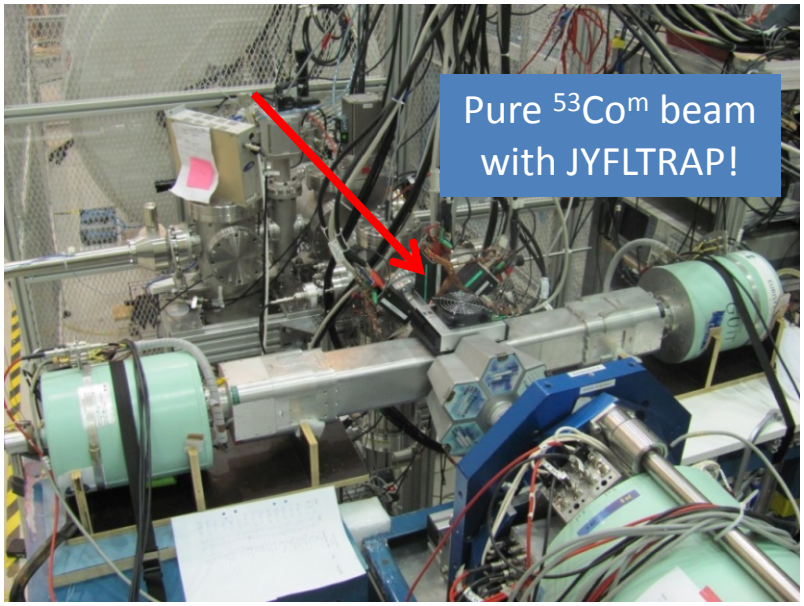
R. Page: talk on p emission

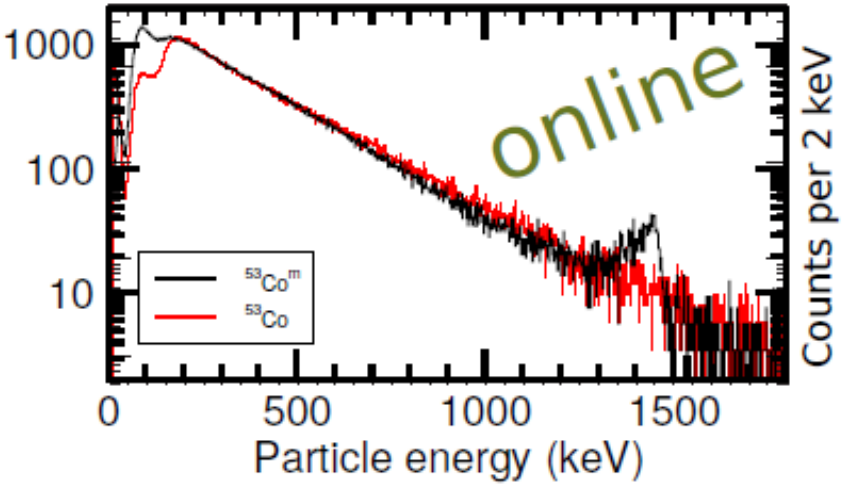
Energy (MeV)	1.59 ± 0.03
Half-life (ms)	247 ± 12
Branching ratio	≈ 1.5 %

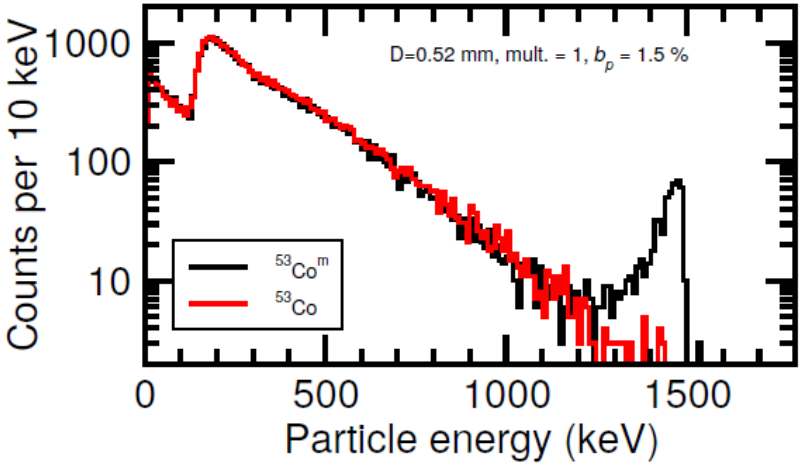
- Ground state & isomer similar $T_{1/2}$
- Require JYFLTRAP (Ramsey cleaing)
- Direct measurement of branching ratio with TASISpec

JYFL – Lund - GSI collaboration
Experiment I199 using TASISpec:
L.G. Sarmiento, D. Rudolph, A. Kankainen et al.

^{53m}Co at JYFLTRAP (April 2015)







- p decay energy determined via JYFLTRAP mass measurements of ^{53}Co, ^{53m}Co and ^{52}Fe

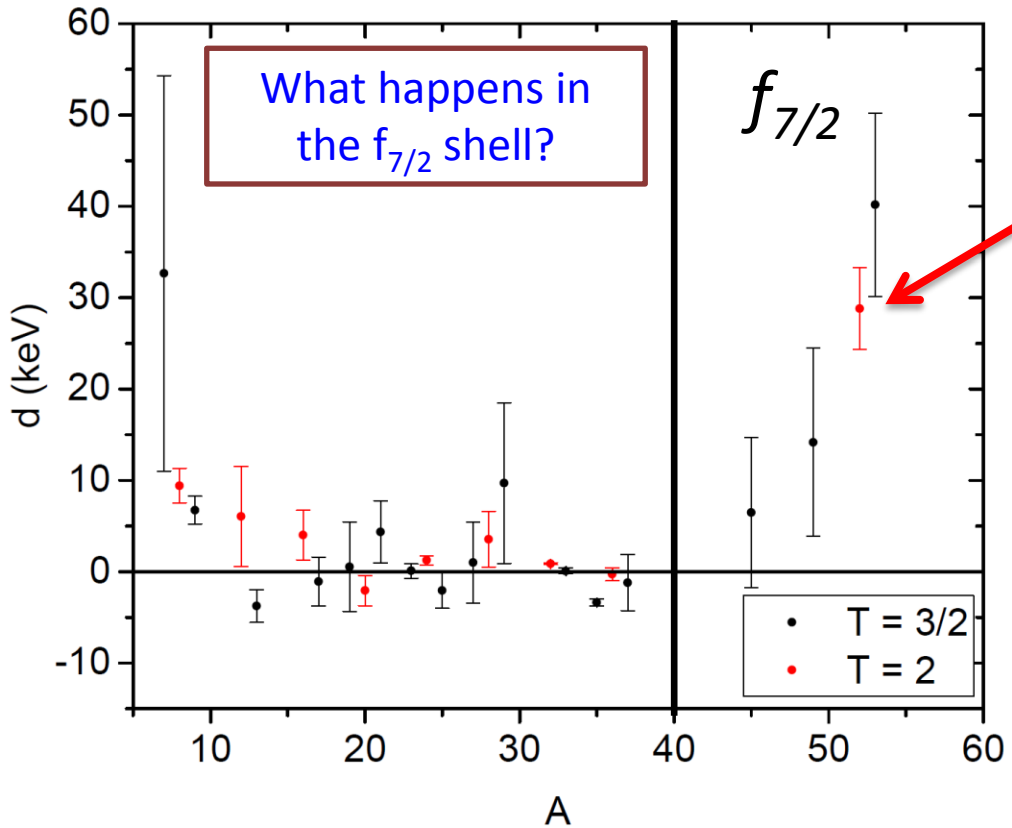
Expect a future TASISpec campaign of measurements at IGISOL

Courtesy of L.G. Sarmiento

Tests of isobaric mass multiplet equation

IMME $$M(A,T,T_Z) = a + b \cdot T_Z + c \cdot {T_Z}^2$$

Sometimes a cubic term needed to fit the data: $+d \cdot {T_Z}^3$



A=52

d=28.82±4.47 keV

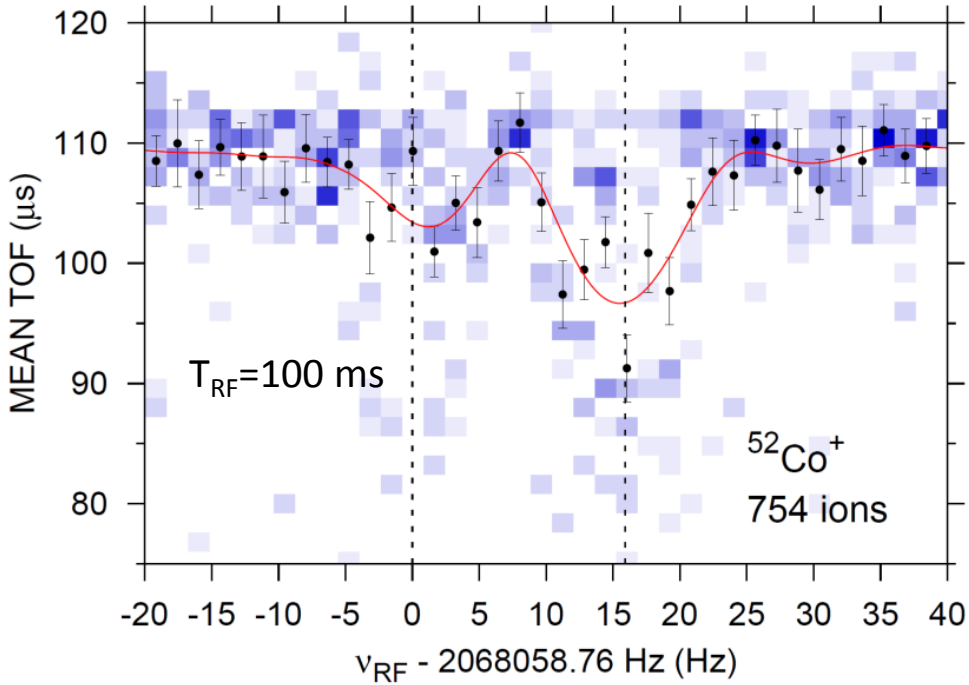
^{52}Co not directly measured (identified via p decay to ^{51}Fe)

Values from M. MacCormick & G. Audi, Nucl. Phys. A 925 (2014) 94

IMME for the T=2 quintet at A=52

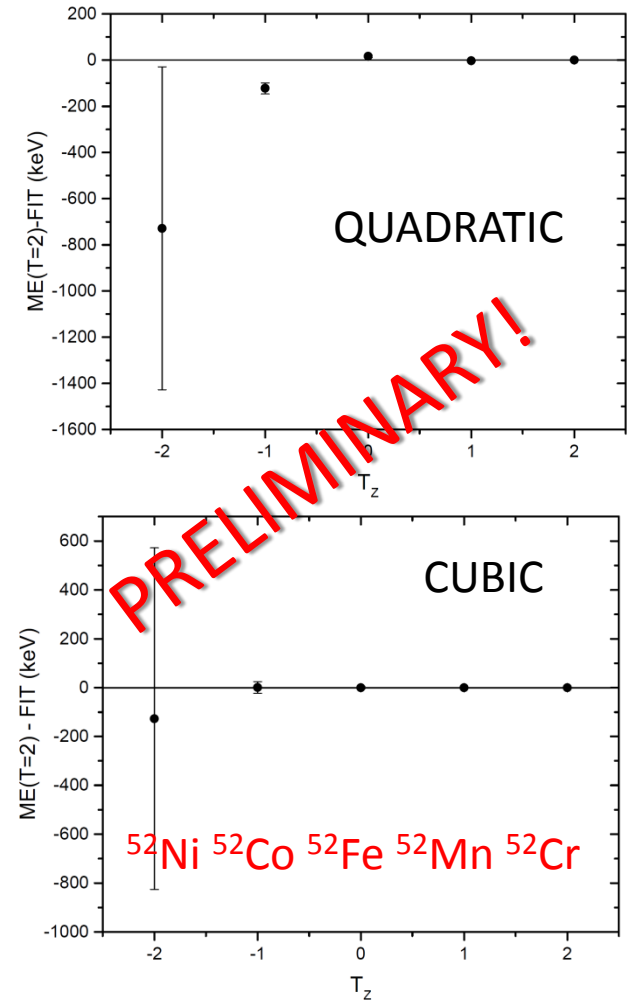
JYFLTRAP April 2015:

- ^{52}Fe, ^{52m}Fe
- ^{52}Co ($T_{½}$=115(23) ms)
- ^{52m}Co ($T_{½}$=104(11) ms)

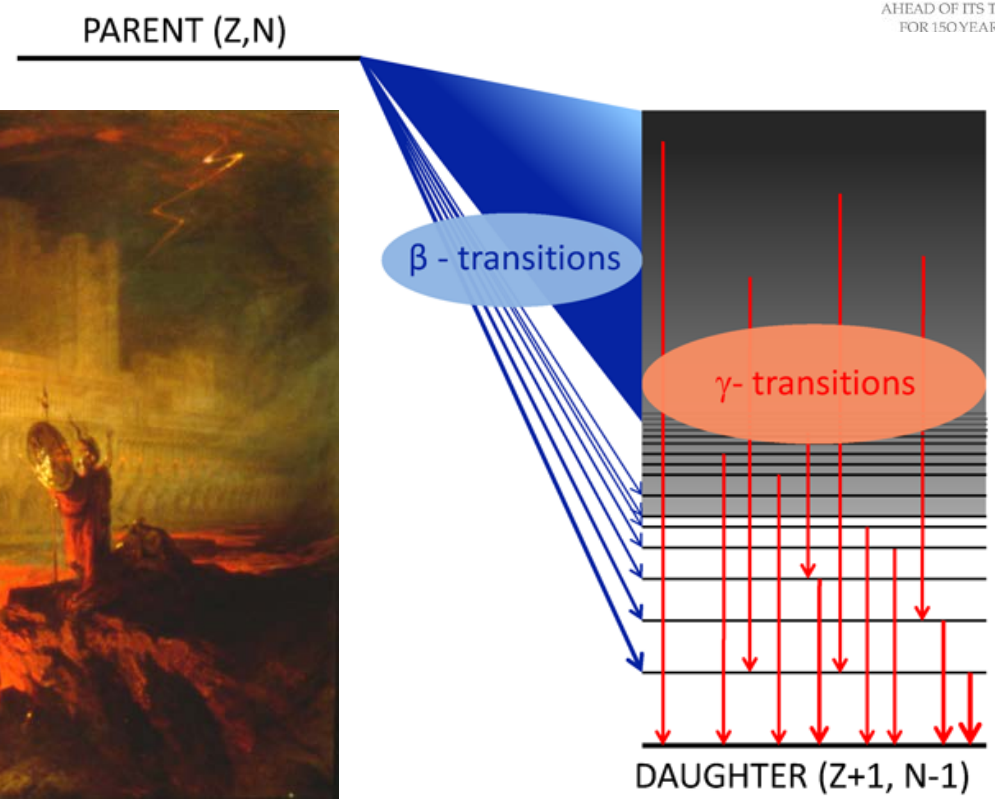


A few µb cross section, the lowest at IGISOL

Non-zero d coefficient

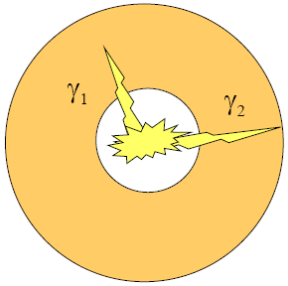


The Pandemonium Effect – TAS at JYFL

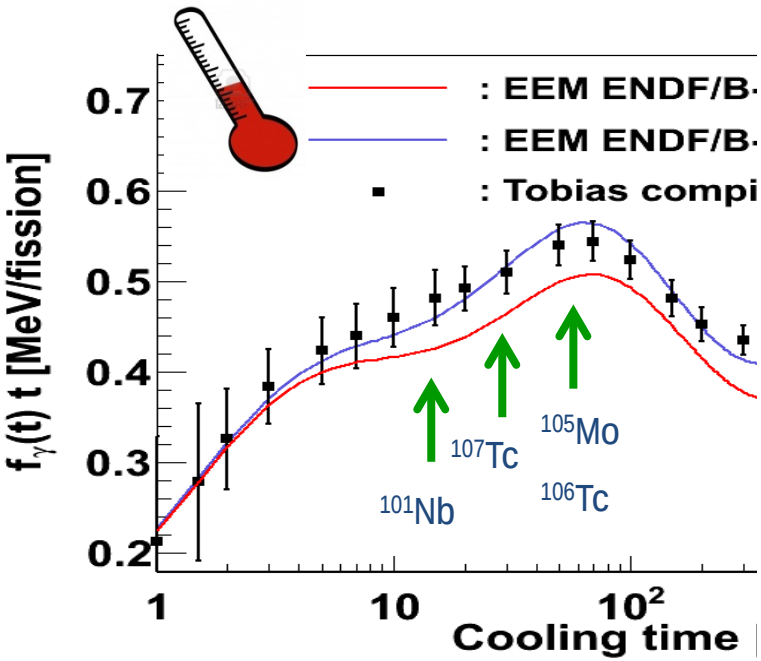


Hardy et al., Phys. Lett. 71B (1977) 307

- As a result of the Pandemonium, betas and neutrinos are incorrectly estimated in databases
- TAS measurements are very important for decay heat and neutrino summation calculations

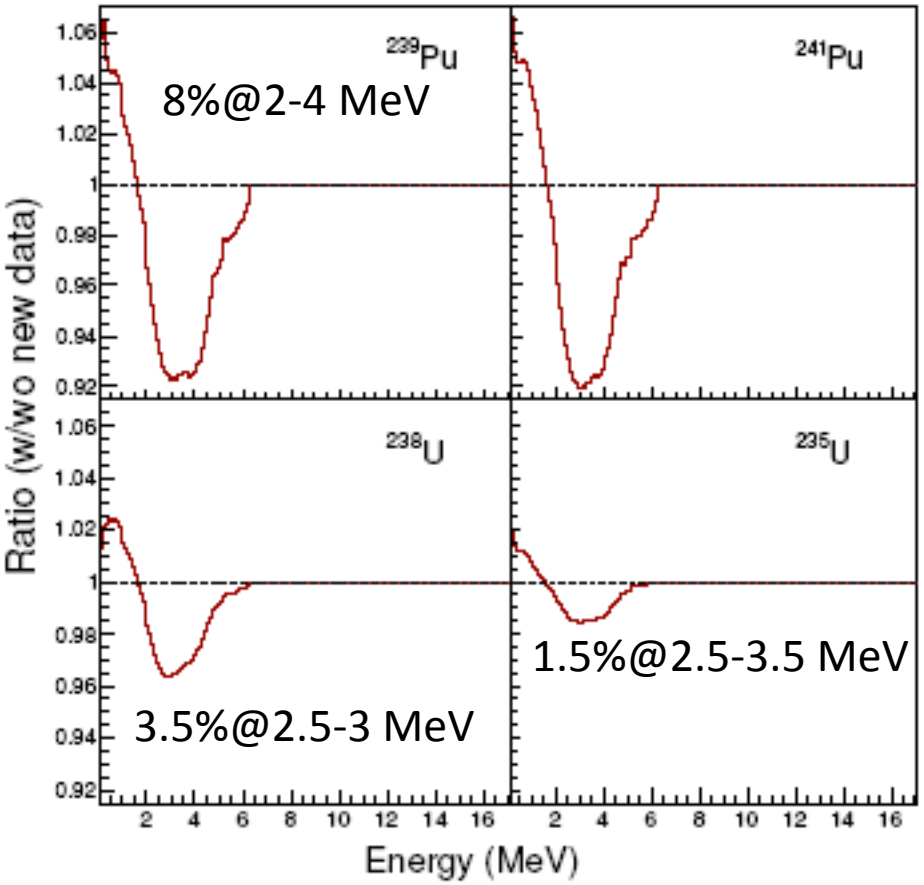


Impact of published data from JYFL



Algora et al., PRL 105 (2010) 202501
Dolores Jordan, PhD thesis, 2010

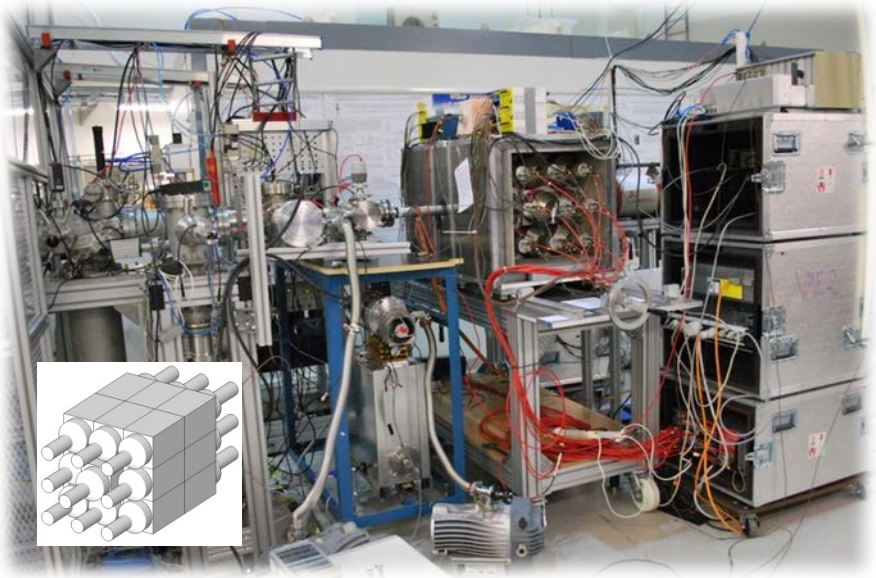
M. Fallot et al., PRL 109 (2012) 202504

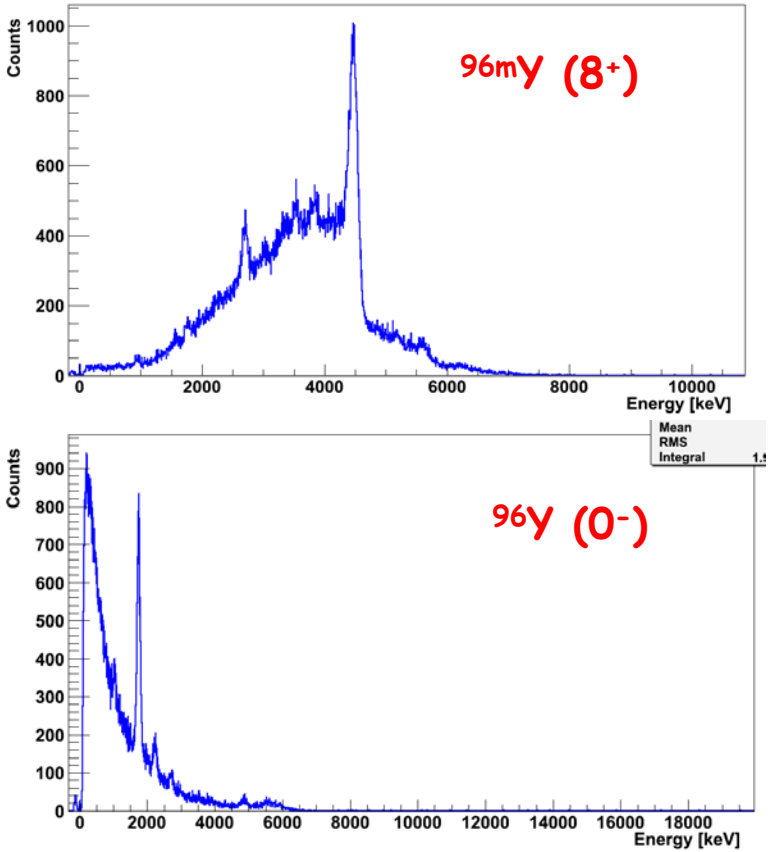


Ratio between 2 antineutrino spectra built with and without the TAS data of ^{102,104,105,106,107}Tc, ^{105}Mo, ^{101}Nb

DTAS detector for DESPEC at IGISOL

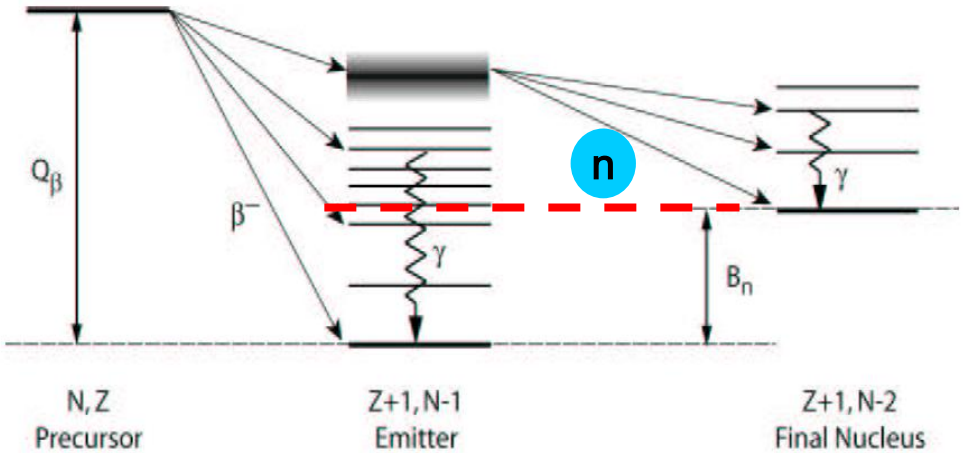
- 16 (+2) NaI(Tl) modules
- 5” PMT (50% light collection)
- Commissioning at IFIC (01/2014)
- JYFL (02-03/2014)
- PHASE 0 experiments for NUSTAR



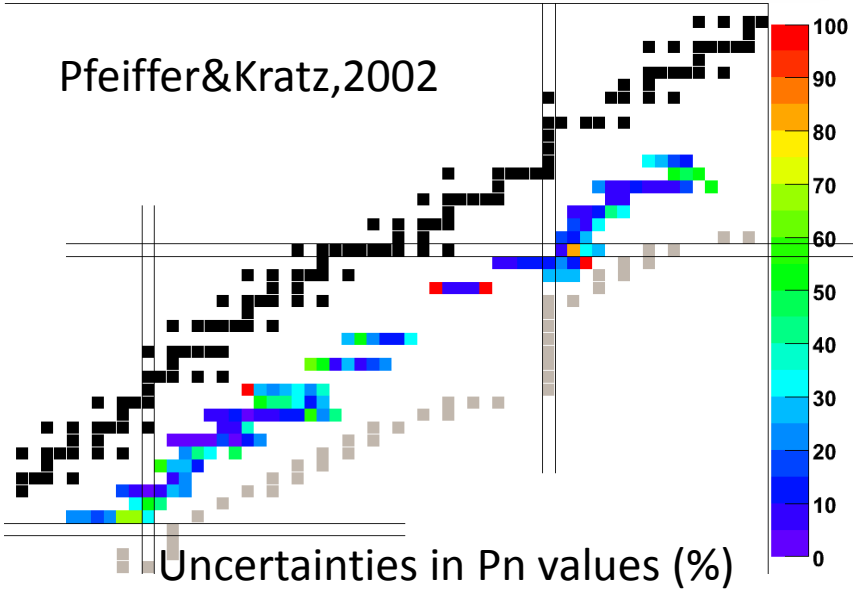


- 18 nuclei relevant for precise predictions of neutrino spectra from reactors
- non-proliferation studies (IAEA)

Delayed neutron measurements

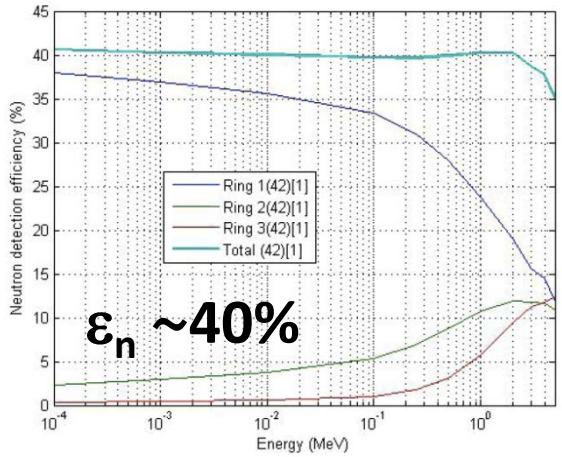


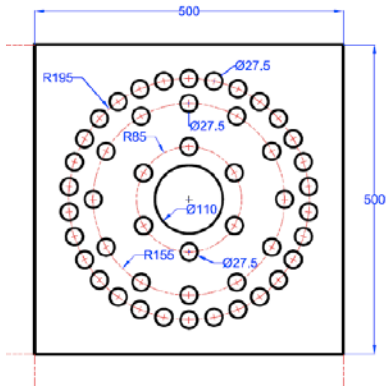
- The delayed neutron fraction β_{eff} is a key parameter in the control of reactor power
- Improvement of summation calculations for unusual fuel compositions and/or burnups
- Nuclei close to the r-process path
- Comparison with theoretical β-strength function calculations

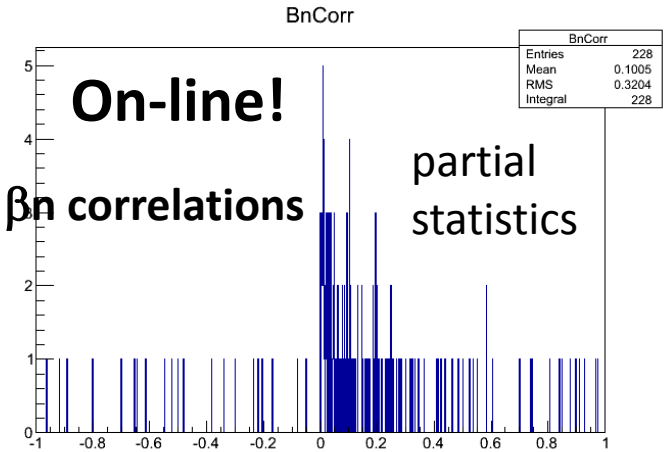


BELEN-48 for 1- and 2n emission

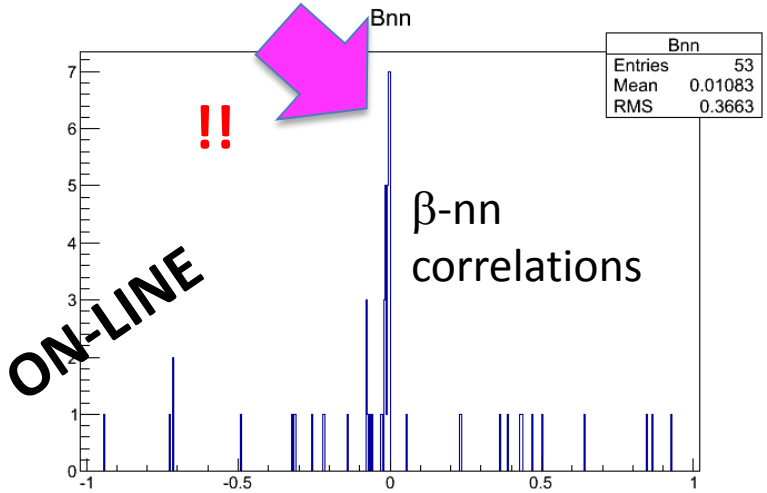
- Data acquired for: ^{98,98m,99}Y, ^{135,137}Sb (0.5 cps implantation rate), ^{138}Te, ^{138,139,140}I





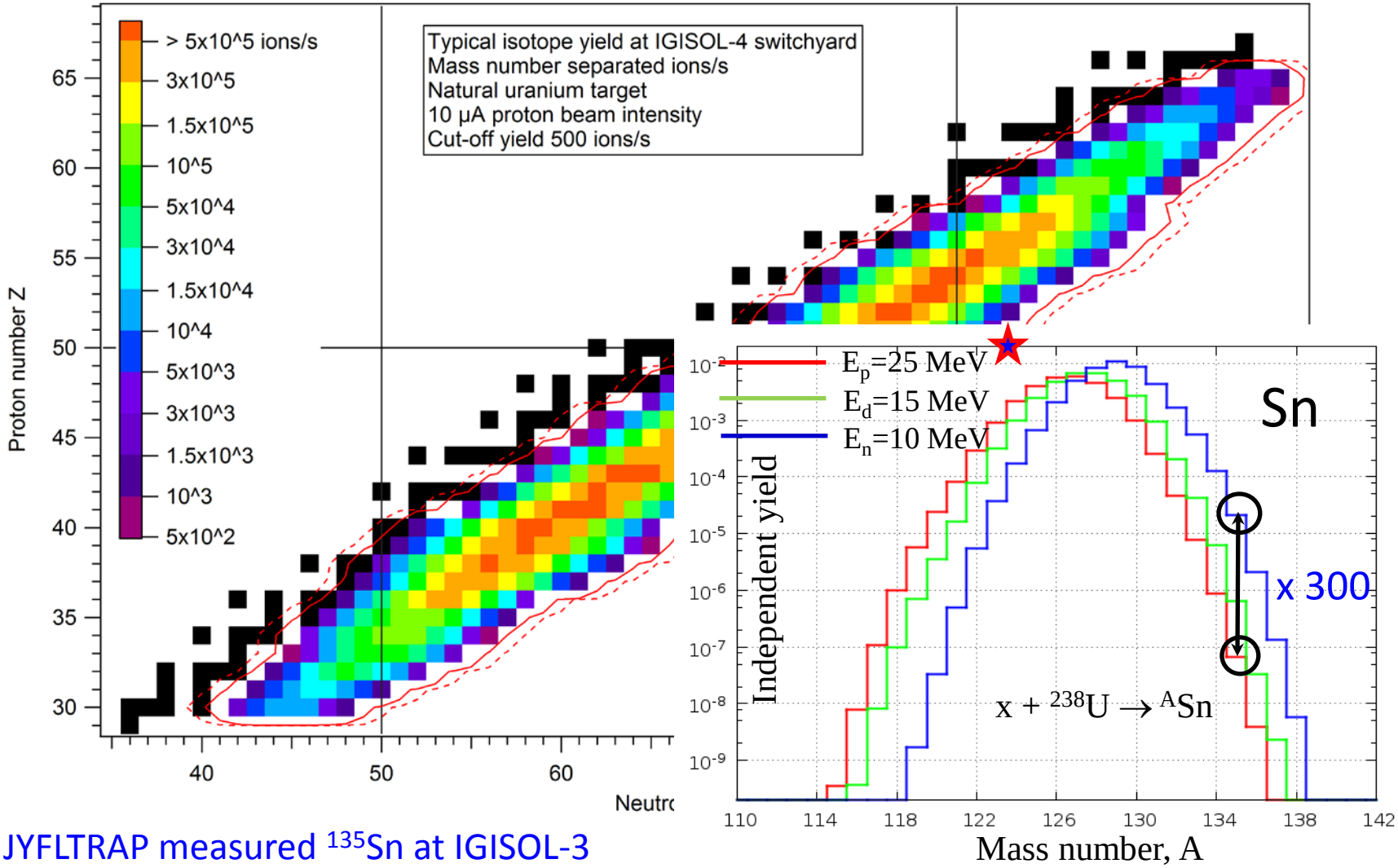


- Measurement of β-delayed 2n emitter ^{136}Sb (sizeable P_{2n} predicted, close to r process path and ^{132}Sn)
- Implantation rate 1.5 cps
- Data under analysis (Iris Dillmann)



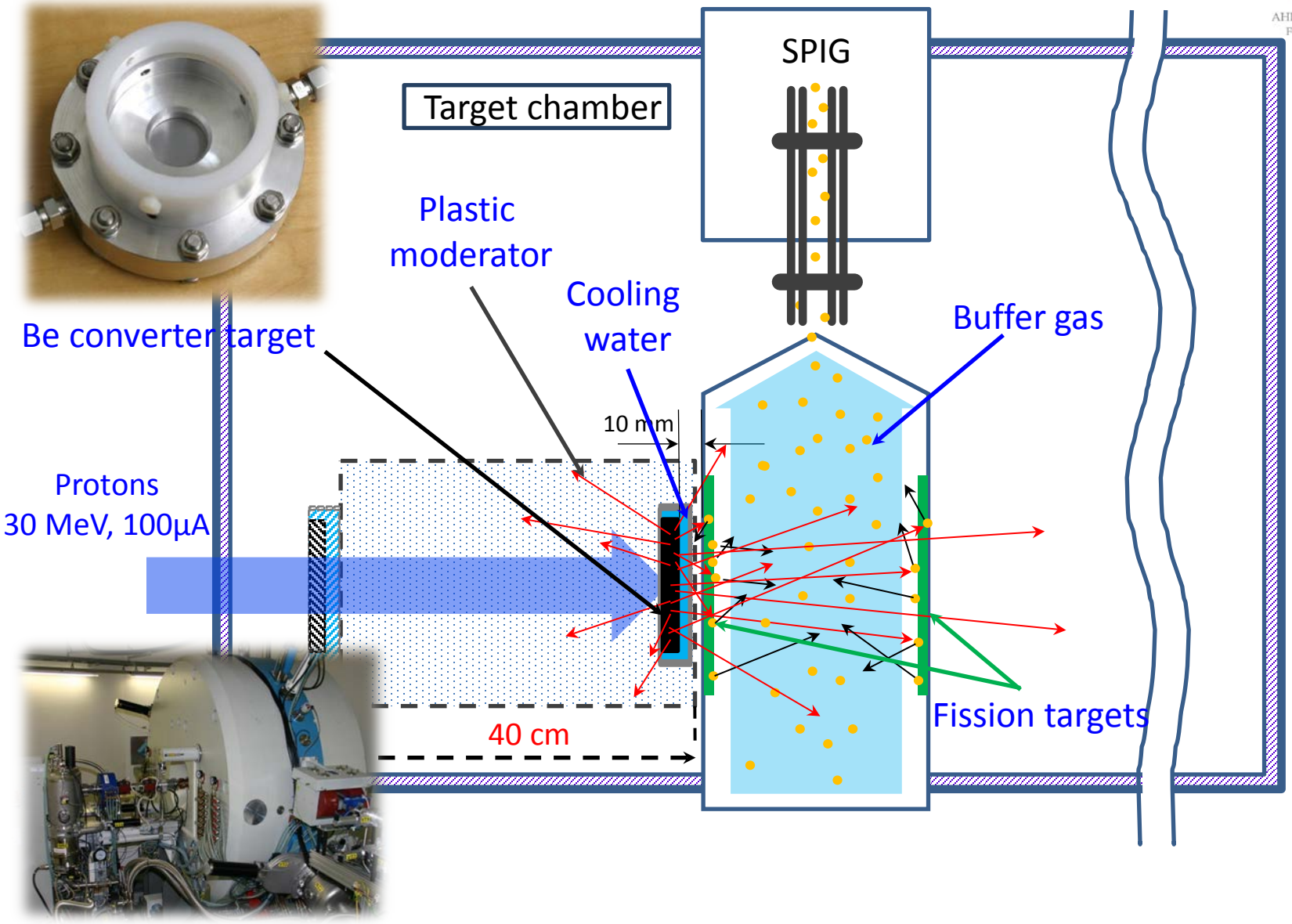
Fission of ^{238}U with 25 MeV protons

- Typical isotope yield at IGISOL-4 switchyard, 10μA beam intensity

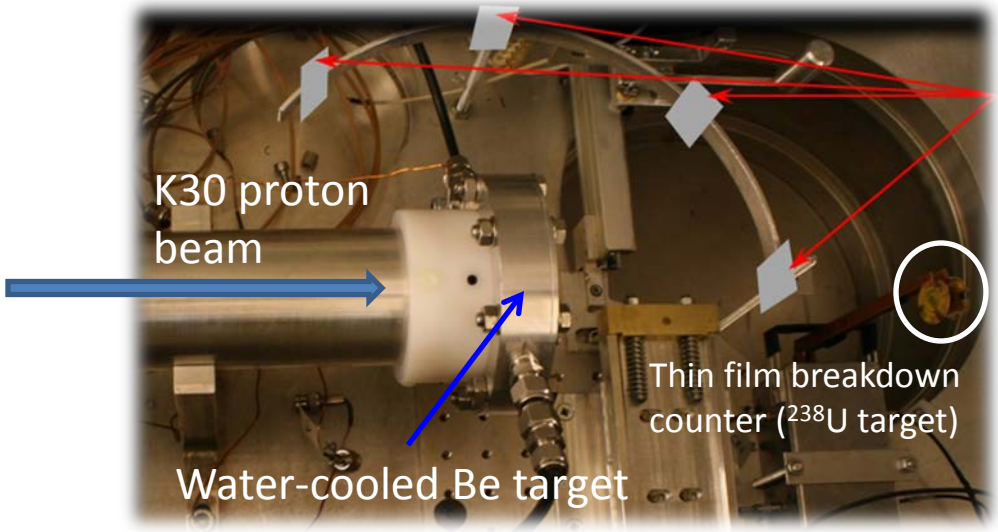


JYFLTRAP measured ^{135}Sn at IGISOL-3

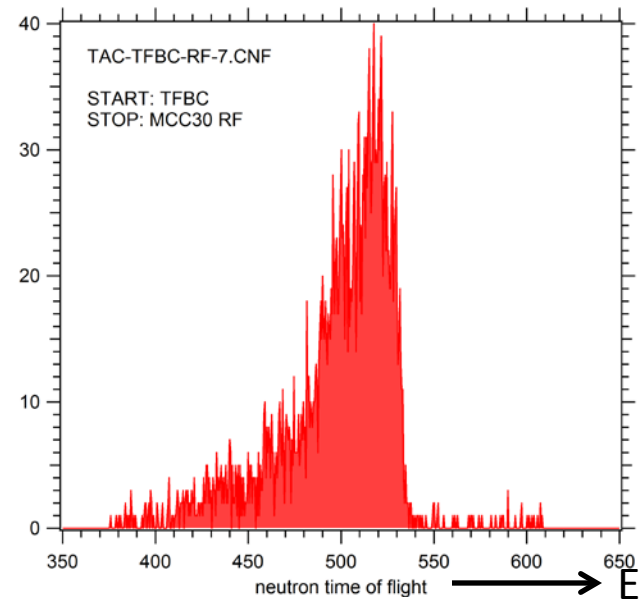
Towards n-induced fission at IGISOL

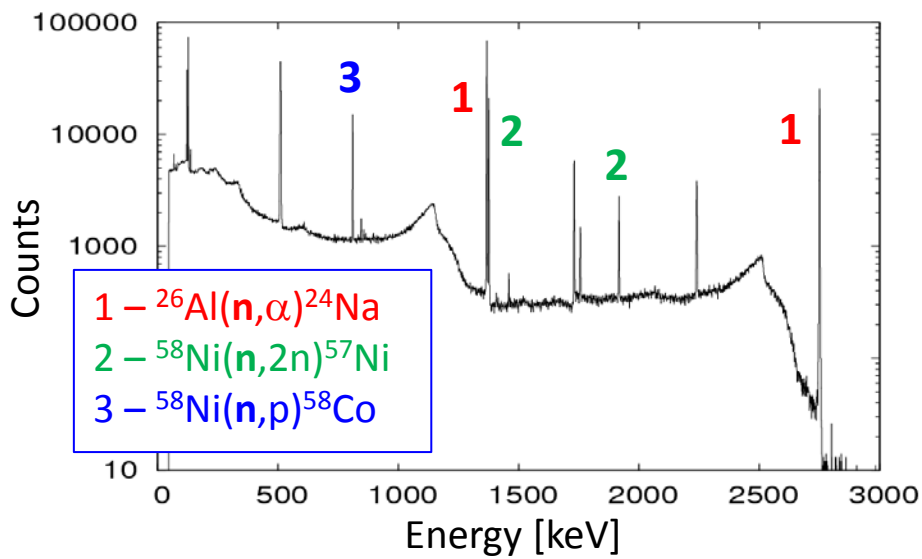


Characterising the neutron flux



Foils for neutron activation measurement

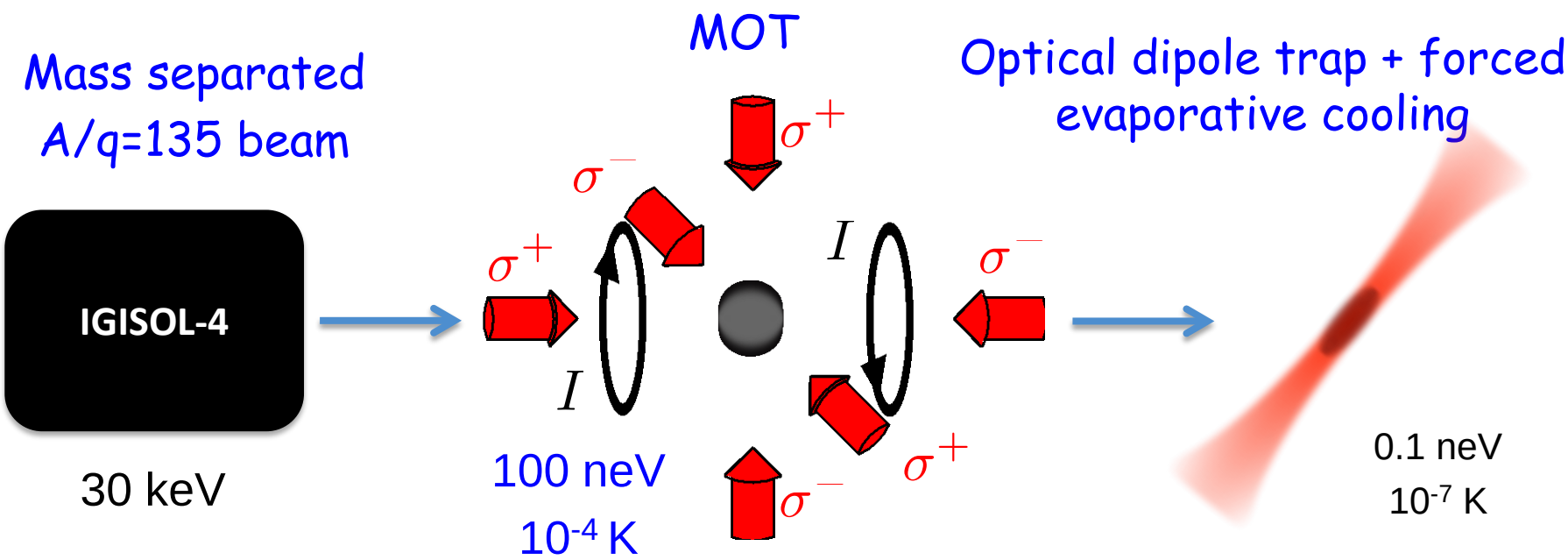




- Neutron time-of-flight spectrum
- Energy information (at 0°)
- ~10^8 n/s/cm^2 for 1 μA protons
- γ spectrum of Al and Ni (at 0°)

^{135m}Cs Bose-Einstein Condensation

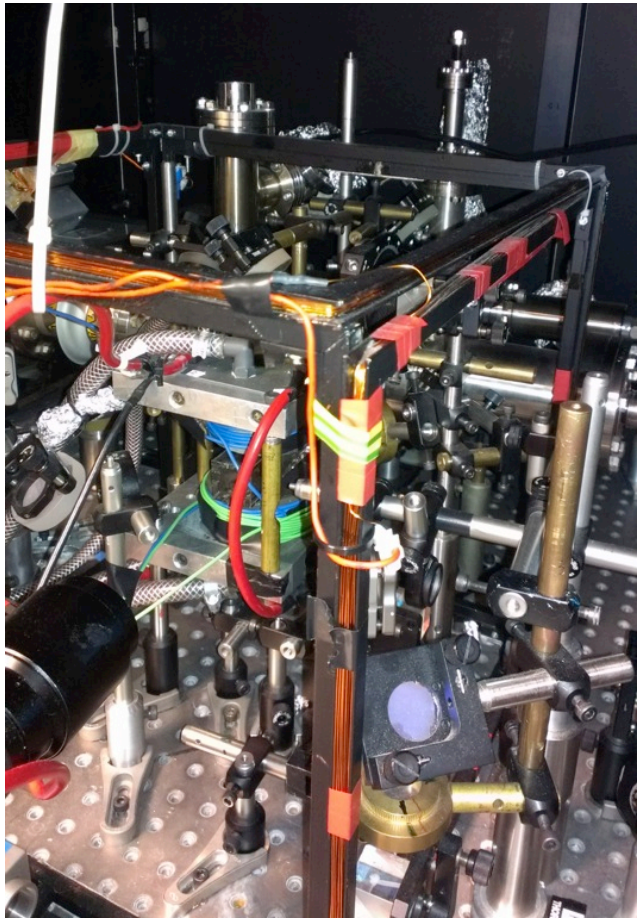
- Coherent sample of ultra-cold Cs atoms produced in fission



Ultra-cold nuclear matter

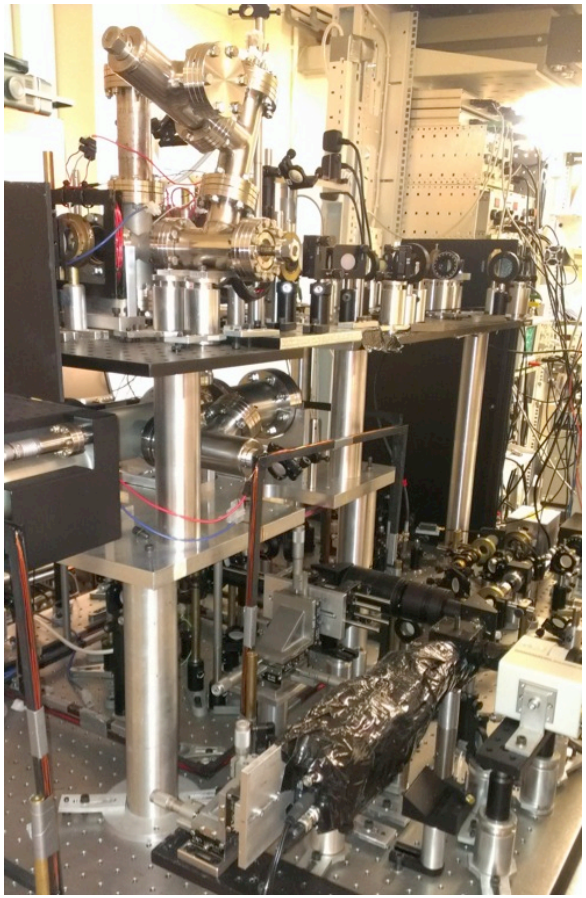
University College London atom traps

^{87}Rb hybrid ODT



Cs multi-isotopes ODT

(work in progress)



Many-body nuclear effects mediated by BEC

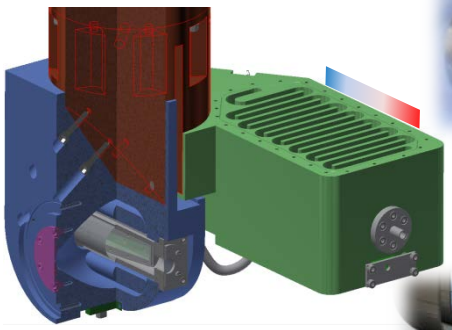
F. Renzoni

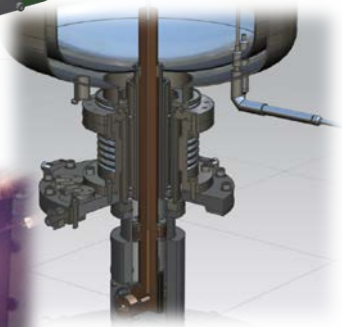
L. Marmugi

Summary and Outlook

- IGISOL-4 has been fully operational since 2014
  - light ion & fission, heavy-ion reactions (summer 2015)
- Collinear laser spectroscopy, post-trap spectroscopy, decay spectroscopy, mass measurements

- Infrastructure investments: MR-TOF-MS, PI-ICR, cw Matisse laser
- Submitted infrastructure requests: Upgrade of lasers, MARA-LEB
- Cone trap developments (Manchester)
- RF hot cavity (towards ^{94}Ag)
- Cryocooler and IGQMS facility
- ^{252}Cf source





- More beam time for longer and more complex experiments.
- New projects

IGISOL team

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https://www.jyu.fi/fysiikka/en/research/accelerator/igisol

Thank you