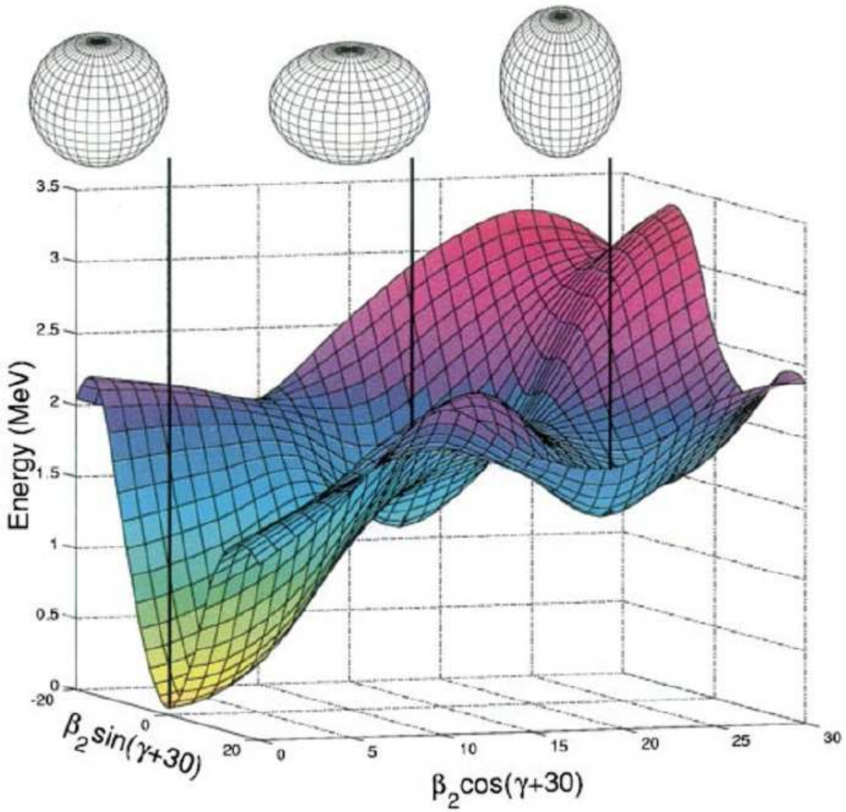
Shape coexistence in atomic nuclei studied through β decay at ISOLDE, CERN

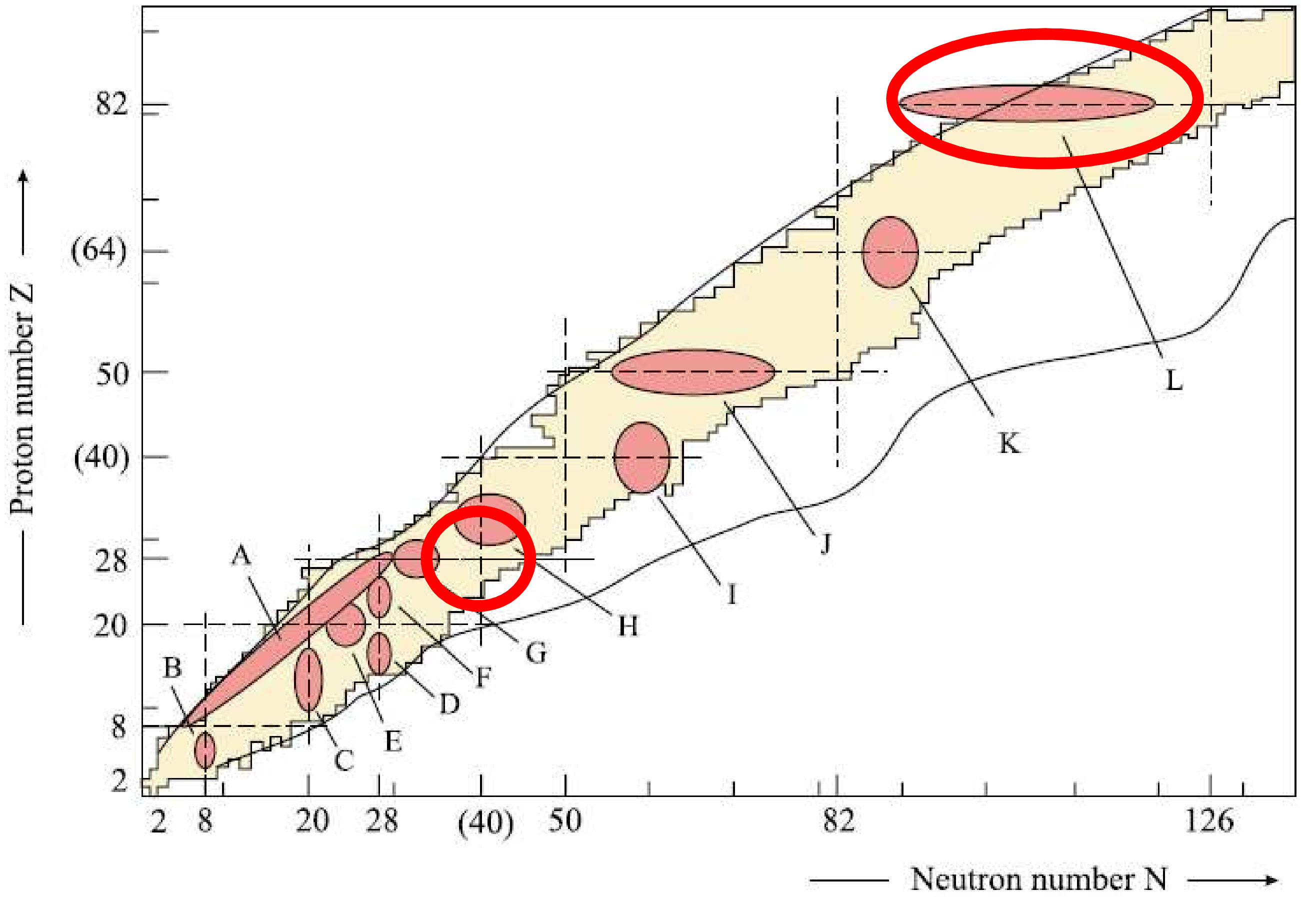
Marek Stryjczyk

Outline

- Introduction
- Decay studies of ^{66}Ni
- Decay studies of ^{182}Hg
- Outlook & summary

Shape coexistence

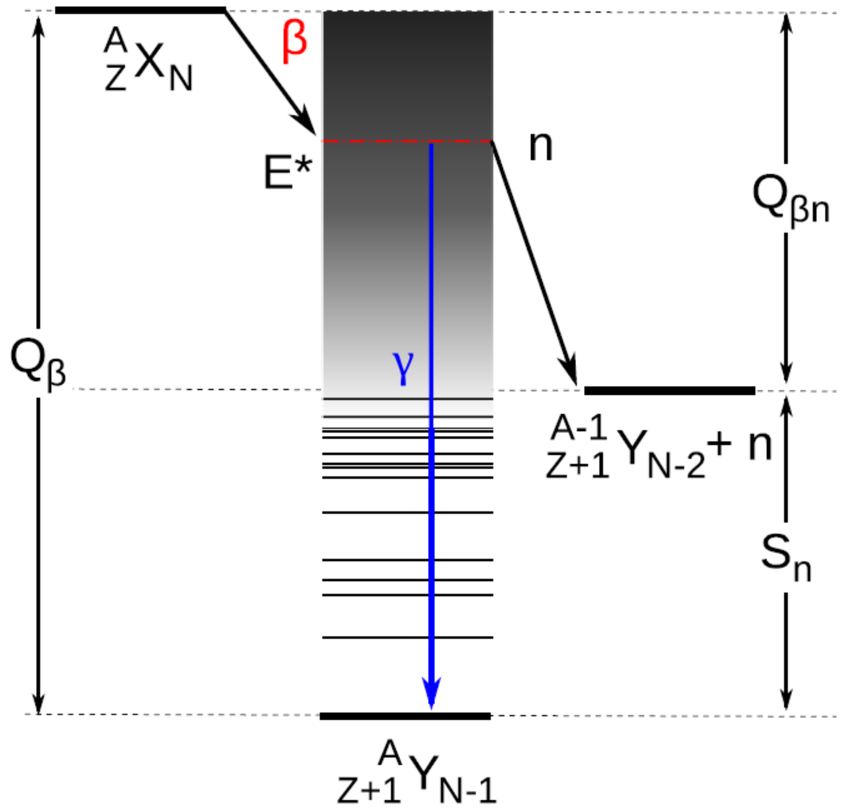


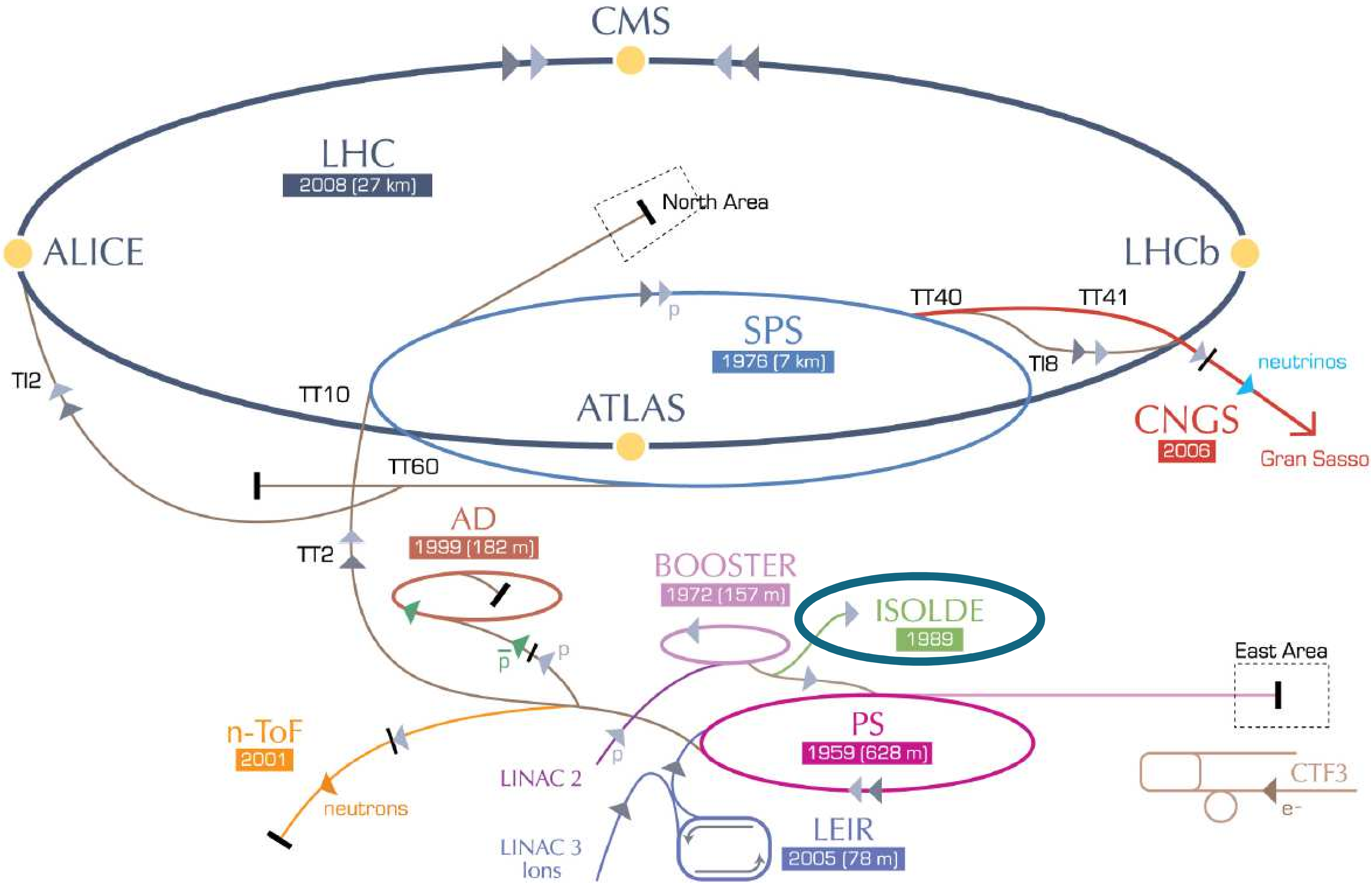


K. Heyde, J.L. Wood, Rev. Mod. Phys. **83**, 1467 (2011)
A.N. Andreyev *et al.*, Nature **405**, 430 (2000)

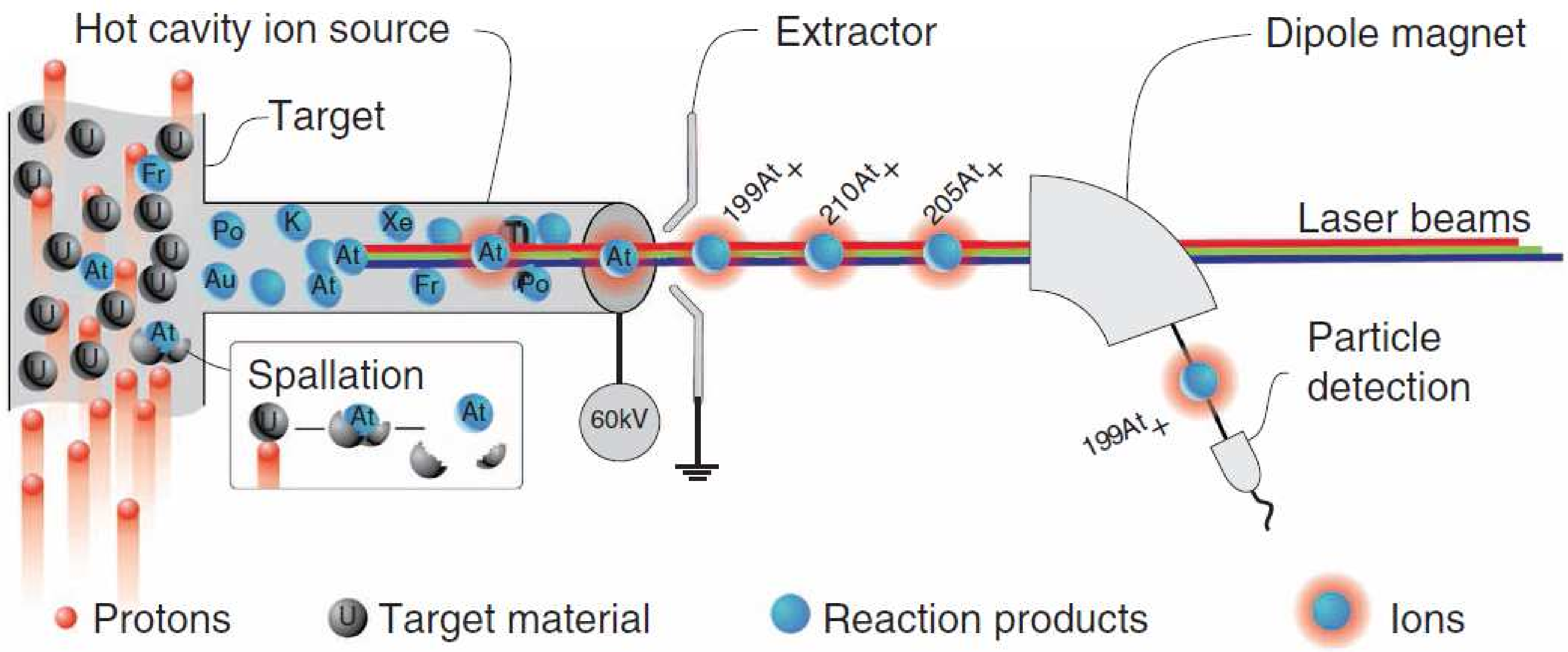
β-decay studies

- Access to excited states
- Multiple observables ($T_{1/2}$, P(*n/p/f*), I_β, log(*ft*), B(F/GT), I_γ, E_γ, α, τ, B($\sigma\lambda$)...)
- (Relatively) easy experiment

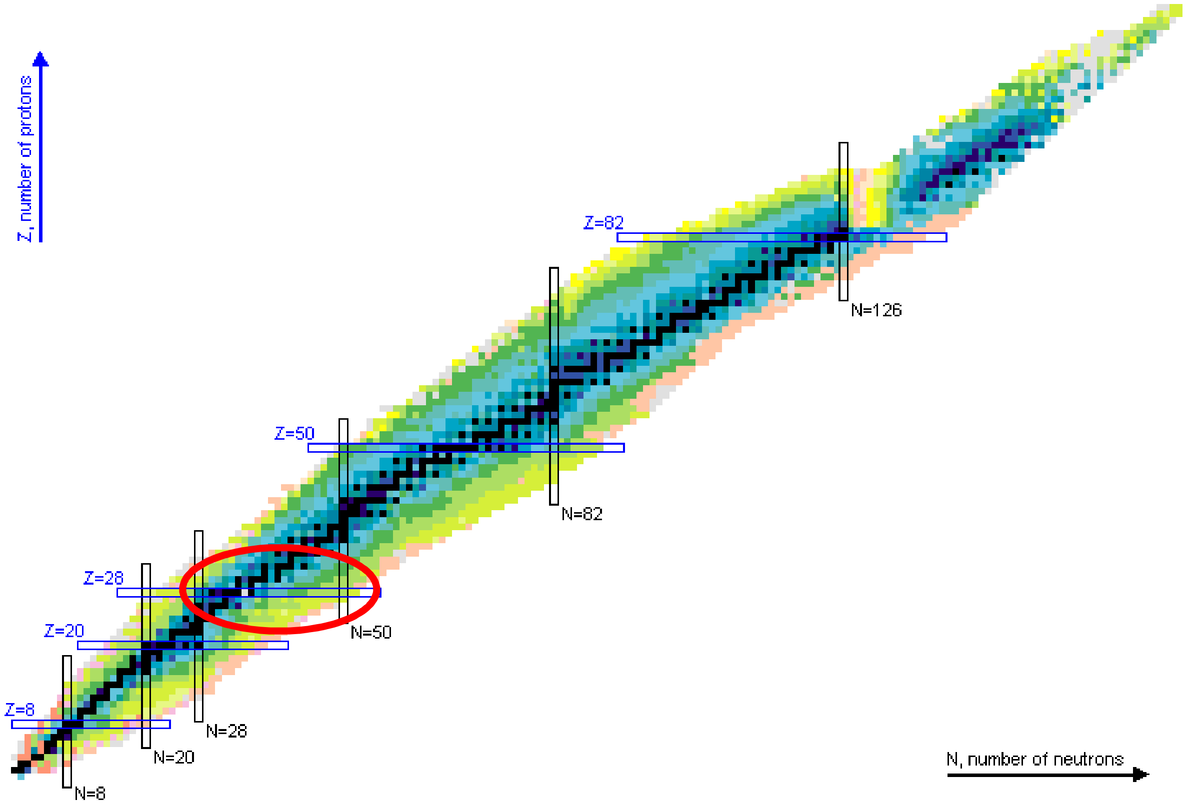



CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
CTF3
e-
neutrons
LINAC 2
LINAC 3
Ions
LEIR
2005 (78 m)

Beam production



Motivation – why nickel?



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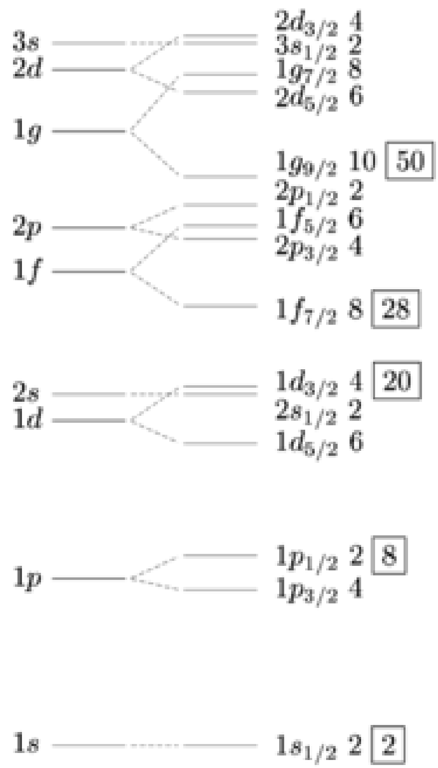
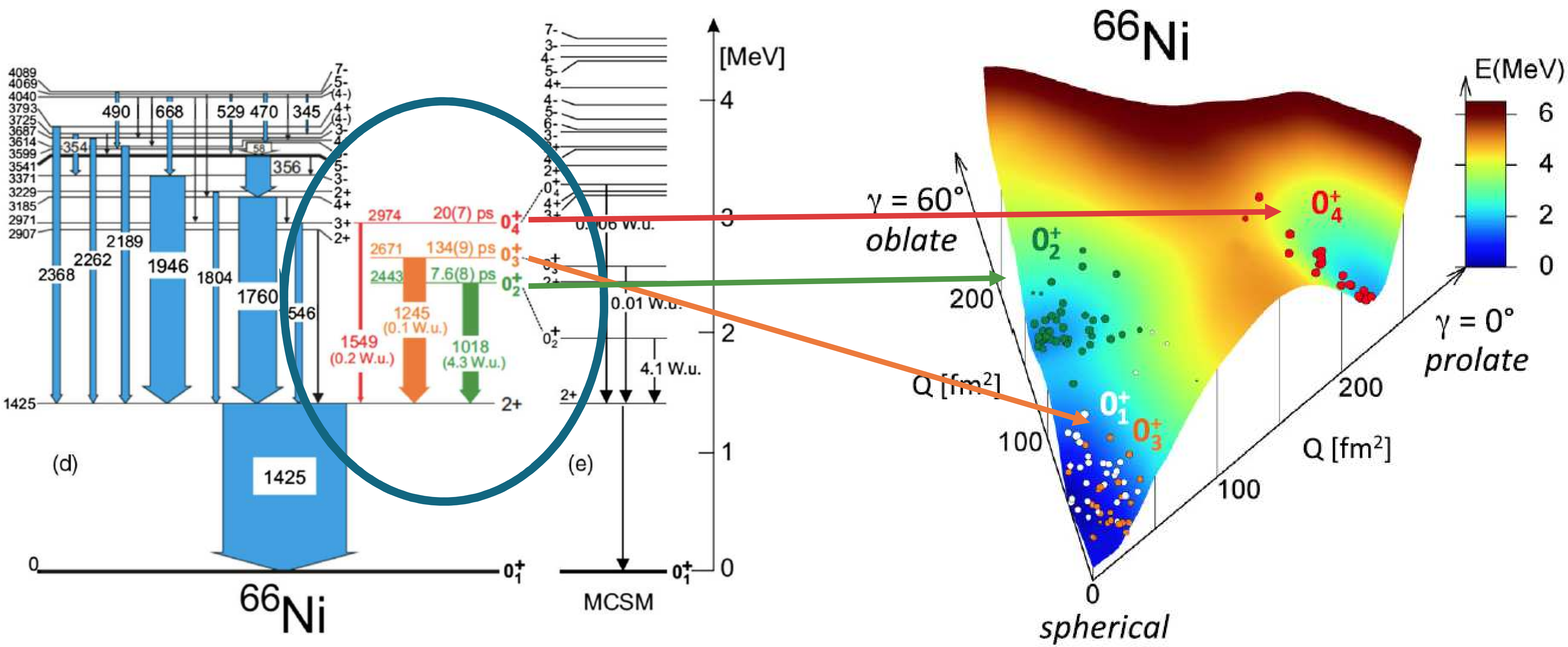
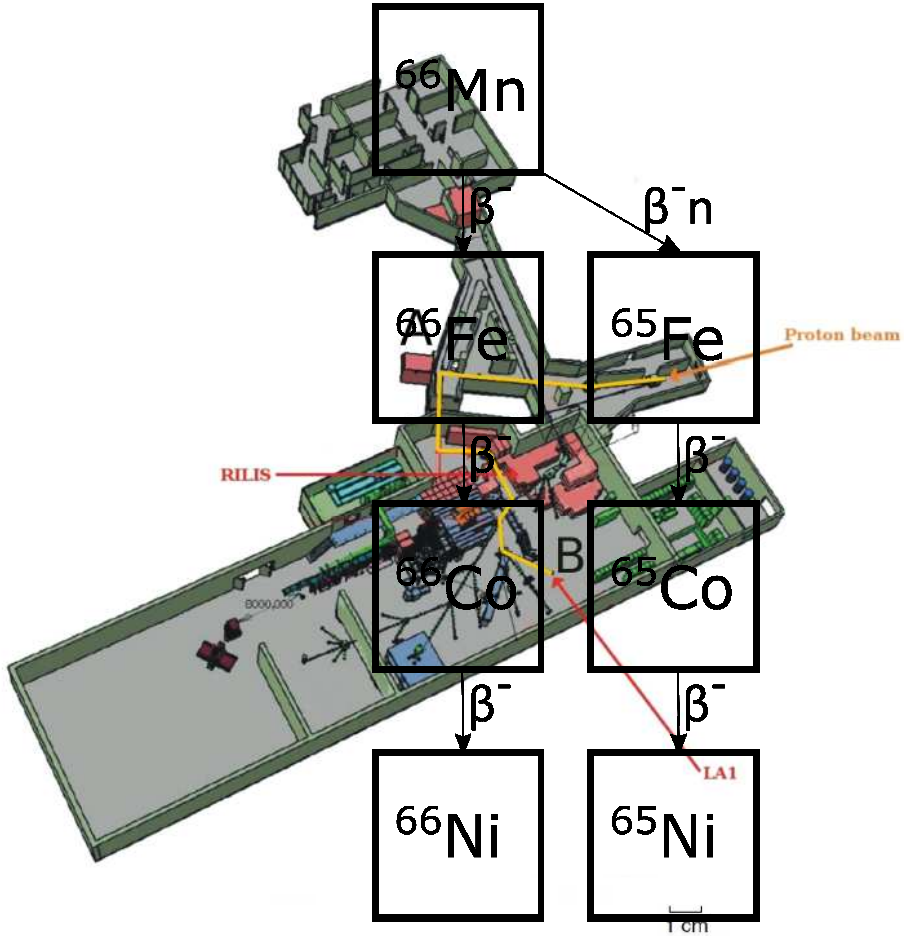


Motivation – why nickel?

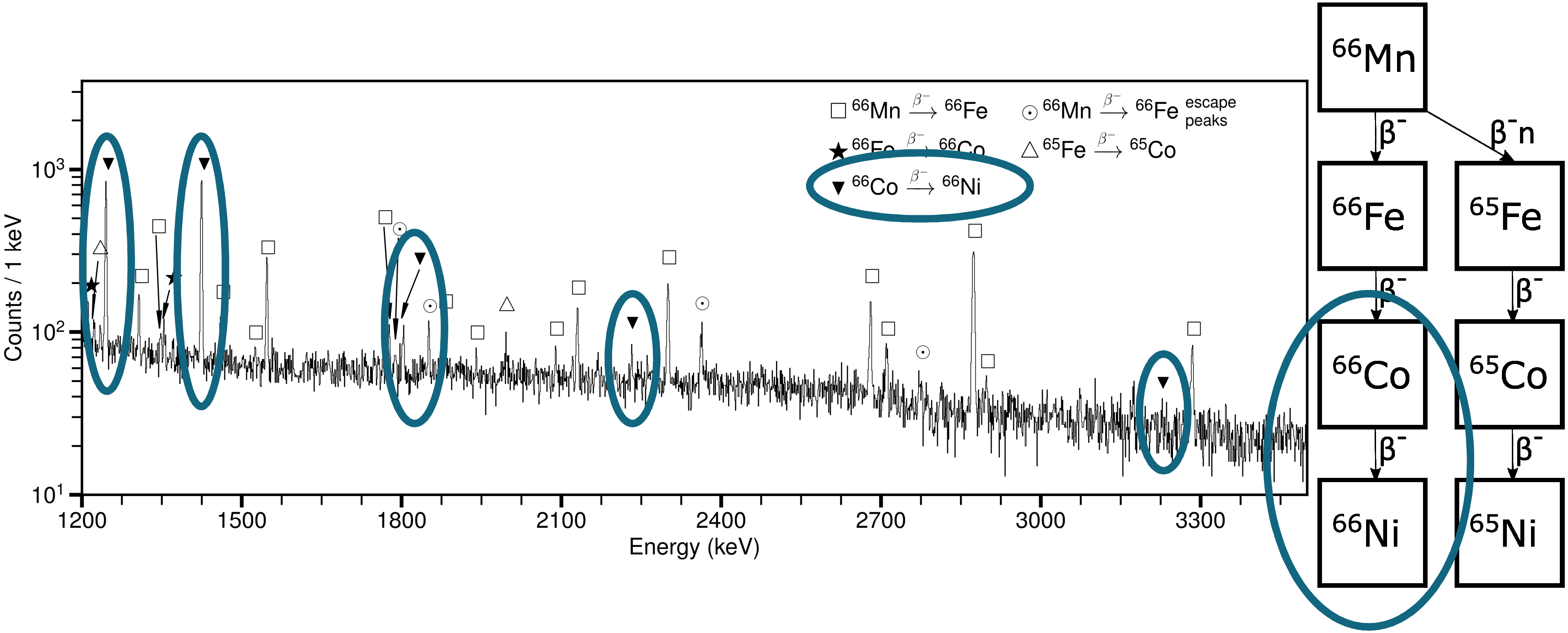


Experimental set-up

- Experiment IS467@LA1
- Pure beam of ^{66}Mn implanted on a movable aluminized mylar tape
- γ detection: 2 HPGe Miniball clusters
  β deteciton: 3 ΔE plastic scintillators
- Digital data acquisition system based on XIA-DGF4C modules



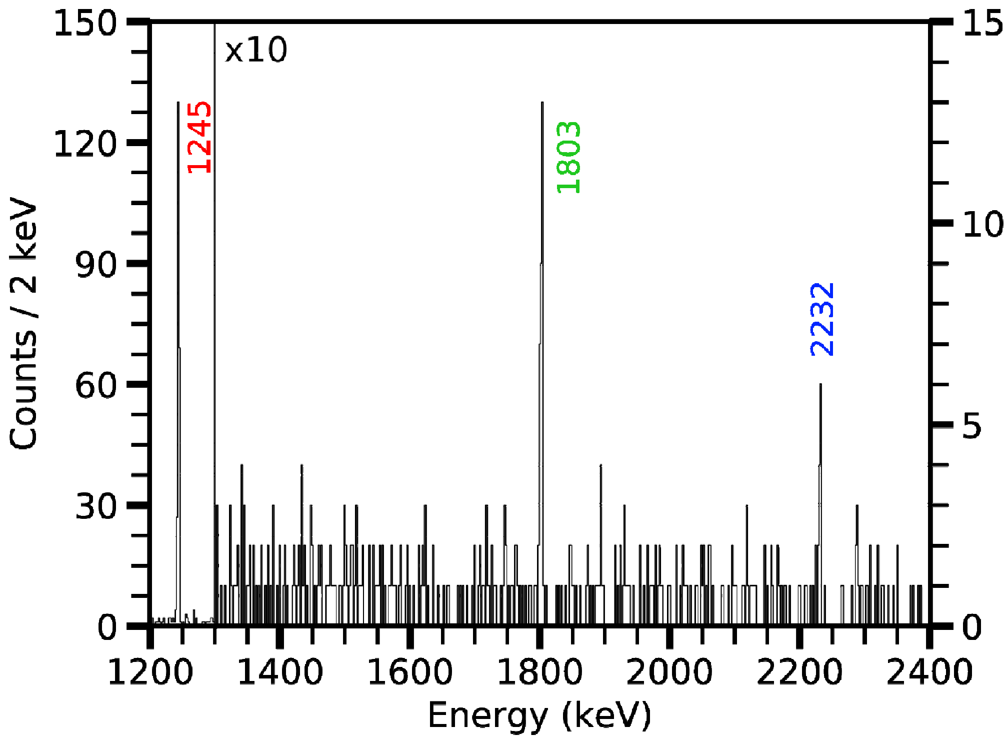
Results

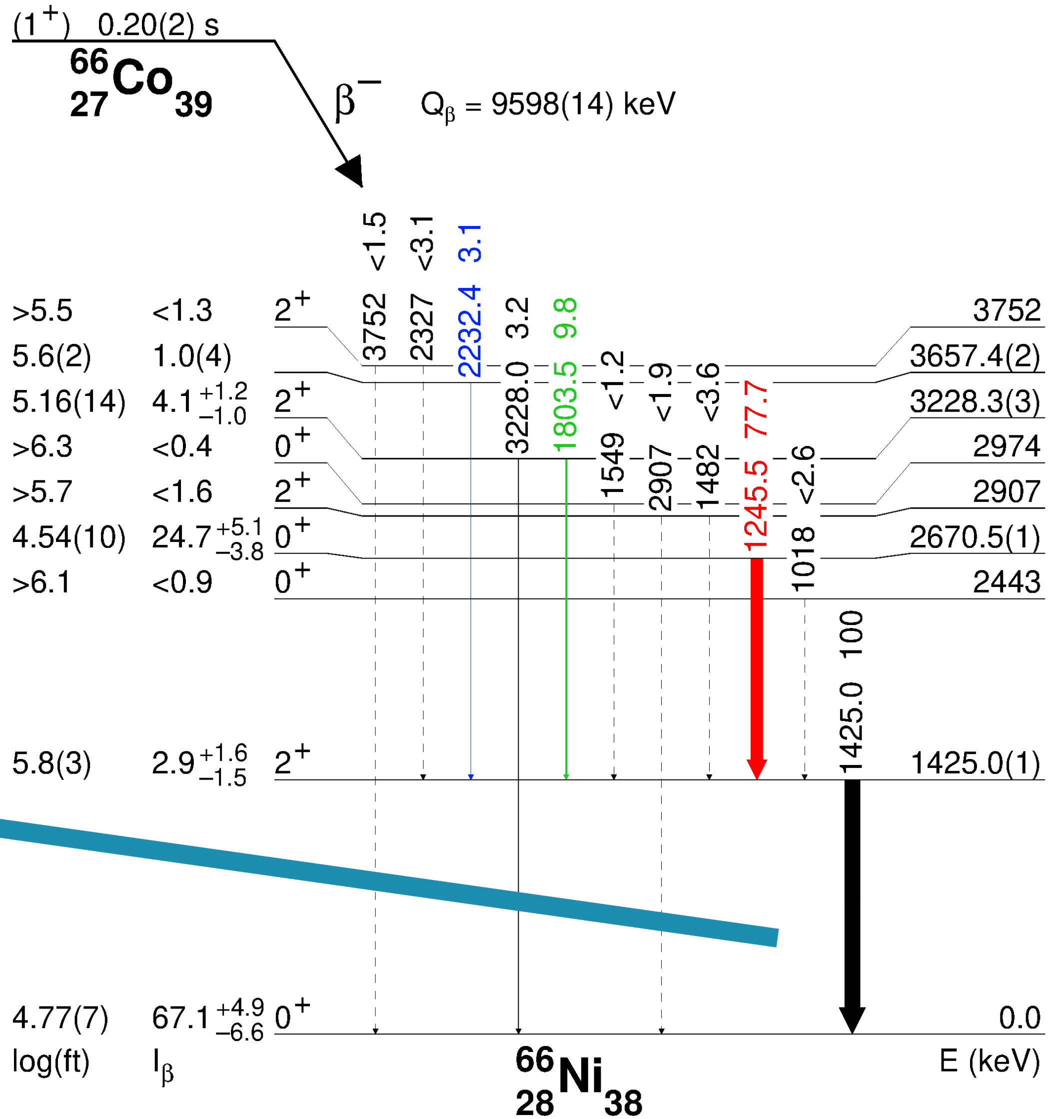


66Mn →β− 66Fe
66Mn →β− 66Fe escape peaks
66Fe →β− 66Co
65Fe →β− 65Co
66Co →β− 66Ni
Counts / 1 keV
10^1
10^2
10^3
1200
1500
1800
2100
2400
2700
3000
3300
Energy (keV)
66Mn
66Fe
65Fe
66Co
65Co
66Ni
65Ni
β−
β−n

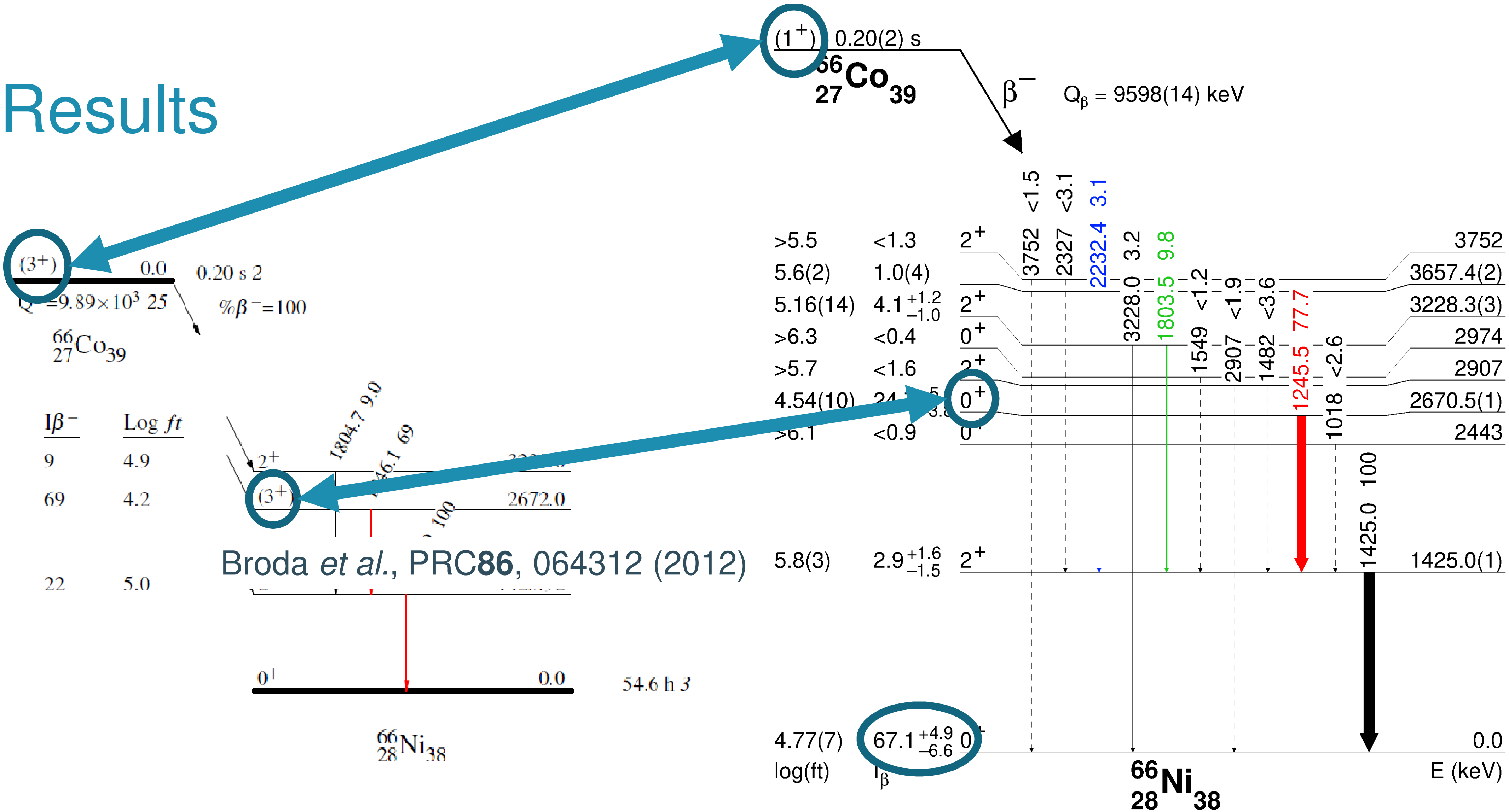
Results

γγ coincidence spectrum gated on 1425 keV





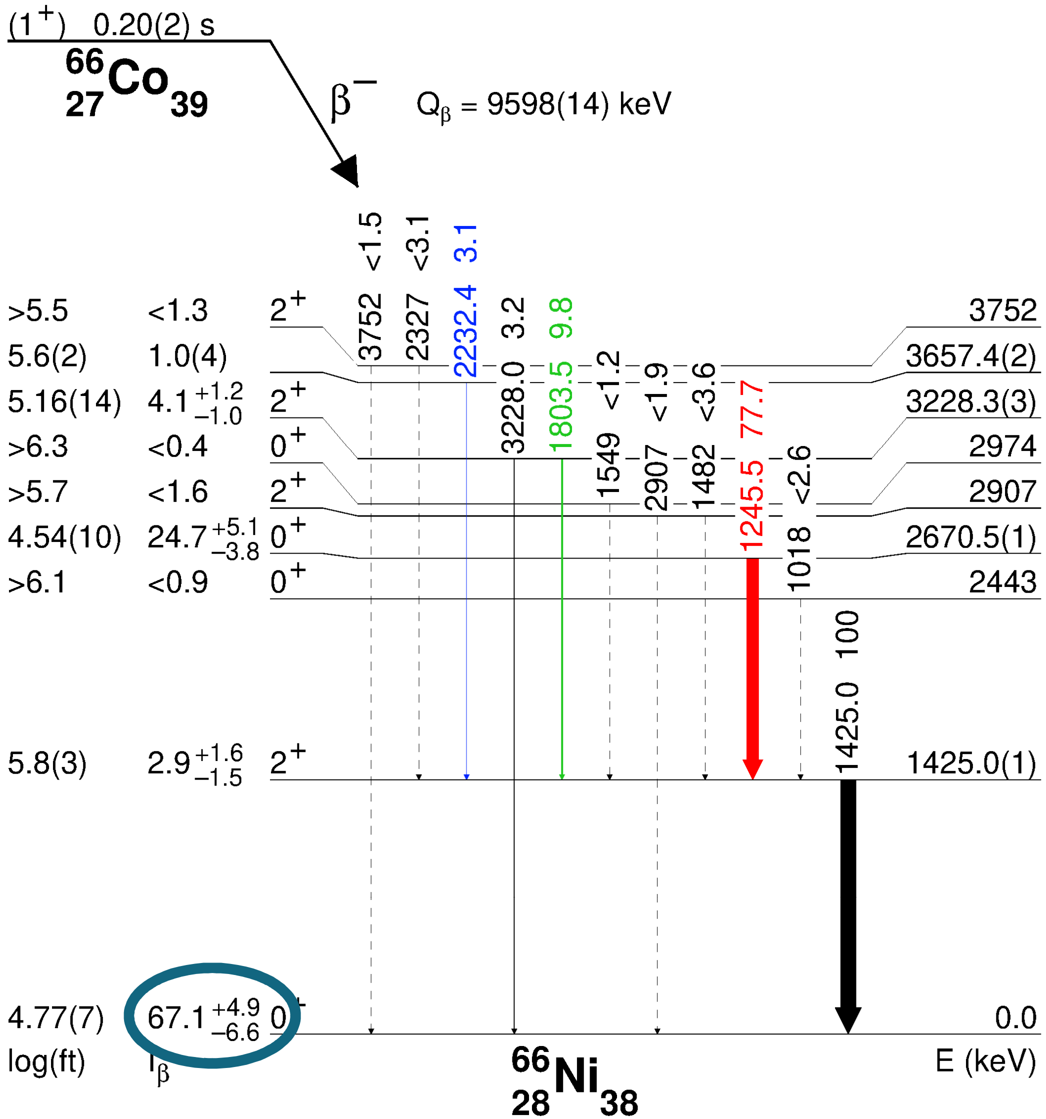
Results



Broda *et al.*, PRC**86**, 064312 (2012)

Ground state feeding

- Idea: compare the number of β particles and β-gated-γ-rays
- Problems:
    - mixed radioactive source: decay of ^{66}Mn, $^{65,66}Fe$, $^{65,66}Co$, $^{65,66}Ni$...
    - dependence on the half-lives
    - limited statistics (in some cases)
- What to do?



Bayes theorem

Posterior probability density function (*pdf*)

Likelihood function

Prior

$$P(model|data) = \frac{P(data|model)P(model)}{P(data)}$$

Evidence

Bayes theorem

All the information we know BEFORE the analysis (branchings, lifetimes etc.)

Posterior probability density function (*pdf*)

Likelihood function

Prior

$$P(model|data) = \frac{P(data|model)P(model)}{P(data)}$$

It can be χ^2 or something more sophisticated

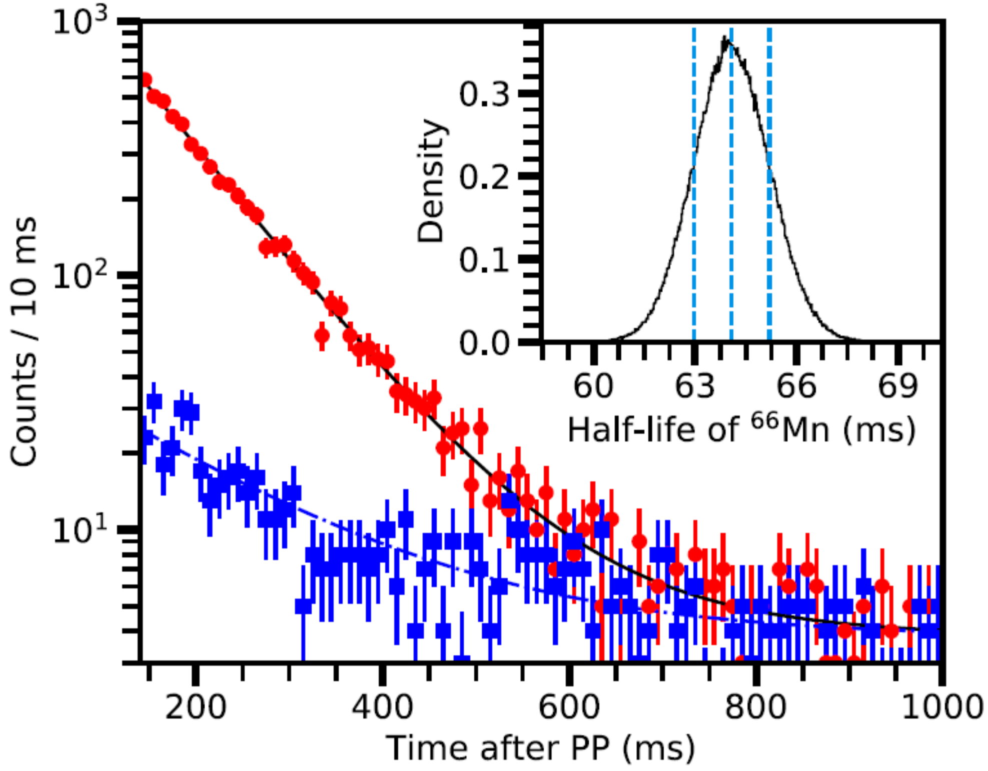
Evidence

It does NOT depend on the model!

Ground state feedings – assumptions

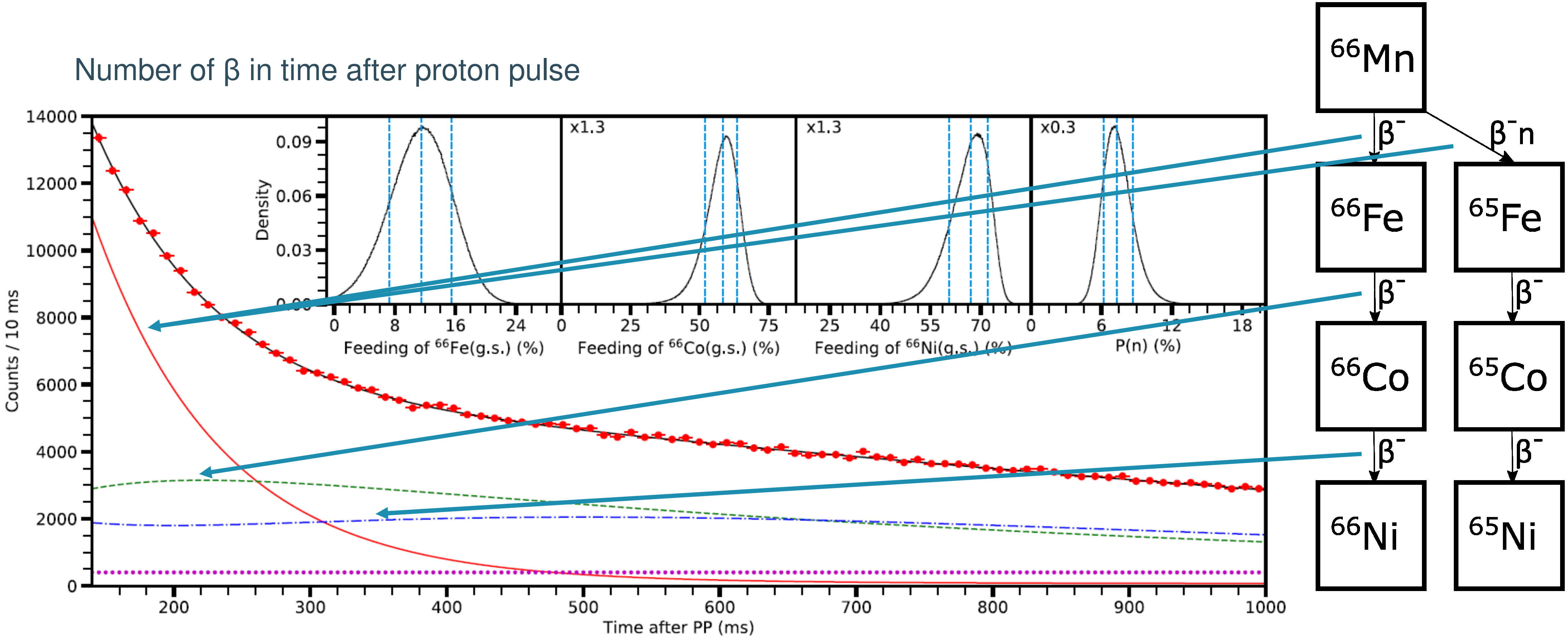
- $\beta(t) = A_{Fe}\gamma_{Fe}^{sig}(t) + A_{66Co}\gamma_{66Co}^{sig}(t) + A_{66Ni}\gamma_{66Ni}^{sig}(t) + C$
- The excess of β particles ($A > 1$) is interpreted as a ground state feeding
- $gsf = 1 - \frac{1}{A \times \varepsilon_\gamma \times f_I}$,

$$f_I = I_\gamma \times \left(\sum I_{\gamma\ to\ gs}\right)^{-1}$$

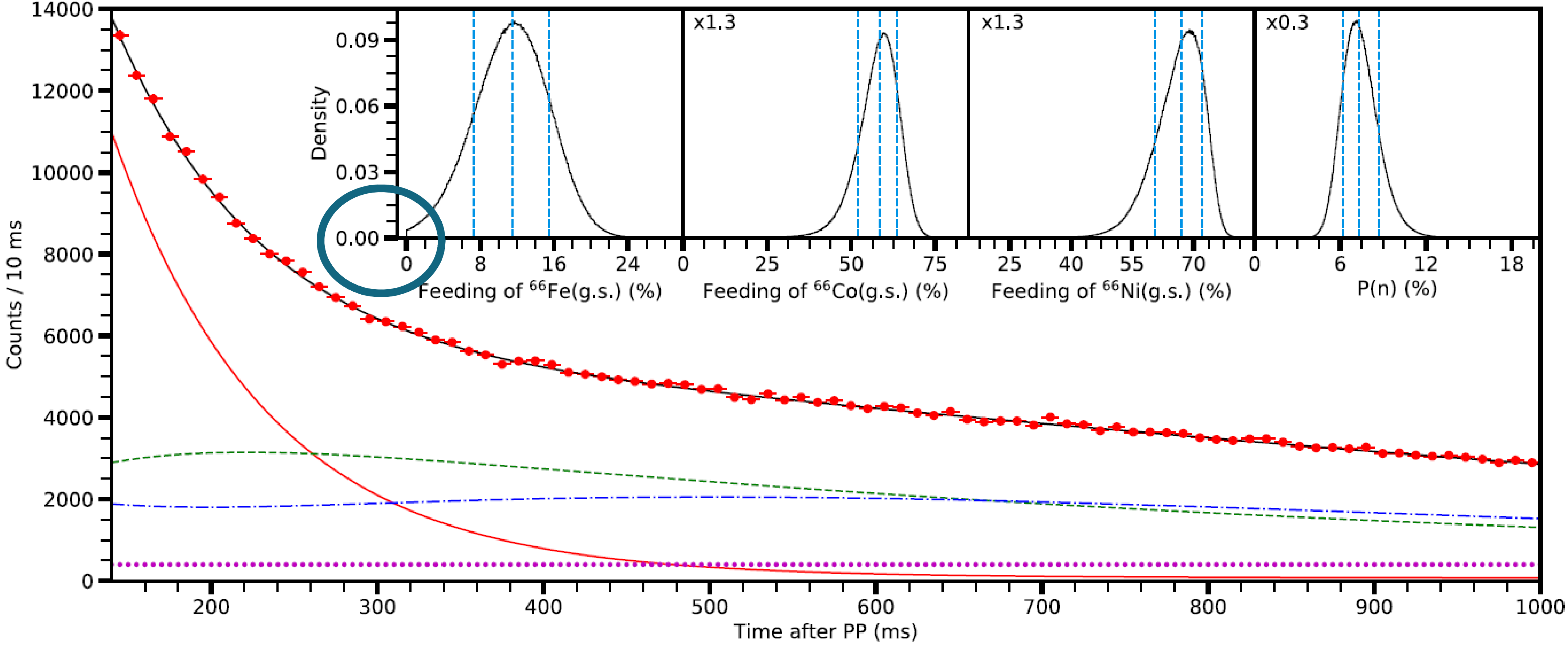


Ground state feedings

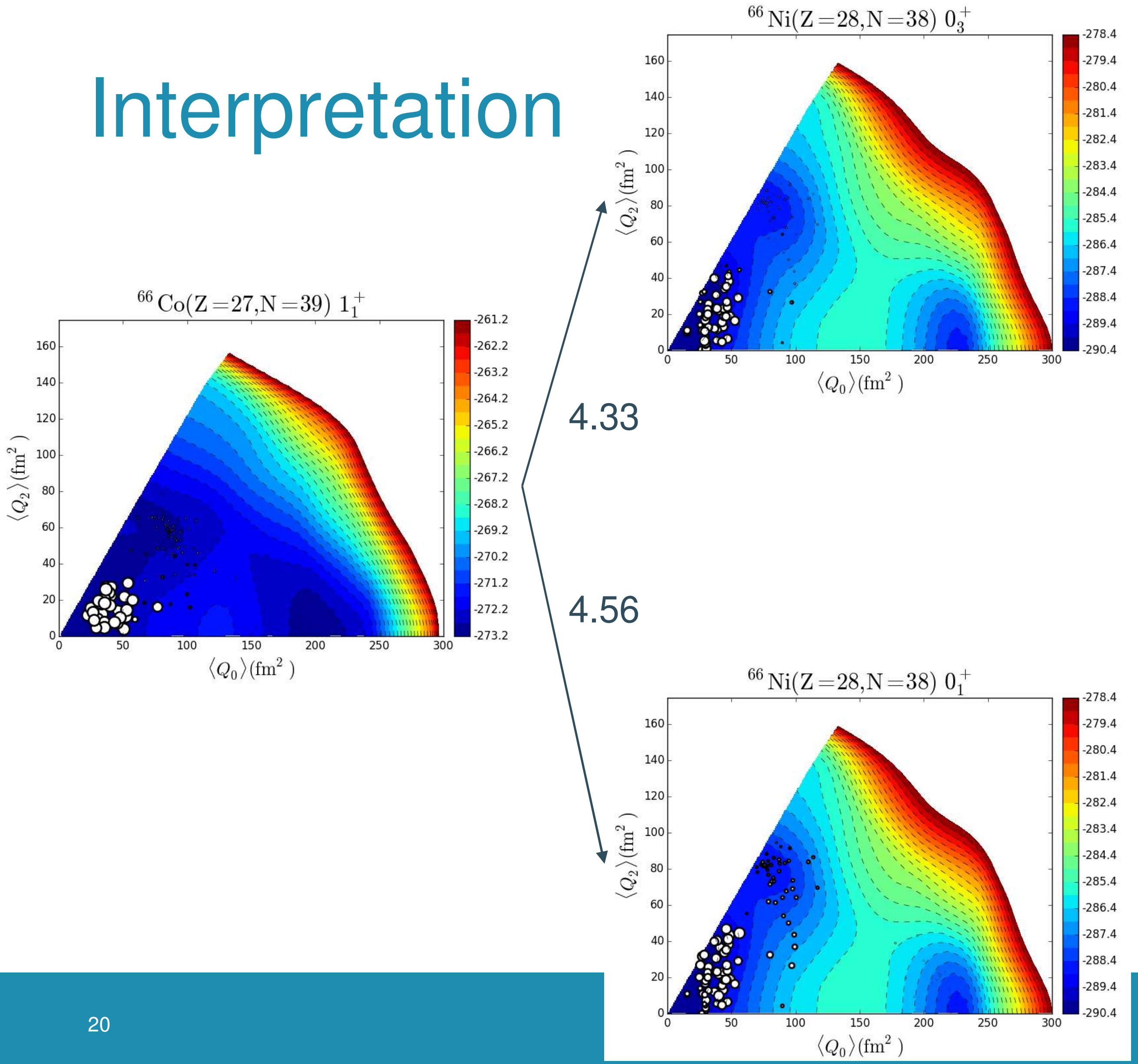
Number of β in time after proton pulse

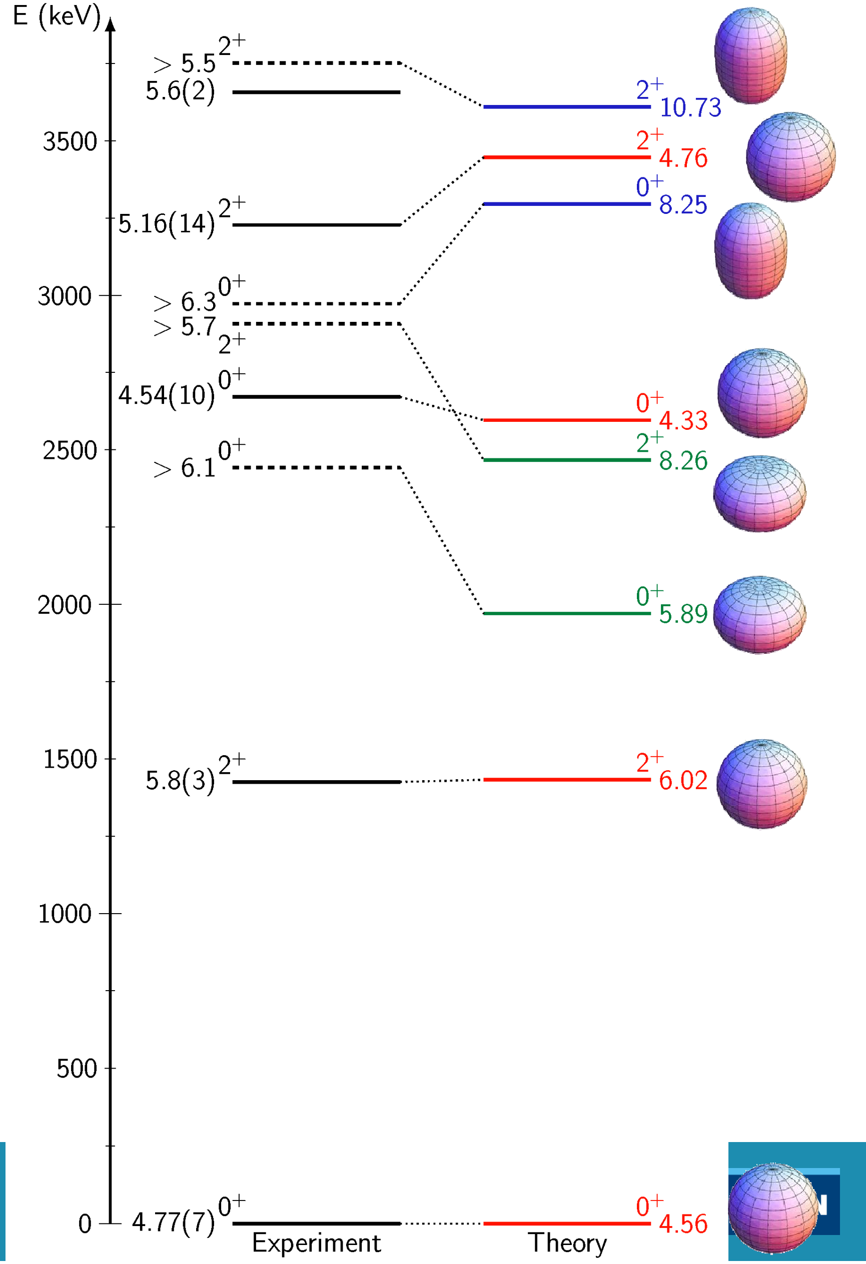


Ground state feedings

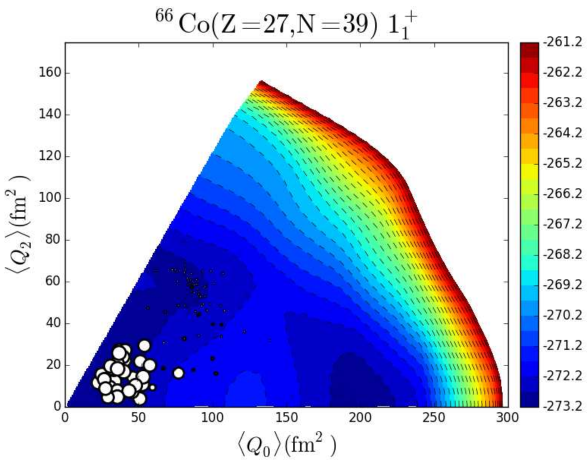


Interpretation



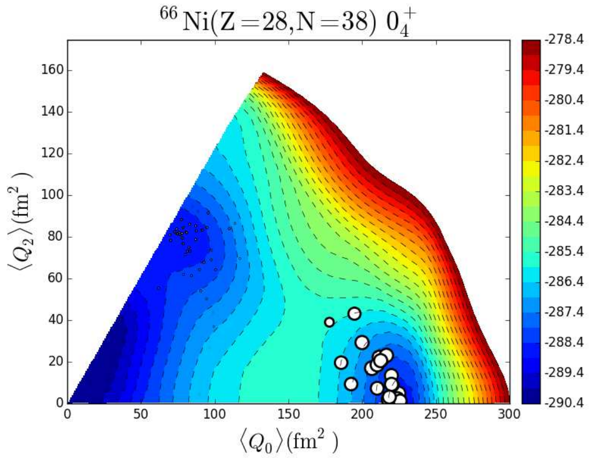


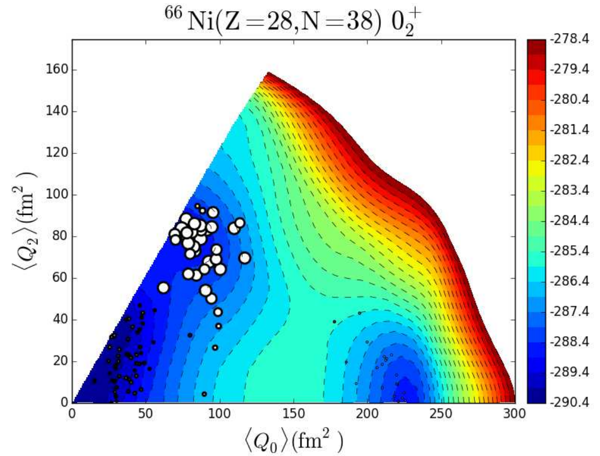
Interpretation

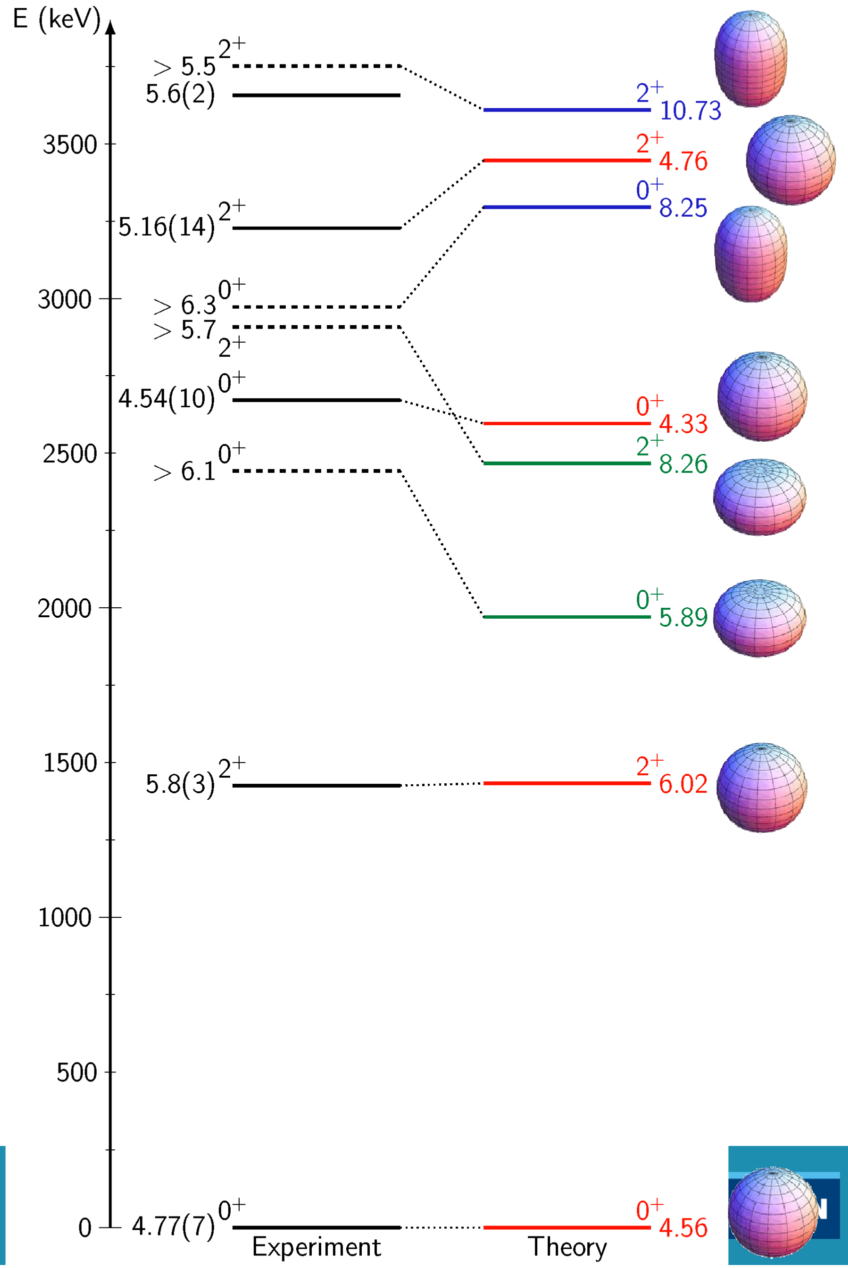


8.25

5.89







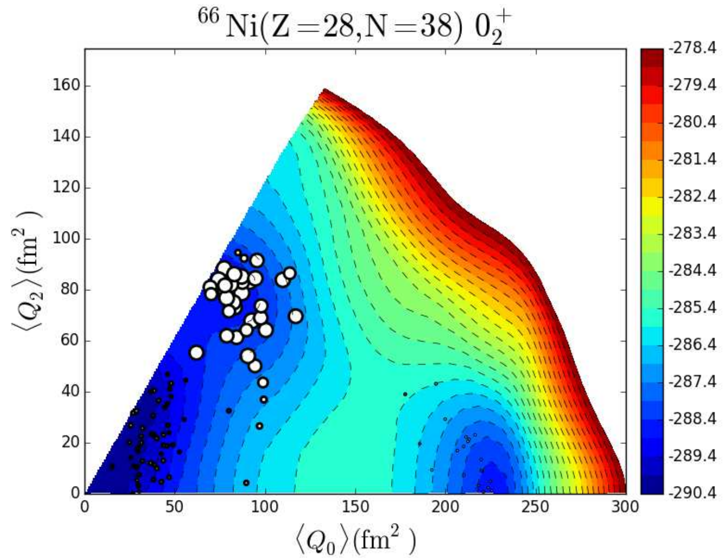
Interpretation

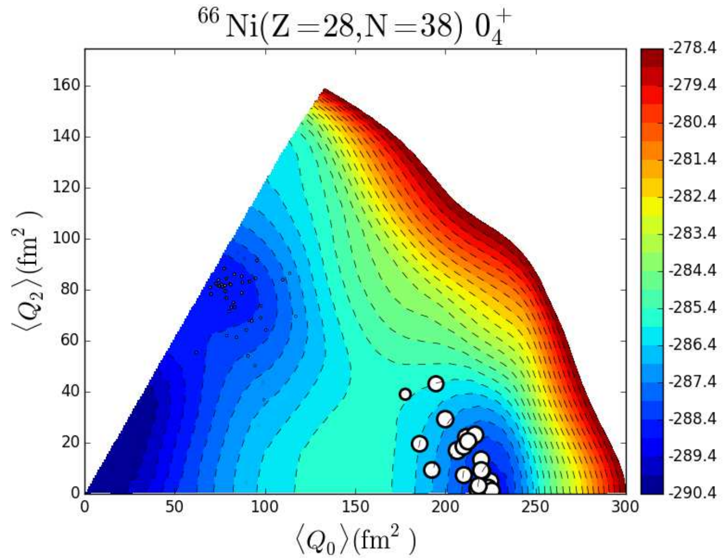
Z=28

J^π	Proton occupation					
	$0f_{7/2}$	$1p_{3/2}$	$0f_{5/2}$	$1p_{1/2}$	$0g_{9/2}$	$1d_{5/2}$
$0_1{}^+$(g.s.)	7.59	0.22	0.06	0.01	0.10	0.01
$0_2{}^+$	6.61	0.92	0.30	0.08	0.07	0.01
$0_3{}^+$	7.71	0.12	0.05	0.01	0.10	0.02
$0_4{}^+$	5.34	0.75	1.37	0.48	0.06	0.01

J^π	Neutron occupation					
	$0f_{7/2}$	$1p_{3/2}$	$0f_{5/2}$	$1p_{1/2}$	$0g_{9/2}$	$1d_{5/2}$
$0_1{}^+$(g.s.)	7.86	3.49	4.74	1.08	0.77	0.06
$0_2{}^+$	7.83	3.30	3.44	1.30	2.07	0.06
$0_3{}^+$	7.89	3.75	4.83	0.99	0.50	0.05
$0_4{}^+$	7.77	2.30	3.35	0.52	3.51	0.55

N=40 N=50

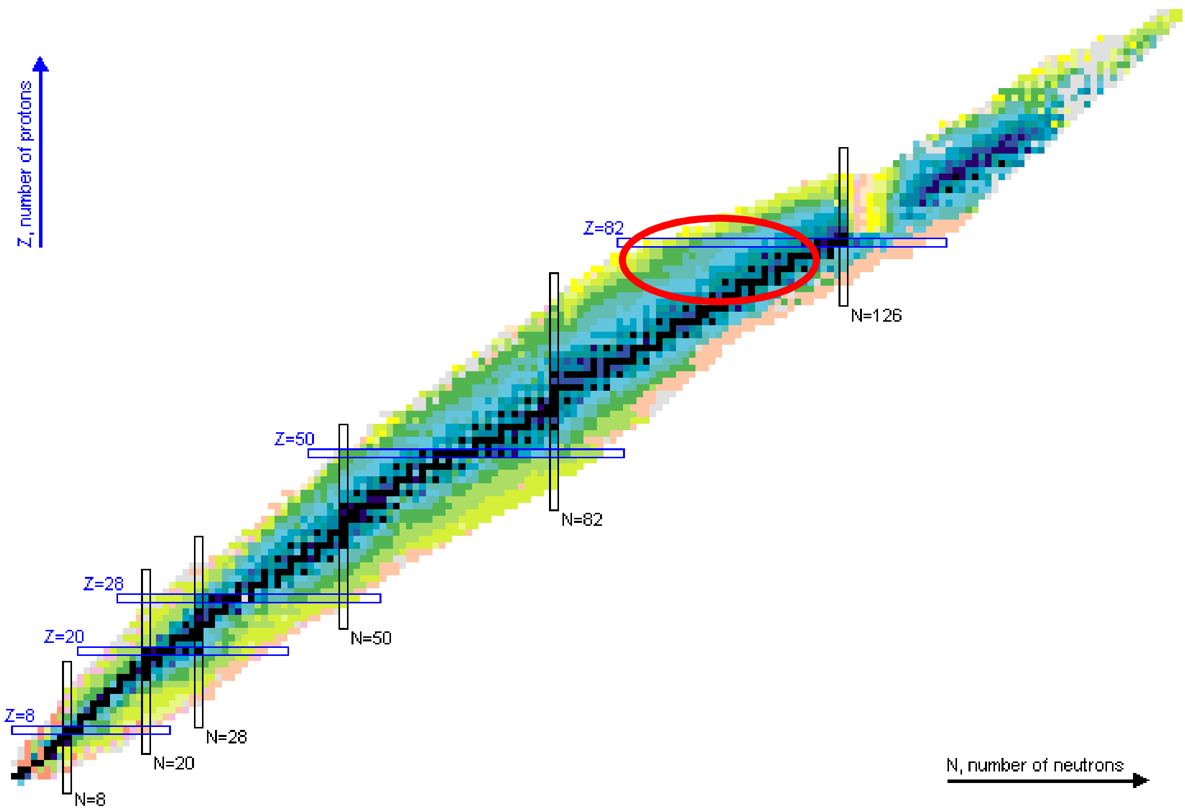




Intermediate summary / take home message

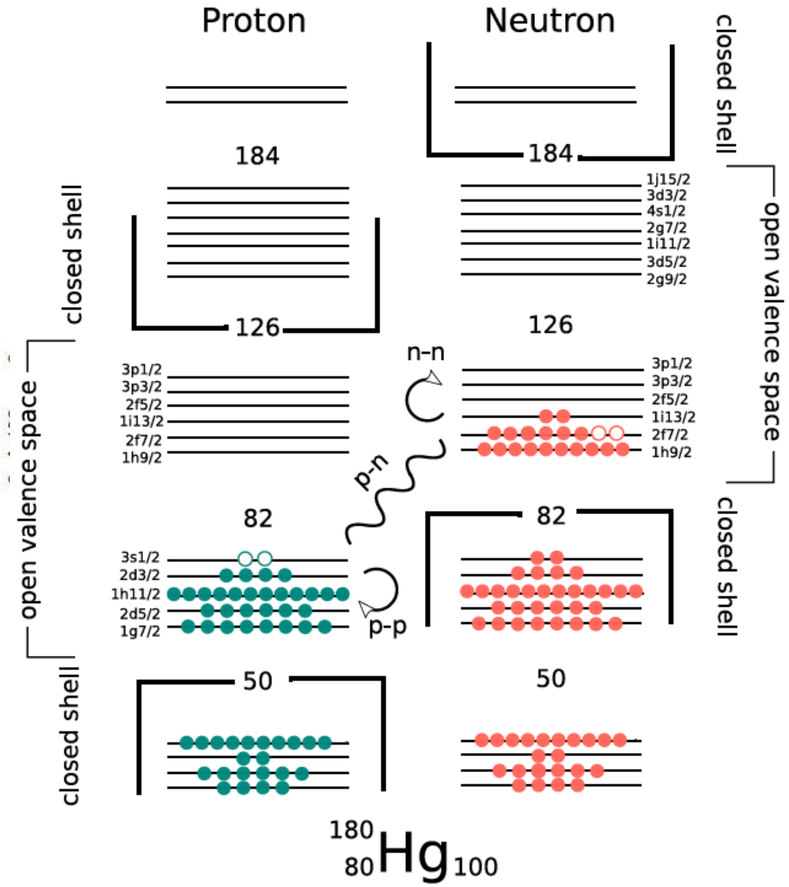
- Bayesian analysis allowed to determine the ground state feeding of ^{66}Ni
- Selective β-feeding of 0^+ and 2^+ states was observed
- Monte Carlo shell model reproduced experimental observables by implying the shape coexistence
- More data to come: Coulomb excitation of ^{66}Ni@HIE-ISOLDE (IS587)
- Shape coexistence also observed in ^{66}Co: check M. Stryjczyk et al., PRC98, 064326 (2018)

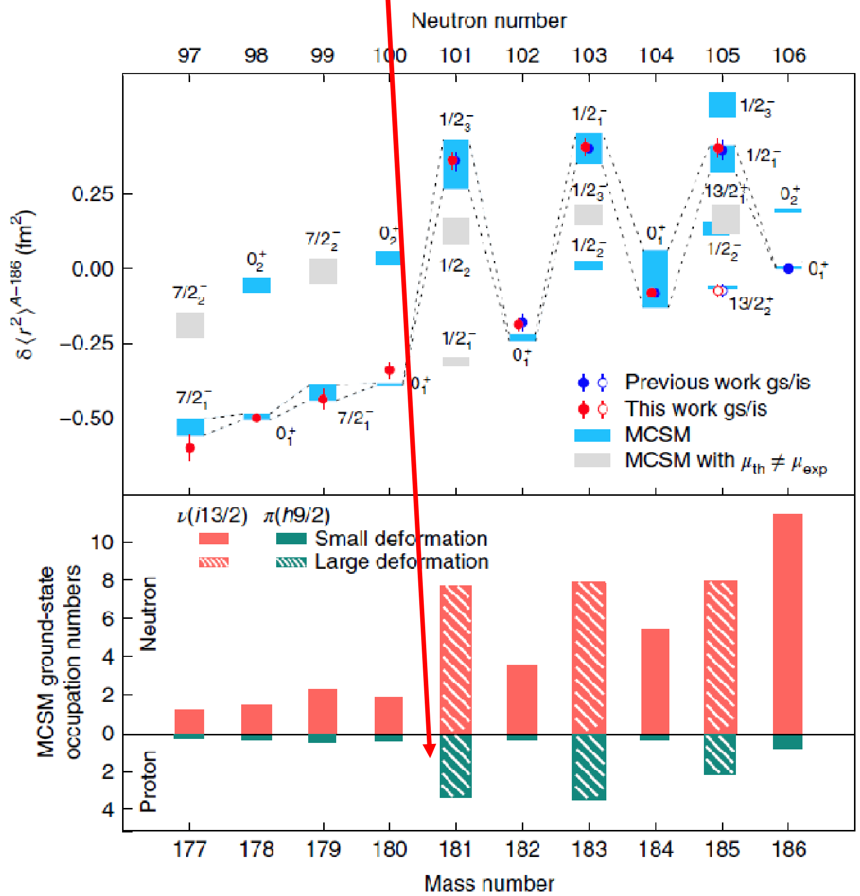
Motivation – why mercury?



Motivation – why mercury?

Excitation across Z=82!





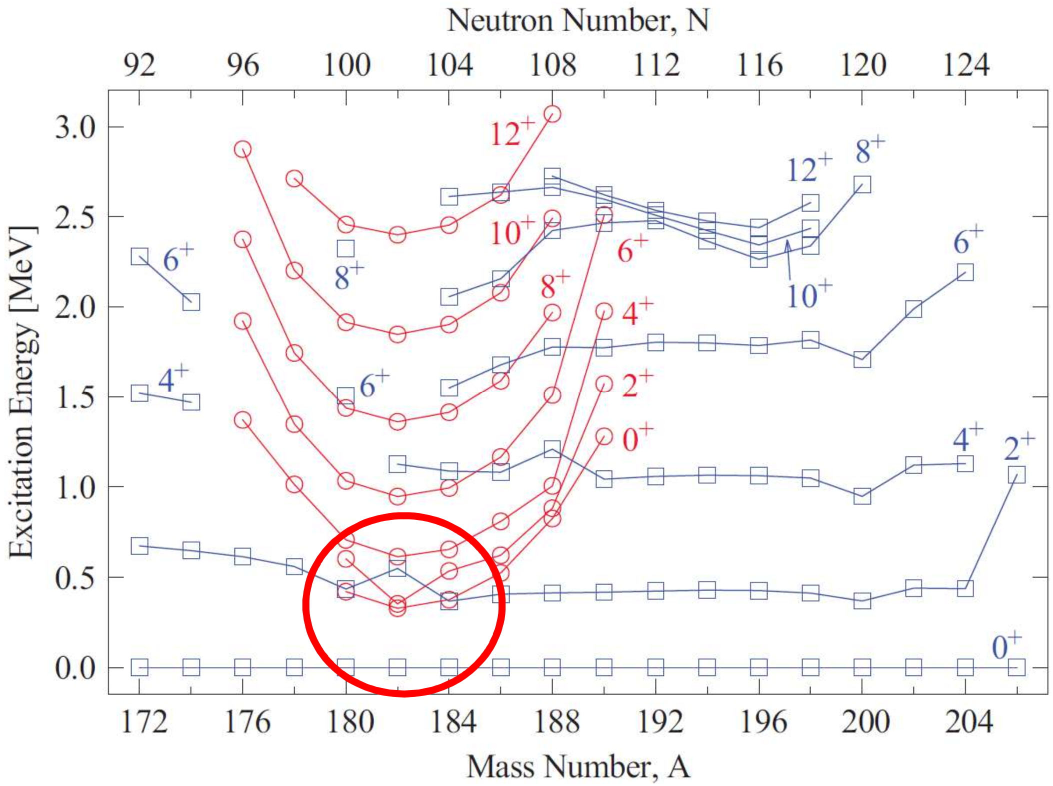
B. A. Marsh, T. Day Goodacre, S. Sels *et al.*, Nature Physics **14**, 1163 (2018)

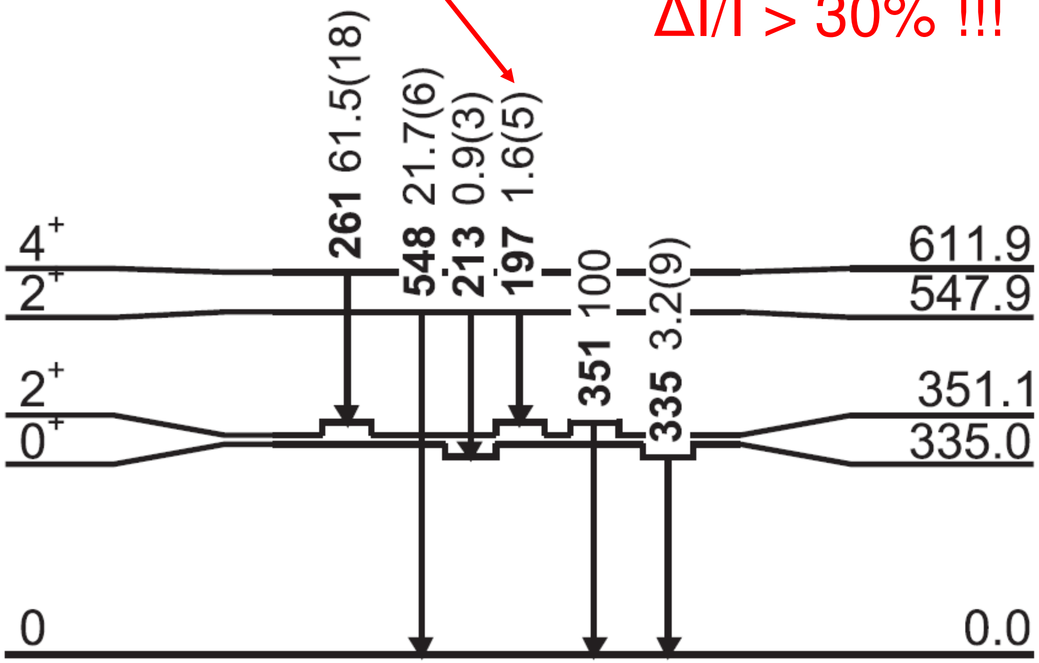
Motivation – why mercury?

α(exp) = 7.2(13)

α(M1) = 1.153
α(E2) = 0.412

Δα/α = 18% !
ΔI/I > 30% !!!

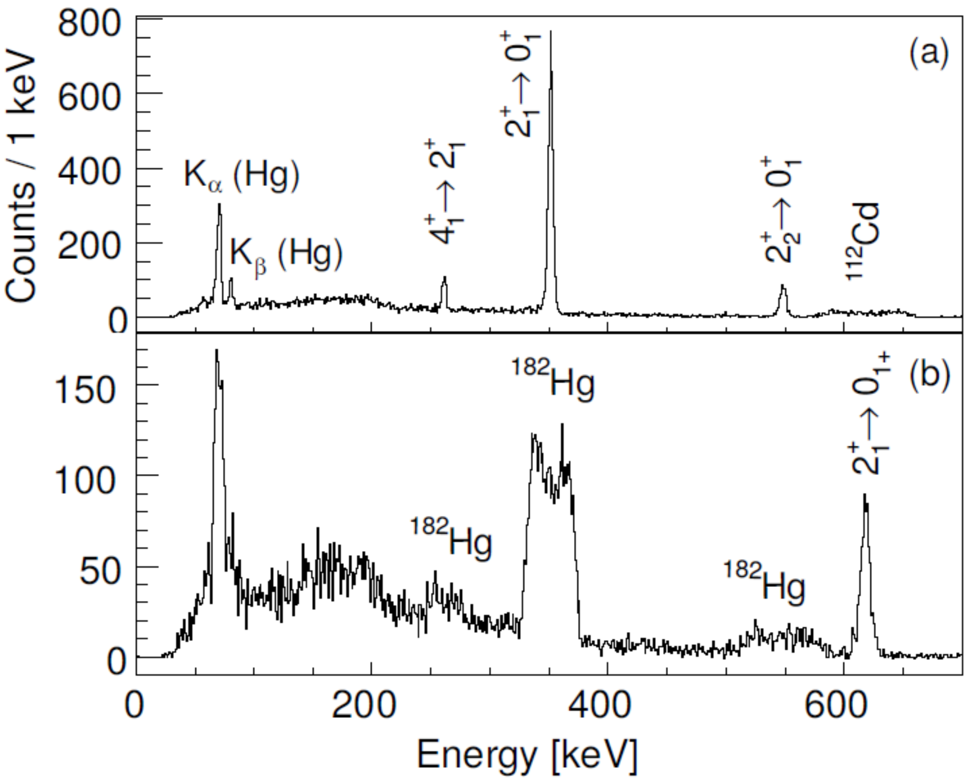




^{182}Hg

L.P. Gaffney *et al.*, PRC**89**, 024307 (2014)
E. Rapisarda *et al.*, JPG**44**, 074001 (2017)

Motivation - Coulex



$\langle I_i \| E2 \| I_f \rangle$ (eb)	^{182}Hg	^{184}Hg	^{186}Hg	^{188}Hg
$\langle 0_1^+ \| E2 \| 2_1^+ \rangle$	1.29 (4)	1.27 (3)	1.25 $^{+0.10}_{-0.07}$	1.31 (10)
$\langle 2_1^+ \| E2 \| 4_1^+ \rangle$	3.70 (6)	3.31 (6)	3.4 (2)	2.07 (8)
$\langle 0_1^+ \| E2 \| 2_2^+ \rangle$	-0.6 (1)	0.348 (14)	(±) 0.05 (1)	
$\langle 0_2^+ \| E2 \| 2_1^+ \rangle$	[-2.2,0.9]	-1.2 $^{+0.3}_{-0.2}$		
$\langle 0_2^+ \| E2 \| 2_2^+ \rangle$	-1.25 (30)	0.93 $^{+0.20}_{-0.25}$	≥2.9	
$\langle 2_1^+ \| E2 \| 2_2^+ \rangle$	-2.0 (3)	1.64 $^{+0.14}_{-0.16}$		
$\langle 2_2^+ \| E2 \| 4_1^+ \rangle$	3.3 (4)	[-3,0]*	-5.3 $^{+1.3}_{-0.5}$	
$\langle 2_1^+ \| E2 \| 2_1^+ \rangle$				1.0 $^{+0.6}_{-0.4}$
$\langle 2_2^+ \| E2 \| 2_2^+ \rangle$				

* the value of the $\langle 2_2^+ \| E2 \| 4_1^+ \rangle$ in ^{184}Hg is $-3 \leq \langle 2_2^+ \| E2 \| 4_1^+ \rangle < 0$.

K. Wrzosek-Lipska, K. Rezynkina *et al.*, EPJ A**55**, 130 (2019)

Motivation - Coulex

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

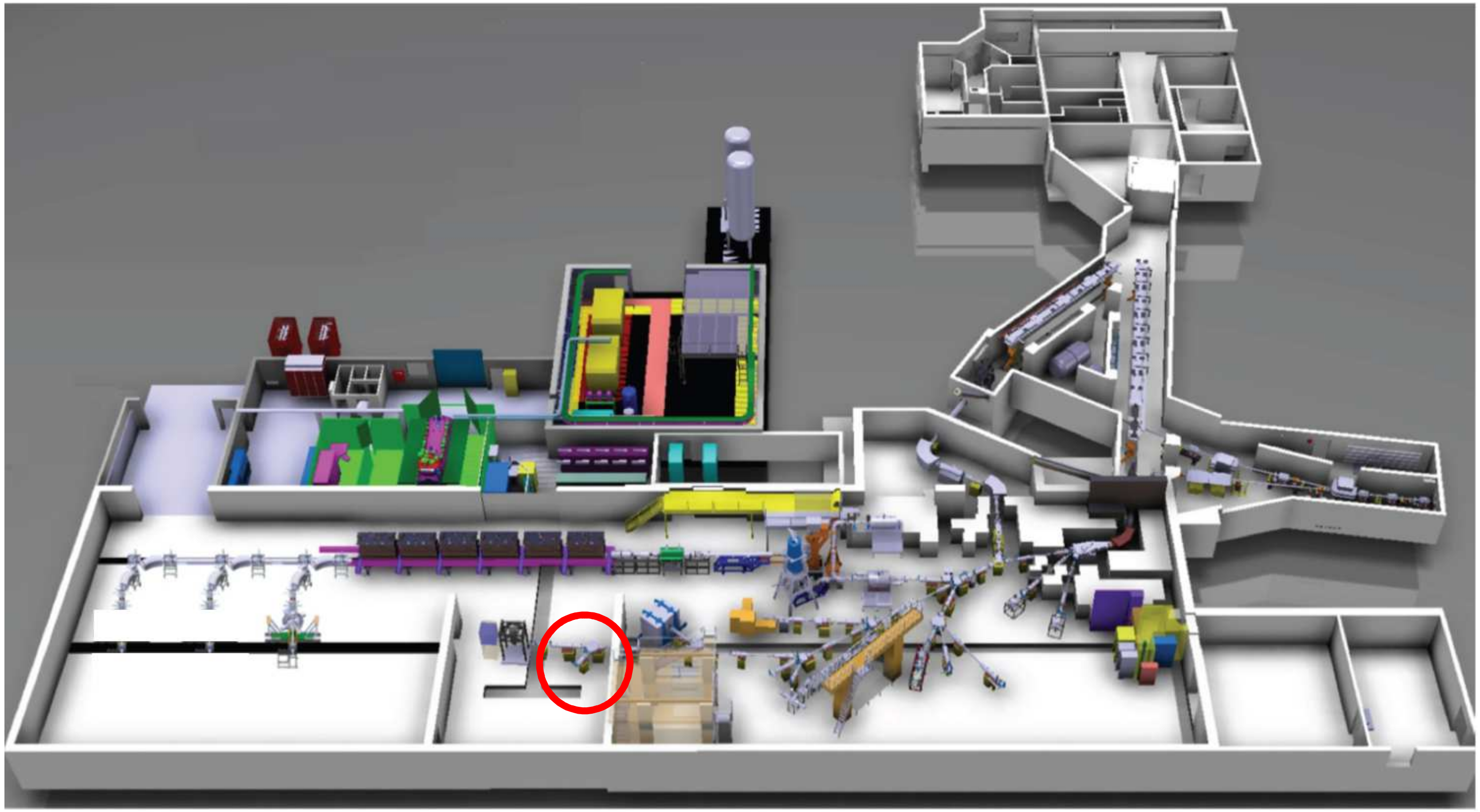
Following HIE-ISOLDE Letter of Intent I-110

Coulomb excitation of $^{182\text{-}184}$Hg:
Shape coexistence in the neutron-deficient lead region

October 05, 2012

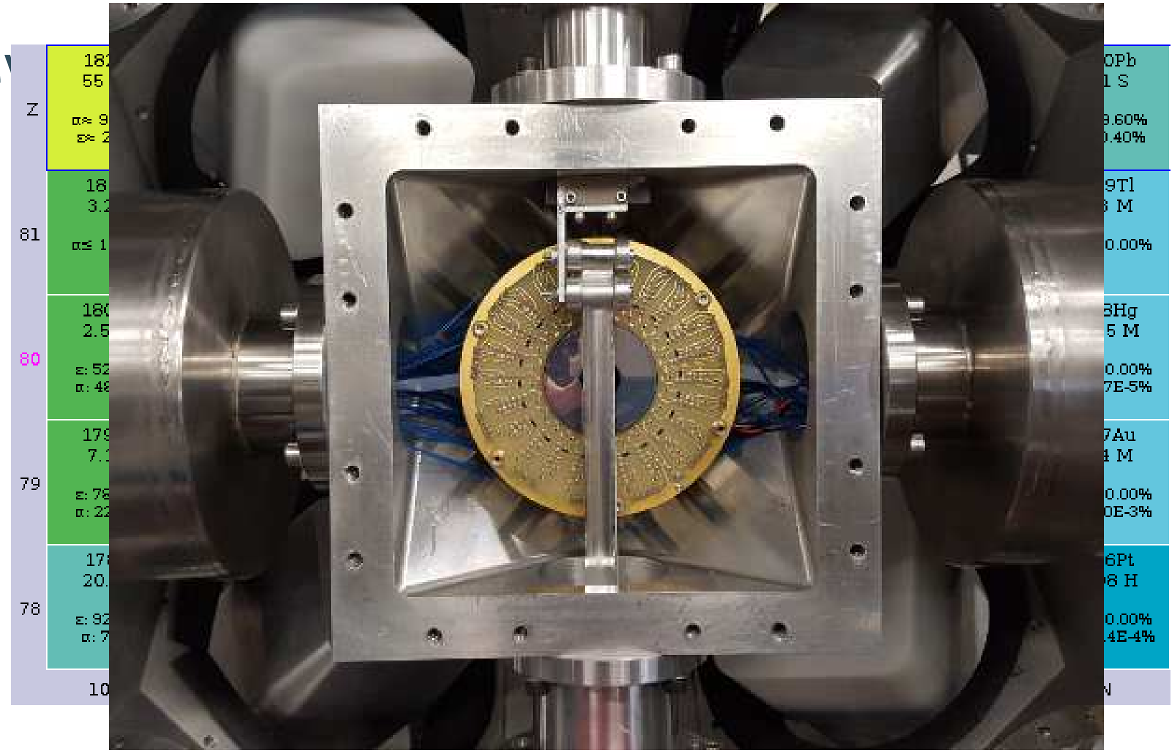
K. Wrzosek-Lipska[1], P. Van Duppen[1], M. Huyse[1], N. Kesteloot[1], H. De Witte[1], J. Pakarinen[2,3], P.T. Greenlees[2,3], T. Grahn[2,3], P. Rahkila[2,3], D.T. Joss[4], P. A . Butler[4], L. Gaffney[4], R. D. Page[4], G. O'Neil[4], P. Papadakis[4], D.G. Jenkins[5], A. N. Andreyev[5], E. Rapisarda[6], D. Voulot[6], F. Wenander[6], T. E. Cocolios[7], S. Freeman[7], V. Bildstein[8], R. Gernhäuser[8], R. Krücken[8], K. Nowak[8], D. Mücher[8] , Th. Kröll[9], M. Scheck[9], N. Pietralla[9], W. Korten[10], M. Zielinska[10], M.-D. Salsac[10], T. Duguet[10], F. Dechery[10], P. Napiorkowski[11], J. Srebrny[11], K. Hadynska-Klek[11], L.Prochniak[11], A. Blazhev[12], J. Jolie[12], N. Warr[12], P. Reiter[12], H. Duckwitz[12], N. Patronis[13], J. L. Wood[14], K. Heyde[15], P-H. Heenen[16], M. Bender[17], J.-E. Garcia Ramos[18], A. Goergen[19], M. Guttormsen[19], A.C. Larsen[19], S. Siem[19]

ISOLDE Decay Station (IDS)



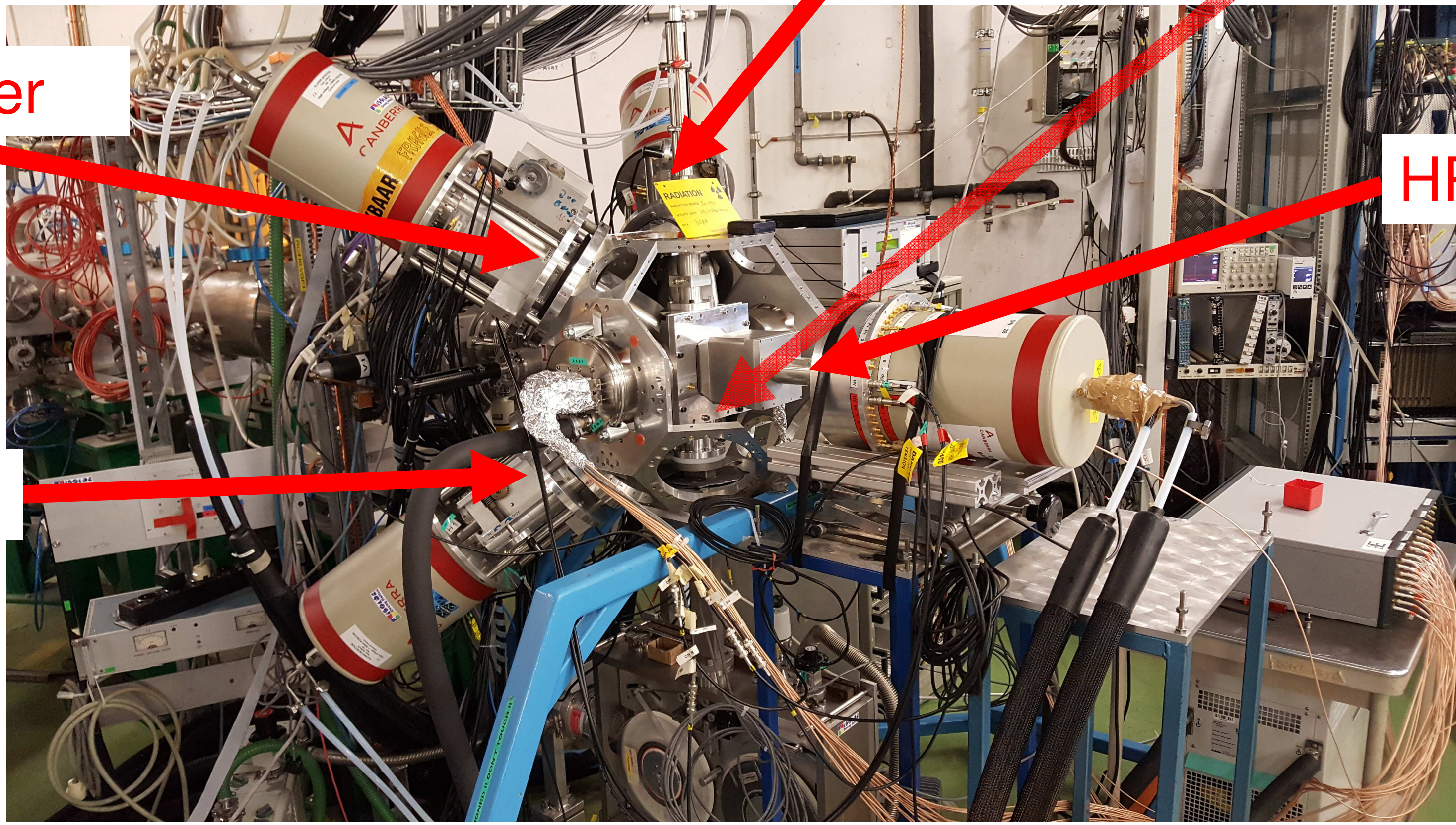
Experimental details

- Pure thallium beam produced in spallation of UC_x target with 1.4 GeV protons
- No surface-ionized isobaric contaminants!
- RILIS in a broadband mode: no isomer selectivity
- Tape moved every 30-40s (supercycle)

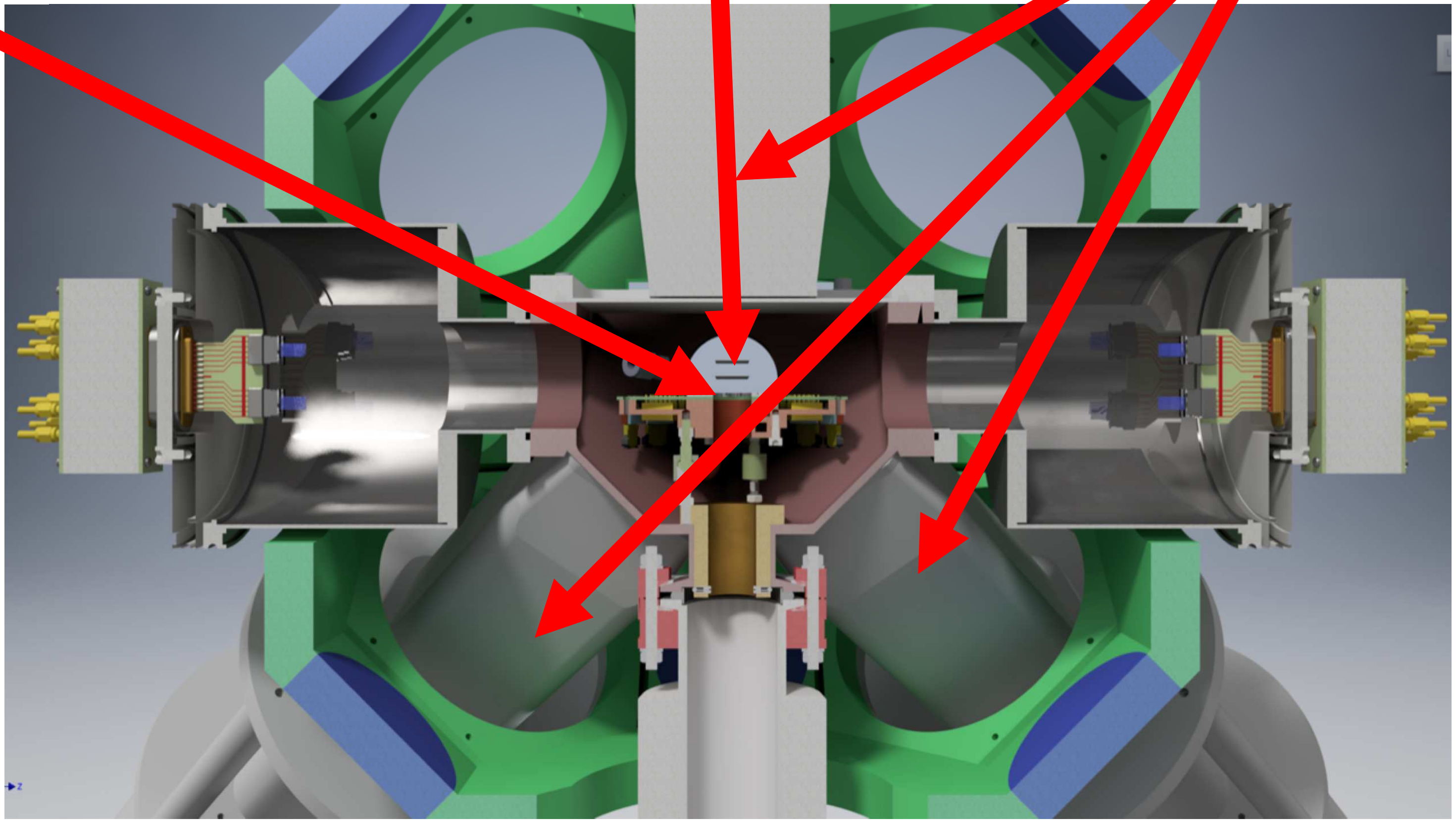


R. Lica, PhD Thesis (2017)
E. Rapisarda *et al.*, JPG**44**, 074001 (2017)
NNDC, Chart of Nuclides

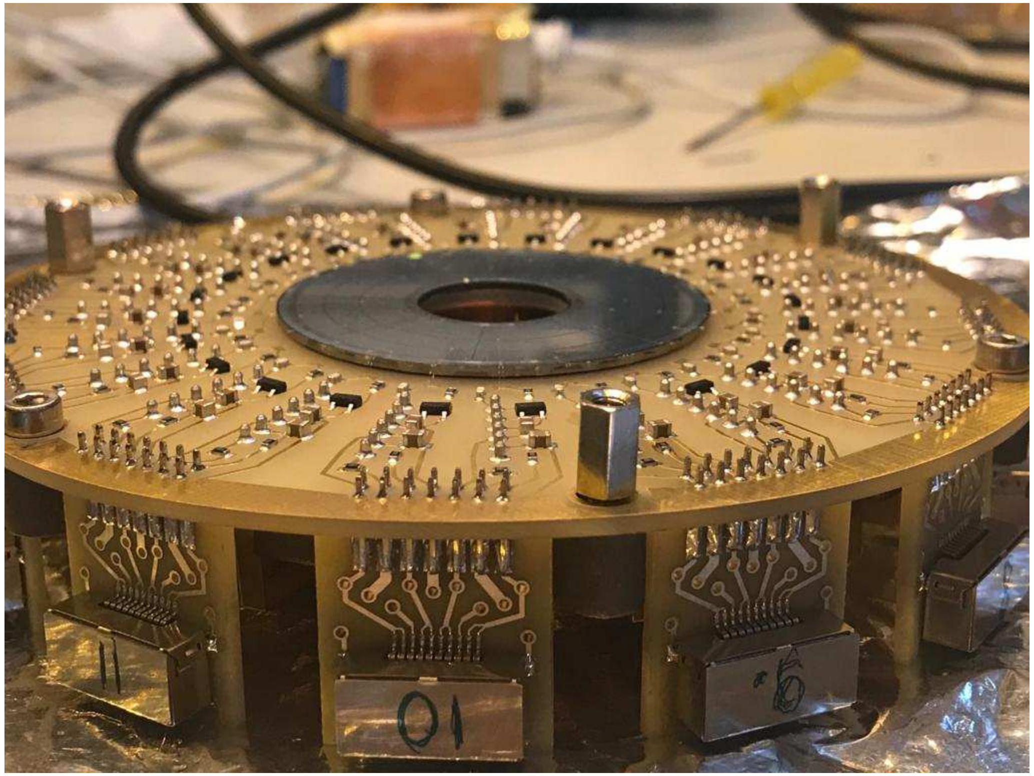
Experimental setup

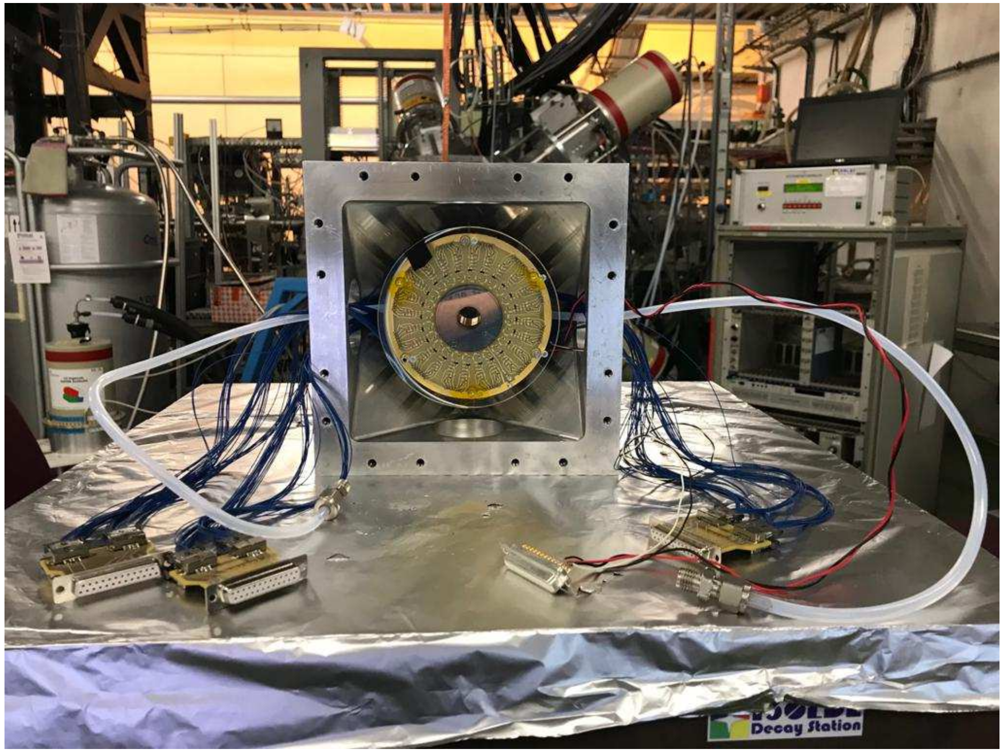


Experimental setup



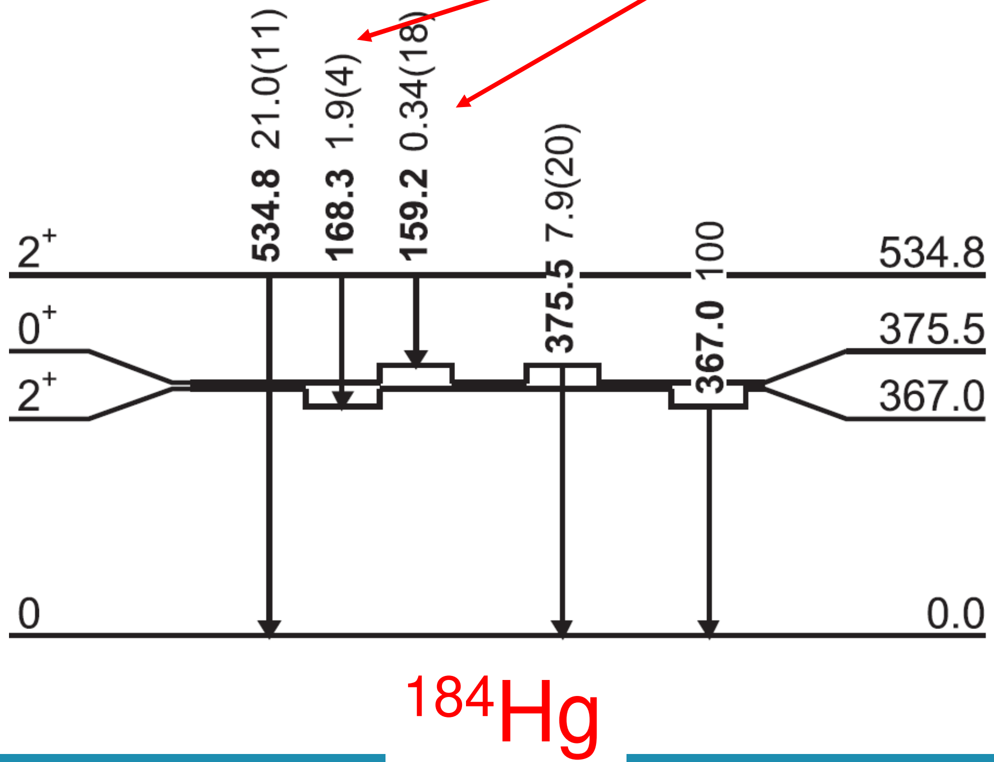
SPEDE@IDS

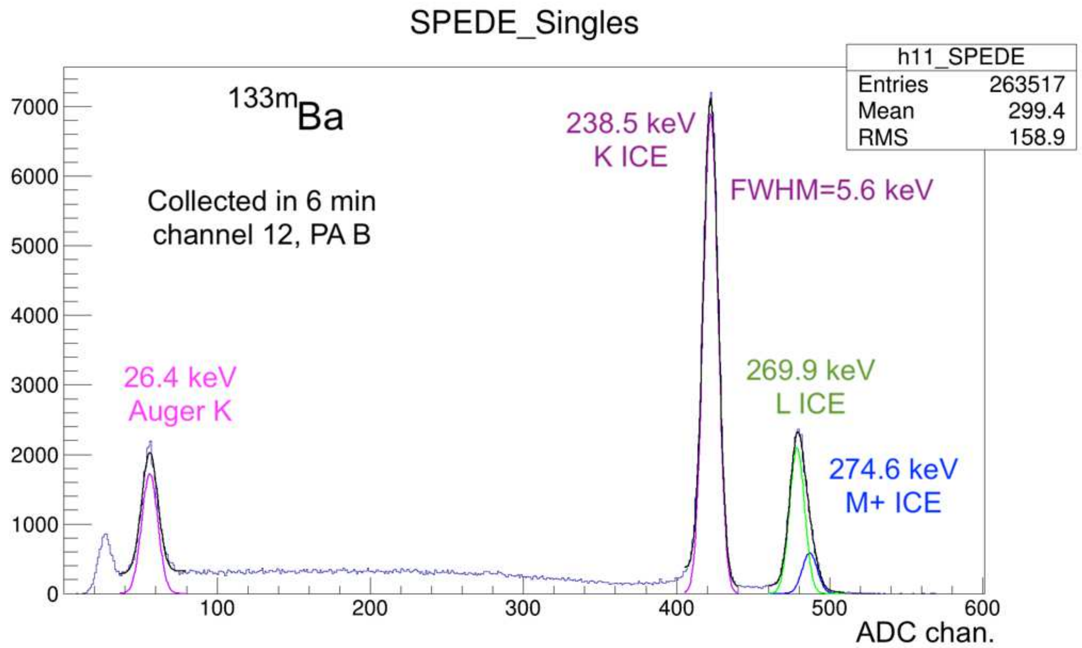




SPEDE@IDS

~9 keV difference

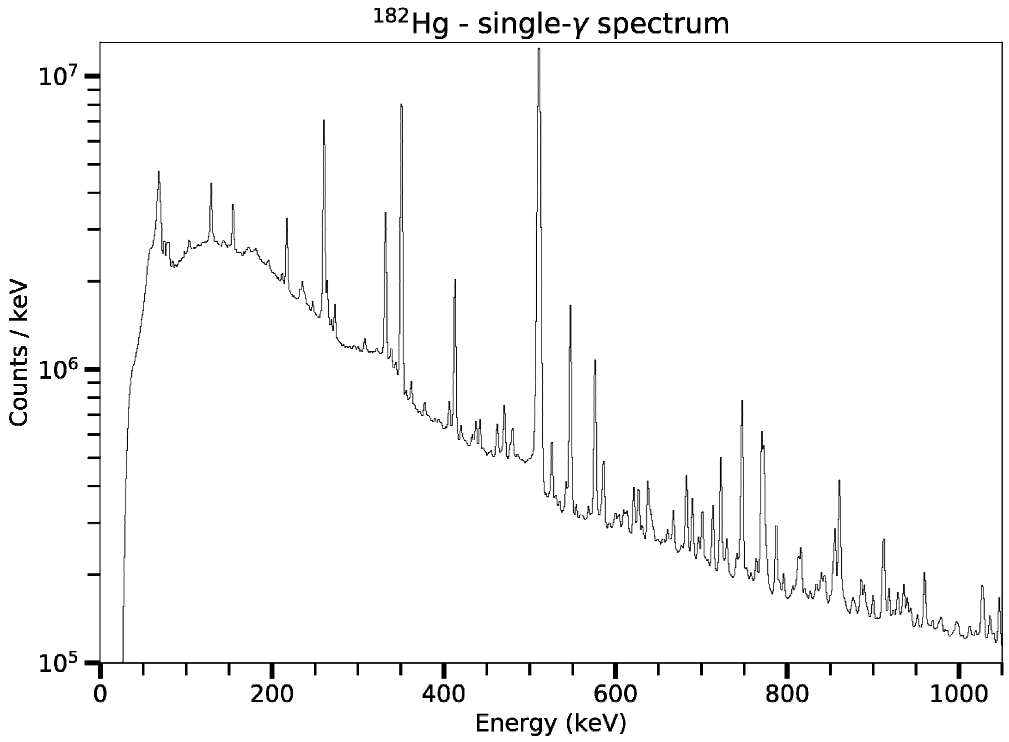


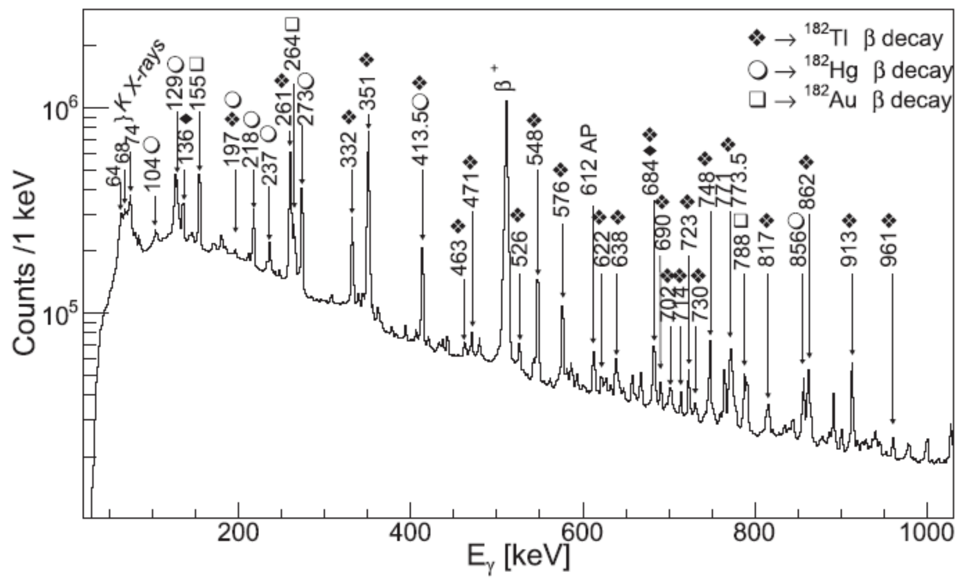


E. Rapisarda *et al.*, JPG**44**, 074001 (2017)

Results: Hg-182

Order of magnitude more statistics!

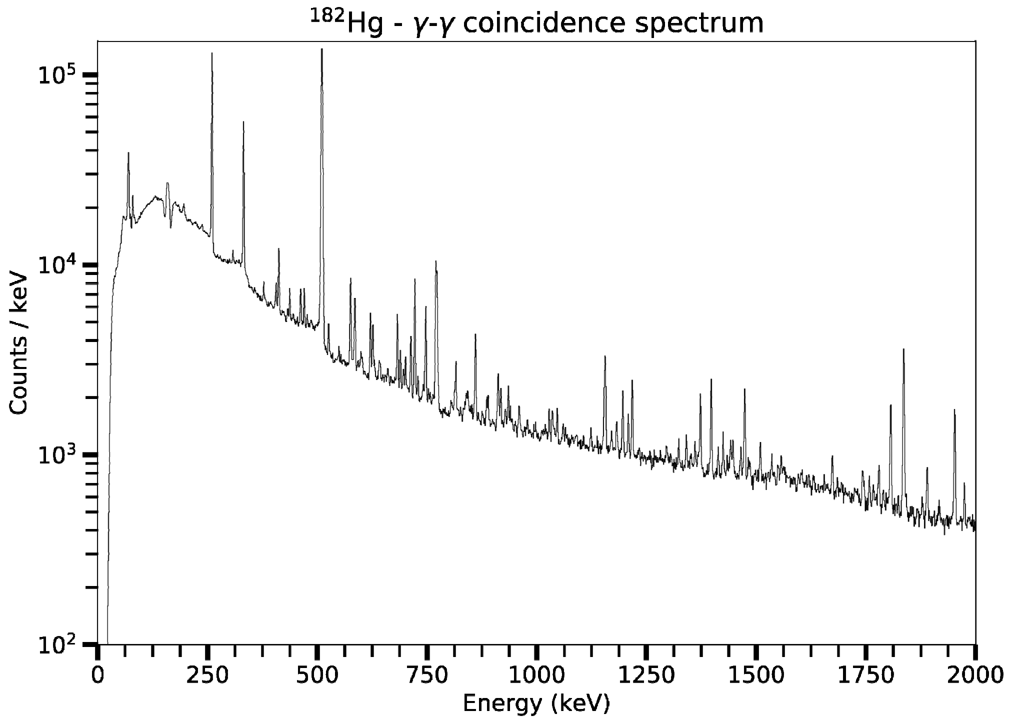


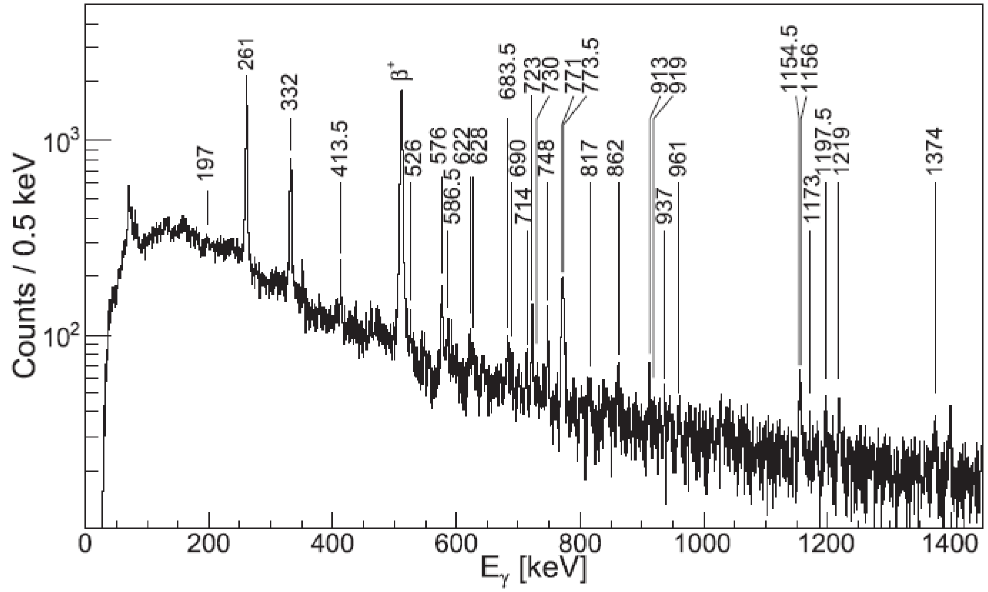


E. Rapisarda *et al.*, JPG**44**, 074001 (2017)

Results: Hg-182

Gate on 351 keV ($2^+ \rightarrow 0^+$)

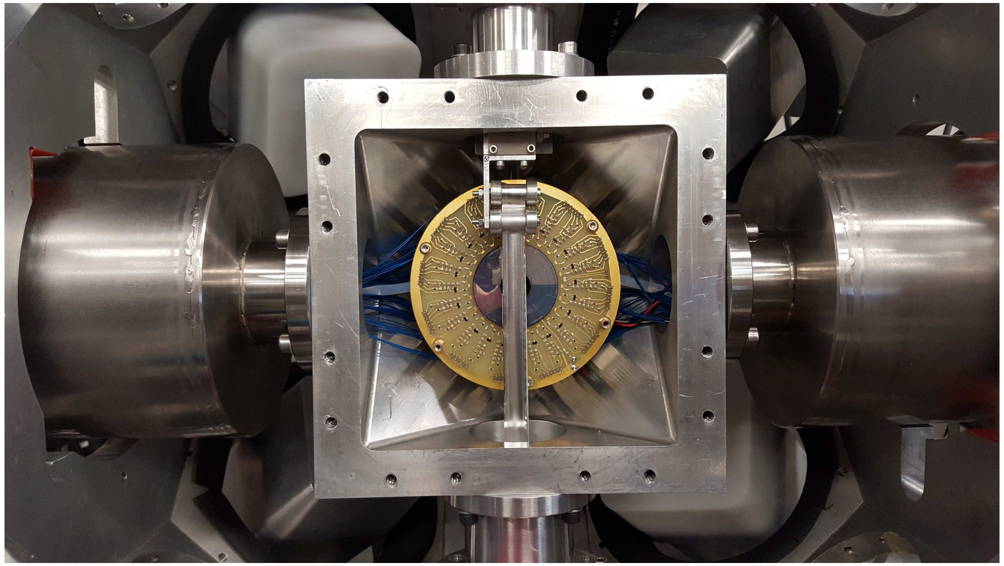




E. Rapisarda *et al.*, JPG**44**, 074001 (2017)

Summary & outlook

- Preliminary results in agreement with the known experimental data
- More exciting results to come: stay tuned!
- Problems with the theory
- Coulex of ^{182,184}Hg@HIE-ISOLDE with SPEDE after LS2!



- β-decay is a powerful experimental technique

IS467 collaboration

M. Stryjczyk,[1,*] Y. Tsunoda,[2] I. G. Darby,[1] H. De Witte,[1] J. Diriken,[1,3] D. V. Fedorov,[4] V. N. Fedosseev,[5] L. M. Fraile,[6] M. Huyse,[1] U. Köster,[7] B. A. Marsh,[5] T. Otsuka,[2,8,9,10,1] D. Pauwels,[1] L. Popescu,[3] D. Radulov,[1,†] M. D. Seliverstov,[1,4,11] A. M. Sjödin,[5] P. Van den Bergh,[1] P. Van Duppen,[1] M. Venhart,[1,12] W. B. Walters,[13] and K. Wimmer[8,14]

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Thank you for your attention!