Nuclear Structure Studies with Radioactive Ion Beams

Riccardo Raabe

KU Leuven, Instituut voor Kern- en Stralingsfysica

General Scientific Meeting 2016
of the
Belgian Physical Society

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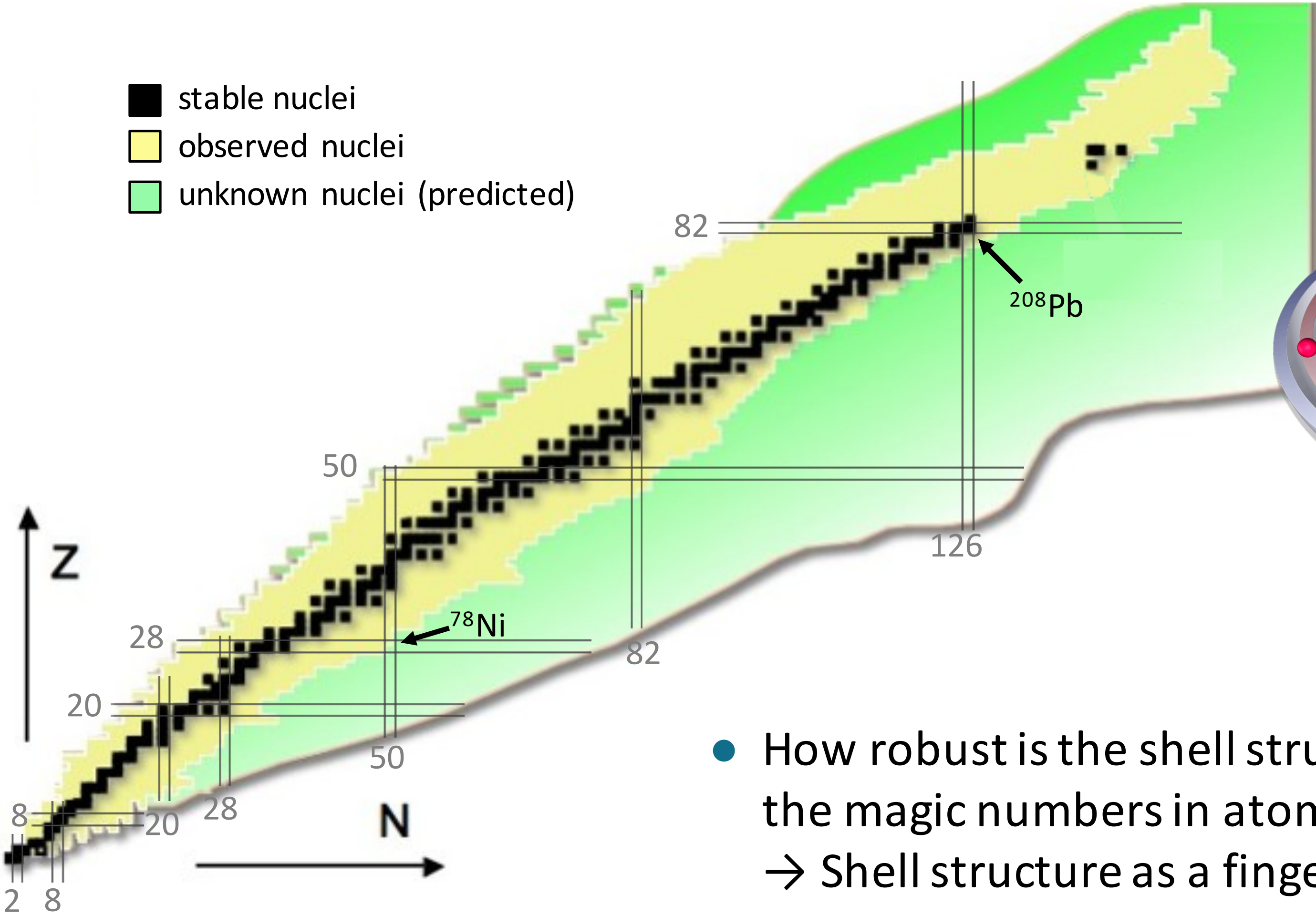
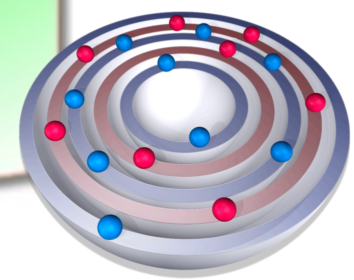
The nuclear landscape

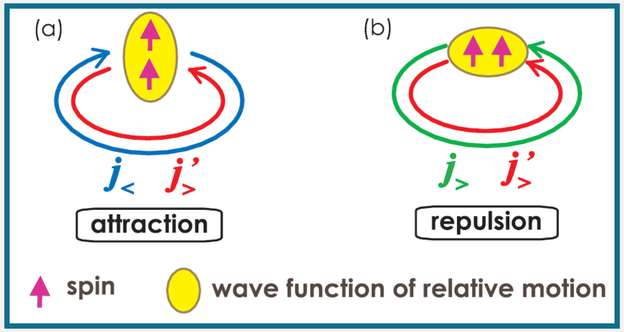




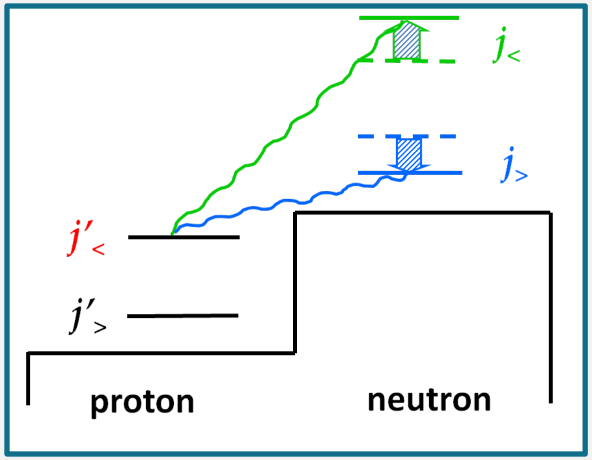
- How robust is the shell structure and thus the magic numbers in atomic nuclei?
  → Shell structure as a fingerprint of the strong interaction

Features in the N-N interaction

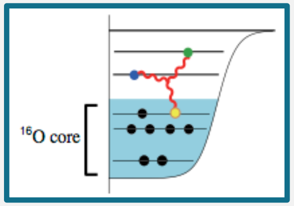
- Tensor interaction (only if S=1)

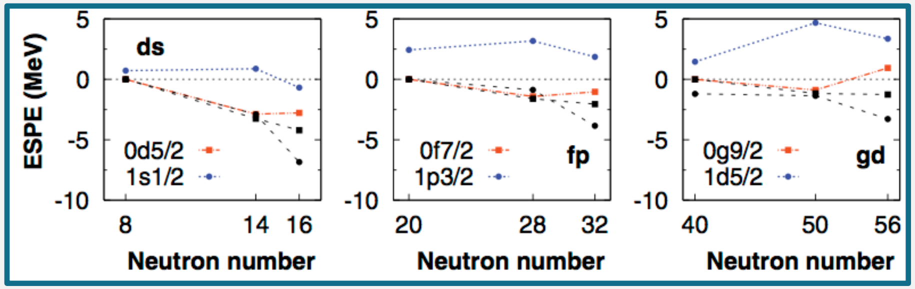


T. Otsuka et al., PRL 95 (2005) 232502



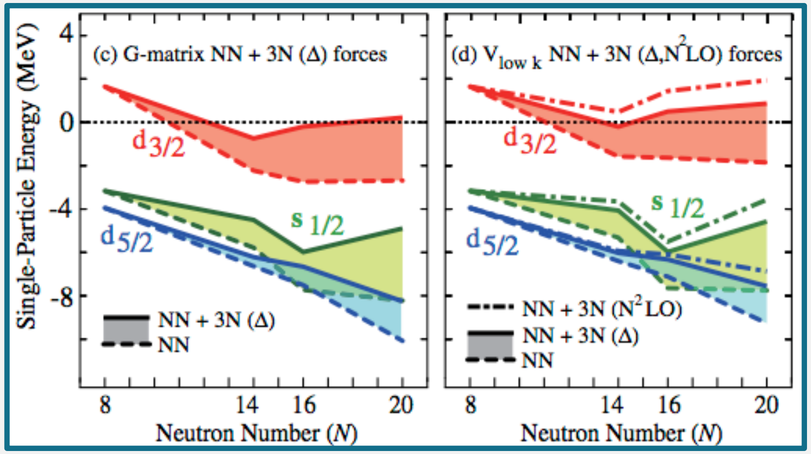
- 3-body forces





K. Sieja & F. Nowacki, PRC 85 (2012) 051301(R)

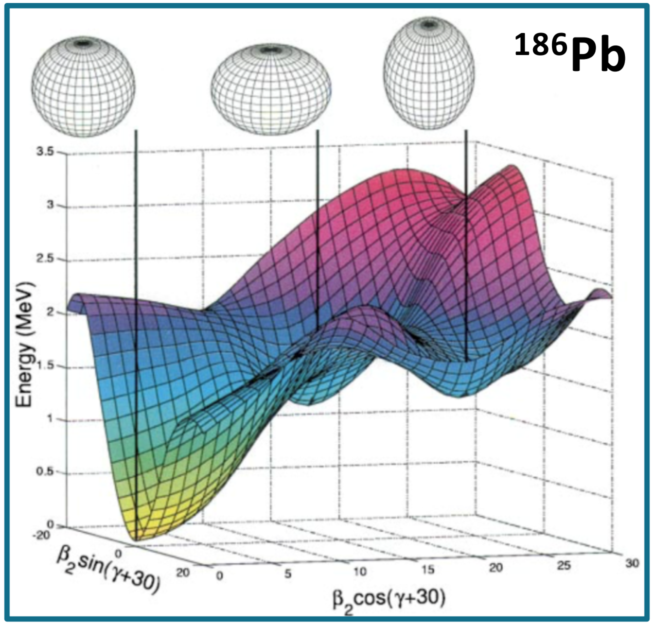
T. Otsuka et al., PRL 105 (2010) 032501

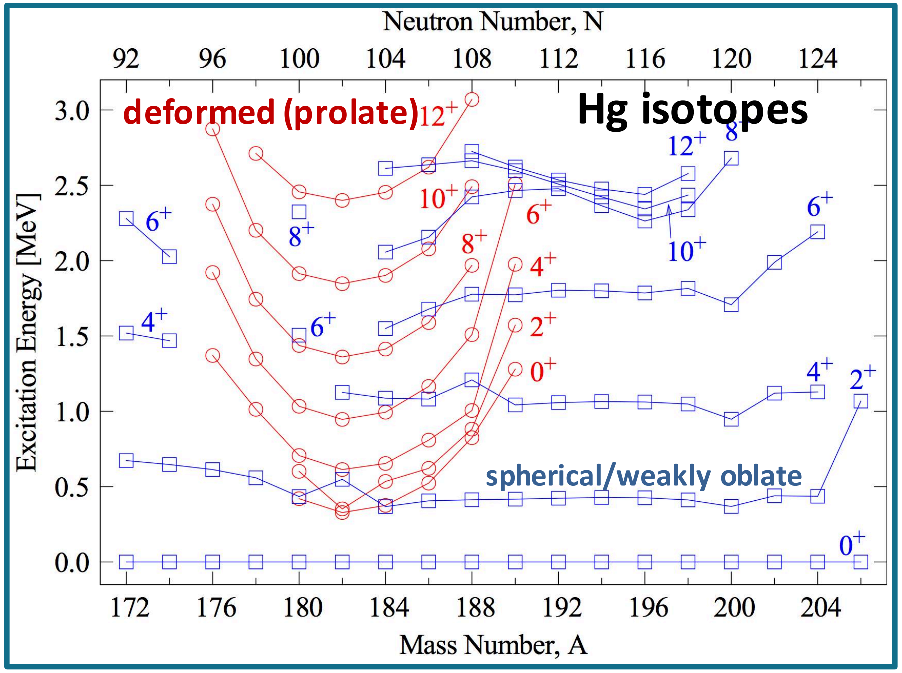


Shape coexistence

- States characterised by different shapes appear at low excitation energy
- Example: n-deficient Pb region
  ^{186}Pb triple-shape coexistence
  Hg nuclei: “parabolic intrusion” at mid-shell

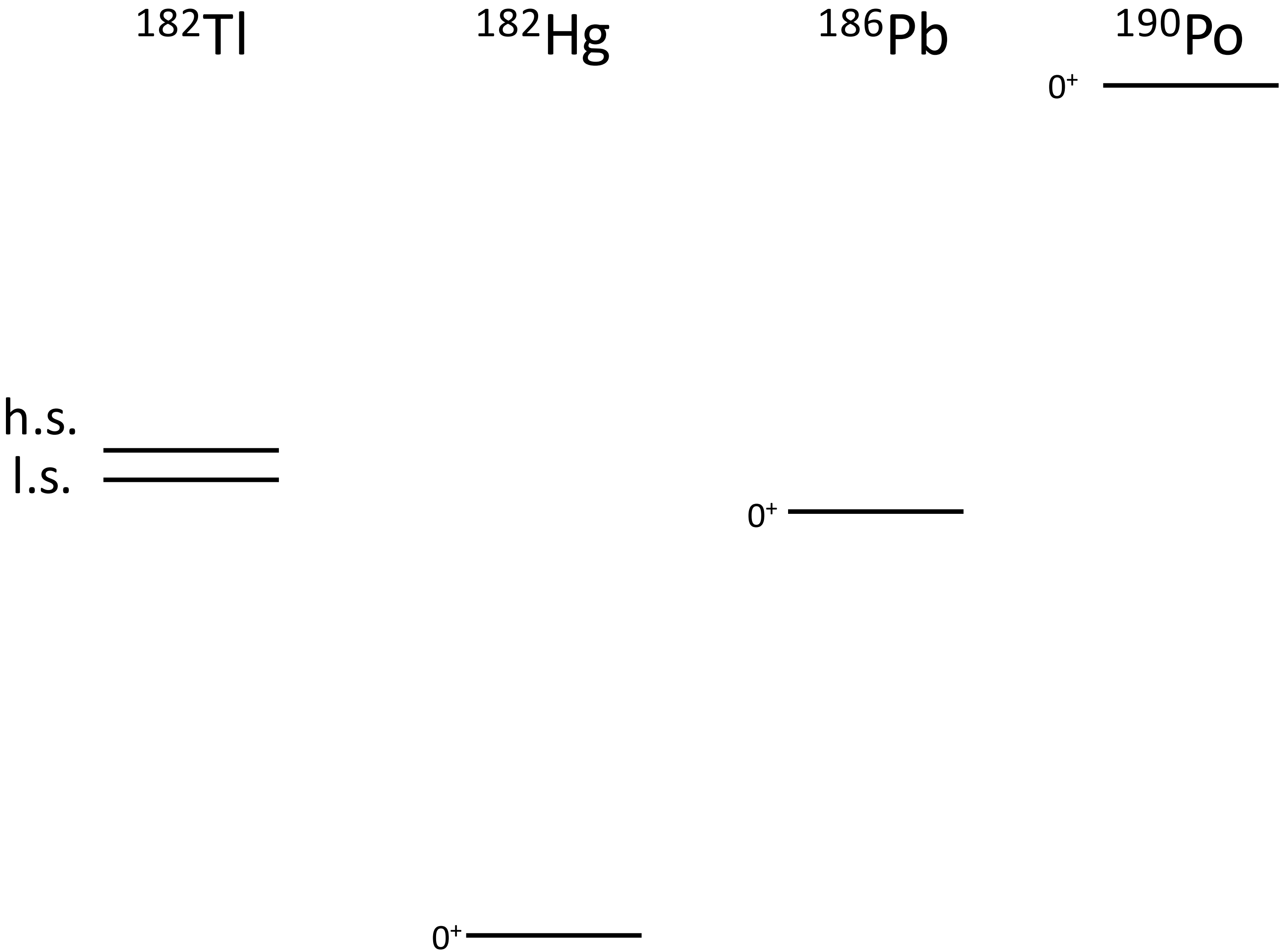
A. Andreyev et al., Nature 405 (2000) 430





Data: NNDC, figure courtesy of L. Gaffney
Original figure in R. Julin et al., J. Phys. G 27 (2001) R109

A coordinated experimental (and theoretical) effort



A coordinated experimental (and theoretical) effort

^{182}Tl ^{182}Hg ^{186}Pb ^{190}Po

0^+

h.s.
l.s.

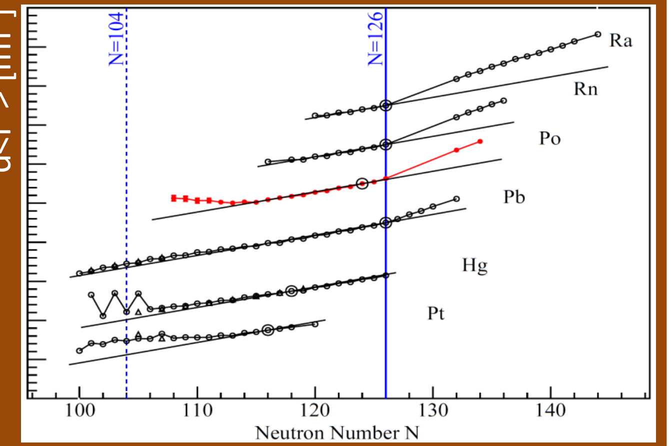
0^+

0^+

Ground state properties

Mass measurements (direct, α decay)

Laser spectroscopy



T. Cocolios et al. PRL106 (2011) 052503

H. De Witte et al., PRL98(2007) 112502

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0^+

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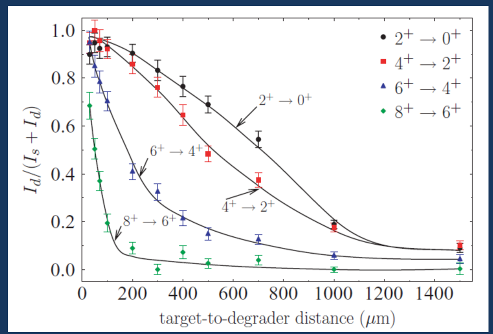
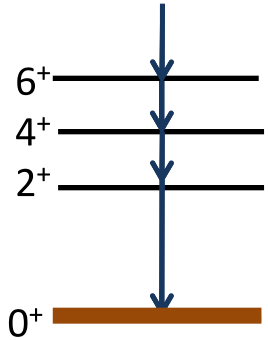
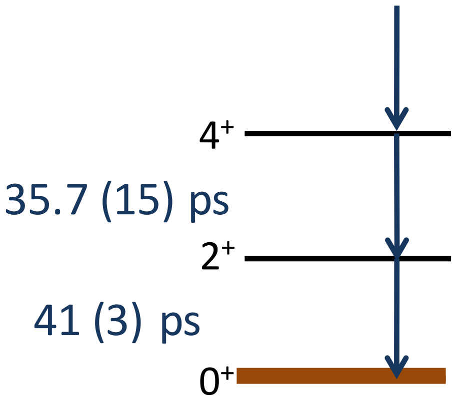
In-beam spectroscopy



J. Pakarinen et al., PRC75 (2007) 014302



T. Grahn et al. PRC80 (2009) 014324



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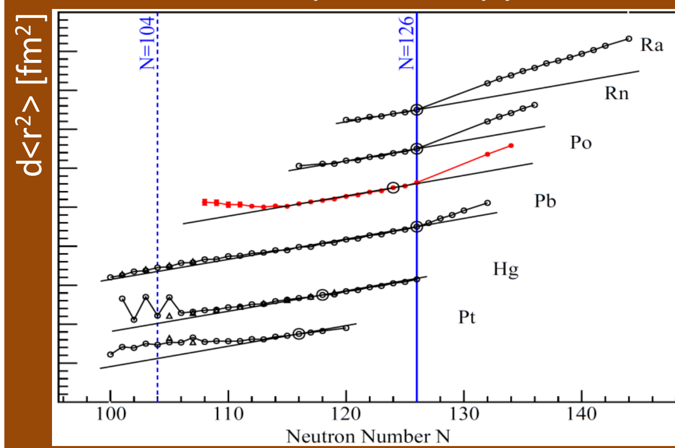

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A coordinated experimental (and theoretical) effort

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h.s.
l.s.

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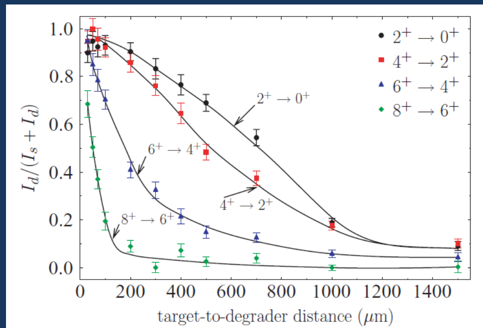

J. Pakarinen et al., PRC75 (2007) 014302

6^+
4^+
2^+
0^+
0^+
0^+

0^+

α decay

A. Andreyev et al. Nature 405 (2000) 430

T. Grahn et al. PRC80 (2009) 014324

4^+
35.7 (15) ps
2^+
0^+
41 (3) ps
0^+

Ground state properties

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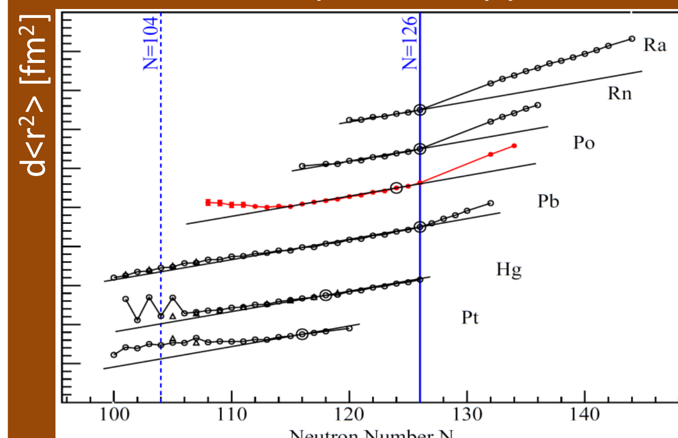
Laser spectroscopy



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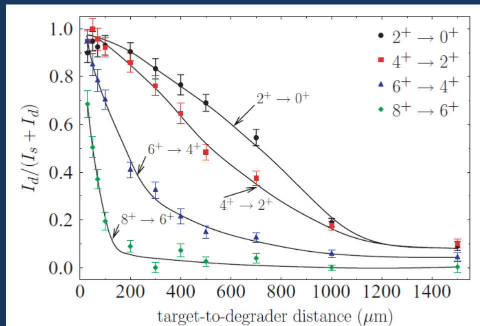


J. Pakarinen et al., PRC75 (2007) 014302

0^+

6^+ 4^+ 2^+ 0^+ 0^+ 0^+

α decay

A. Andreyev et al. Nature 405 (2000) 430

h.s.
l.s.

β decay

J. Elseviers et al. PRC (2011)

β-DF fission (^{180}Tl) Andreyev et al. PRL105 (2010) 252502

T. Grahn et al. PRC80 (2009) 014324

4^+

35.7 (15) ps

2^+ 0^+

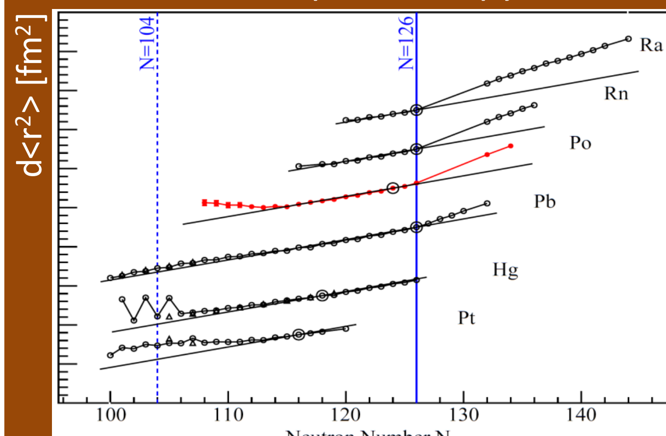
41 (3) ps

0^+

Ground state properties

Mass measurements (direct, α decay)

Laser spectroscopy



T. Cocolios et al. PRL106 (2011) 052503
H. De Witte et al., PRL98(2007) 112502

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^{182}Tl ^{182}Hg ^{186}Pb ^{190}Po

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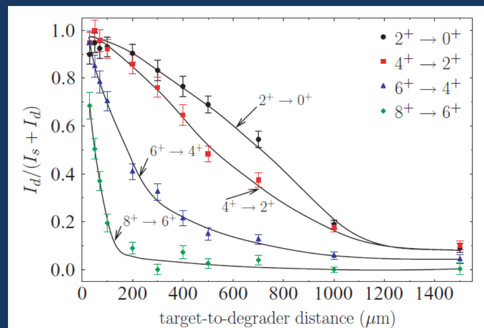


J. Pakarinen et al., PRC75 (2007) 014302

^{186}Pb: 6^+, 4^+, 2^+, 0^+, 0^+, 0^+

^{190}Po: 0^+

α decay

A. Andreyev et al.
Nature 405 (2000) 430

^{182}Tl: h.s., l.s.

β decay

J. Elseviers et al.
PRC (2011)

β-DF fission (^{180}Tl)
Andreyev et al.
PRL105 (2010) 252502

T. Grahn et al.
PRC80 (2009) 014324

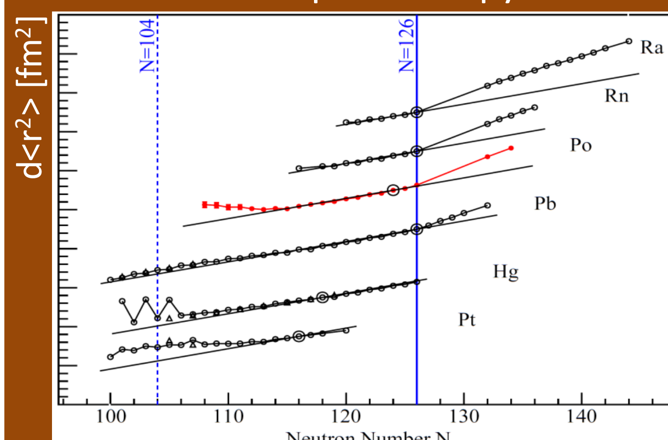
^{182}Hg: 4^+, 2^+, 0^+, 0^+

35.7 (15) ps

41 (3) ps

Ground state properties

Mass measurements (direct, α decay)
Laser spectroscopy



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H. De Witte et al., PRL98(2007) 112502

Coulex N. Bree & A. Petts

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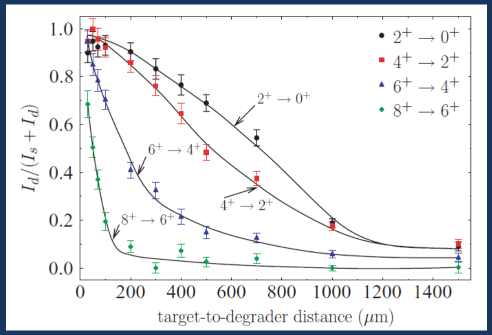

J. Pakarinen et al., PRC75 (2007) 014302

6$^+$ 4$^+$ 2$^+$ 0$^+$ 0$^+$ 0$^+$

0$^+$

α decay

A. Andreyev et al. Nature 405 (2000) 430

h.s.
l.s.

β decay

J. Elseviers et al. PRC (2011)

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T. Grahn et al. PRC80 (2009) 014324

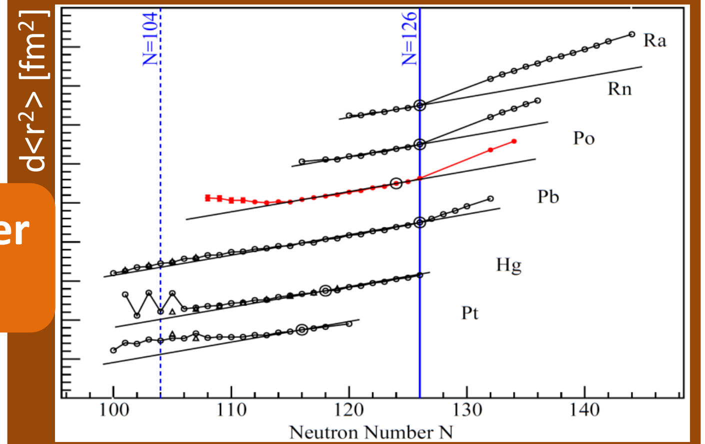
4$^+$
35.7 (15) ps
2$^+$
0$^+$
41 (3) ps
0$^+$

One, two-nucleon transfer and other reactions

Ground state properties

Mass measurements (direct, α decay)

Laser spectroscopy



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Coulex

N. Bree & A. Petts

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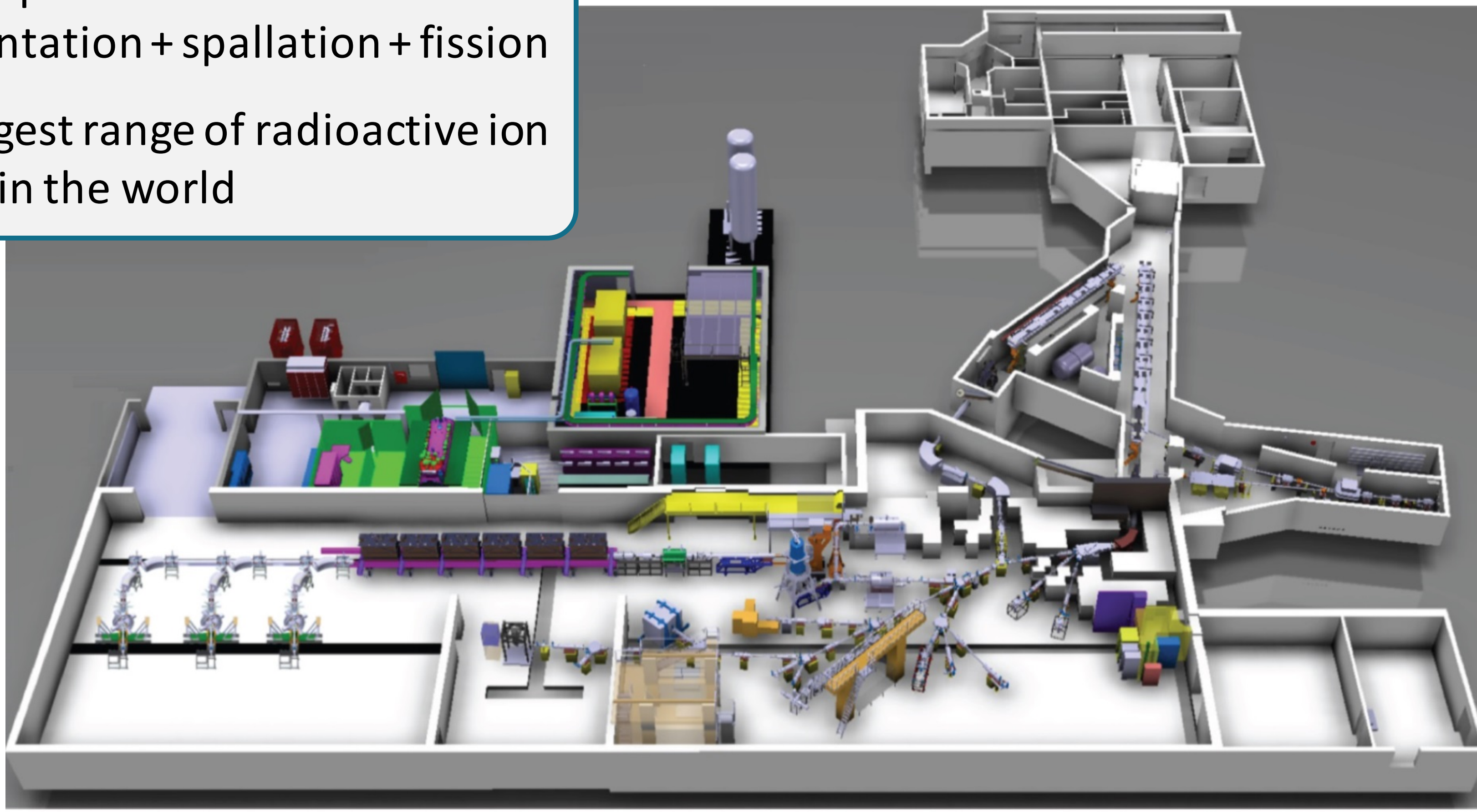
ISOLDE at CERN

- 1.4 GeV protons
  fragmentation + spallation + fission
- The largest range of radioactive ion beams in the world



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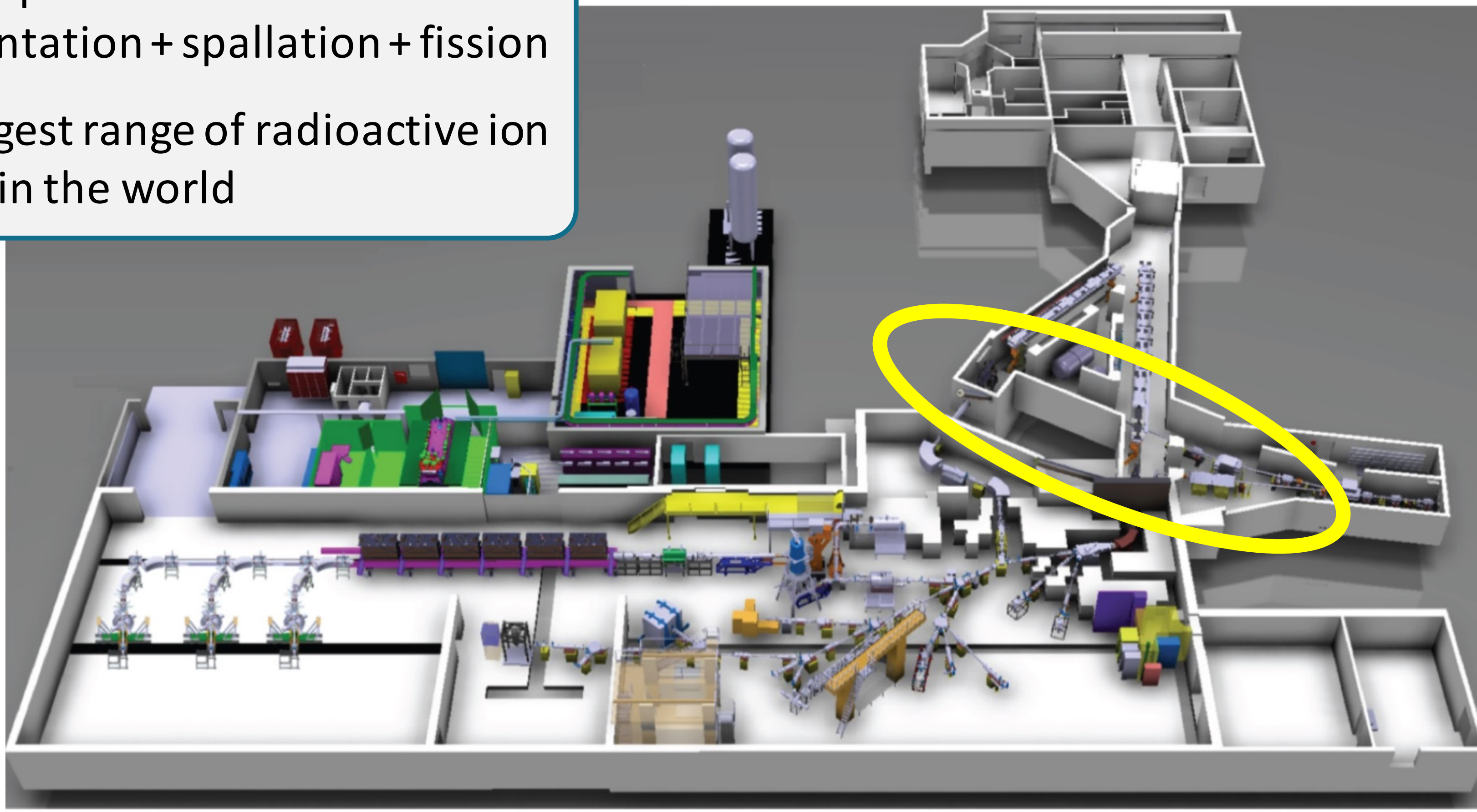

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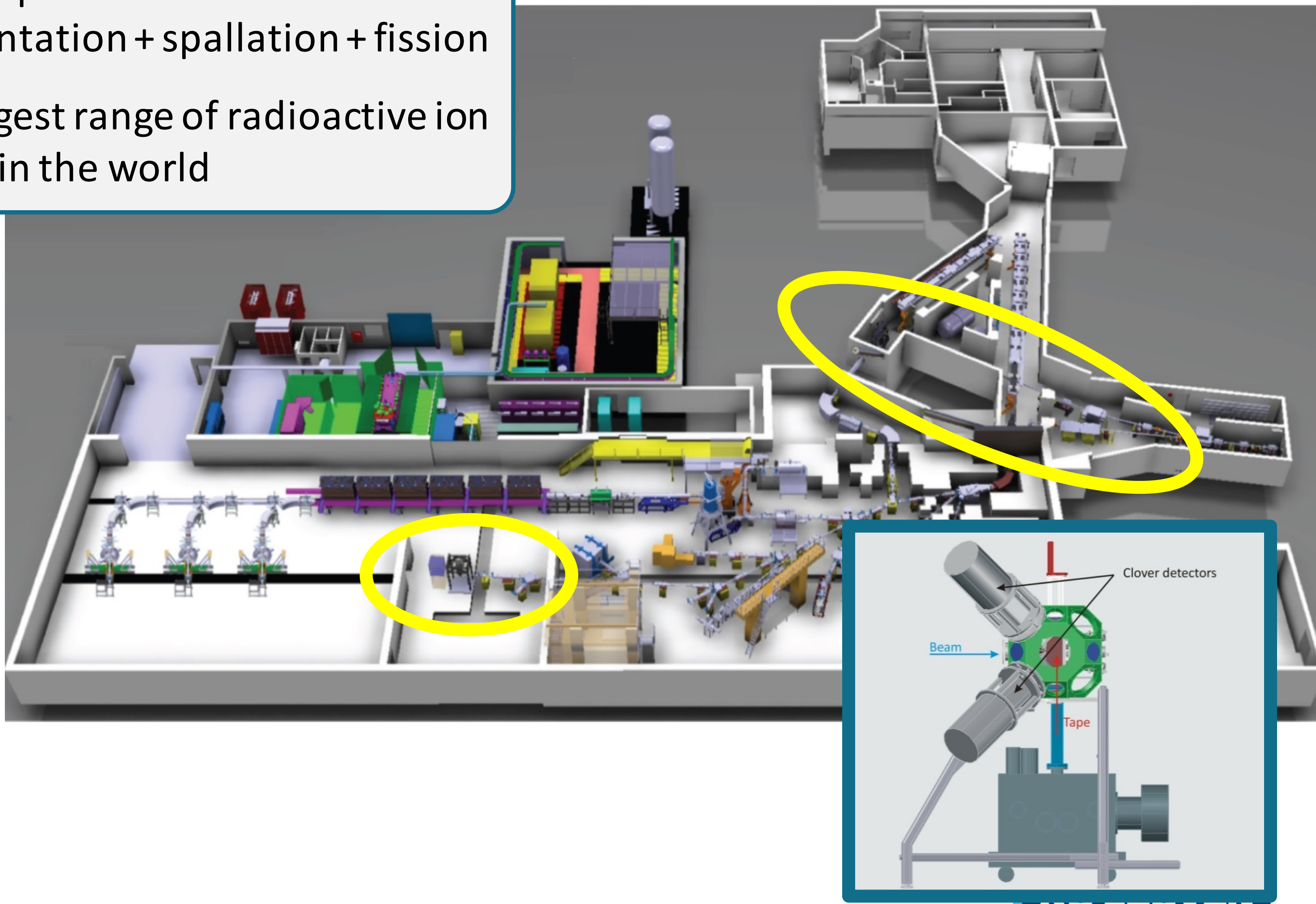

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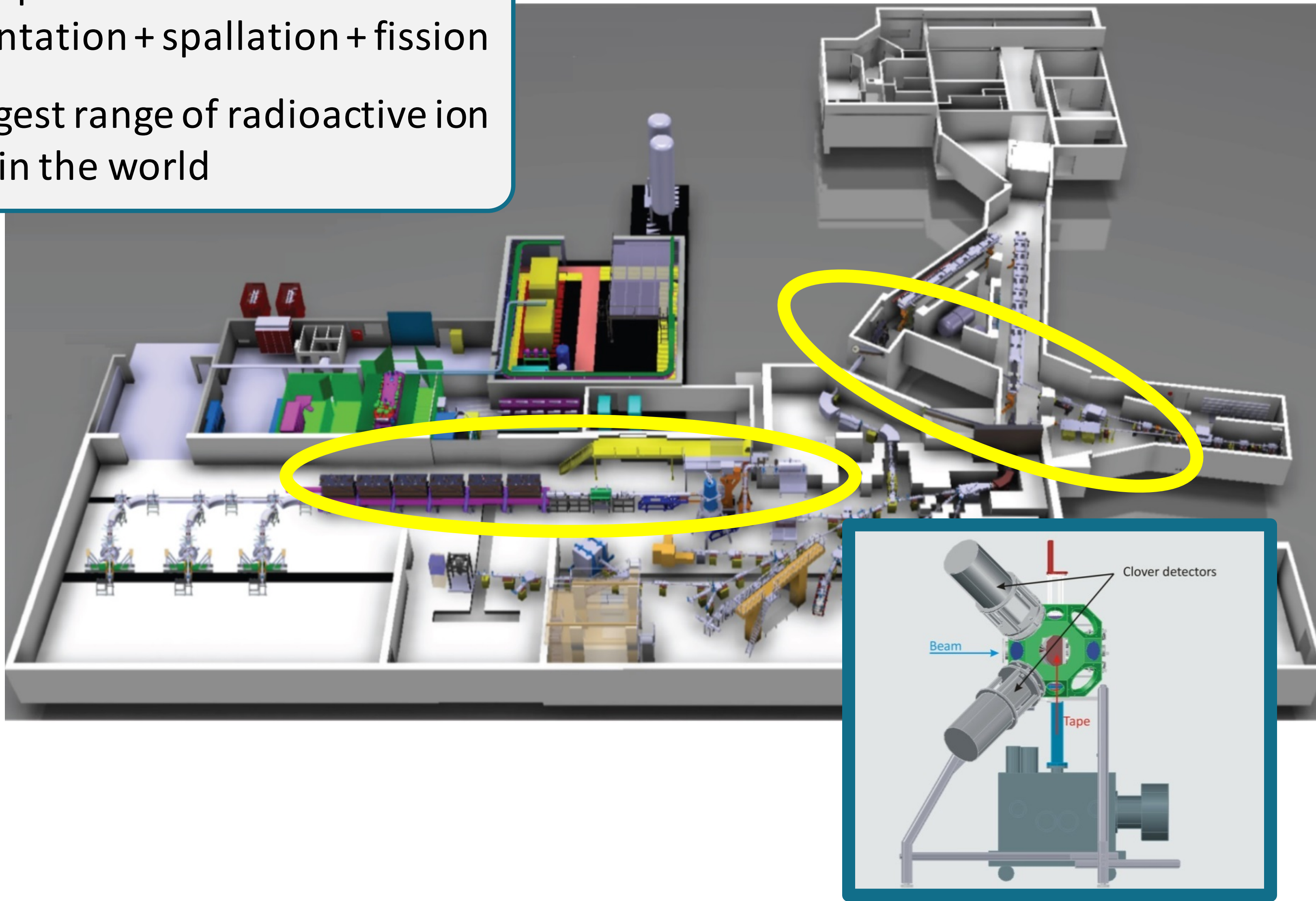

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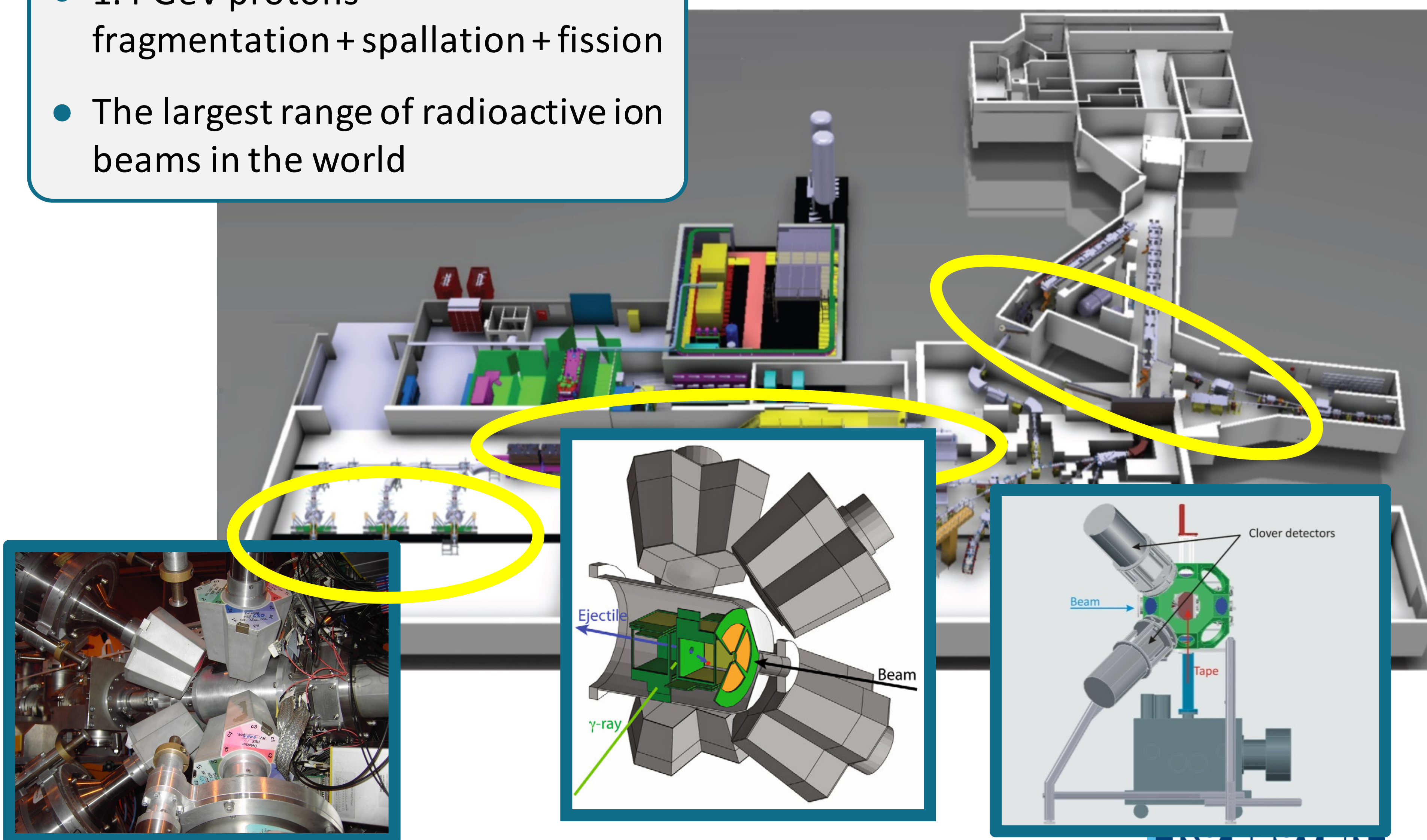
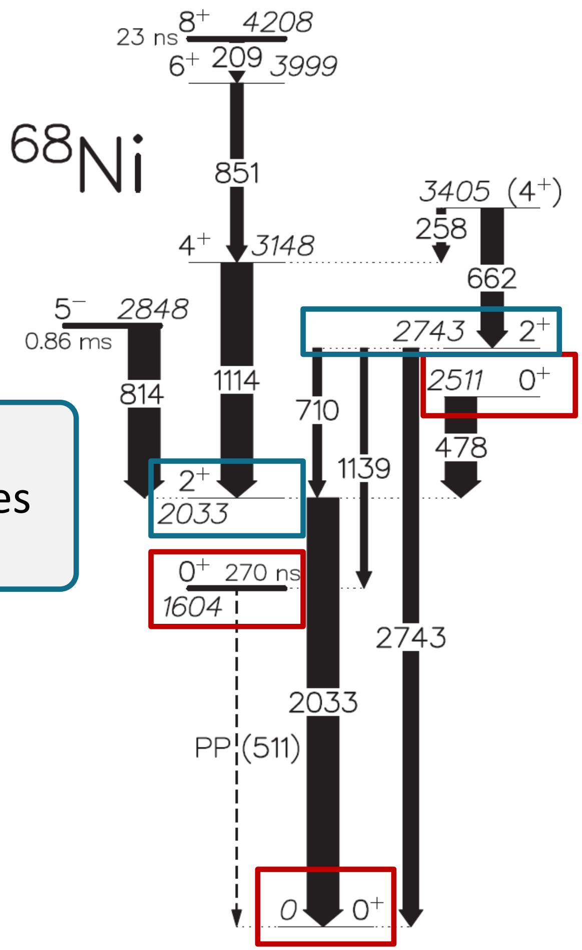


What do we know about ^{68}Ni

Recent experimental work

- **J. Elseviers et al., submitted**
- **F. Flavigny et al., PRC 91 (2015) 034310**
- S. Suchyta et al., PRC 89 (2013) 021301R
- F. Recchia et al., PRC 88 (2013) 041302R
- R. Broda et al., PRC 86 (2012) 064312
- C. J. Chiara et al., PRC 86 (2012) 041304R
- A. Dijon et al., PRC 85 (2012) 031301R

Three 0^+ states and two 2^+ states below 2.8 MeV



Level scheme from F. Recchia et al. PRC 88 (2013) 041302R

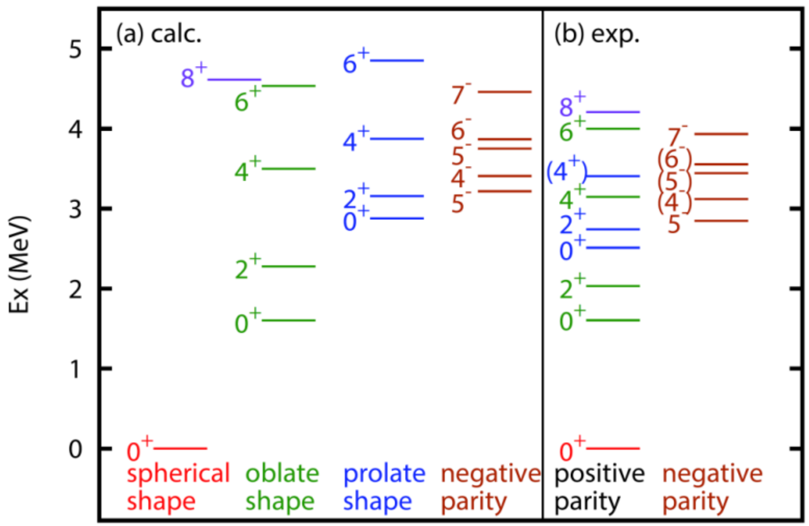
Crucial information

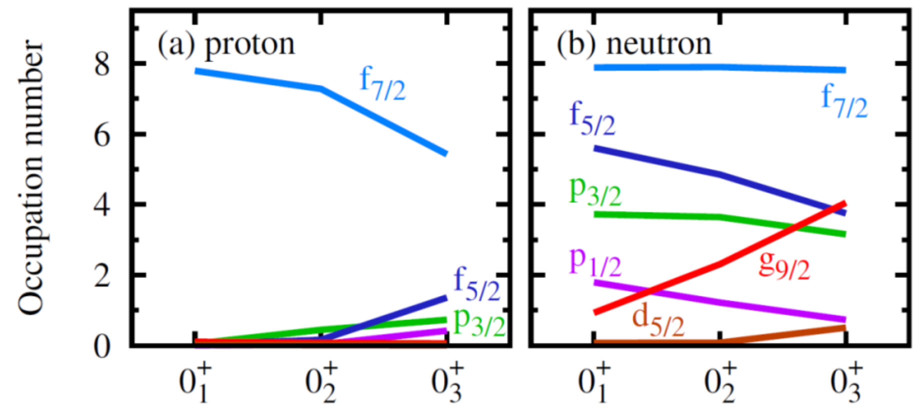
- Precise measurement of 0^+_2 energy
  Since 1982: 1770(30) keV from ^{70}Zn(^{14}C,^{16}O)^{68}Ni
  Now: 1603.5(3) keV
- Two transitions feeding 0^+_2 (1139 and 2420 keV)
- Firm assignment of several spin/parities

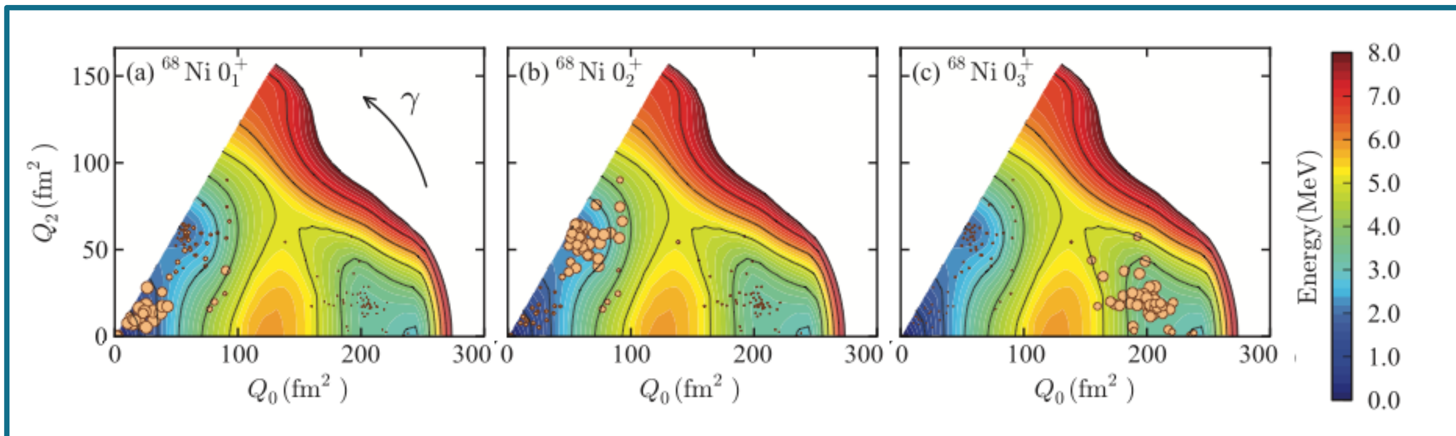
Monte-Carlo Shell-Model calculations

Y. Tsunoda et al., PRC 89 (2014) 031301R

- Full pf + $g_{9/2}$ + $d_{5/2}$ for both neutrons and protons





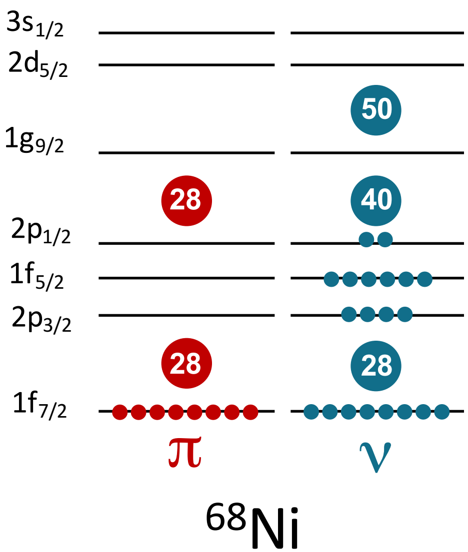


Aiming at complete spectroscopy

IS504 PhD thesis J. Elseviers

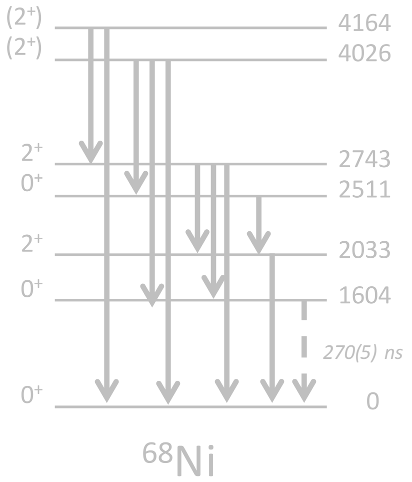
- Nature of 0+ states in ^{68}Ni
- Conf. mixing of 0^+_1 and 0^+_2

^{66}Ni(t,p)^{68}Ni



IS467

- Revised decay scheme
- β-γ-E0 coincidences
- 2^+ to 0^+ connections
- Exp. B(E2) ratios



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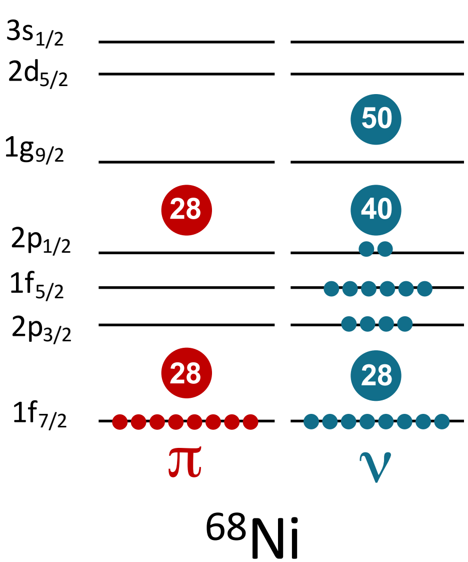
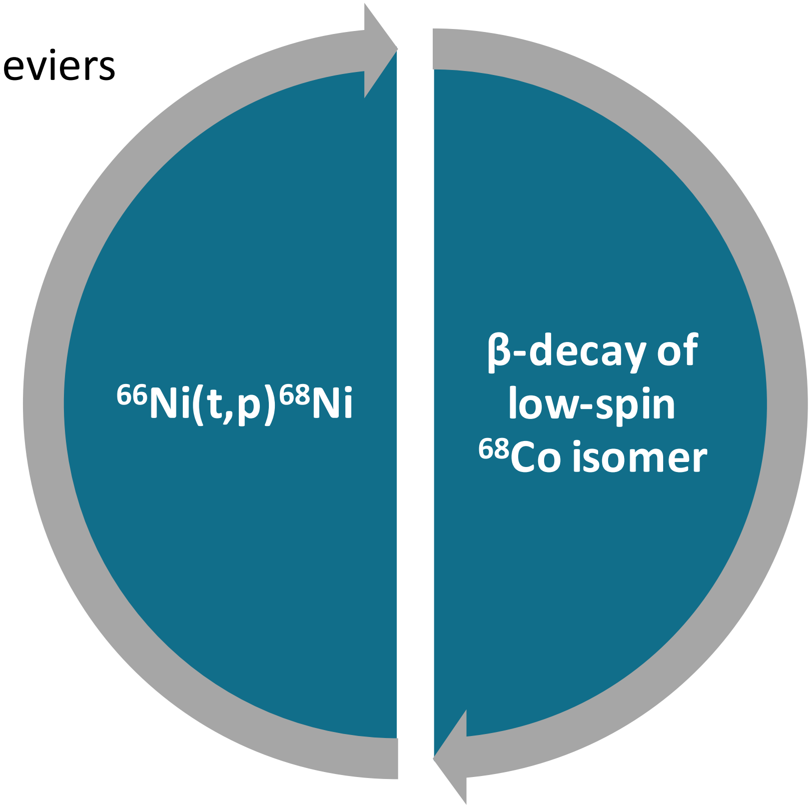
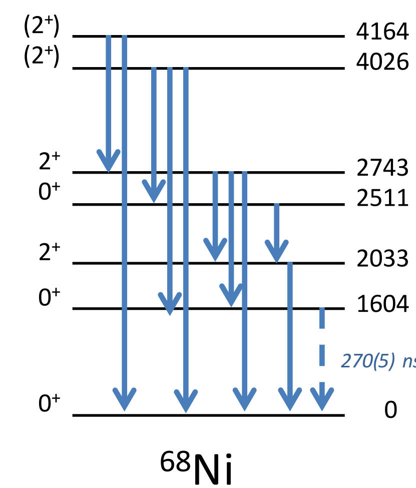




IS467 PRC 91 (2015) 034310

- Revised decay scheme
- β-γ-E0 coincidences
- 2^+ to 0^+ connections
- Exp. $B(E2)$ ratios



+ ^{66}Ni(d,p)^{67}Ni

J. Diriken et al., PLB 736, 533 (2014)
J. Diriken et al., PRC 91, 054321 (2015)

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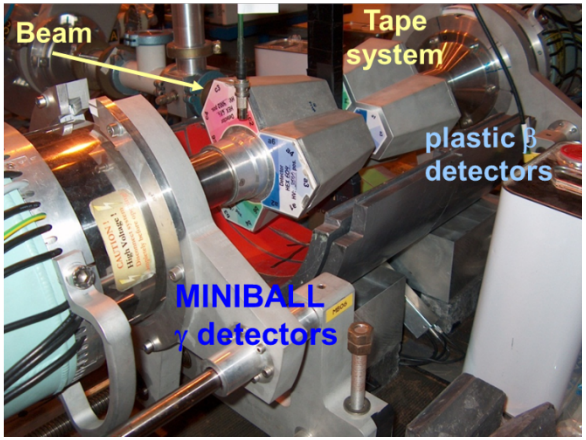
IS467: from ^{68}Mn to ^{68}Ni

F. Flavigny et al., PRC 91 (2015) 034310

Z = 28	^{60}Ni stable	^{61}Ni stable	^{62}Ni stable	^{63}Ni 100(2) y	^{64}Ni stable	^{65}Ni 2.52 h	^{66}Ni 54.6(3) h	^{67}Ni 21(1) s	^{68}Ni* 29(2) s	^{69}Ni* 11.4(3) s	^{70}Ni* 6.0(3) s			
27		^{60}Co 1925 d	^{61}Co 1.650(5)h	^{62}Co 1.50(4)m	^{63}Co 27.4(5) s	^{64}Co 0.30(3)s	^{65}Co* 1.20(6)s	^{66}Co* 0.18(1) s	^{67}Co* 329(28)ms	^{68}Co* 0.23(3) s	^{69}Co* 0.27(5)s	^{70}Co 119(6)ms		
26			^{60}Fe 1.5E6 a	^{61}Fe 5.98(6)m	^{62}Fe 68(2)s	^{63}Fe 6.1(6) s	^{64}Fe 2.0(2) s	^{65}Fe* 1.07(12)s	^{66}Fe* 830(80)ms	^{67}Fe* 411(32)ms	^{68}Fe 132(39)ms	^{69}Fe 0.17(3)s	^{70}Fe 94(17) ms	
25				^{60}Mn 0.28(2)s	^{61}Mn 623(10)ms	^{62}Mn 671(5) ms	^{63}Mn 0.29(2) s	^{64}Mn 90(4) ms	^{65}Mn 88(4) ms	^{66}Mn 66(4) ms	^{67}Mn 47(2) ms	^{68}Mn 28(4) ms	^{69}Mn 14(4) ms	^{70}Mn
N =				35	36	37	38	39	40	41	42	43	44	45

β-decay
* studied at LISOL
□ studied at ISOLDE

- Pure Mn source (RILIS)
- Implantation 69 ms – decay 2.2 s
- β-γ detection setup
- In ^{68}Co: 2 isomers
  7^{-} $T_{1/2} = 0.23(3)$ s
  $(1^{+},3^{+})$ $T_{1/2} = 1.6(3)$ s



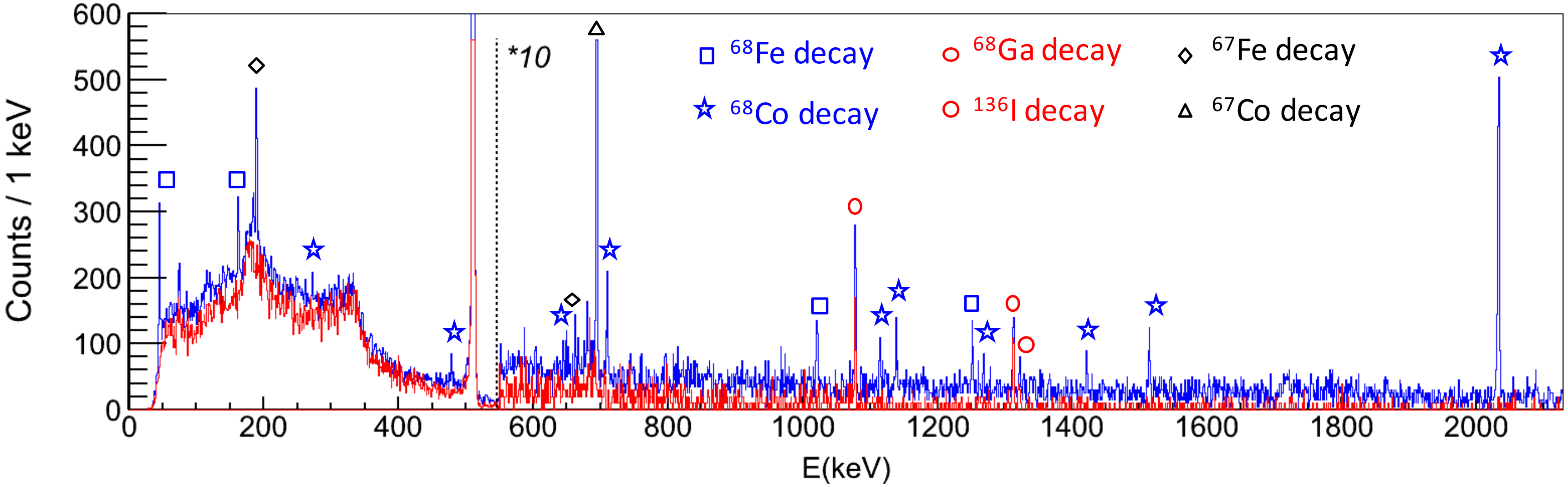
- MINIBALL: 5.8% photo-peak efficiency at 1.332 MeV
- 3 plastic detectors: 50% beta efficiency
- Polyethylene-borax-lead-brass shielding

β-γ coincidences

F. Flavigny et al., PRC 91 (2015) 034310

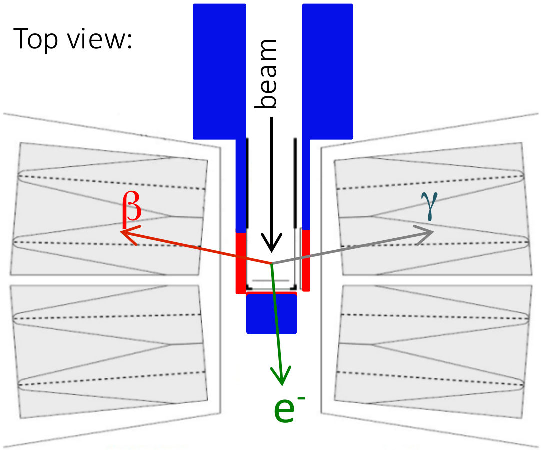
- Low background (shielding)
- Laser ionisation (RILIS)
- Mass separation (HRS)
- Time condition: $t_\beta - t_{PP}$ in [350,2200] ms

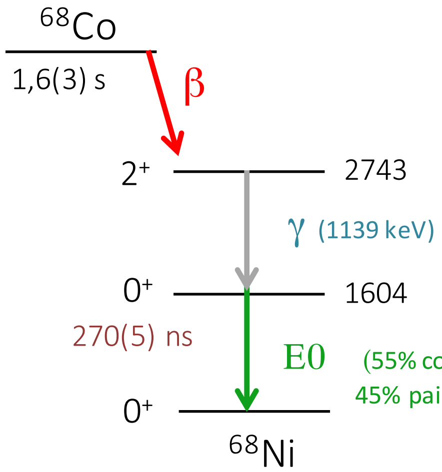
→ Clean ^{68}Co low-spin spectrum

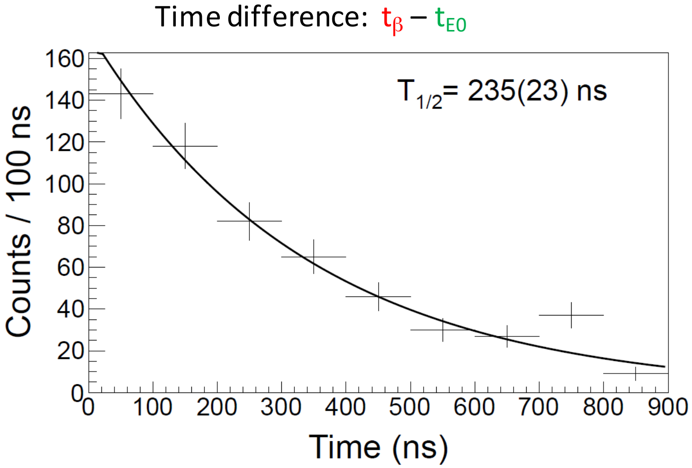


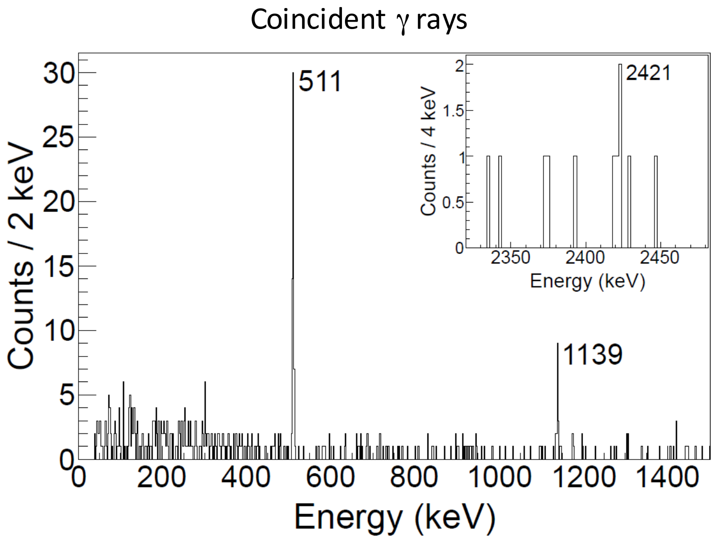
Feeding of 0^+_2 state in ^{68}Ni : β-γ-E0 coincidences

F. Flavigny et al., PRC 91 (2015) 034310









β-γ-E0 coincidences (590 events)

- Highly selective signal
- 1139 and 2421 keV feeding 0^+_2
- $E(0^+_2)$ = 1603.6(6) keV in agreement with recent results

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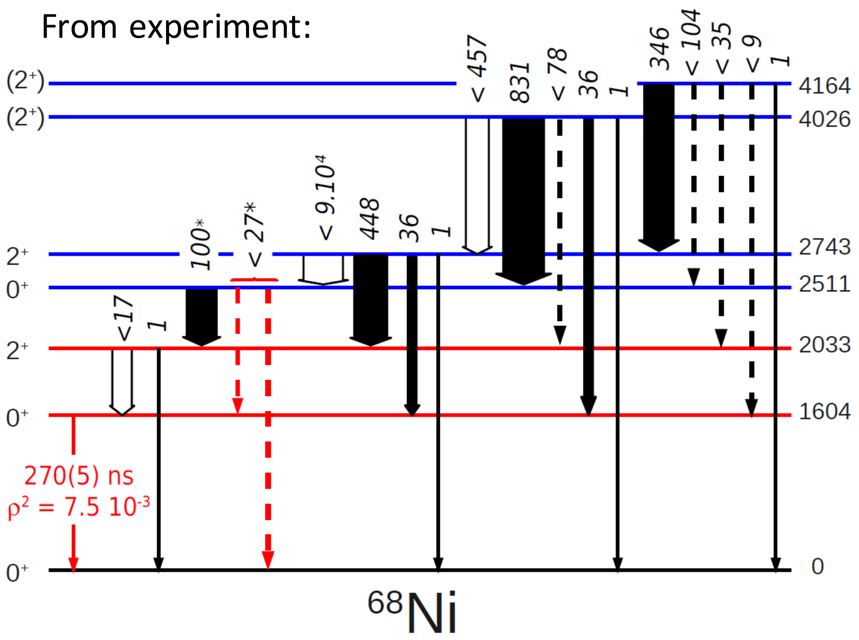
B(*E*2) ratios

F. Flavigny et al., PRC 91 (2015) 034310

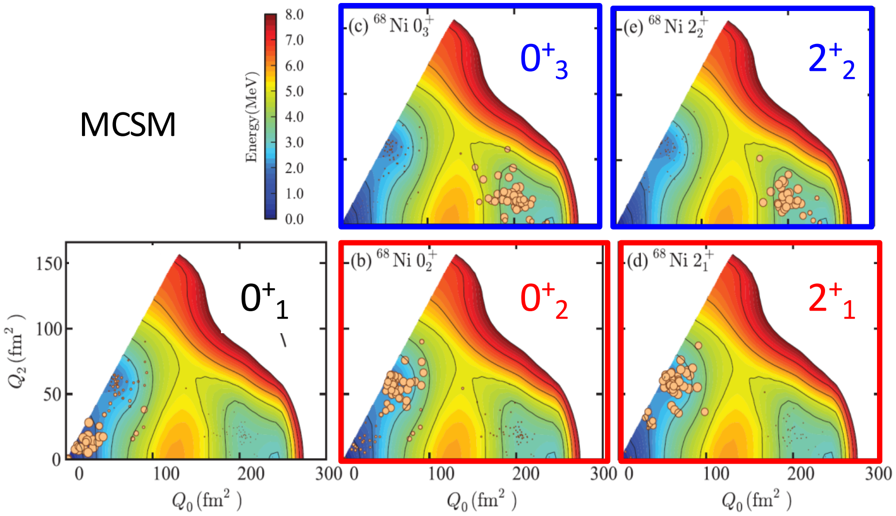
From experiment:



$$R = \frac{B(E2, 2_i^+ \rightarrow I^+)}{B(E2, 2_i^+ \rightarrow 0_1^+)}$$

- 2^+_1 strongly connected to 0^+_2
  R_{exp} < 17, R_{LNPS} = 12, R_{MCSM} = 4
- $2^+_2 \rightarrow 0^+_3$ stronger than $2^+_2 \rightarrow 0^+_2$
  R_{exp} < 9·10^4, $R_{LNPS,MCSM} \approx$ 2200
- 0^+_3 478 keV to 2^+_1
  theoretical $T_{1/2}$ very different
- 2^+_3 and 2^+_4
  Qualitative agreement for (2^+_4)
  Significant discrepancies for (2^+_3)

MCSM



Y. Tsunoda et al., PRC 89 (2014) 031301R

IS504: ^{66}Ni(t,p) at REX-ISOLDE

PhD of Jytte Elseviers (KU Leuven)

T-ReX

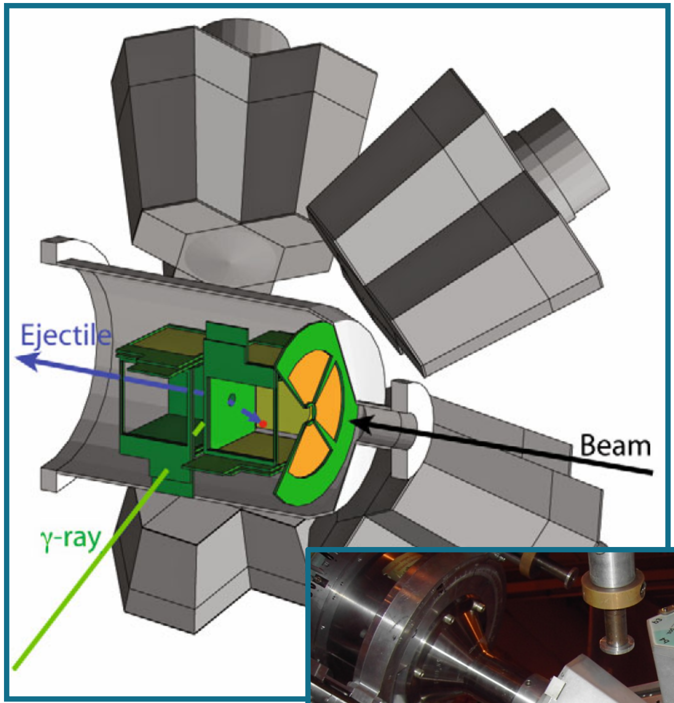
V. Bildstein et al, EPJA 48 (2012) 85

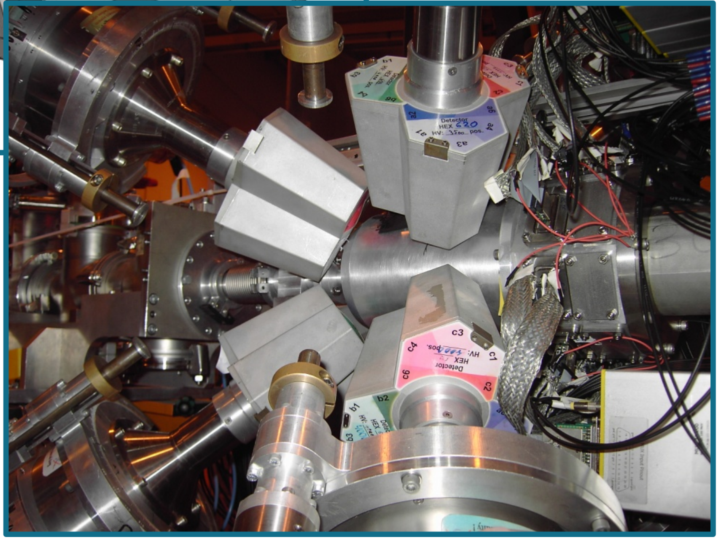
- Resolution ≈1-6 deg
- Δ*E*-*E* for PID
- ε ≈ 60%

Miniball

N. Warr et al, EPJA 49 (2013) 40

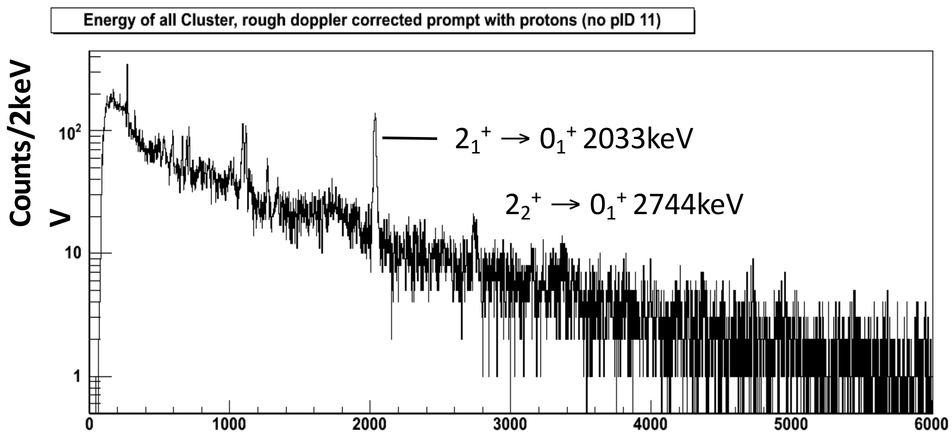
- 24 HPGe
- 6-fold segmented
- ε ≈ 8% @ 1.3 MeV

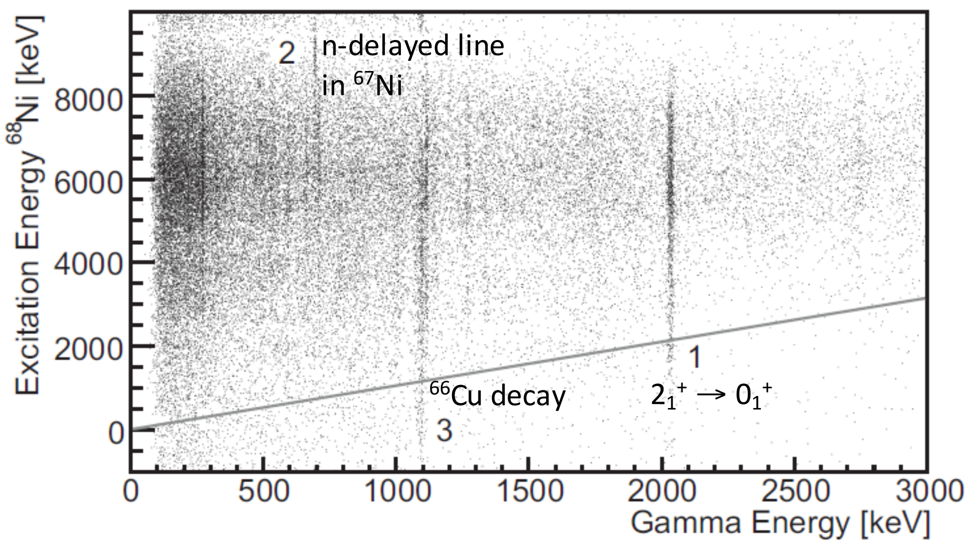


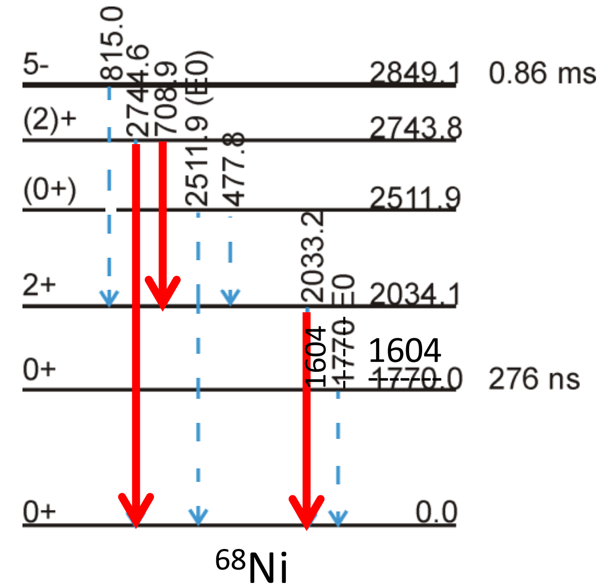


γ's and coincidences

PhD of Jytte Elseviers (KU Leuven)



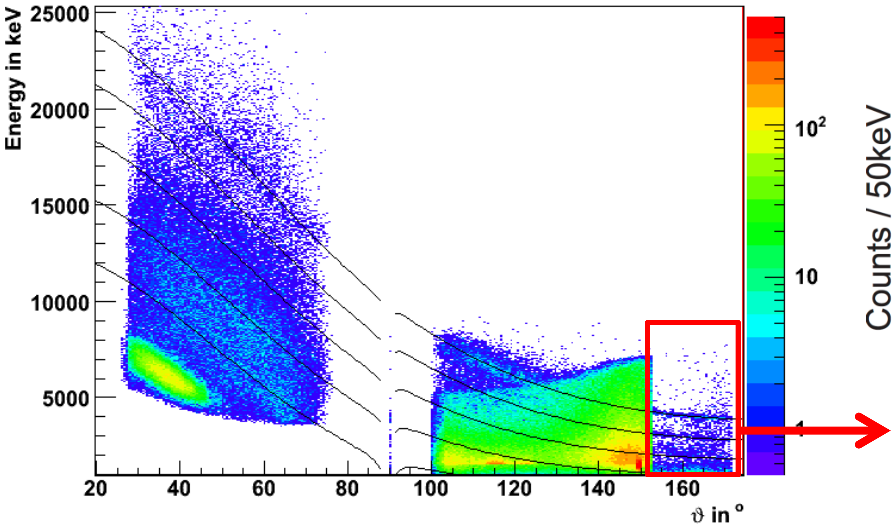


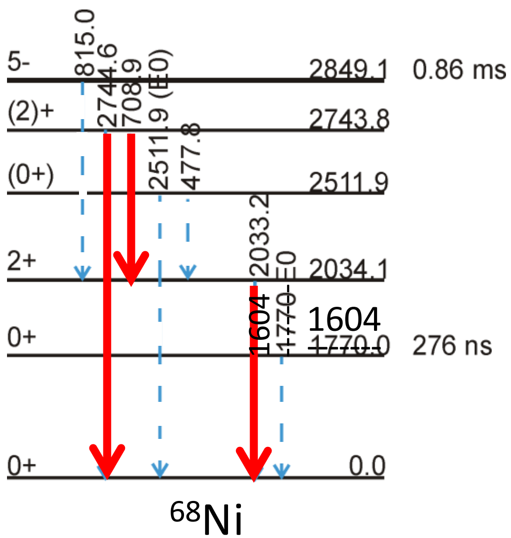


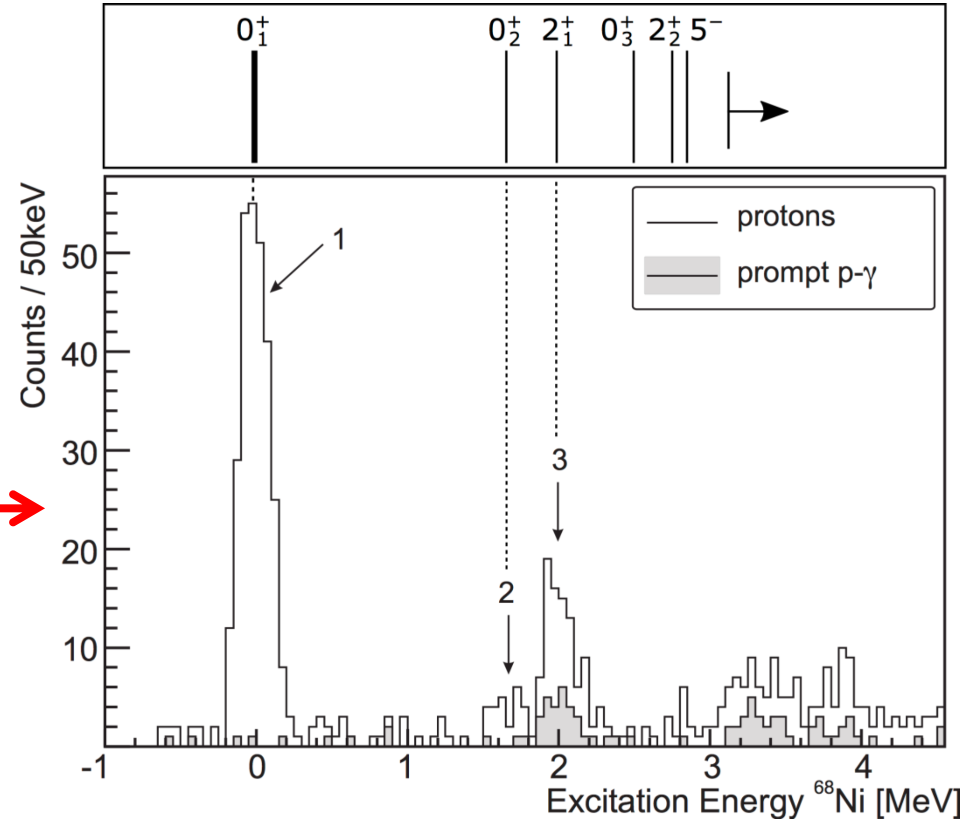
- Few γ's to ground state
- No p-γ-γ coincidences

Population of 0^+ states

PhD of Jytte Elseviers (KU Leuven)







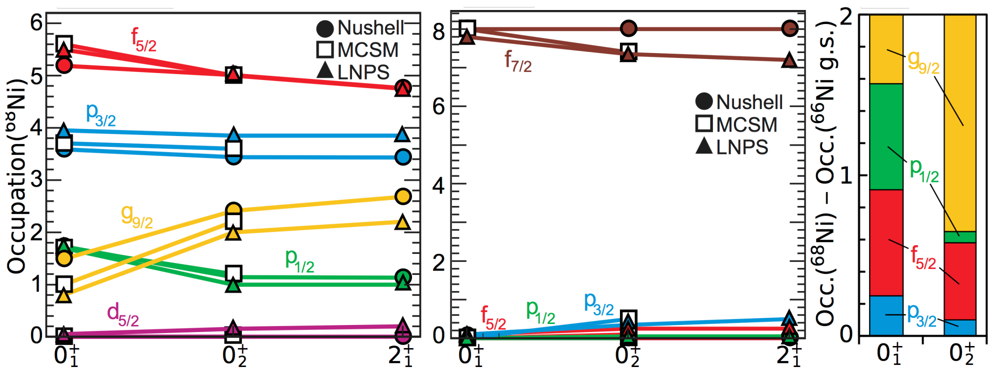
- Population of 0^+_2 : 5.4(11)% of g.s.
- Upper limits (<4%) on population of 0^+_3 and 2^+_2

Calculation of cross sections

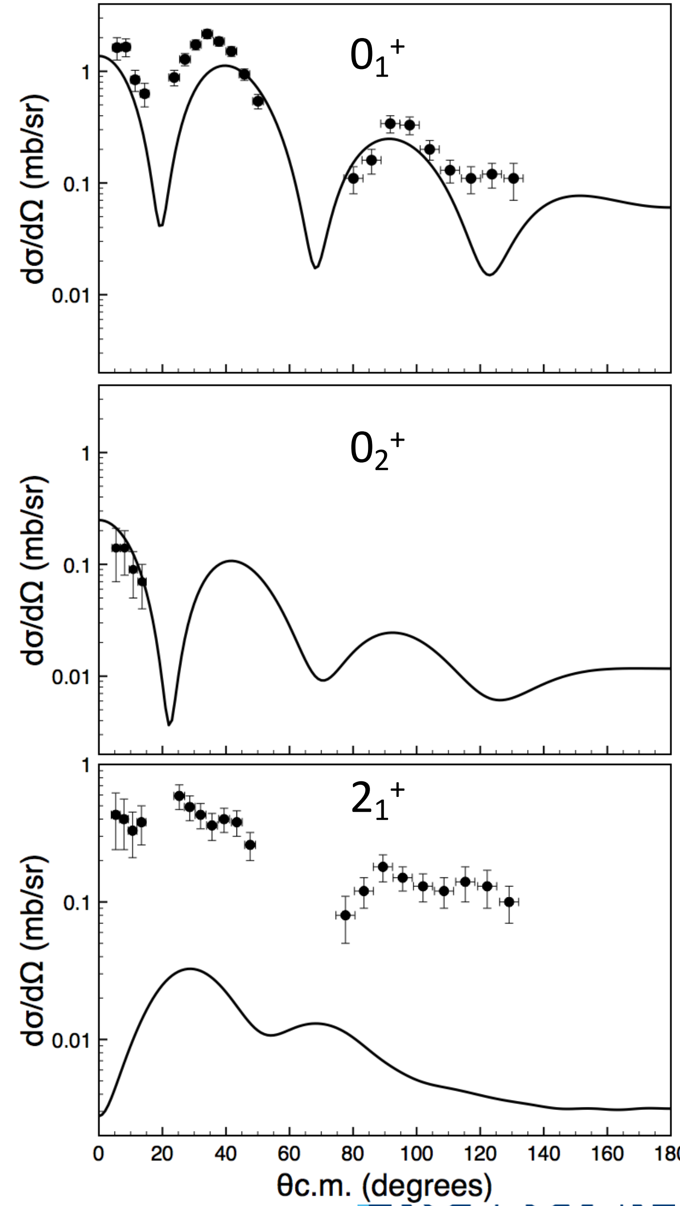
PhD of Jytte Elseviers (KU Leuven)

- Two-neutron overlap amplitudes from MCSM (T. Otsuka) $pf+g_{9/2}+d_{5/2}$ both protons and neutrons

neutron - **occupation numbers** - protons



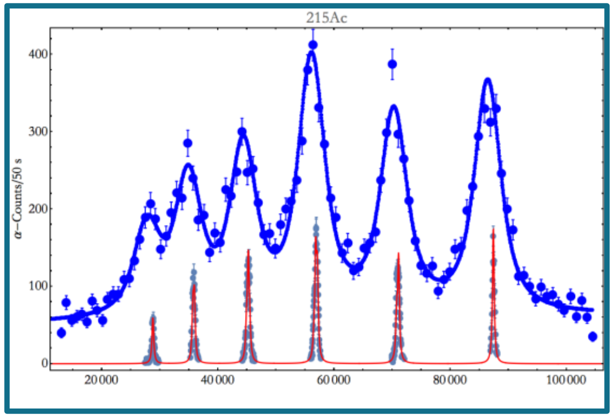
	$f_{5/2}$		$p_{3/2}$		$p_{1/2}$		$g_{9/2}$	
^{66}Ni gs	4.53		3.34		1.07		1.06	
^{68}Ni gs	5.19	**+0.66**	3.59	+0.25	1.73	**+0.66**	1.49	+0.43
^{68}Ni 0^+_2	5.01	+0.48	3.44	+0.10	1.14	+0.07	2.41	**+1.35**

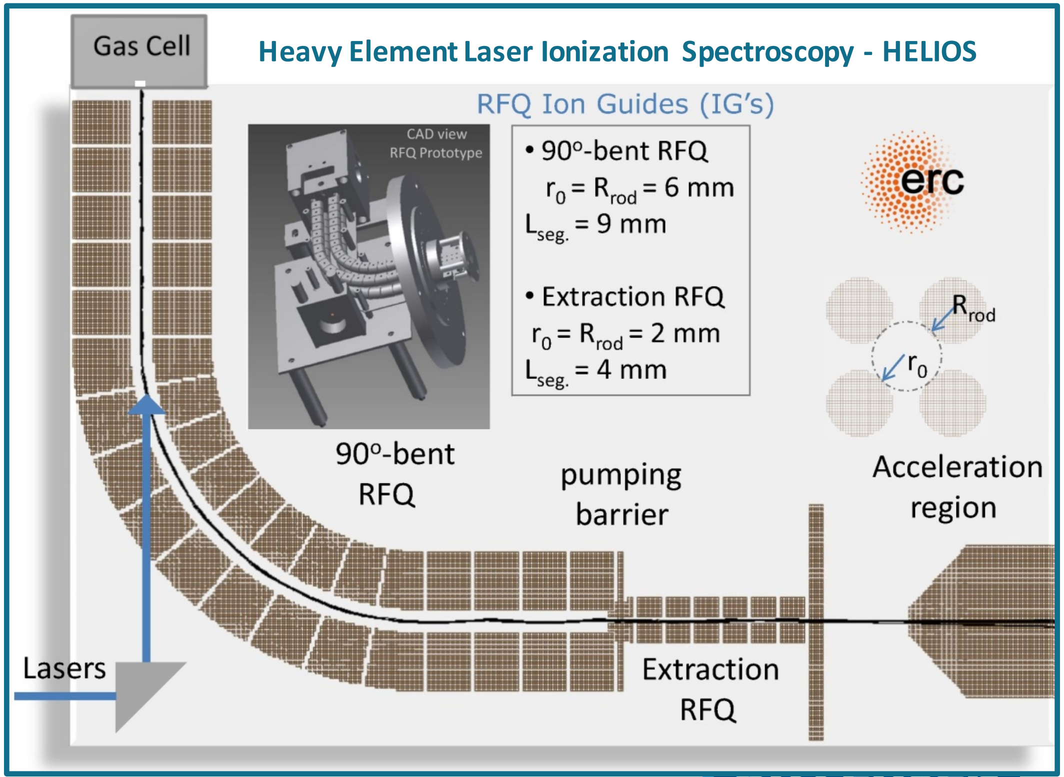


Outlook I - HELIOS

In-jet laser spectroscopy

- Strong reduction of broadening effects
  → improved resolution
  Proof-of-principle: ^{215}Ac at LISOL
- New dedicated laser facility at the IKS, KU Leuven
  Towards the heaviest elements
- To be installed at SPIRAL2 in GANIL, France





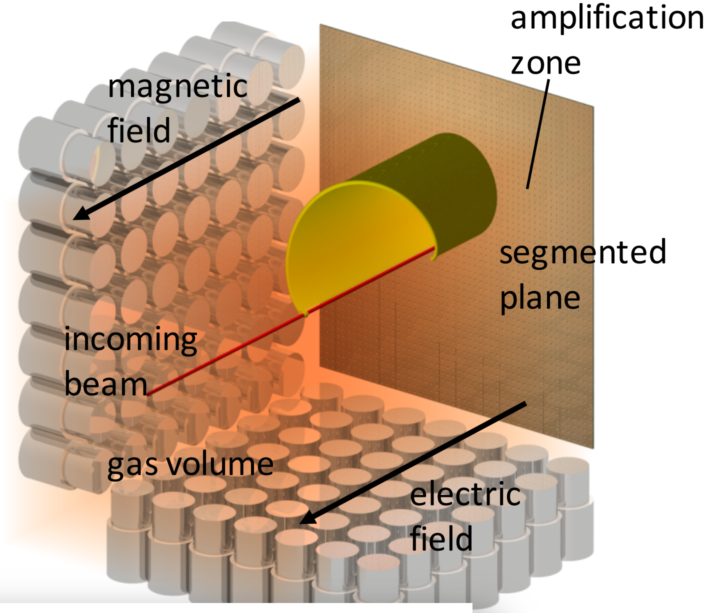
European Research Council
Established by the European Commission

Advanced Grant
Piet Van Duppen

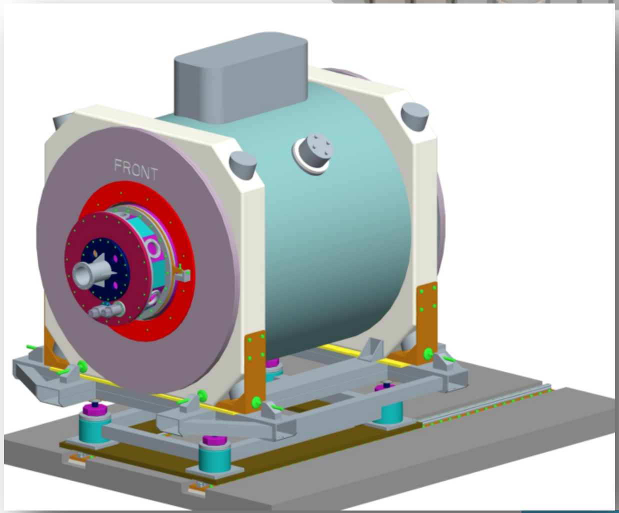
Outlook II - SpecMAT

Transfer reactions with very weak beams

- Active target: Time-projection chamber where detection gas is the target
- Magnetic field parallel to beam direction to confine emitted particles
- Array of γ-ray detectors within the field LaBr3 preferred for best compromise efficiency/resolution



- **High luminosity**
- **Large dynamic range**
- **High resolution**
- **Versatile**



European Research Council
Established by the European Commission

Consolidator Grant
RR

Summary

- Study of nuclei far from stability reveals details of the underlying nucleon-nucleon interaction
- Link collective properties (deformation) with single-particle structure
- Use all spectroscopic probes available
  Nuclear reactions are becoming available at present and forthcoming facilities
- First results in Ni region
  Pb region is the next step
- Strong support from (and to) theory is necessary

Characterization of the low-lying 0^+ and 2^+ states in ^{68}Ni via β decay of the low-spin ^{68}Co isomer

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

[1]*KU Leuven, Instituut voor Kern- en Stralingsfysica, Celestijnenlaan 200D, 3001 Leuven, Belgium*
[2]*Belgian Nuclear Research Centre SCKCEN, Boeretang 200, B-2400 Mol, Belgium*
[3]*Petersburg Nuclear Physics Institute, NRC Kurchatov Institute, 188300 Gatchina, Russia*
[4]*EN Department, CERN, CH-1211 Geneva 23, Switzerland*
[5]*Grupo de Física Nuclear, Universidad Complutense, CEI Moncloa, 28040 Madrid, Spain*
[6]*Institut Laue-Langevin, 71 avenue des Martyrs, 38042 Grenoble, France*
[7]*Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[8]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[9]*Department of Physics, University of York, York YO10 5DD, United Kingdom*
[10]*PH Department, CERN, CH-1211 Geneva 23, Switzerland*
[11]*Institute of Physics, Slovak Academy of Sciences, SK-84511 Bratislava, Slovakia*
[12]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*
[13]*Physik Department E12, Technische Universitat Munchen, D-85748 Garching, Germany*

IS467

BriX

belspo

fwo

Probing the 0^+ States in ^{68}Ni via the two-Neutron Transfer Reaction ^{66}Ni(t,p)

J. Elseviers,[1] F. Flavigny,[1] A. N. Andreyev,[2,3] V. Bildstein,[4] B. A. Brown,[5] J. Diriken,[1,6] V. N. Fedosseev,[7] S. Franchoo,[8] R. Gernhauser,[9] M. Huyse,[1] S. Ilieva,[10] S. Klupp,[9] Th. Kröll,[10] R. Lutter,[9] B. A. Marsh,[7] D. Muecher,[9] K. Nowak,[9] J. Pakarinen,[11] N. Patronis,[12] R. Raabe,[1] F. Recchia,[13] T. Roger,[14] S. Sambi,[1] M. D. Seliverstov,[1,7] P. Van Duppen,[1] M. Von Schmid,[10] D. Voulot,[7] N. Warr,[15] F. Wenander,[7] and K. Wimmer[16]

[1]*KU Leuven, Instituut voor Kern- en Stralingsfysica, 3001 Leuven, Belgium*
[2]*Department of Physics, University of York, York, YO10 5DD, United Kingdom*
[3]*Advanced Science Research Center (ASRC), Japan Atomic Energy Agency (JAEA), Tokai-mura, Naka-gun, Ibaraki, 319-1195, Japan*
[4]*College of Physics & Engineering Science, University of Guelph, 50 Stone Road East Guelph, Ontario N1G 2W1, Canada*
[5]*Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA*
[6]*SCK•CEN, Boeretang 200, B-2400 Mol, Belgium*
[7]*AB Department, CERN 1211, Geneva 23, Switzerland*
ut de Physique Nucléaire, IN2P3-CNRS/Université Paris-Sud, F-91406 Orsay Cedex, France
[9]*Physik-Departement E12, Technische Universität München, Garching, Germany*
[10]*Institut für Kernphysik, Technische Universität Darmstadt, Germany*
epartment of Physics, University of Jyväskylä, P. O. Box 35, 40351 Jyväskylä, Finland
[12]*Department of Physics, University of Ioannina, GR-45110 Ioannina, Greece*
[13]*Dipartimento di Fisica Galileo Galilei, Via Marzolo 8, 35131 Padova, Italy*
[14]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3, B. P. 55027, F-14076 Caen Cedex 5, France*
[15]*IKP, University of Cologne, D-50937 Cologne, Germany*
[16]*Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA*

IS504

- In particular:
  Freddy Flavigny: β-decay to ^{68}Ni
  Jytte Elseviers: 2n-transfer to ^{68}Ni

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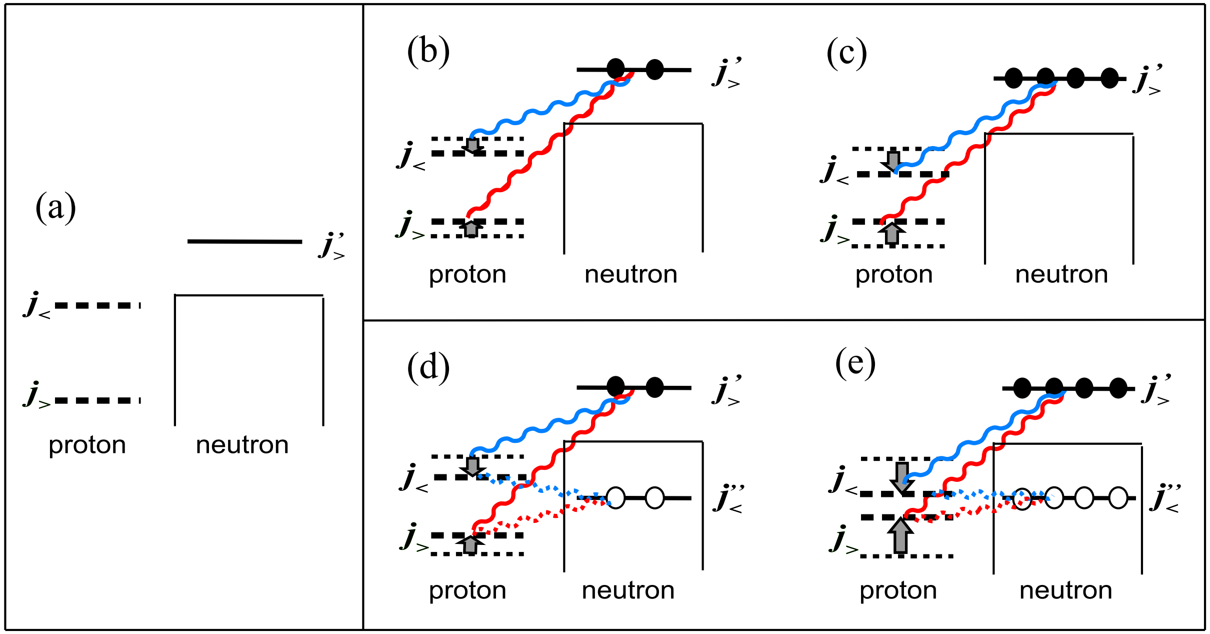
Other slides

Type-II shell evolution

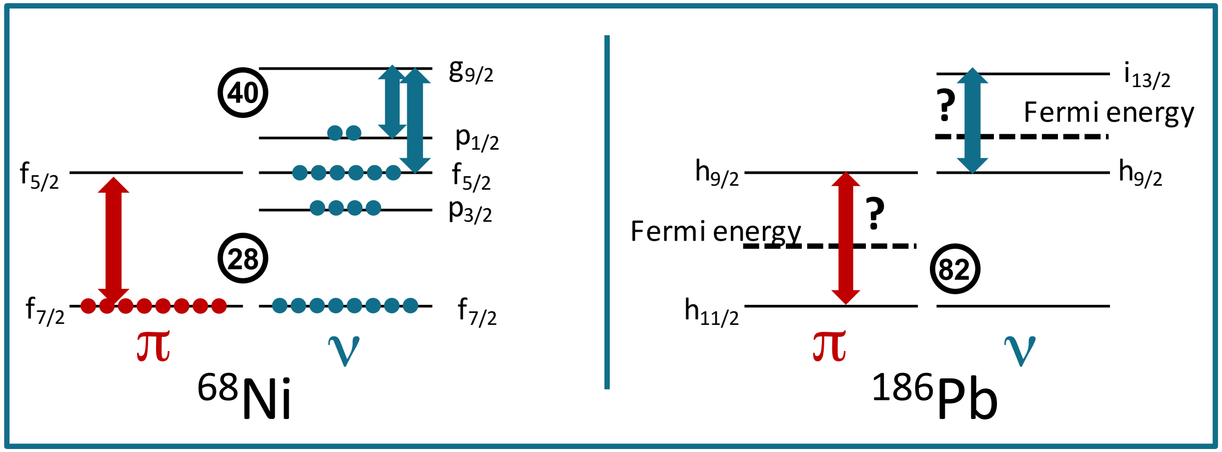
T. Otsuka and Y. Tsunoda, JPG 43 (2016) 024009

- Type-I shell evolution: number of nucleons in different isotopes
- Type-II shell evolution: occupancies within the same nucleus

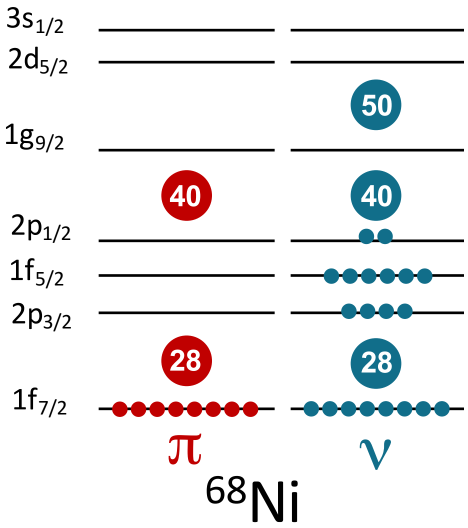


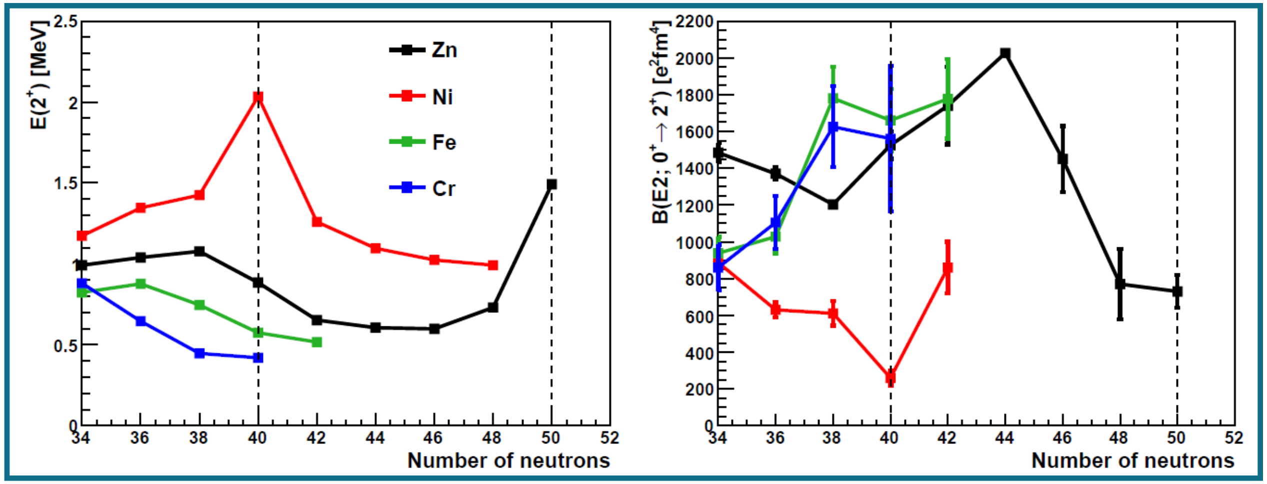
- From Ni to n-deficient Pb region… we need information on energy gaps!

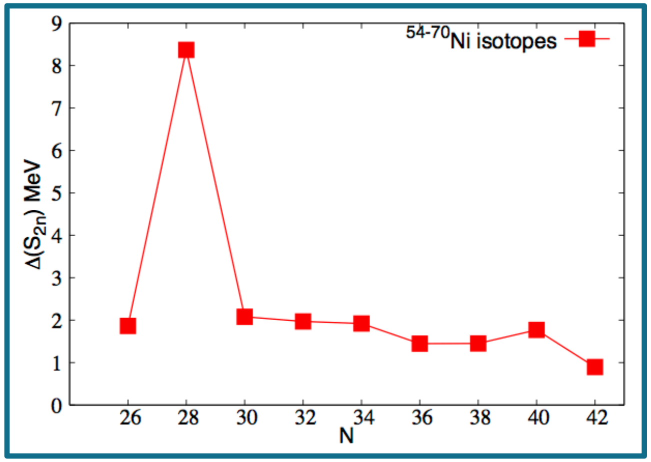
→ nucleon-transfer measurements



What do we know about ^{68}Ni







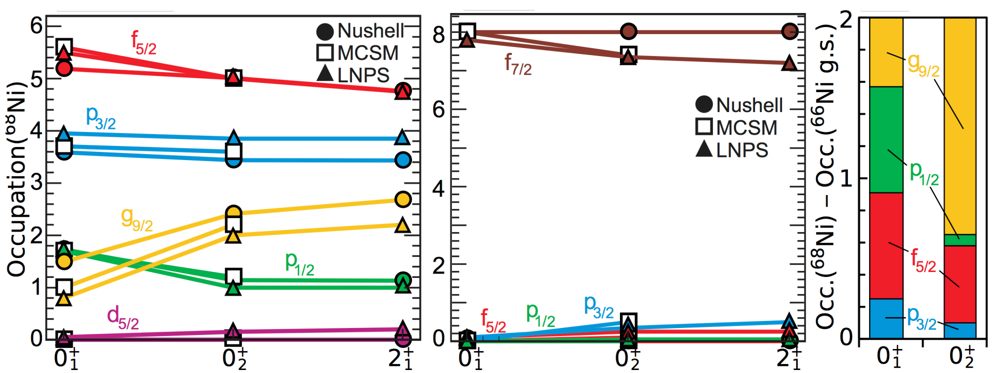
- ^{68}Ni: High $E(2^+_1)$, low $B(E2,2^+\rightarrow0^+)$
- No signature of shell closure from S_{2n}
- In fact, rather weak N = 40 gap

Calculation of cross sections

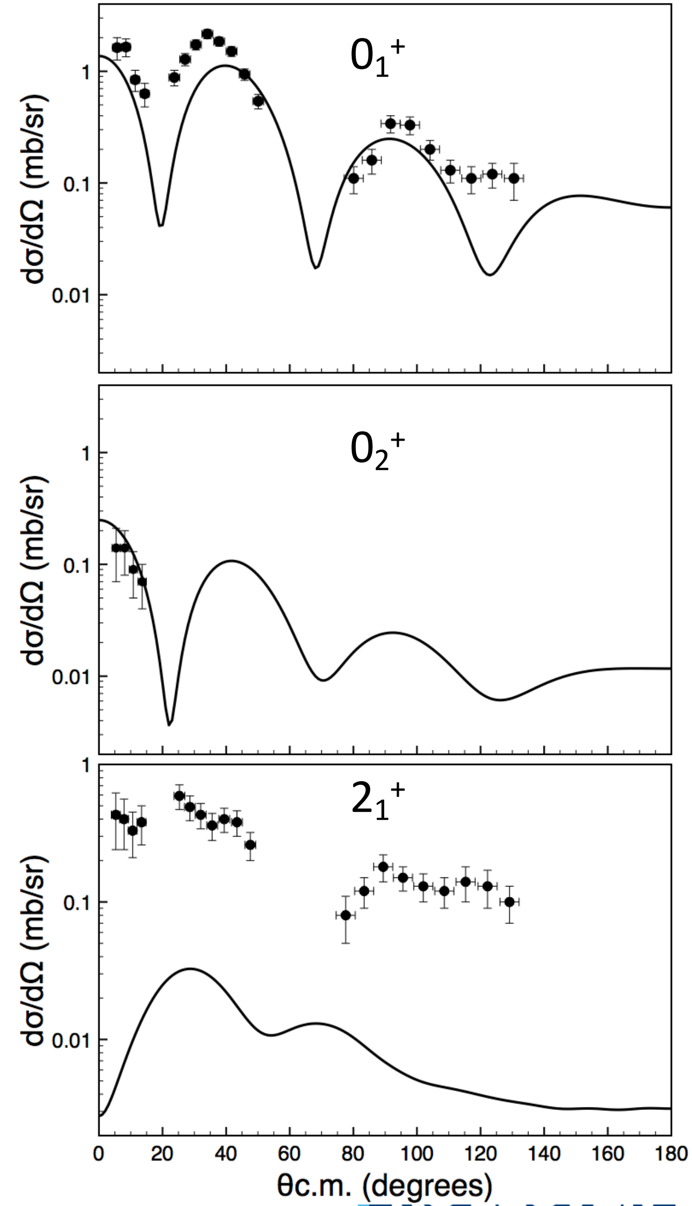
PhD of Jytte Elseviers (KU Leuven)

- Two-neutron overlap amplitudes from MCSM (T. Otsuka) pf+$g_{9/2}$+$d_{5/2}$ both protons and neutrons

neutron - **occupation numbers** - protons



- Agreement for $0^+_{1,2}$ states → the 0^+_2 state is populated by neutrons transferred mainly across N = 40



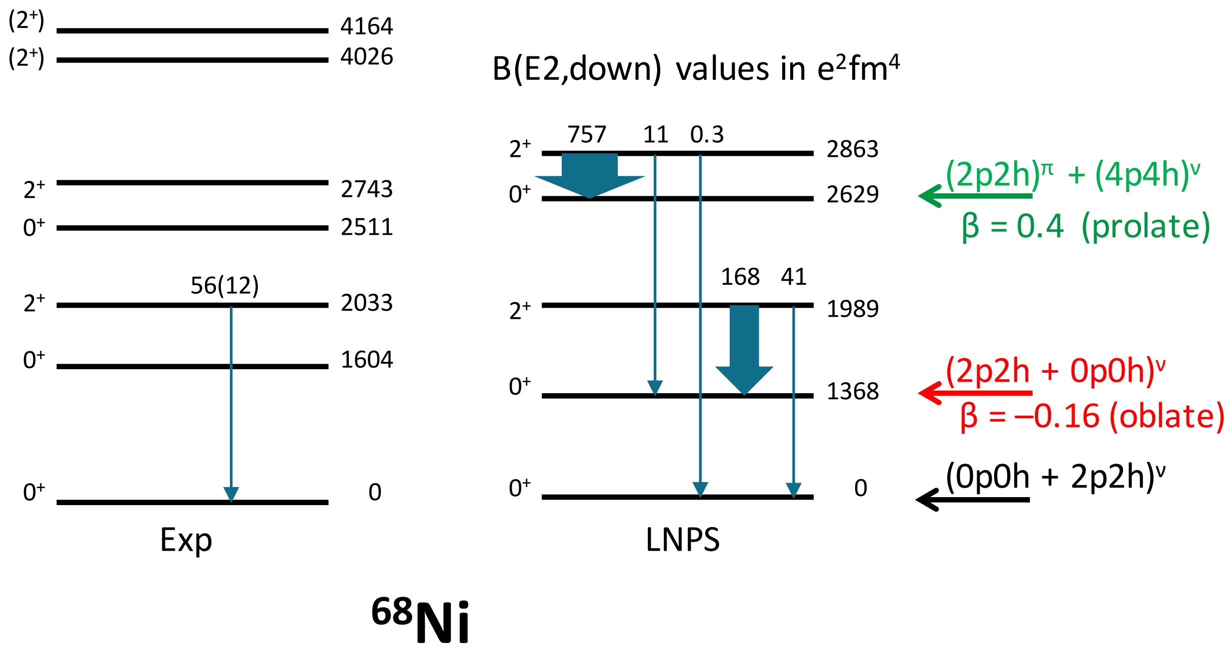
BriX

Large-scale Shell-Model calculations

LNPS interaction

S. Lenzi et al., PRC 82 (2010) 054301

- ^{48}Ca core, π pf – ν pf$g_{9/2}d_{5/2}$ to describe Fe and Cr
- Evolution of the neutron single particle states: ESPE difference $g_{9/2}$-$d_{5/2}$ at ^{68}Ni: ≈1.6 MeV (N=50 gap size)



"dominant proton configuration has exactly two f7/2 protons less than the ground state"

"The 0^+_1 and 0^+_2 states "are characterized by "similar proton occupancies with leading 0p-0h (neutron) configuration for the 0^+_1 ground state and 2p-2h (neutron) configurations for the 0^+_2."

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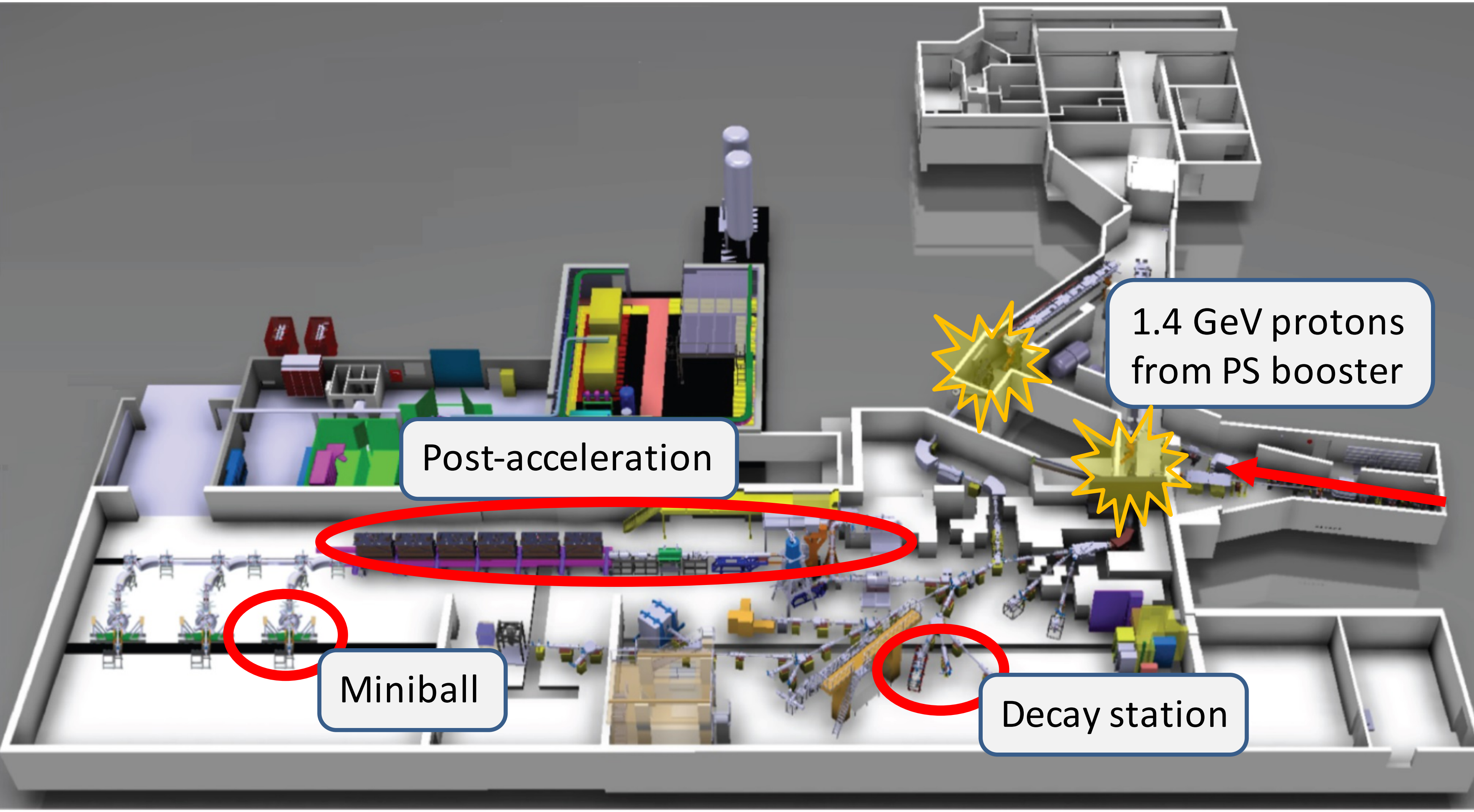
ISOLDE

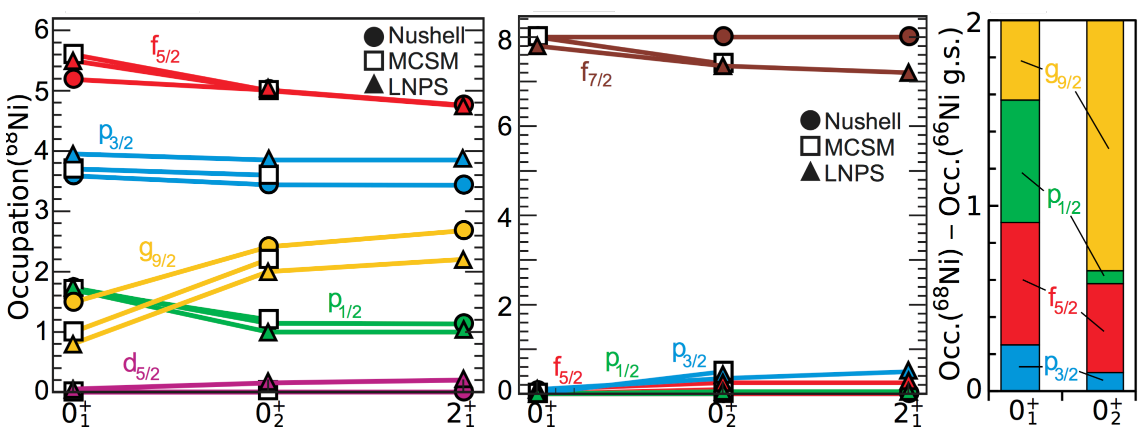

1.4 GeV protons
from PS booster
Post-acceleration
Miniball
Decay station

Calculation of cross sections

PhD of Jytte Elseviers (KU Leuven)

- Structure information from NUSHELL (A. Brown) ν- $f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2}$ model space $\Rightarrow$ two-neutron overlap amplitudes
- FRESCO: direct + sequential paths

neutron - **occupation numbers** - protons



	$f_{5/2}$		$p_{3/2}$		$p_{1/2}$		$g_{9/2}$	
^{66}Ni gs	4.53		3.34		1.07		1.06	
^{68}Ni gs	5.19	**+0.66**	3.59	+0.25	1.73	**+0.66**	1.49	+0.43
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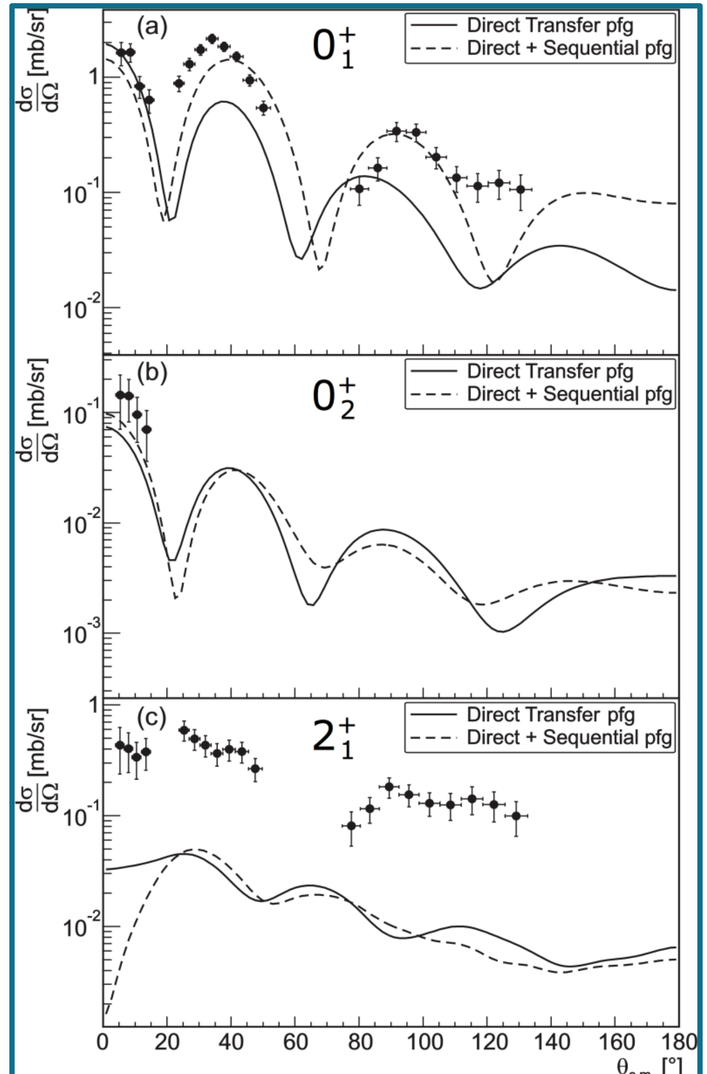

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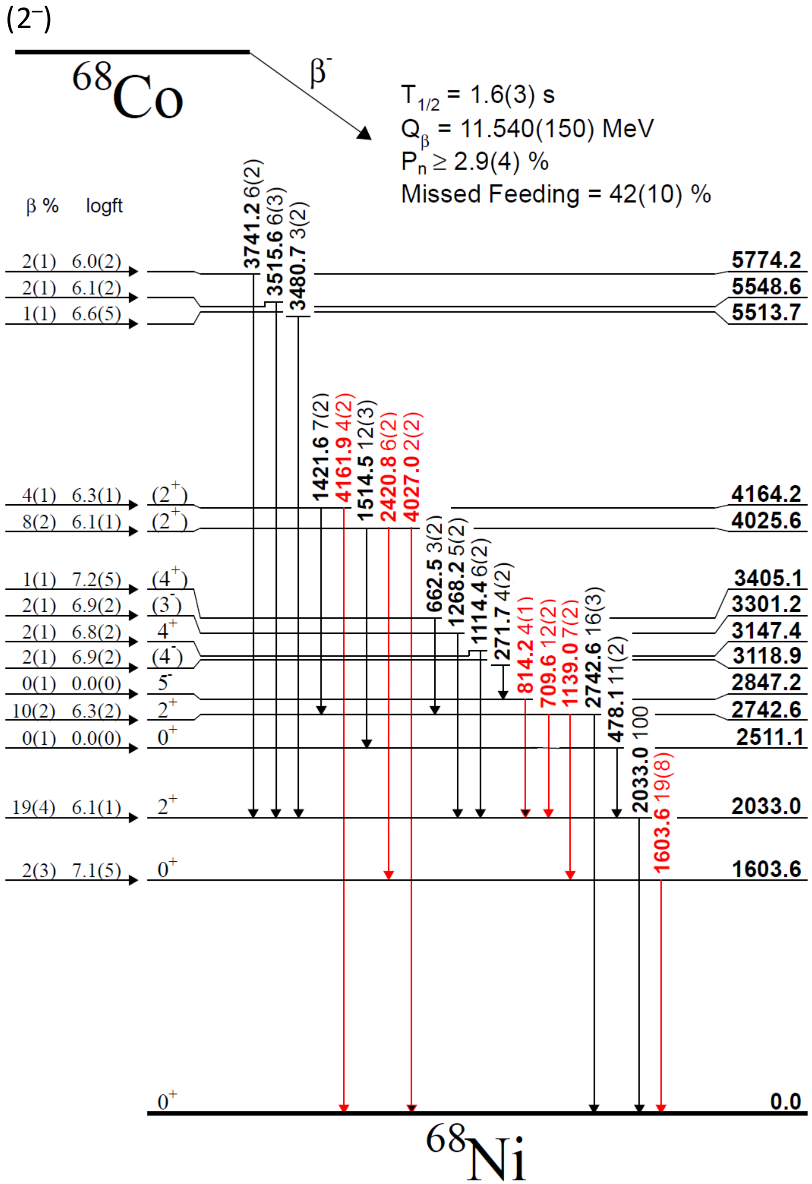
Revised decay scheme

F. Flavigny et al., PRC 91 (2015) 034310



- **New:**
  - 710 keV intensity (clean, no high spin)
  - 1139 and 2421 keV placement
  - Removed 694 keV (after β-delayed n)
  - 814 keV intensity – 5^- isomer
  - $I_{rel}(0^+_2 \rightarrow 0^+_1) = 19(8)$ %
- **Upper limits:**
  - $I_{rel}(0^+_3 \rightarrow 0^+_2) < 2(1)\%$
  - $I_{rel}(0^+_3 \rightarrow 0^+_2)$
  - $I_{rel}(0^+_3 \rightarrow 0^+_1)$

  } < 4(1)%

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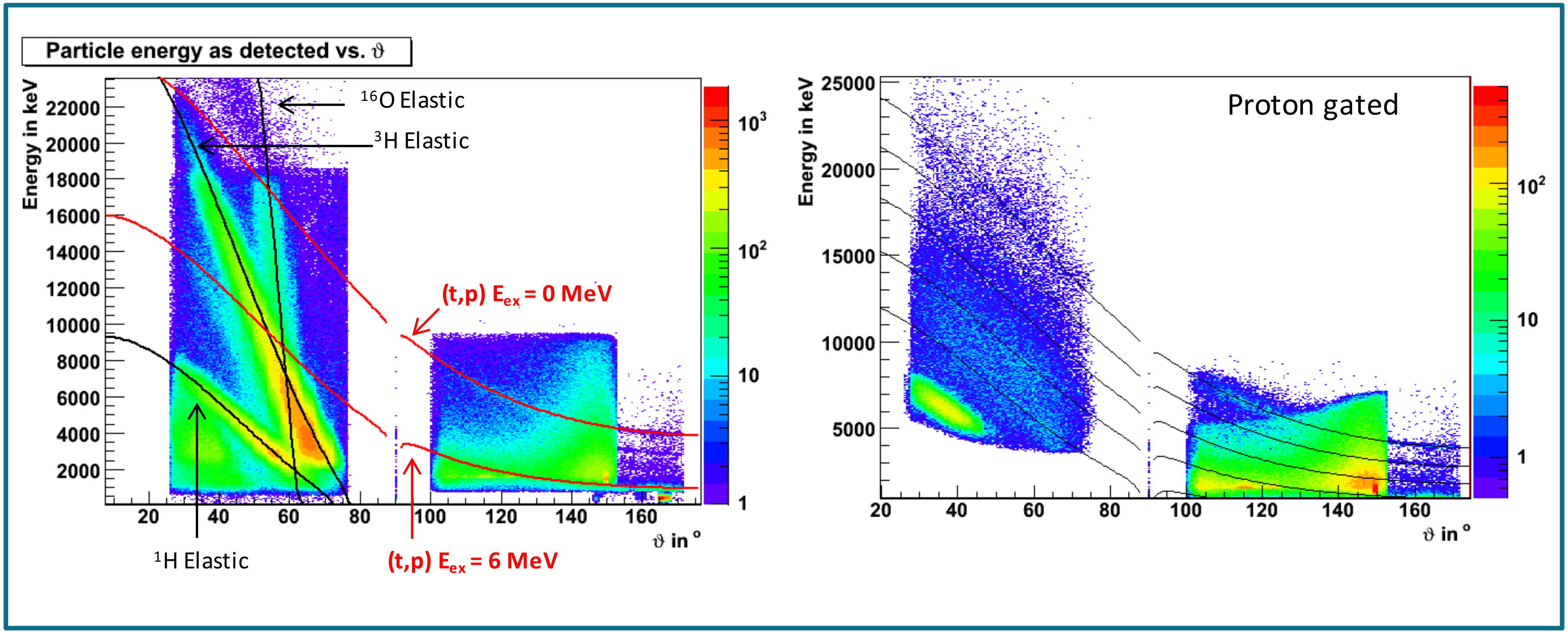
Particle spectra

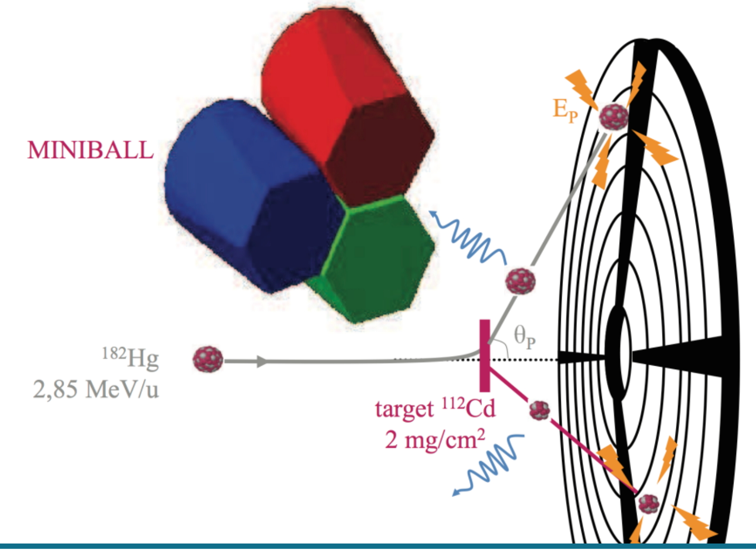
PhD of Jytte Elseviers (KU Leuven)

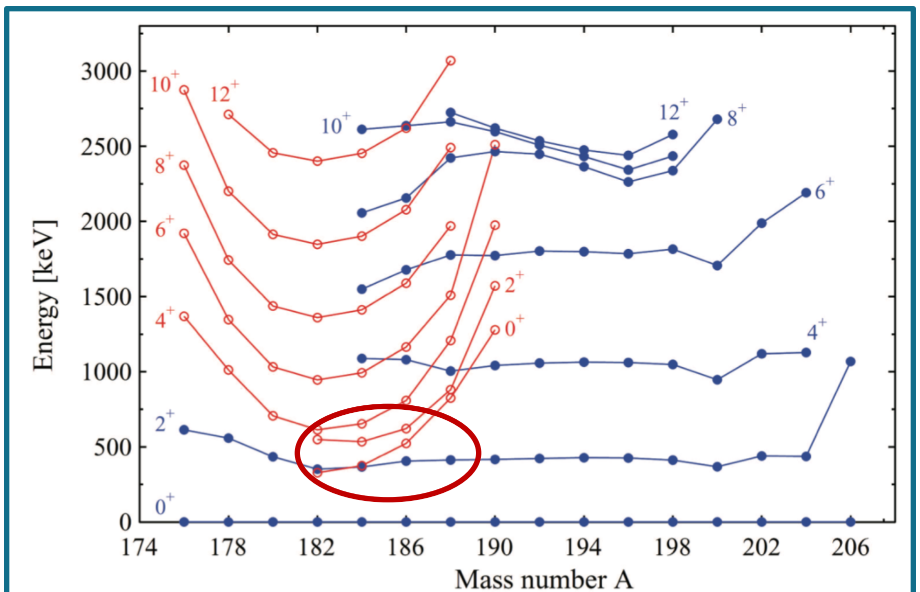


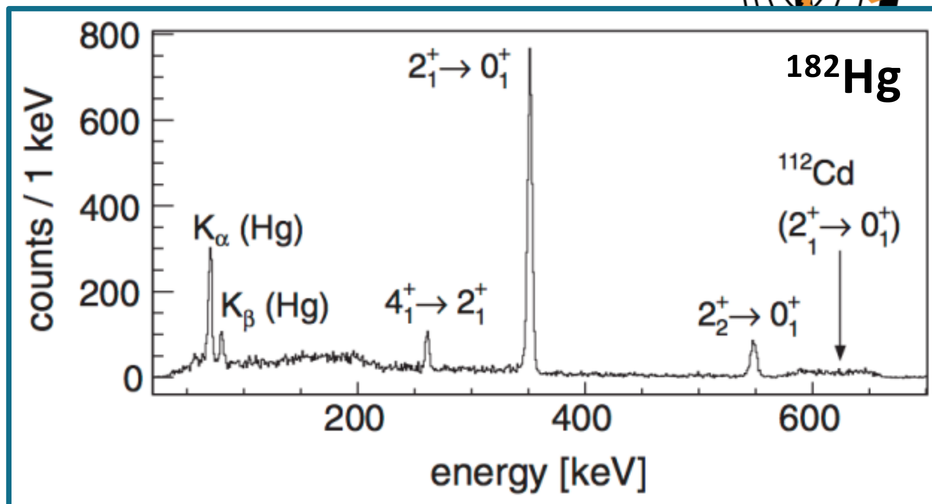
Coulex $^{182\text{-}188}$Hg

N. Bree, PRL 112, 162701 (2014)

- Coulomb excitation:
  nature of quadrupole deformation
  mixing of states with different structure
- Clarify those Hg isotopes:
  No mixing between 0^+ states
  Mixing of 2^+ states (E0 strengths)
- $^{182\text{-}188}$Hg at REX-ISOLDE (PhD thesis N. Bree)

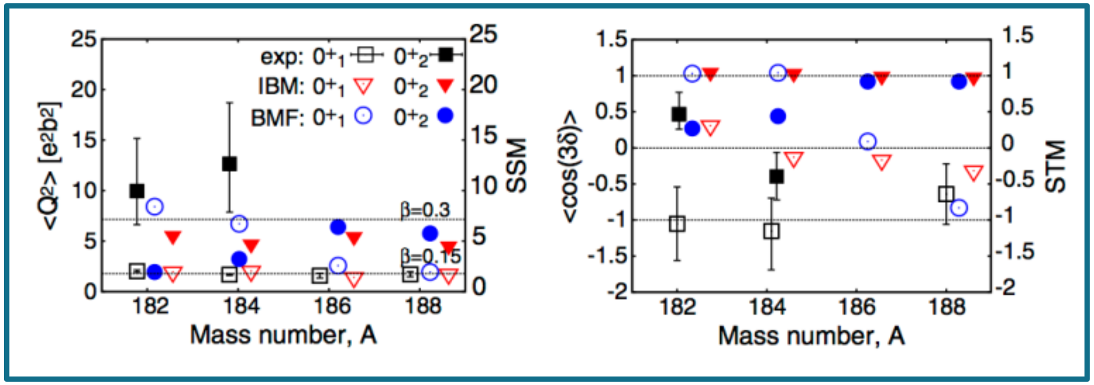




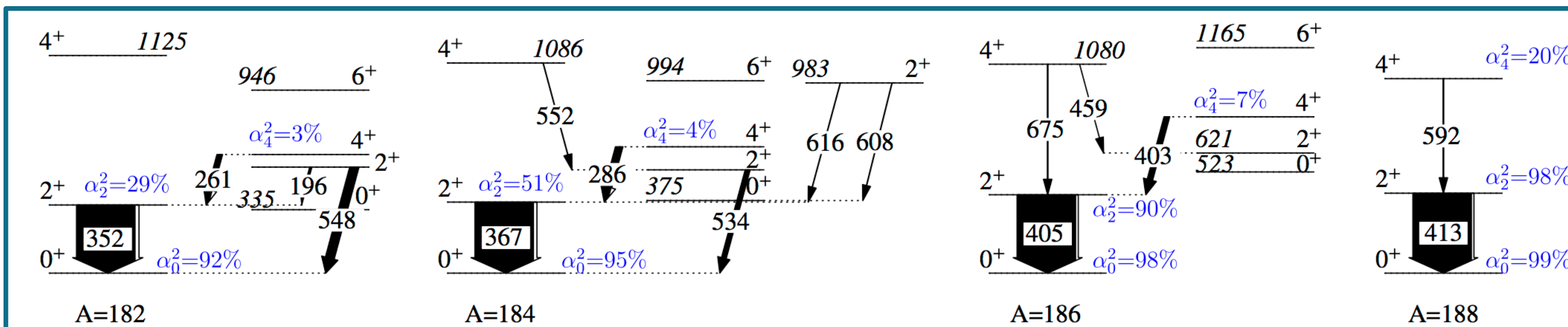


Shape coexistence in n-deficient Pb region

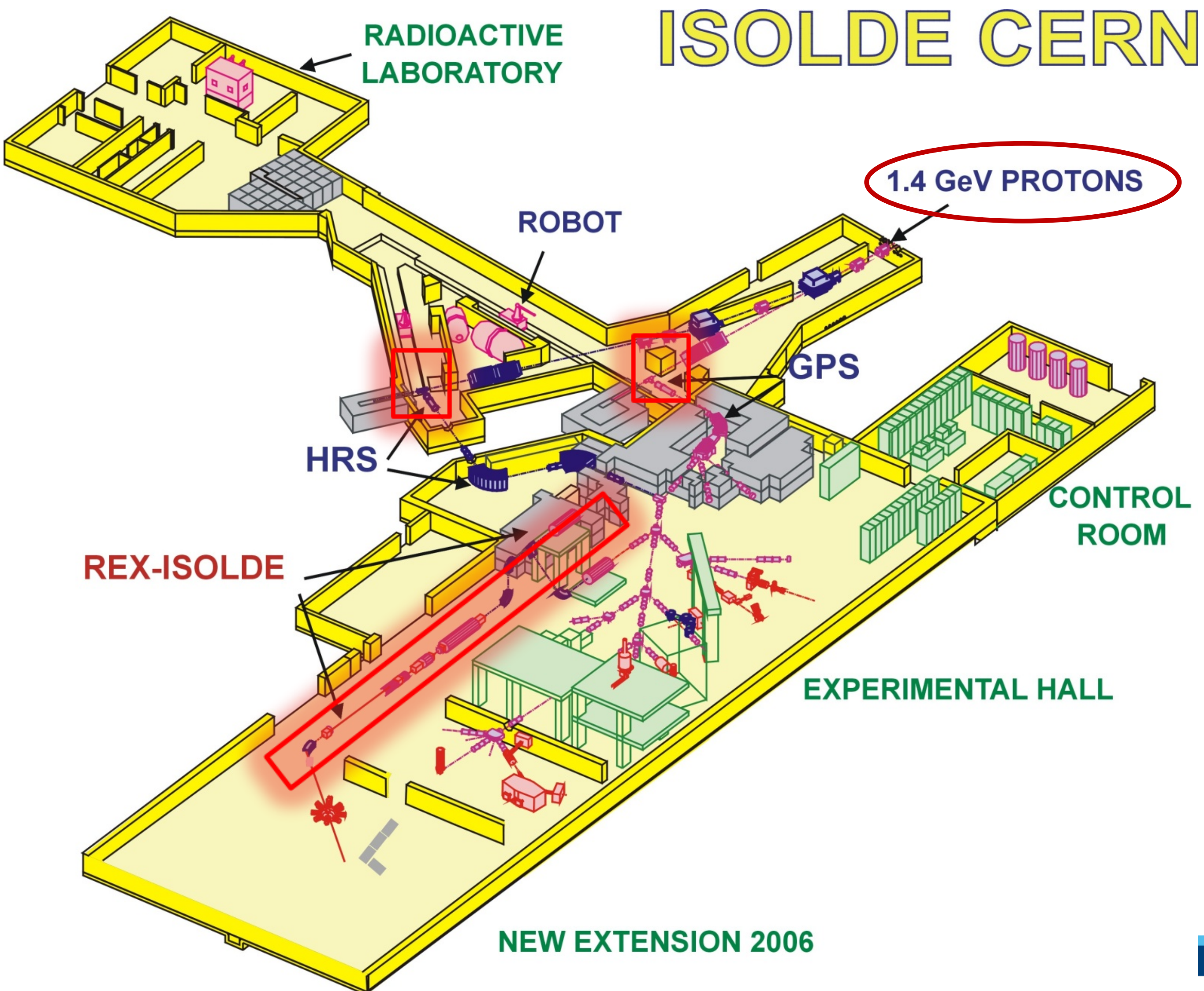
- Radii Hg: **→ Thomas Day Goodacre**, later this evening
- Coulex: **→ Kasia Wrzosek-Lipska**, Friday evening
  - $^{182-188}$Hg: N. Bree, PRL 112, 162701 (2014)



- 0^+_1 slightly oblate
- 0^+_2 more deformed (prolate?)
- The 2^+ changes character!
- Small mixing in the g.s. keeps $E(2^+)$ and $B(E2)$ constant

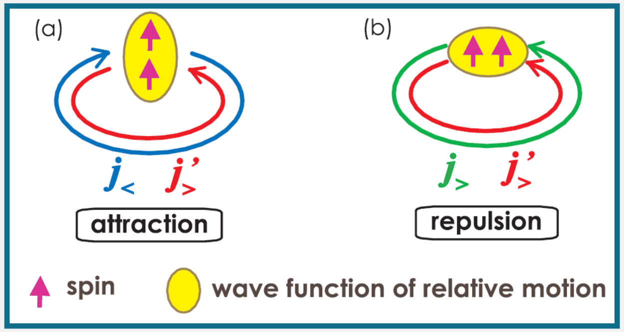


Measurements: ISOLDE @ CERN

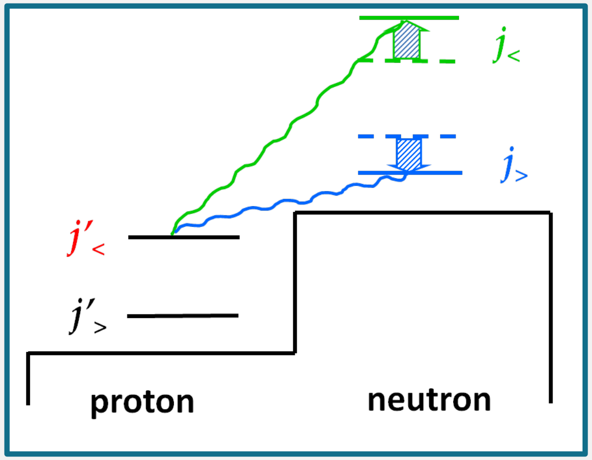


New aspects of the interaction

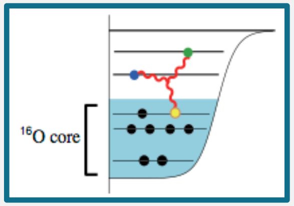
- Tensor interaction (only if S=1)



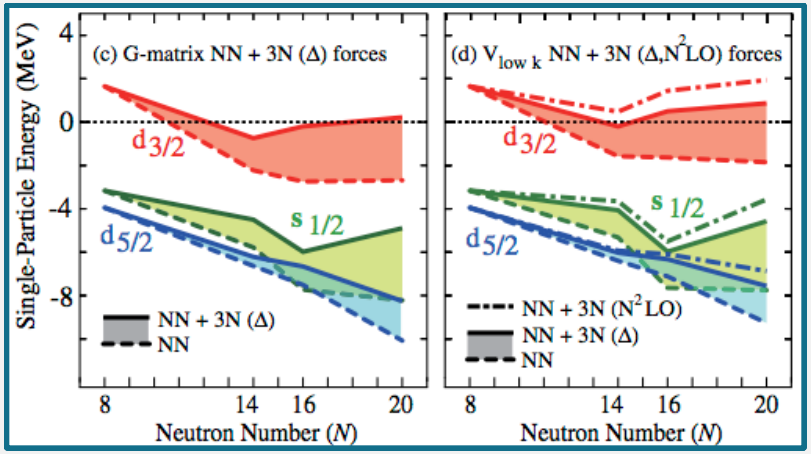
T. Otsuka et al., PRL 95 (2005) 232502

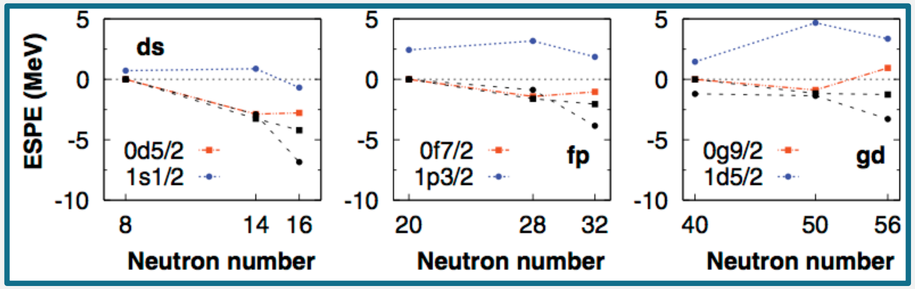


- 3-body forces



T. Otsuka et al., PRL 105 (2010) 032501





K. Sieja & F. Nowacki, PRC 85 (2012) 051301(R)

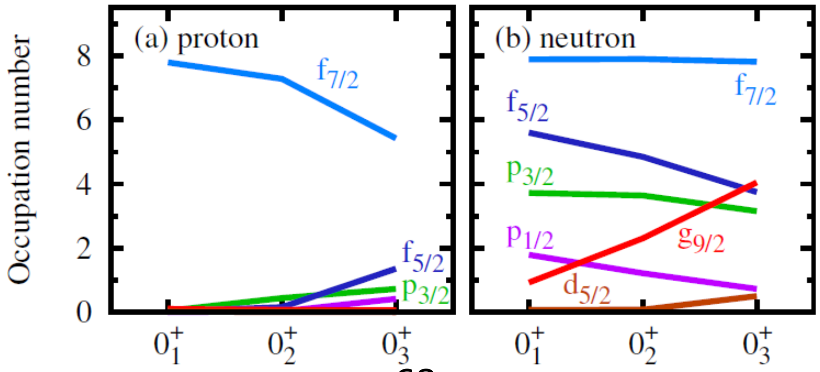
BriX

Shell evolution and deformation

PHYSICAL REVIEW C **89**, 031301(R) (2014)

Novel shape evolution in exotic Ni isotopes and configuration-dependent shell structure

Yusuke Tsunoda,[1] Takaharu Otsuka,[1,2,3] Noritaka Shimizu,[2] Michio Honma,[4] and Yutaka Utsuno[5]
[1] *Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2] *Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[3] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[4] *Center for Mathematical Sciences, University of Aizu, Ikki-machi, Aizu-Wakamatsu, Fukushima 965-8580, Japan*
[5] *Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
(Received 19 September 2013; revised manuscript received 25 November 2013; published 17 March 2014)



^{68}Ni

"Type II" shell evolution

- Deformation can induce changes in occupancy…
- which, through the tensor interaction, modifies the gaps between shells

Shape coexistence and nature of 0^+ states

K. Heyde & J. Wood , Rev. Mod. Phys. 83 (2011) 1467

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