

# Direct reactions with exotic nuclei

## Recent results and future plans at HIE-ISOLDE

Riccardo Raabe

Instituut voor Kern- en Stralingsfysica, KU Leuven



ISOLDE Workshop  
and Users meeting 2013

# Direct reactions: transfer

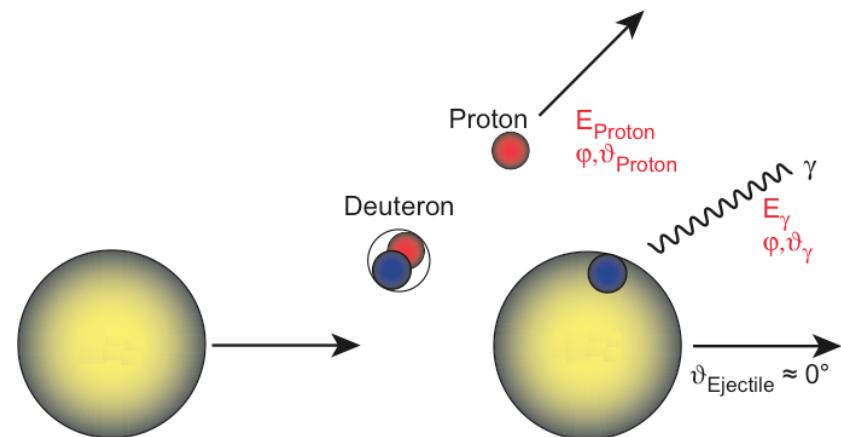
- **Direct reactions at ISOLDE**

- Elastic scattering

- Coulomb excitation (inelastic)

- Transfer reactions**

- From light to heavy nuclei...



- $Q$ -values  $\Rightarrow$  position of levels
- Angular distribution  $\Rightarrow$  spin and parities
- Cross sections
  - $\Rightarrow$  (relative) spectroscopic factors, ANCs
  - $\Rightarrow$  single-particle character of states, centroids of single-particle strengths

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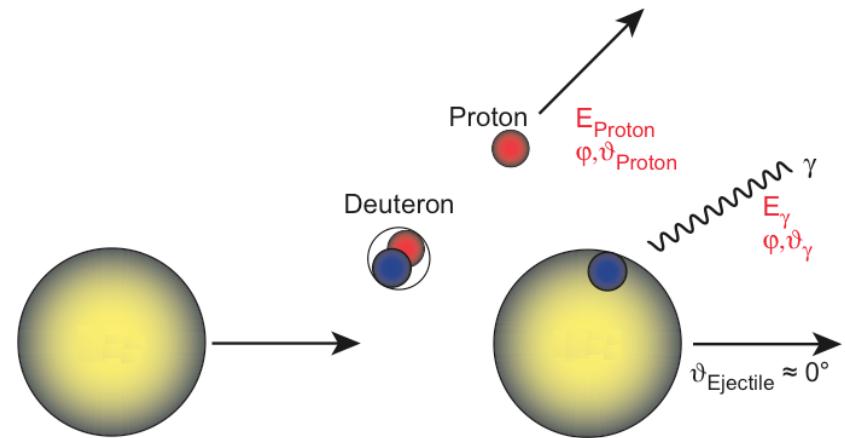
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# Detection setup at REX-ISOLDE

## Miniball

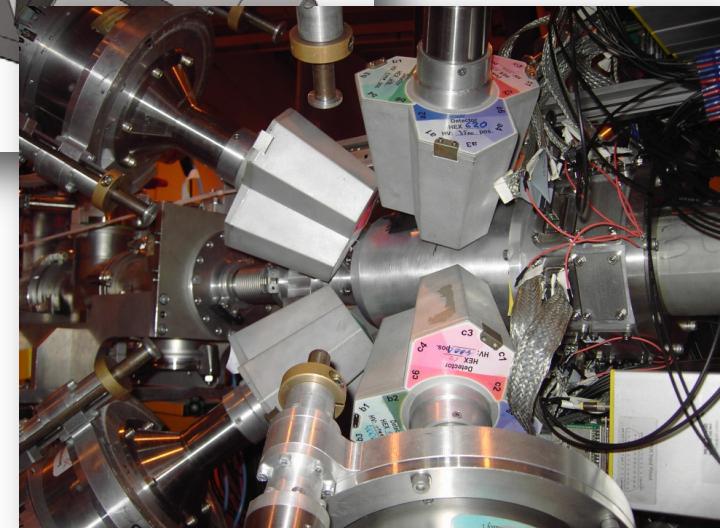
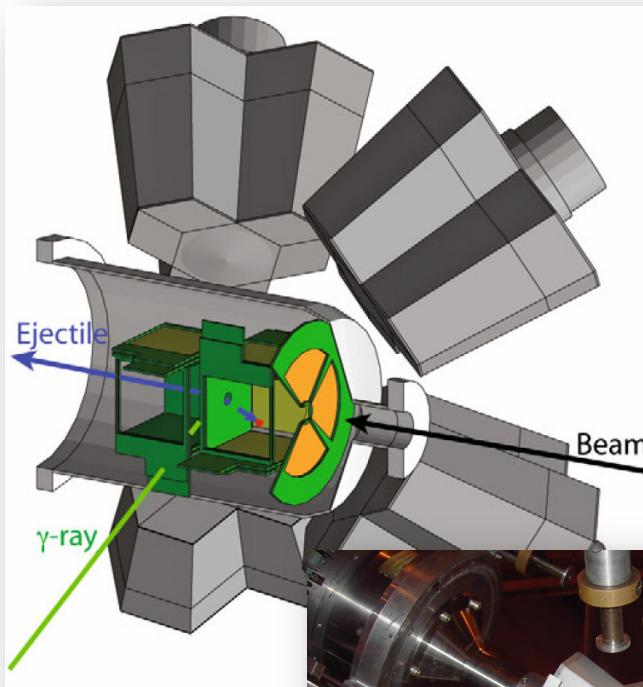
N. Warr et al, EPJA 49 (2013) 40

- 24 HPGe
- 6-fold segmented
- $\varepsilon \approx 8\% @ 1.3 \text{ MeV}$

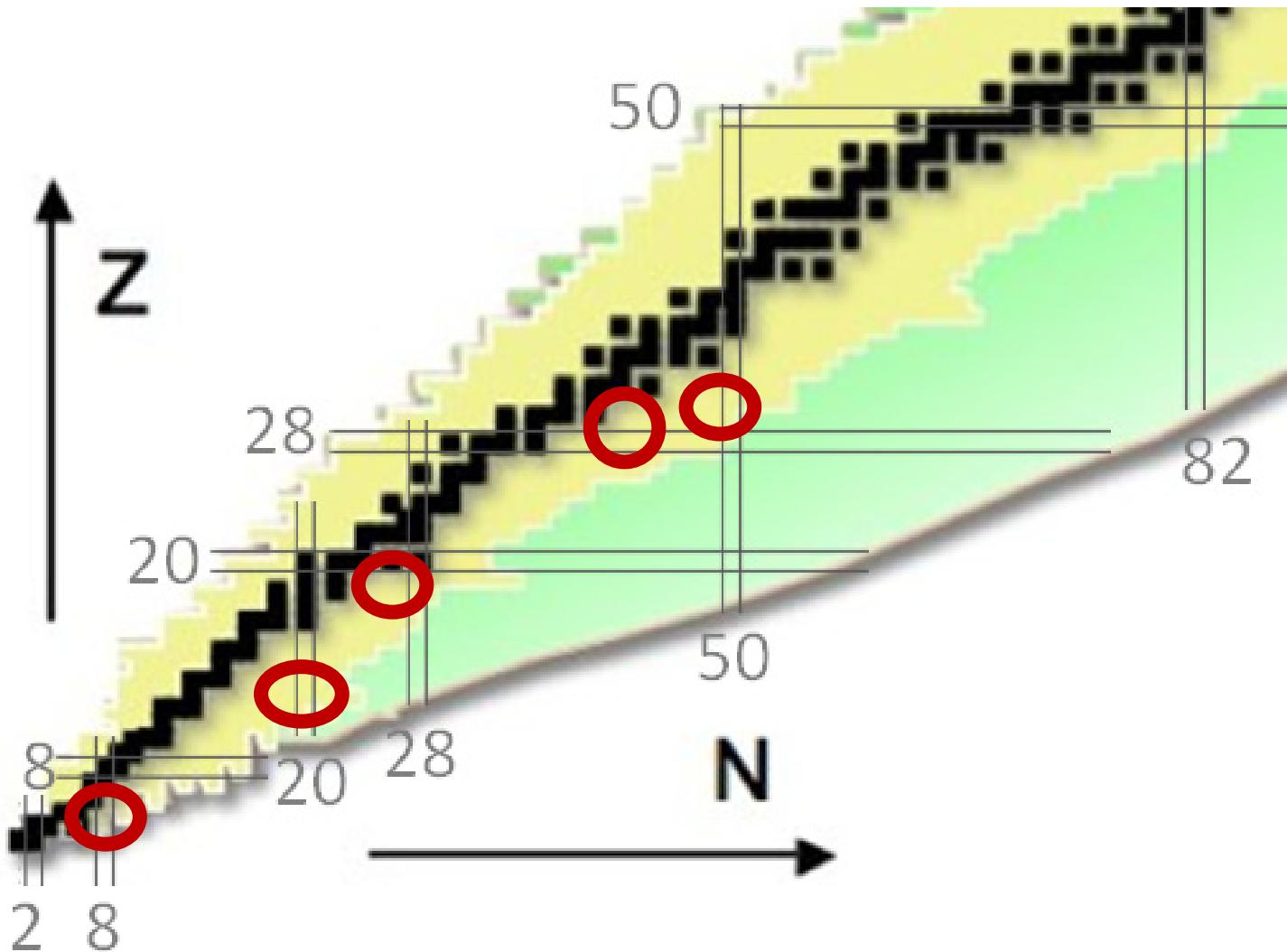
## T-ReX

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

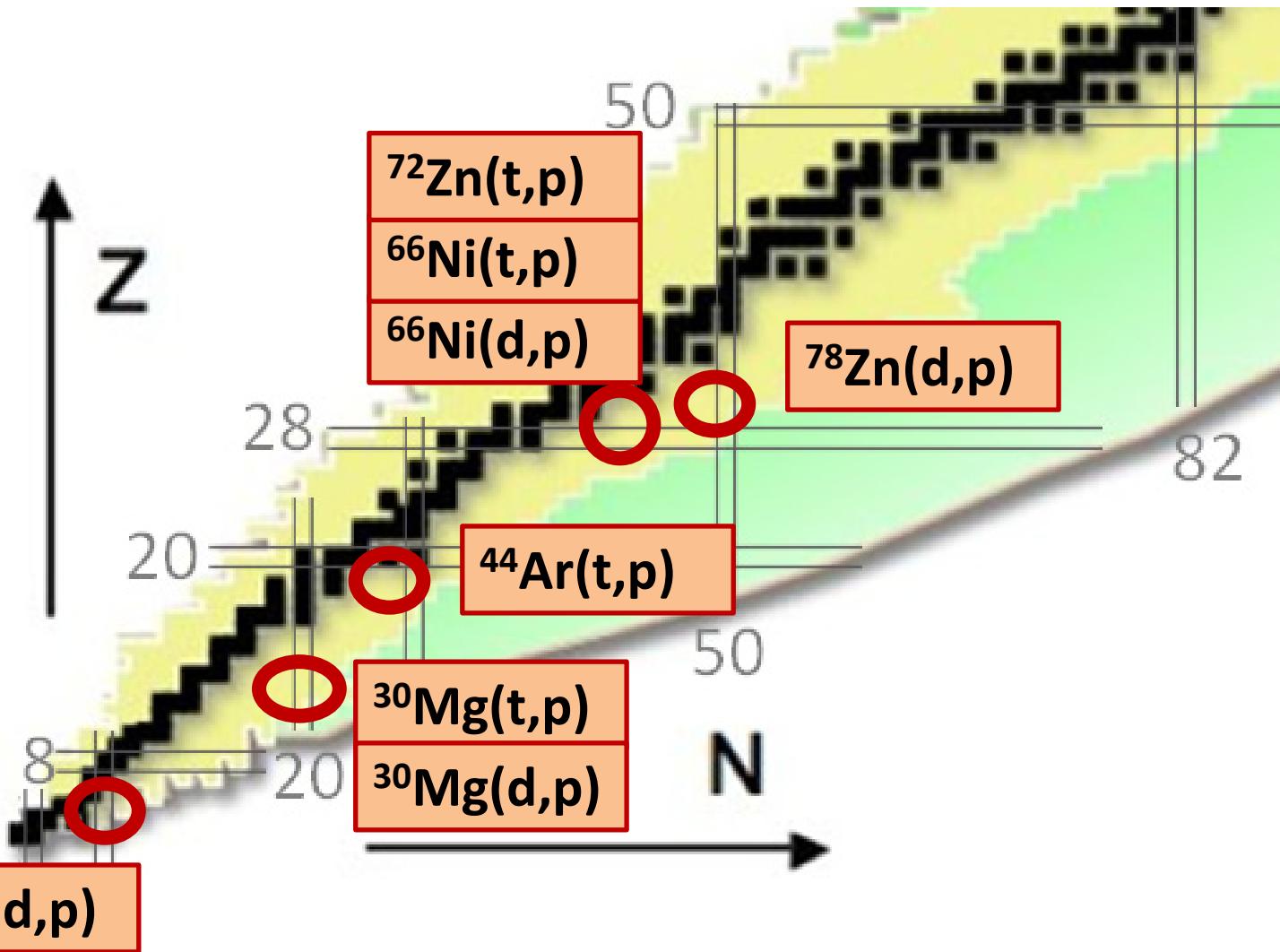
- Resolution  $\approx 1\text{-}6 \text{ deg}$
- $\Delta E - E$  for PID
- $\varepsilon \approx 60\%$



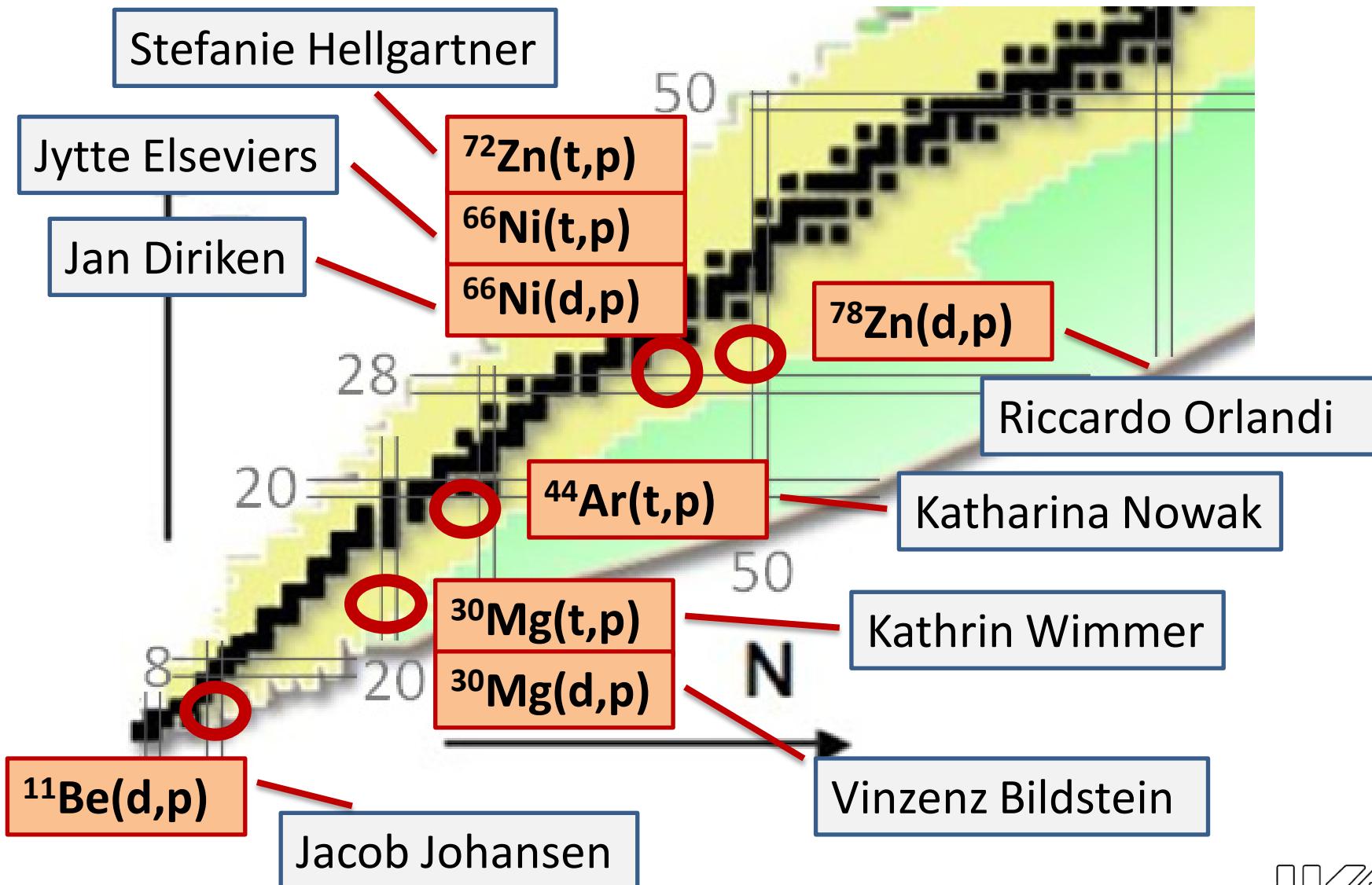
# Transfer reactions at REX



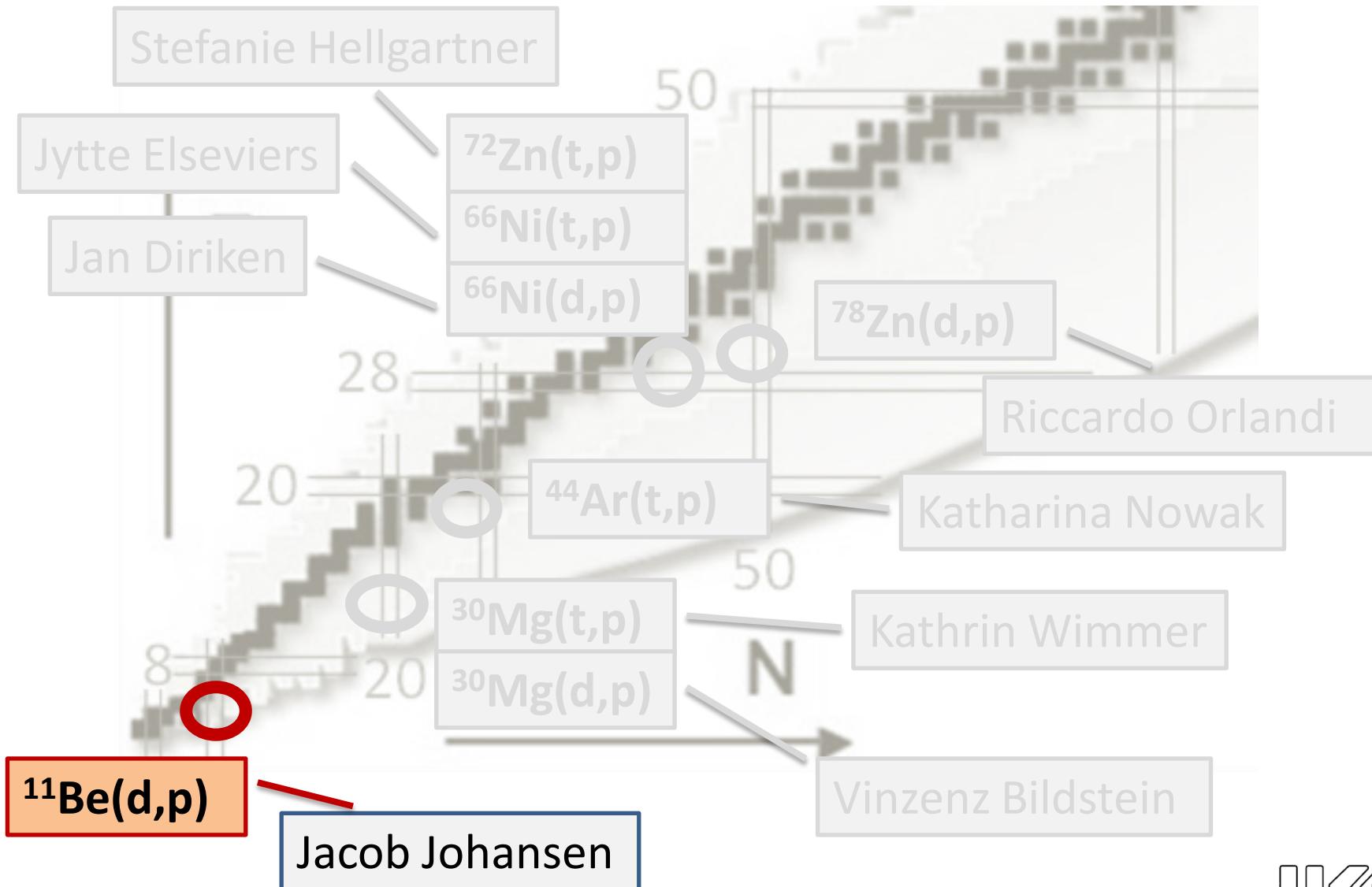
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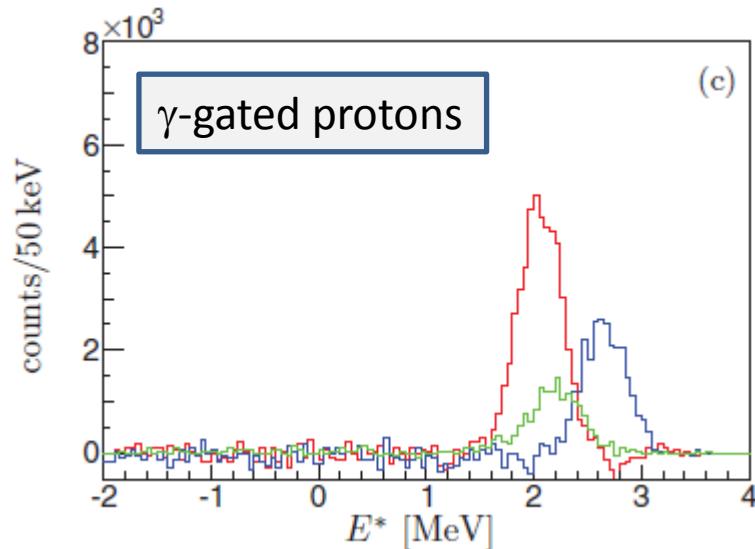
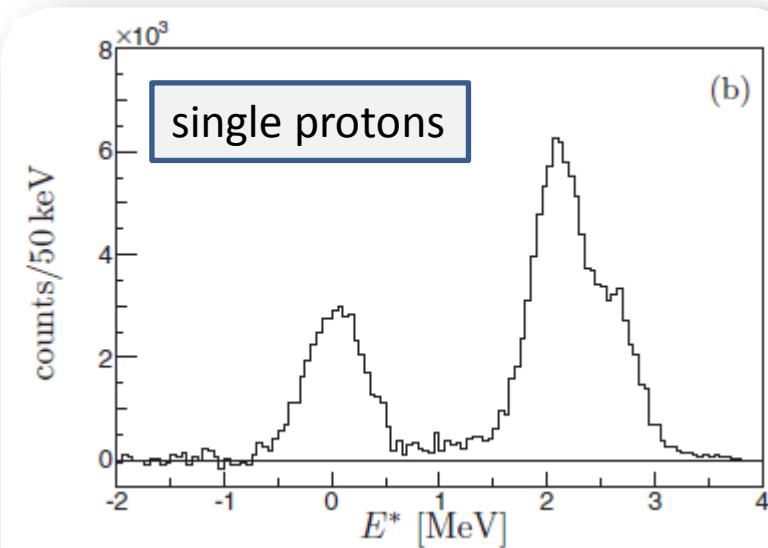
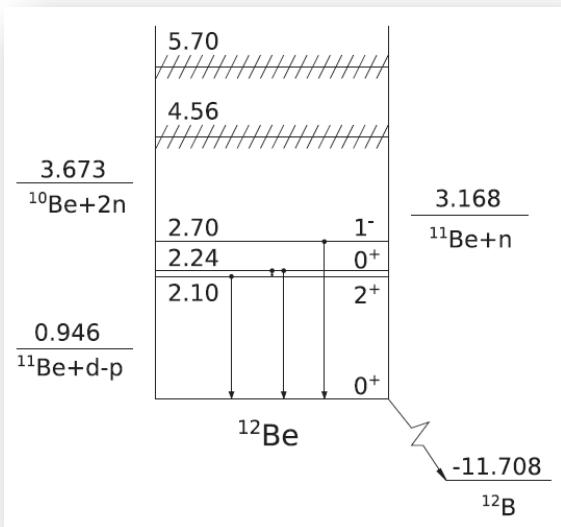
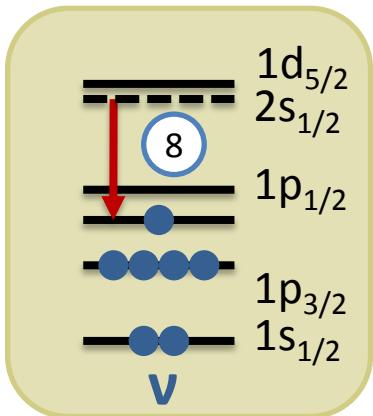
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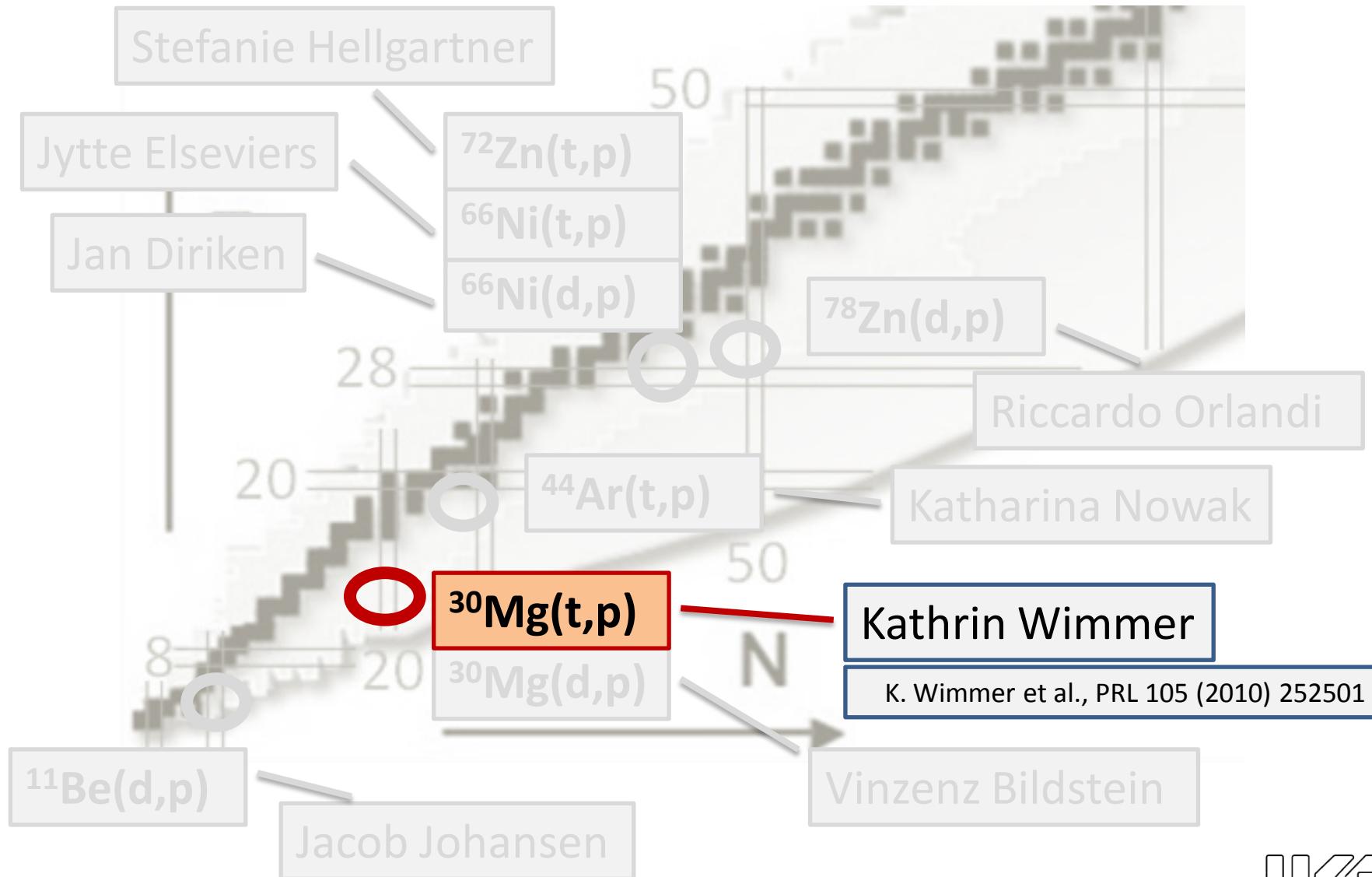
# $^{11}\text{Be}(\text{d},\text{p})$ 2.8 MeV/u

J.G. Johansen et al, PRC 88 (2013) 044619

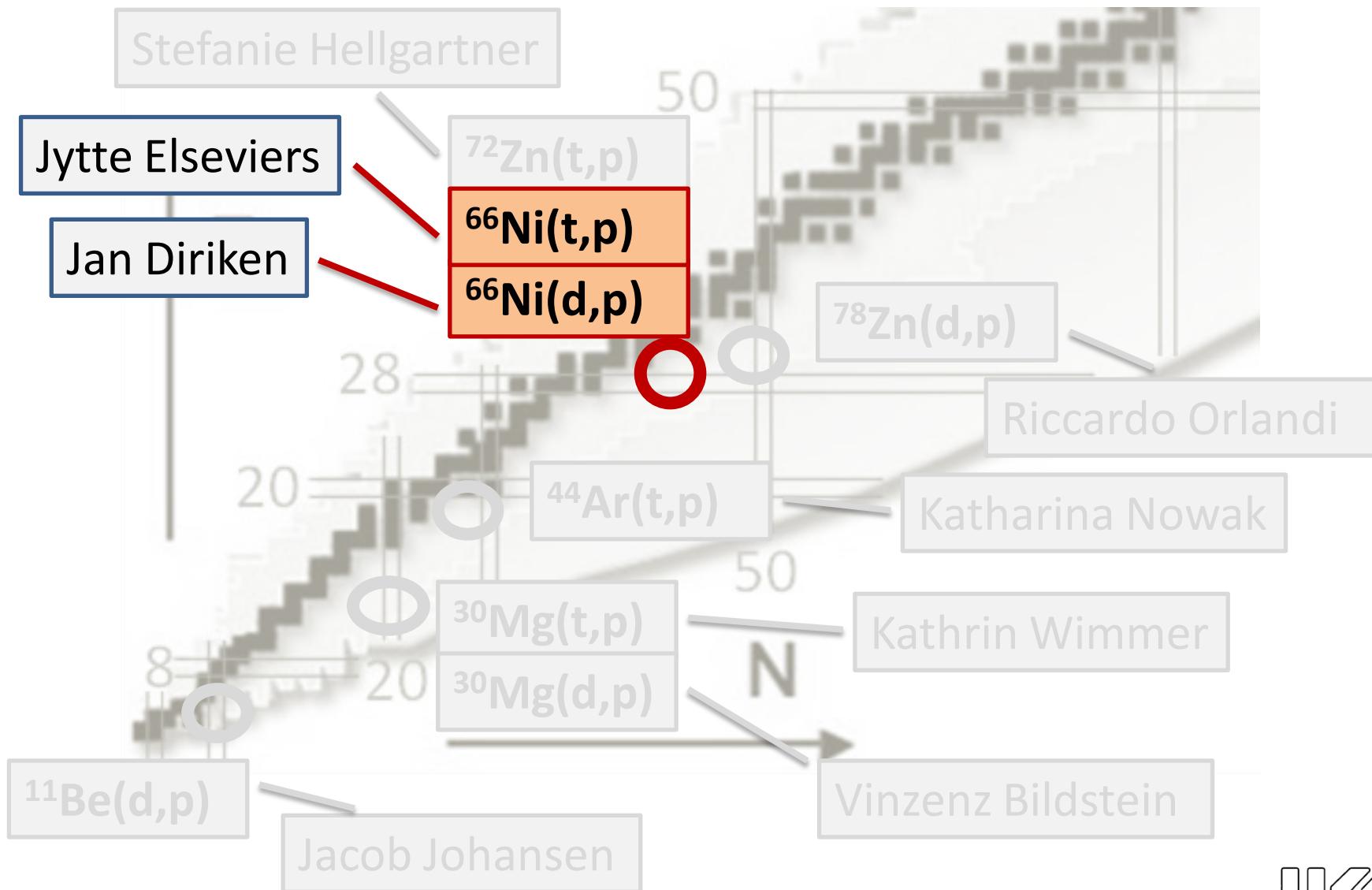
- Structure of bound states in  $^{12}\text{Be}$  ?
- $^{11}\text{Be}$  is  $1/2^+$
- Addition of one neutron:  
 $\Rightarrow$  cross section to  $0^+ \propto (s_{1/2})^2$



# Transfer reactions at REX



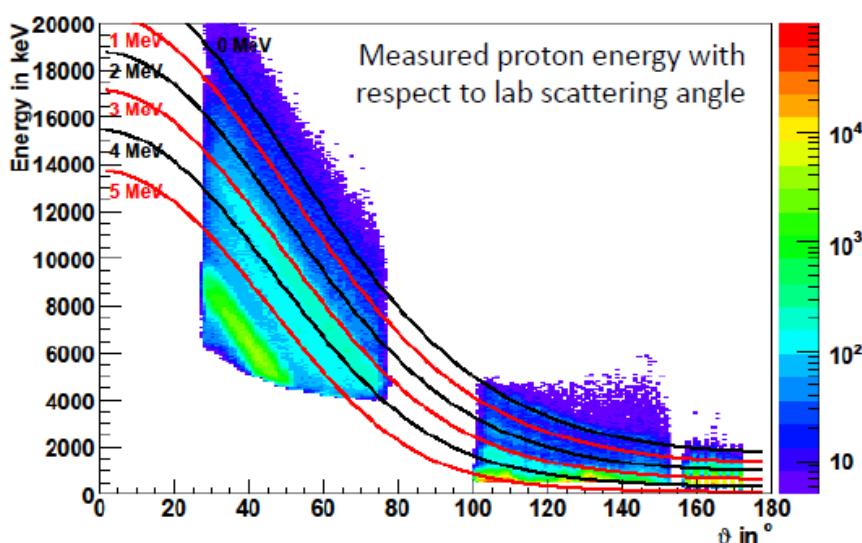
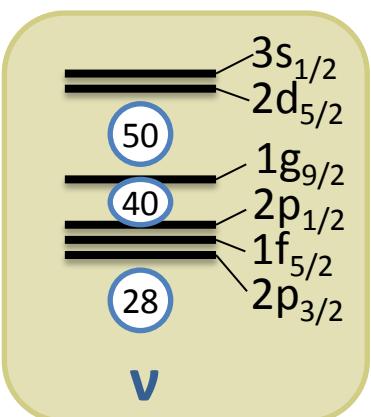
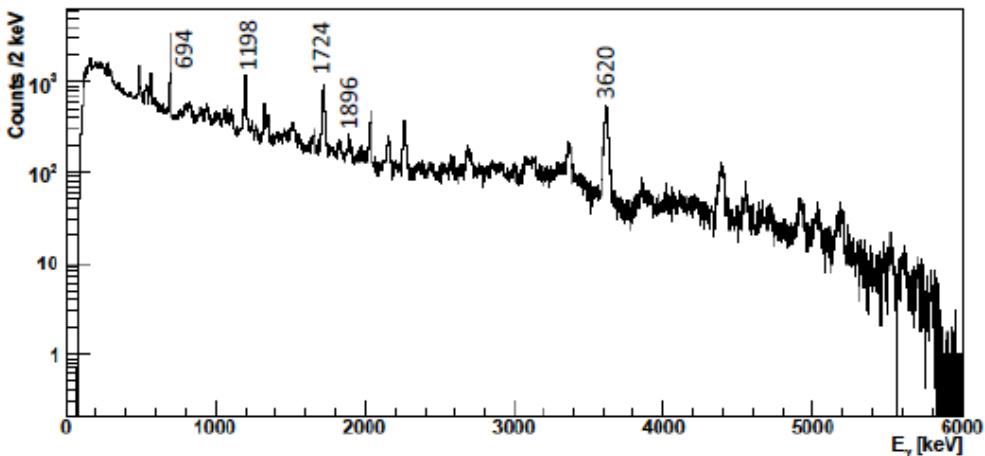
# Transfer reactions at REX



# $^{66}\text{Ni}(\text{d},\text{p})$ 2.85 MeV/u

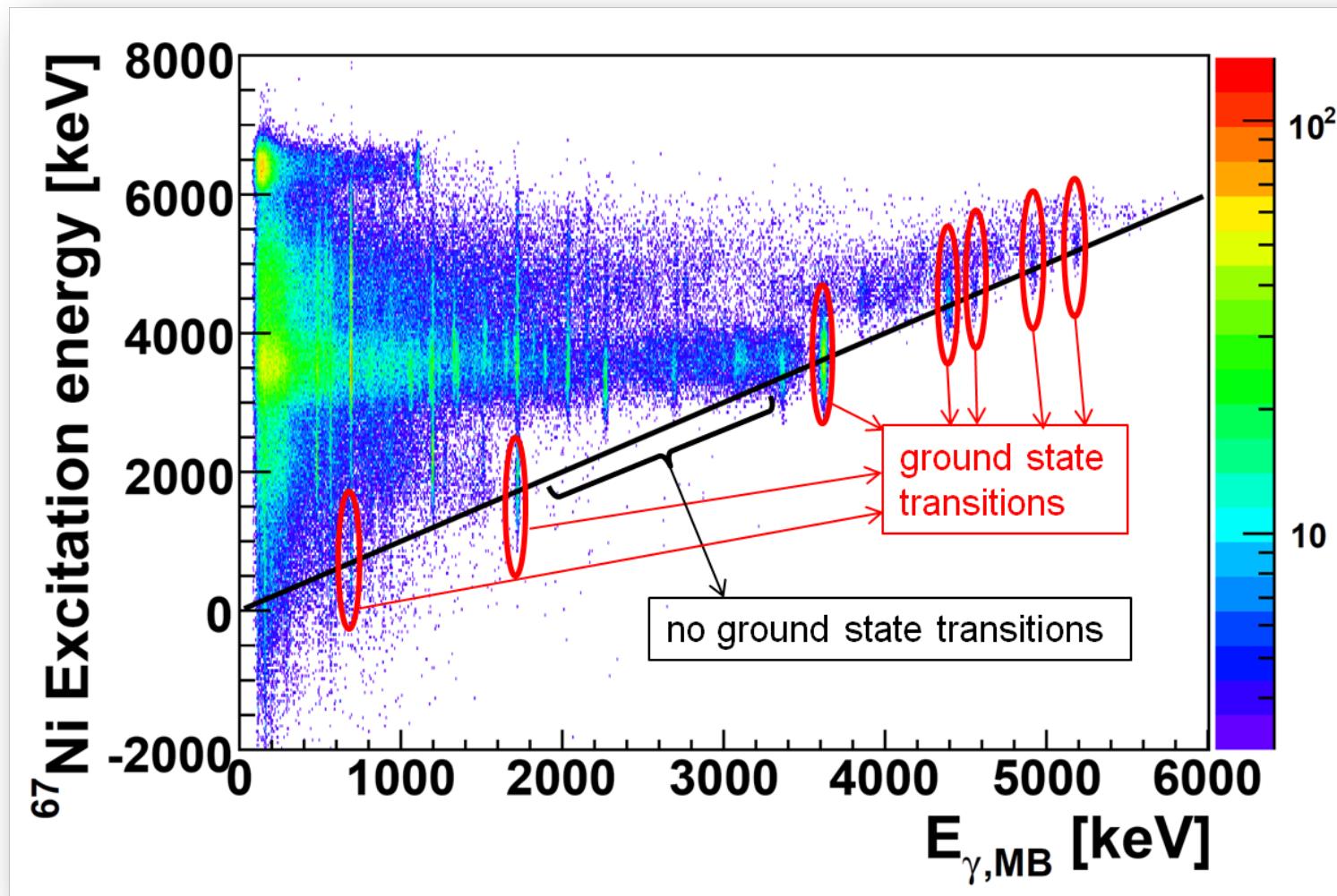
PhD of Jan Diriken (KU Leuven)

- Single particle energies around  $^{68}\text{Ni}$
- $g_{9/2}$ - $d_{5/2}$ - $s_{1/2}$  sequence favours collectivity
- ⇒ Determine  $g_{9/2}$  and  $d_{5/2}$  strength distribution

Proton-gated Doppler corrected  $\gamma$ -ray spectrum

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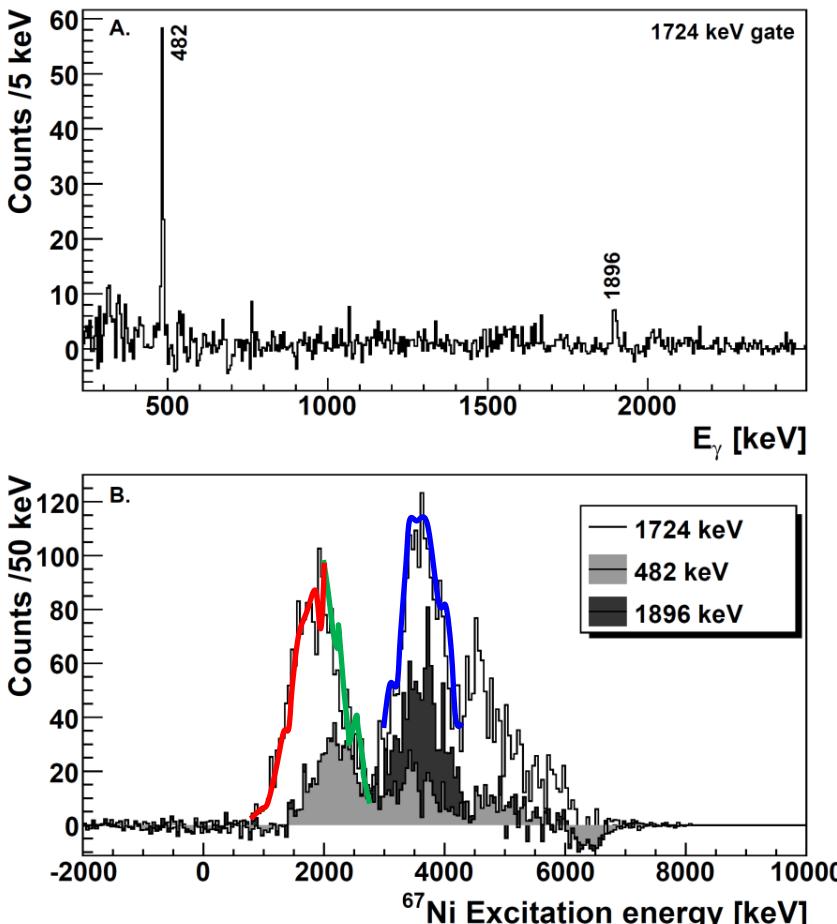
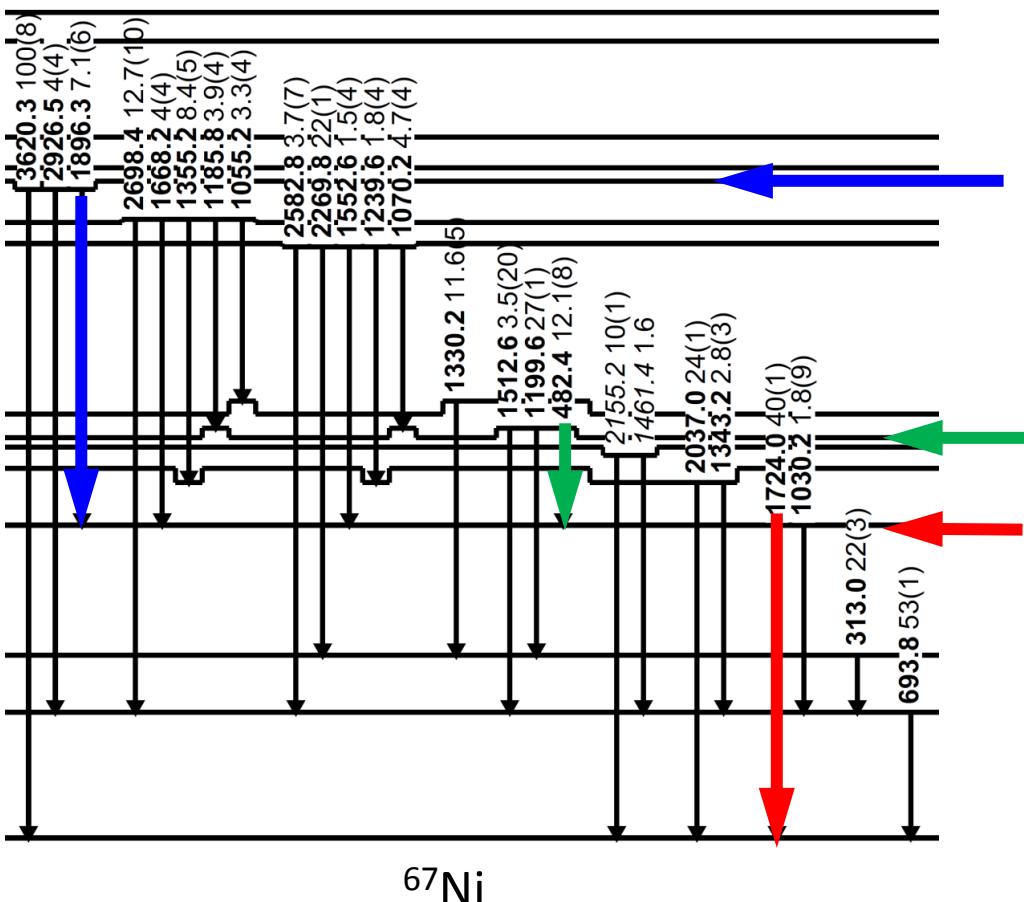
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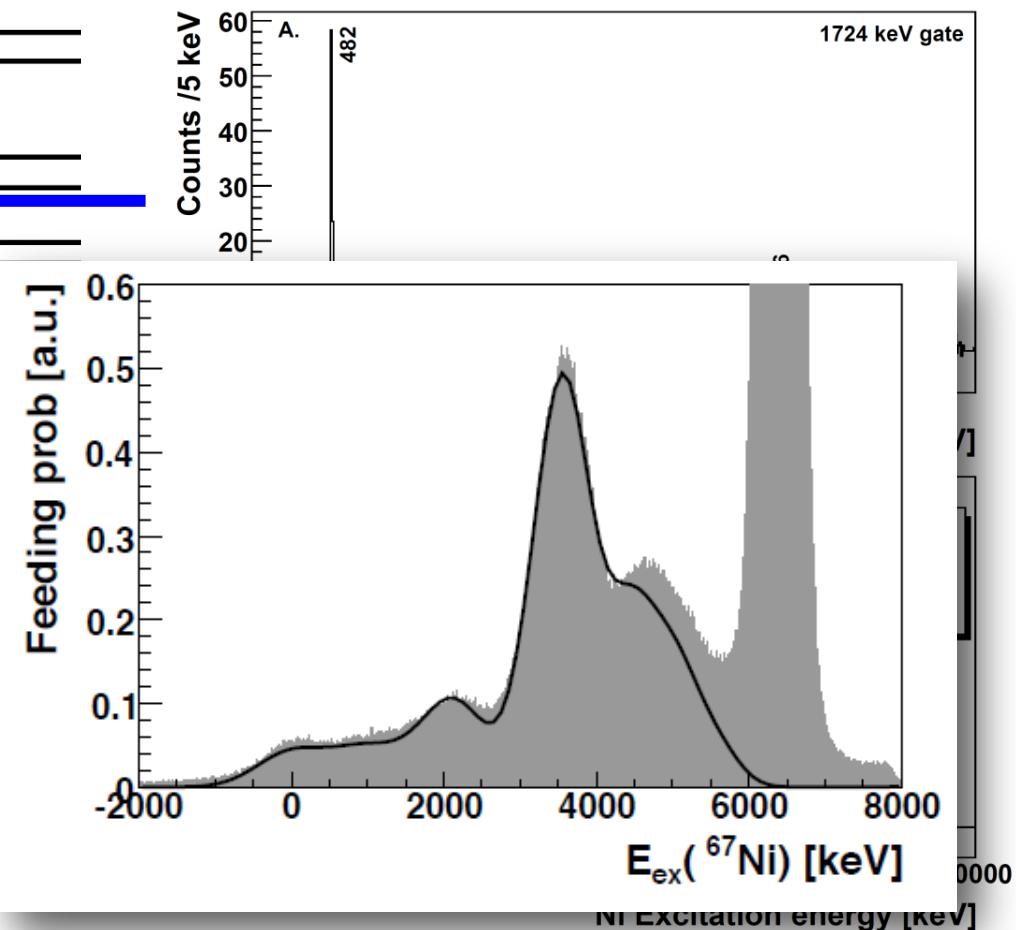
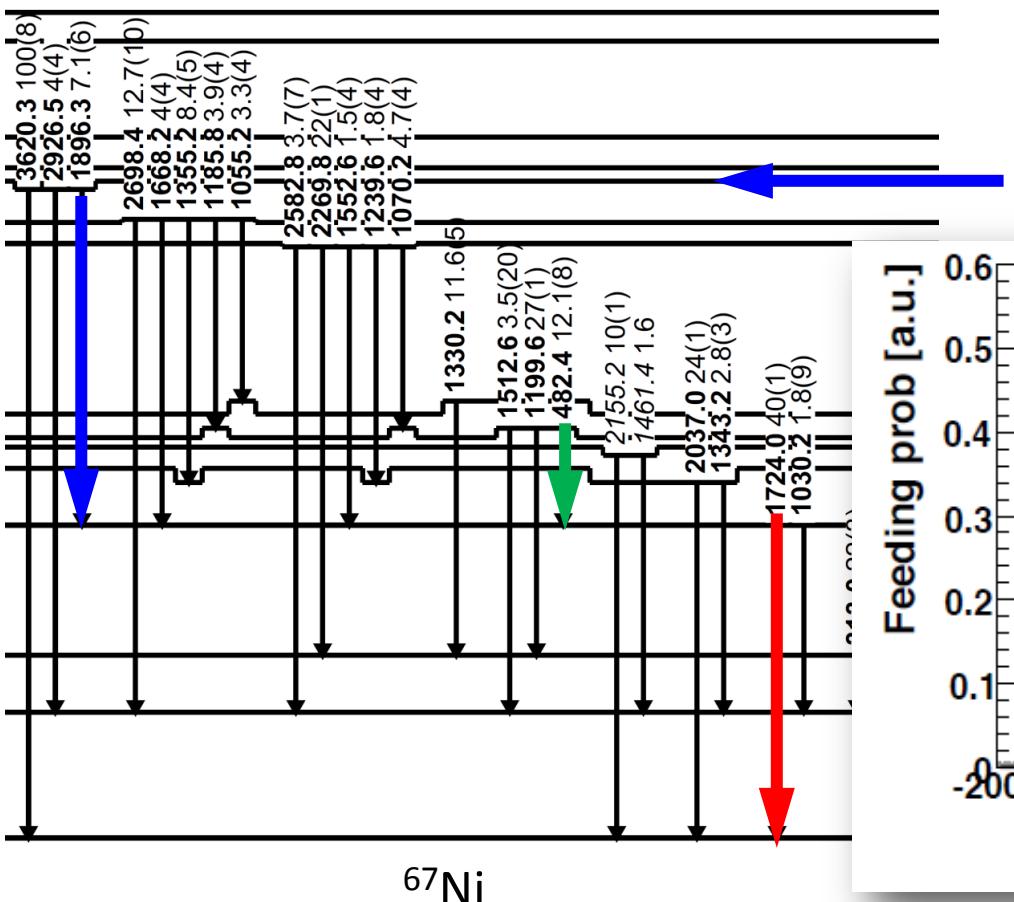
## Building the level scheme



# $^{66}\text{Ni}(\text{d},\text{p})$ 2.85 MeV/u

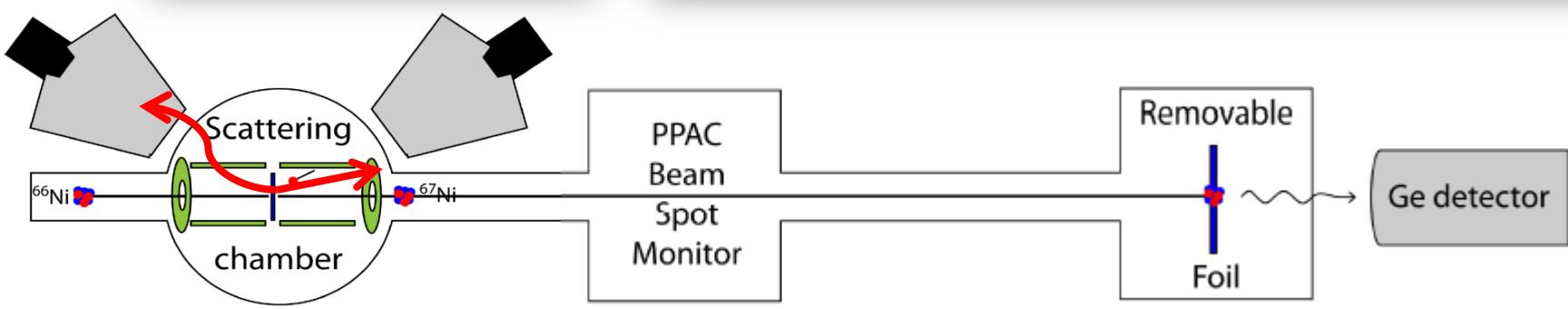
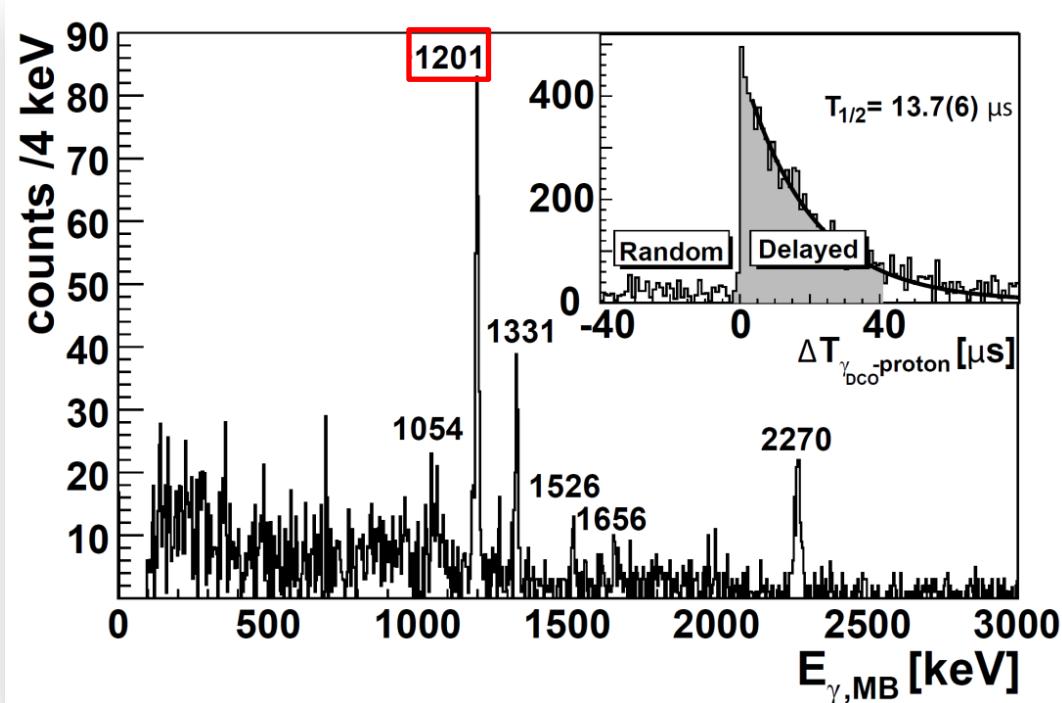
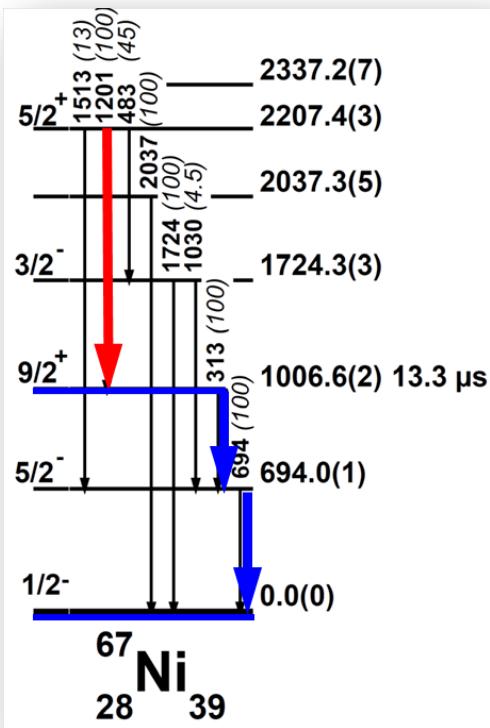
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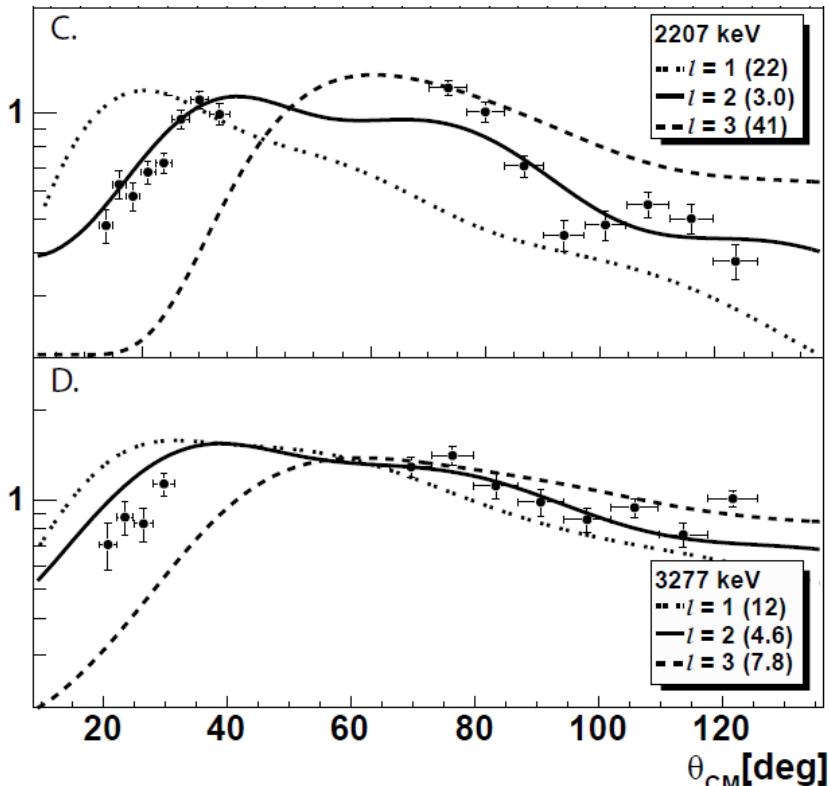
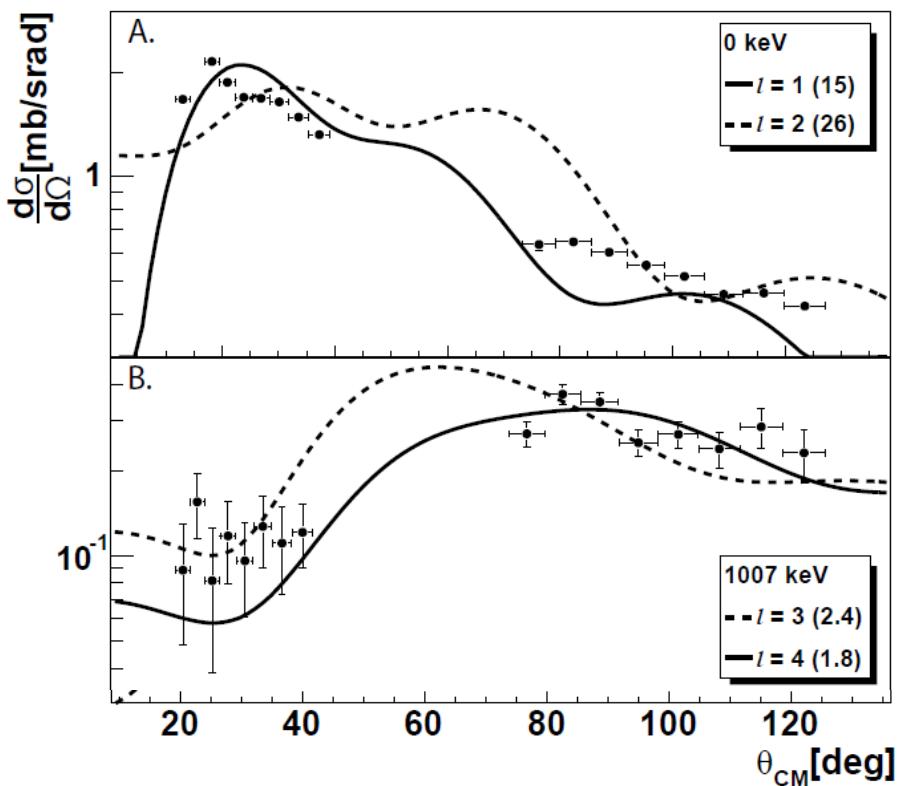
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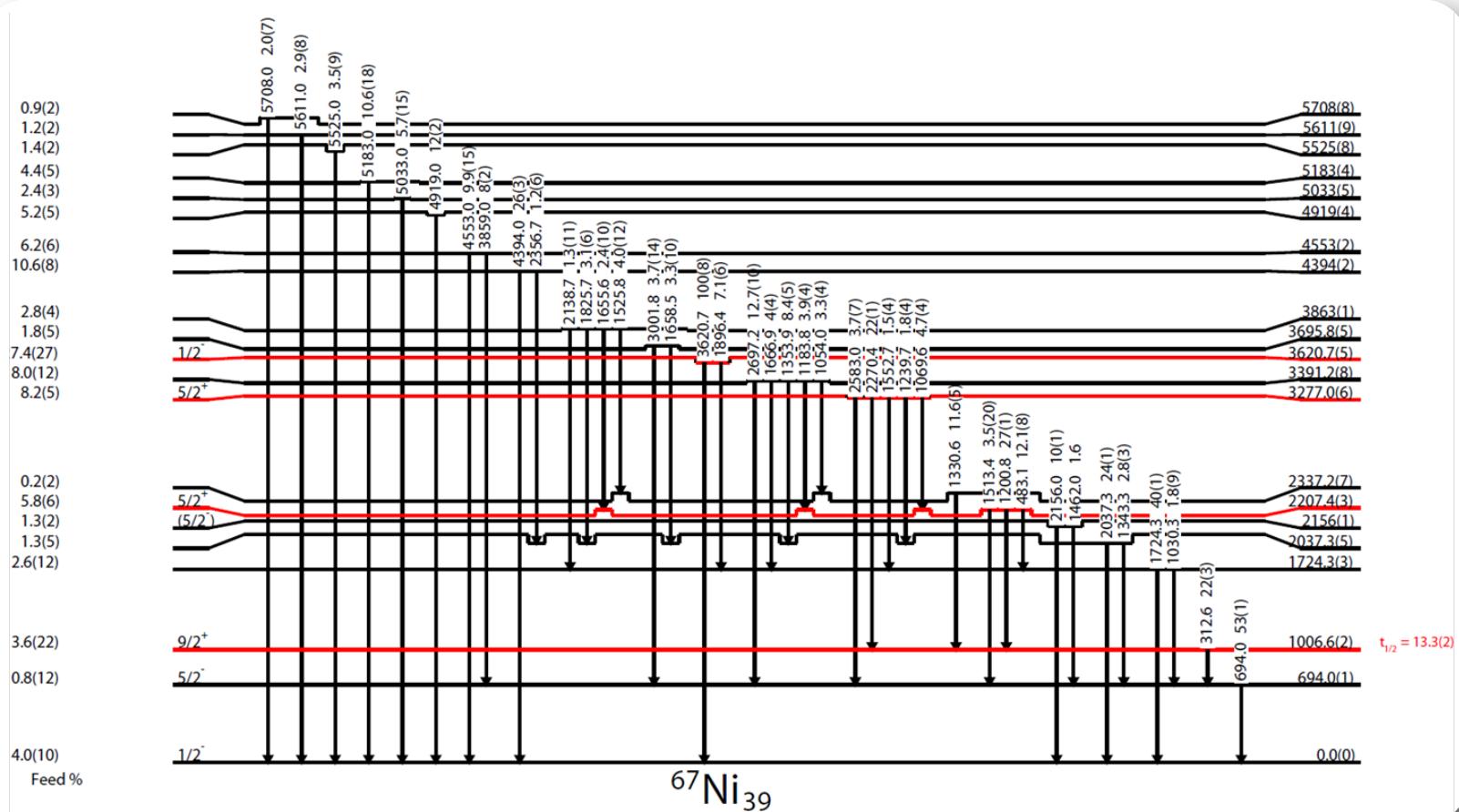
PhD of Jan Diriken (KU Leuven)

Angular distributions (and  $\gamma$  transitions): spin and parity



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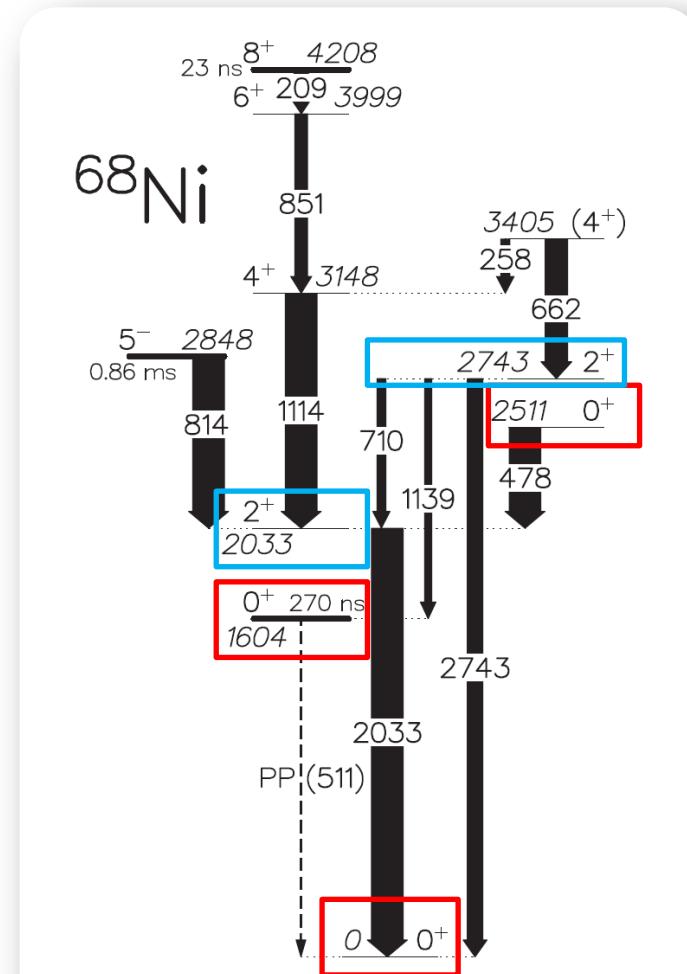


- Identification of  $d_{5/2}$  (and  $s_{1/2}$ ) strength
- $g_{9/2}$ - $d_{5/2}$  gap at  $\approx 2.6$  MeV, larger than shell model calculations

# $^{66}\text{Ni}(t,p)$ 2.6 MeV/u

PhD of Jytte Elseviers (KU Leuven)

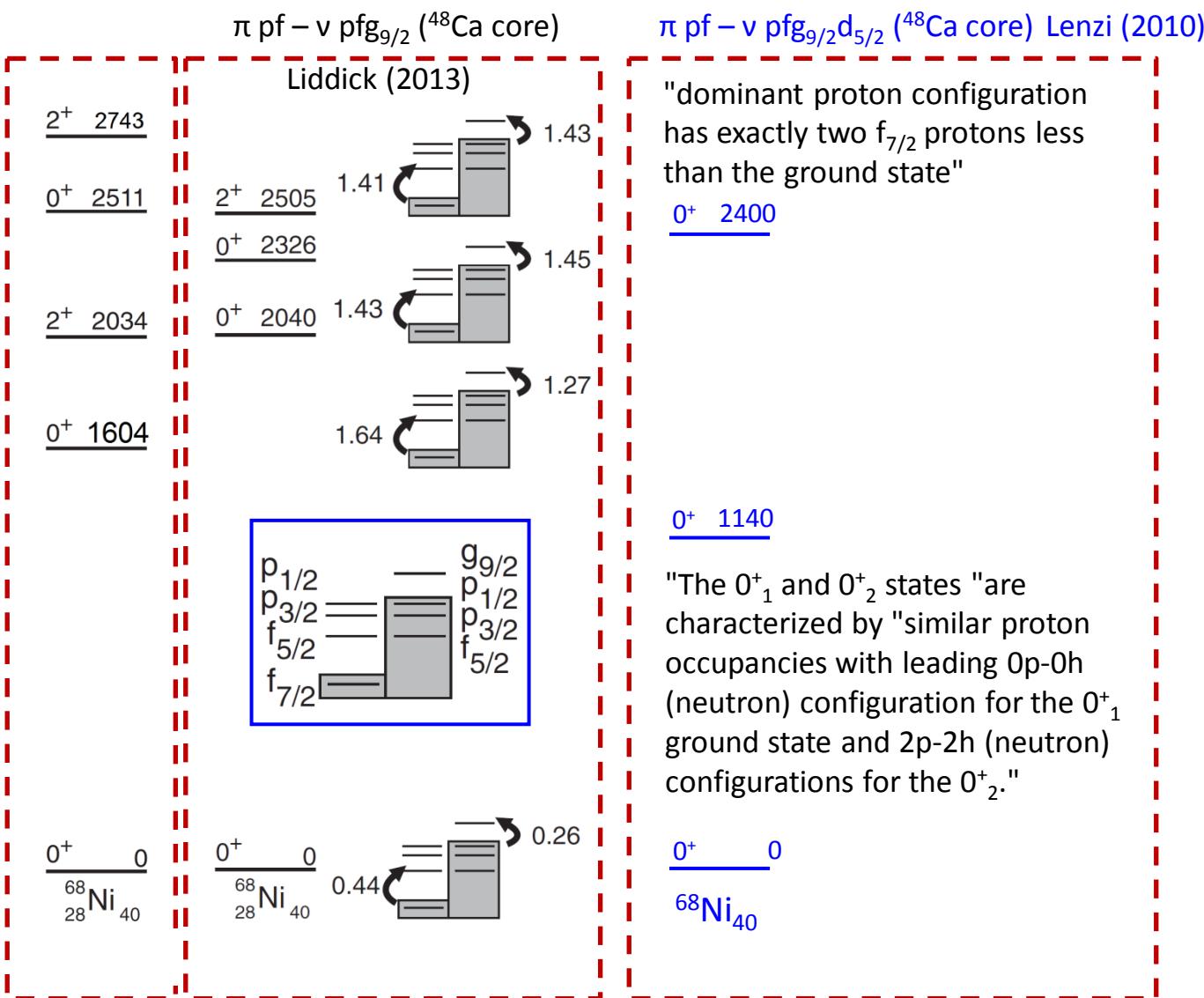
- Characterize  $0^+$  (and  $2^+$ ) states in  $^{68}\text{Ni}$
- Recent experimental results:
  - S. Suchyta et al., submitted to PRL (2013)
  - F. Flavigny et al., in preparation
  - F. Recchia et al., PRC 88, 041302R (2013)
  - R. Broda et al., PRC 86, 064312 (2012)
  - C. J. Chiara et al., PRC 86, 041304R (2012)
  - A. Dijon et al., PRC 85, 031301R (2012)
- Theoretical works:
  - S.M. Lenzi et al., PRC 82 (2010) 054301
  - S.N. Liddick et al., PRC 87 (2013) 014325



F. Recchia et al, PRC 88 (2013) 041302R

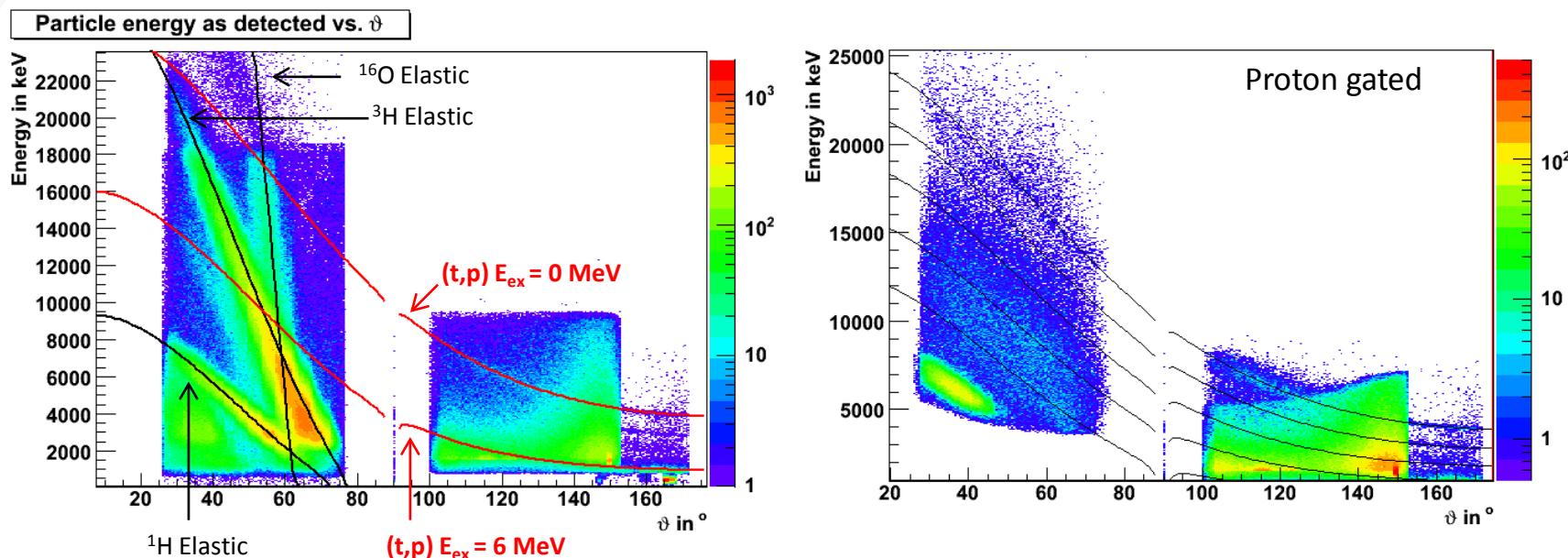
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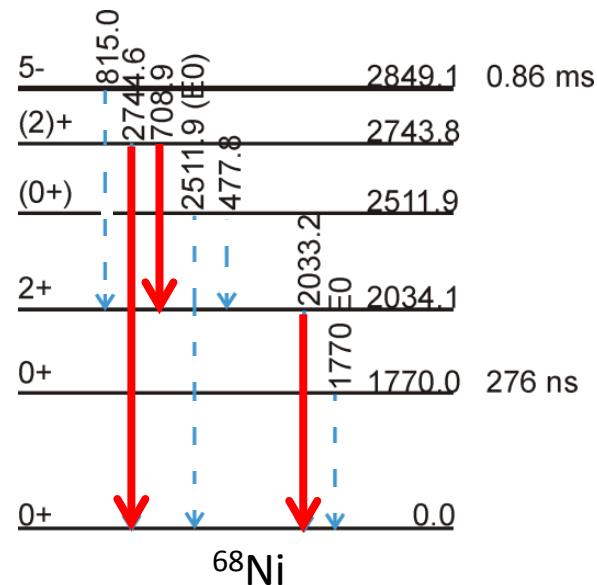
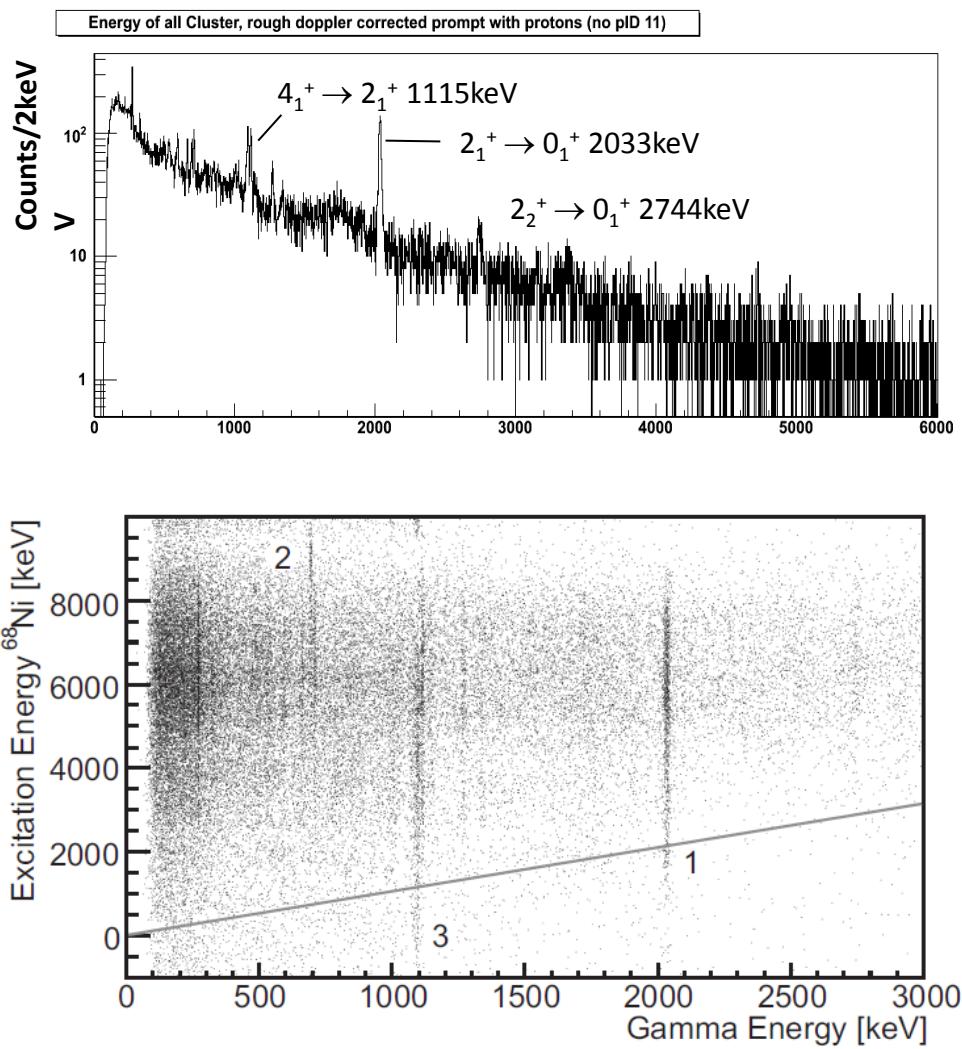
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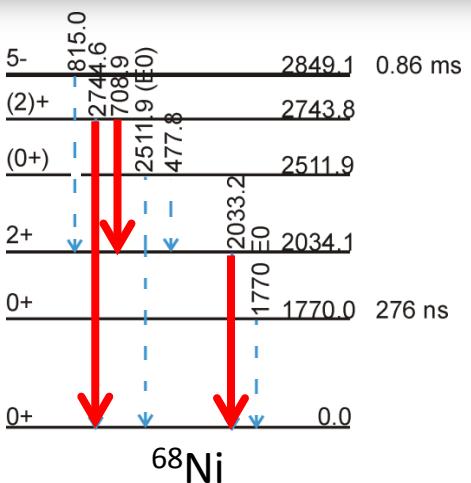
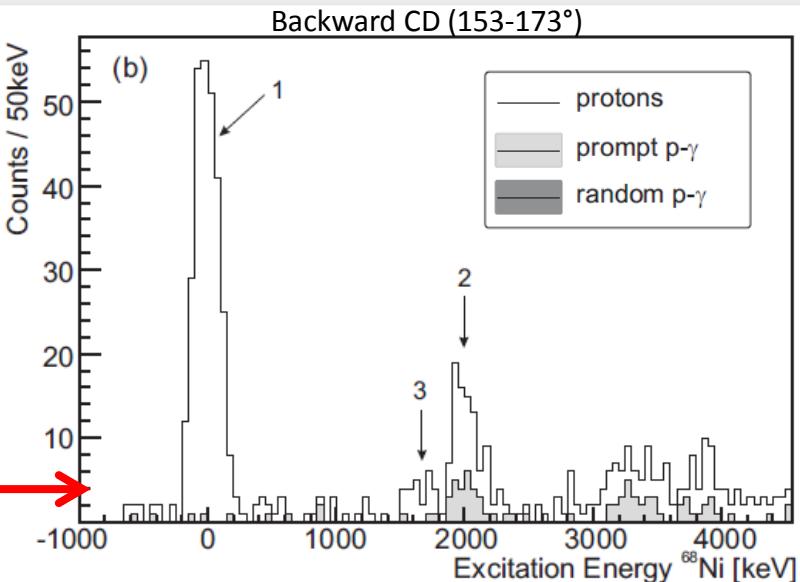
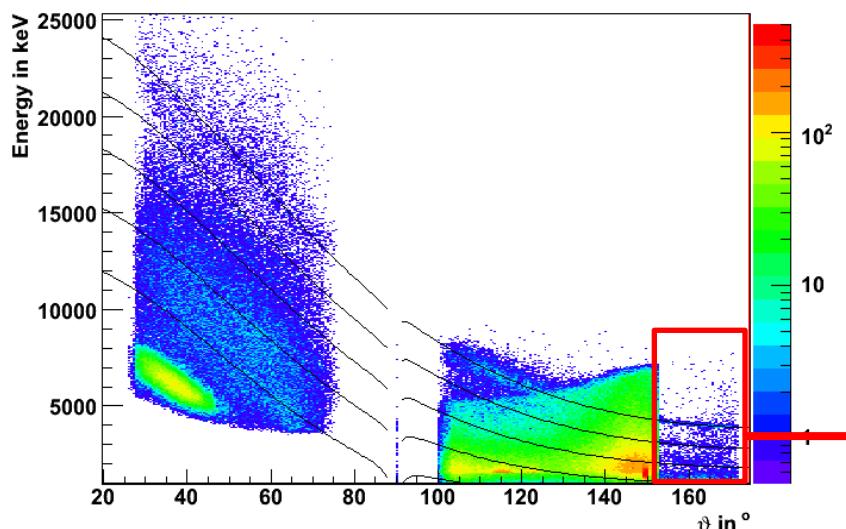
PhD of Jytte Elseviers (KU Leuven)



- Few  $\gamma$ 's to ground state
- No p- $\gamma$ - $\gamma$  coincidences

# $^{66}\text{Ni}(\text{t},\text{p})$ 2.6 MeV/u

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  $2^+_2$

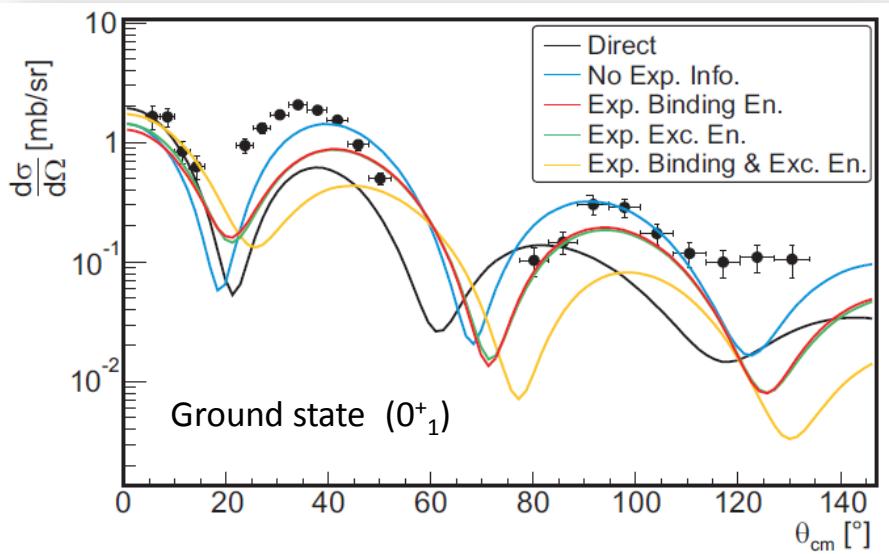
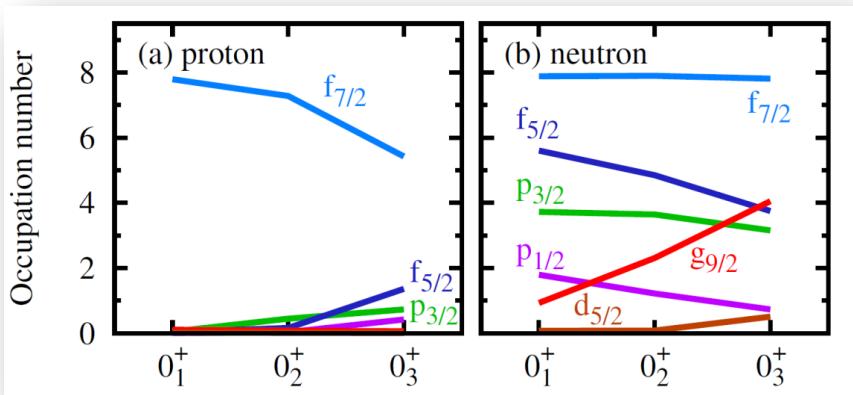
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PhD of Jytte Elseviers (KU Leuven)

## Calculations

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

- Agreement for  $0^+_1, 2$  states
- Fails to reproduce magnitude of cross section to  $2^+_1$  state



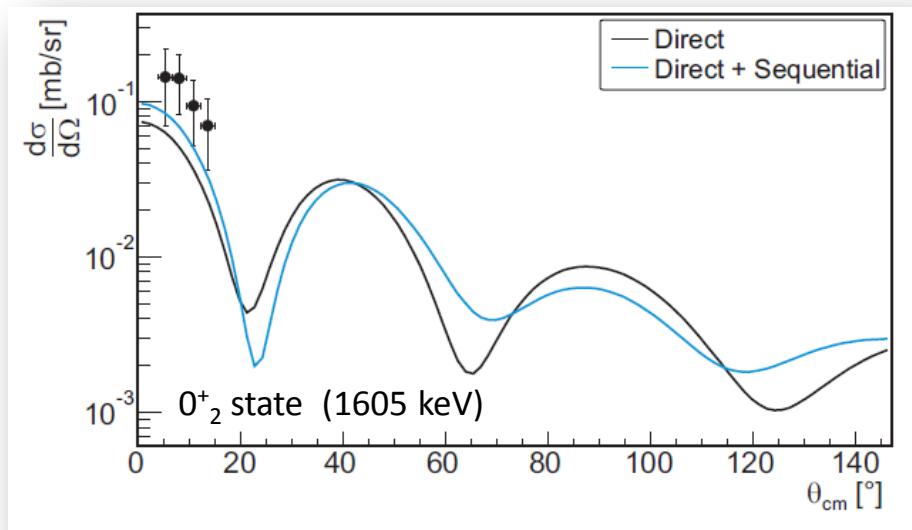
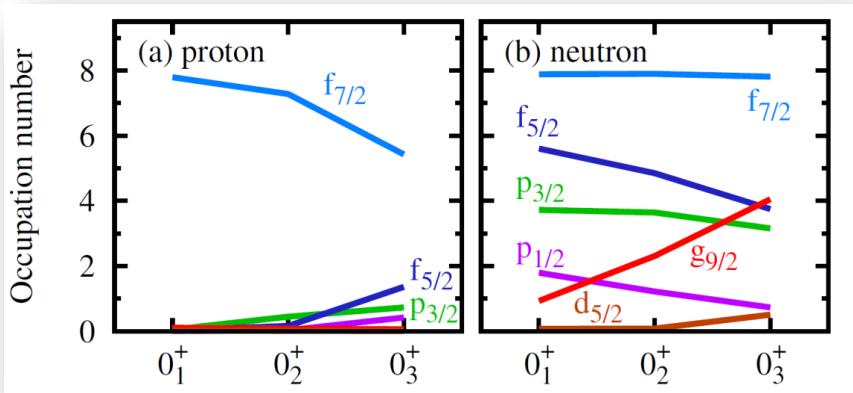
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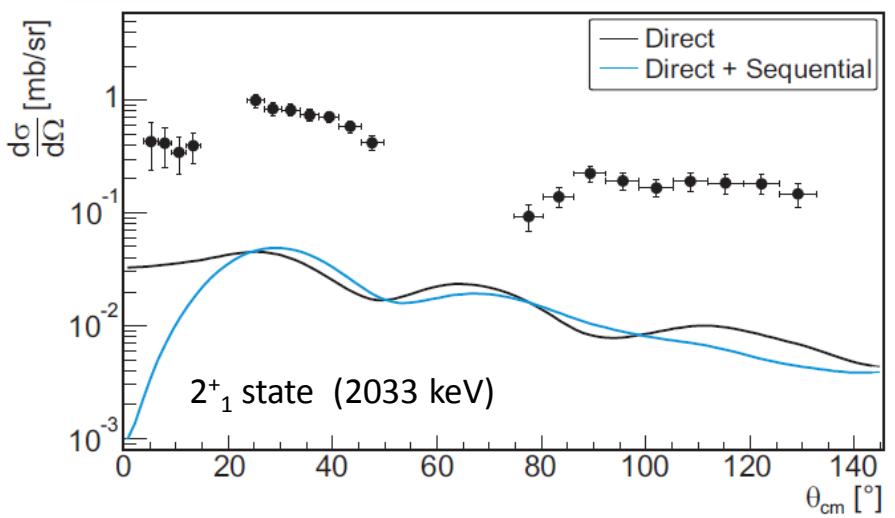
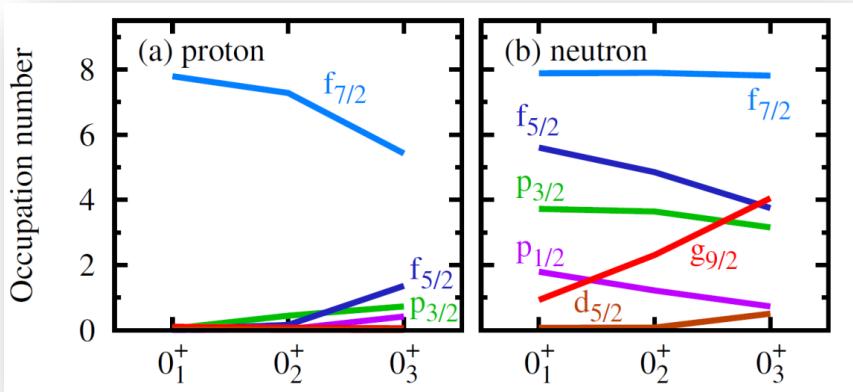
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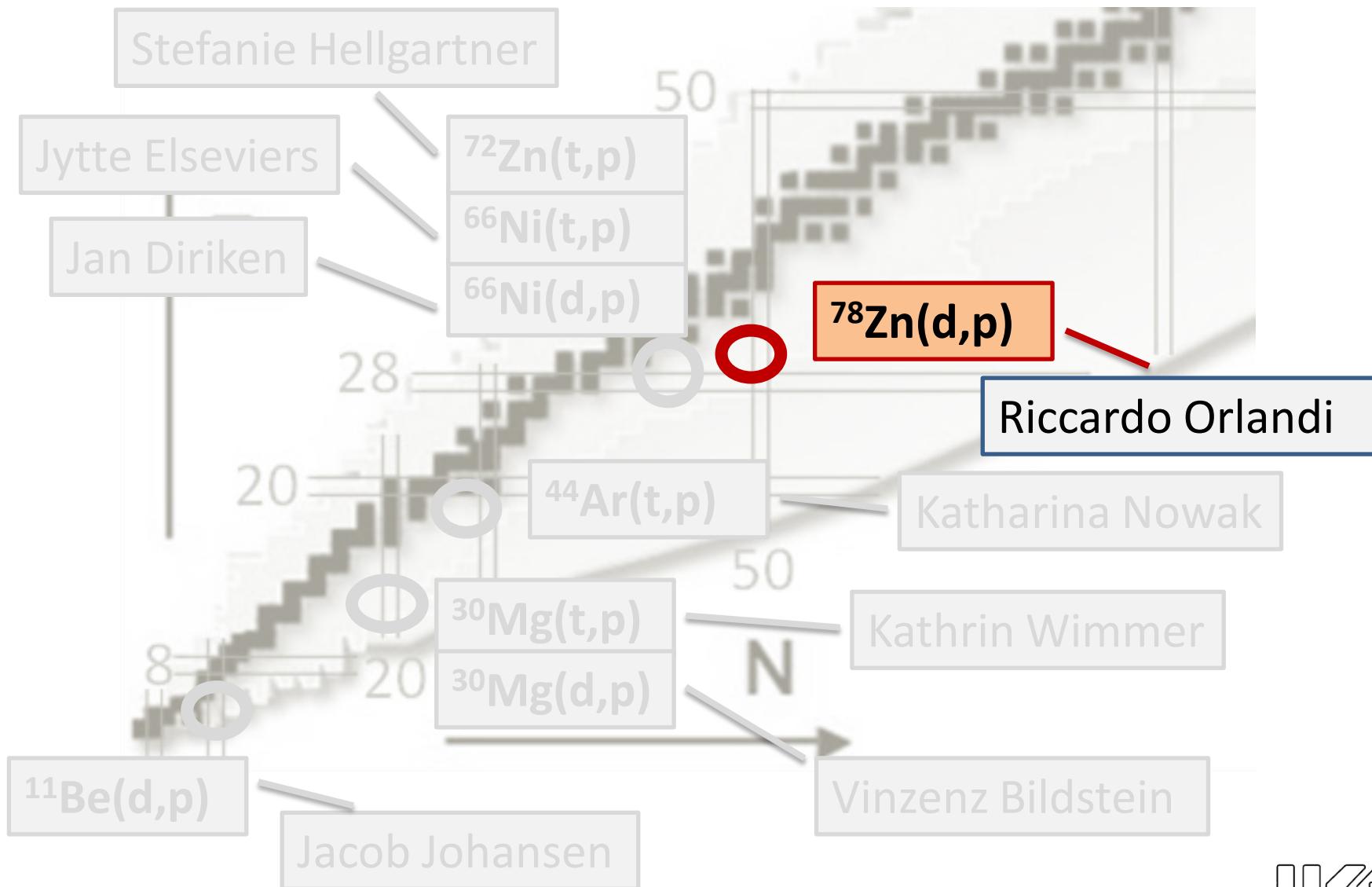
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# Transfer reactions at REX



# $^{78}\text{Zn}(\text{d},\text{p})$ 2.83 MeV/u

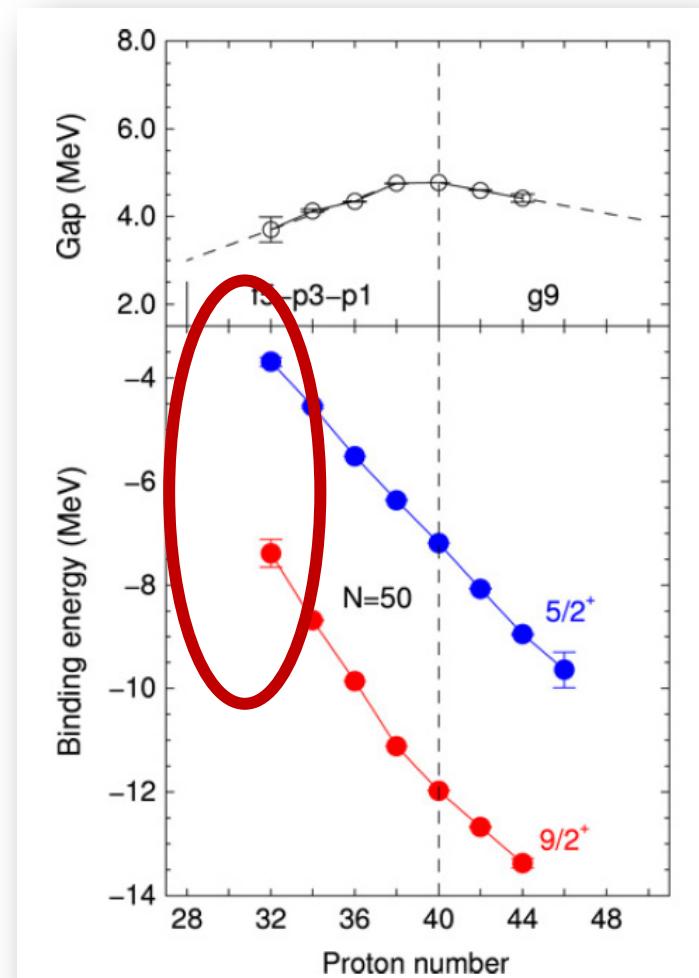
Work of Riccardo Orlandi (IEM-CSIC Madrid, KU Leuven)

## Quenching of $N = 50$

- What is the value of the  $N=50$  gap in  $^{78}\text{Ni}$  ?

M.-G. Porquet and O. Sorlin PRC 81 (2012) 014307

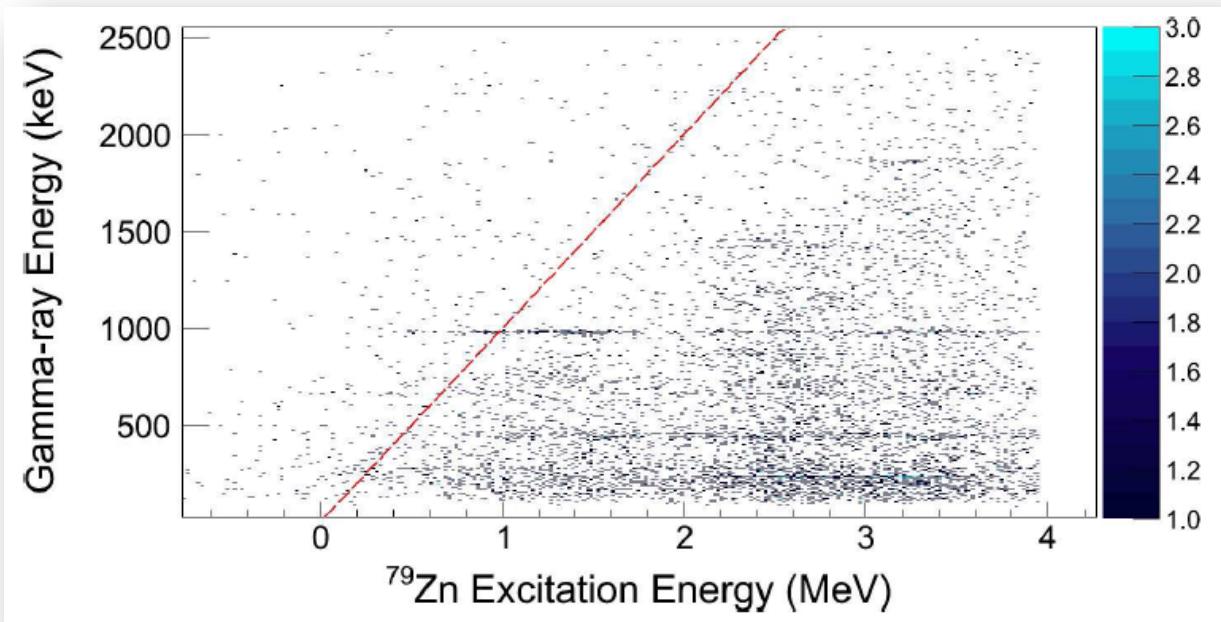
K. Sieja and F. Nowacki, PRC 85 (2012) 051301]



O. Sorlin, M.-G. Porquet  
Prog. Part. Nucl. Phys. 61 (2008) 602

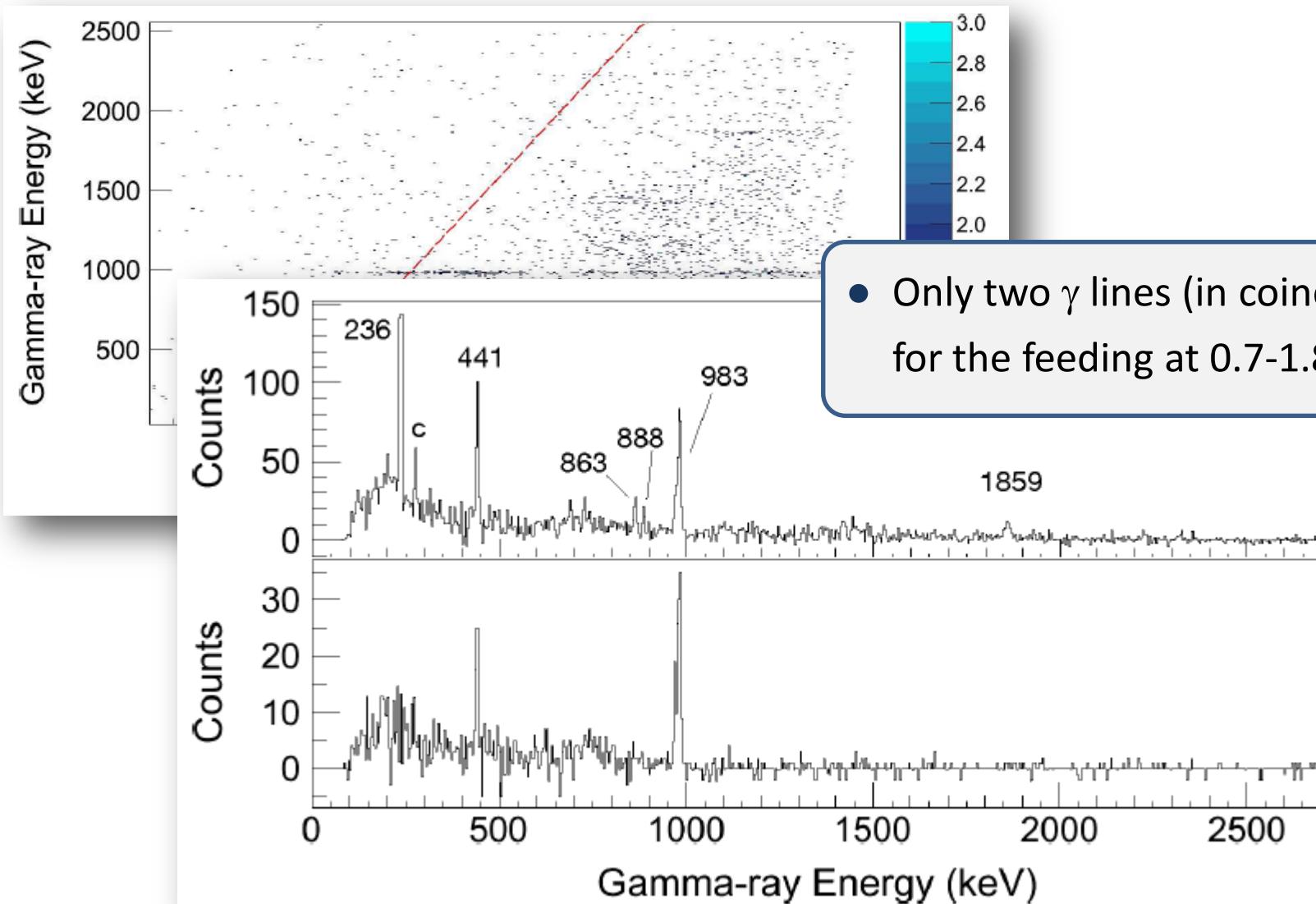
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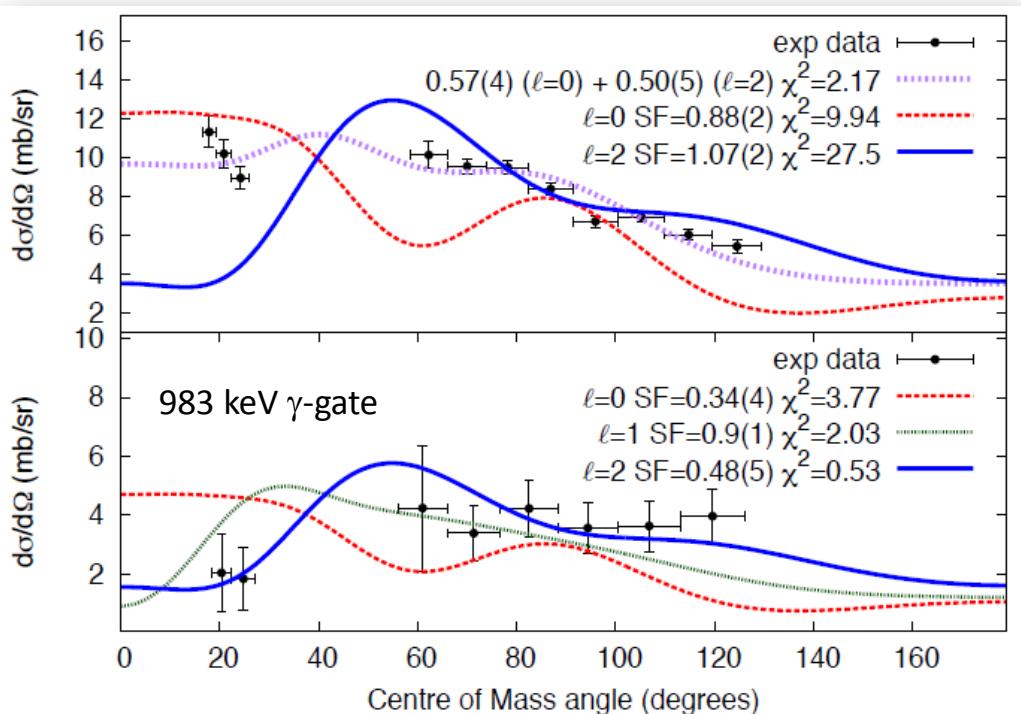
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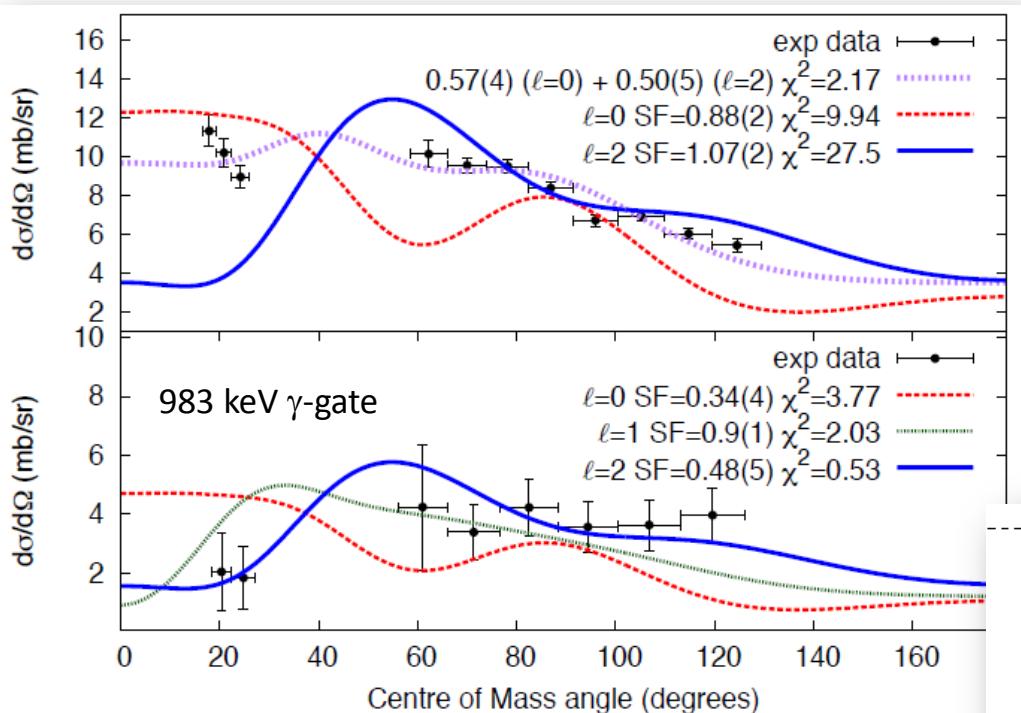
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- ...however the  $\ell$ -character is mixed ( $\ell = 0, 2$ )  
 $\Rightarrow$  other state present
- When gating on 983 keV only  $\ell = 2$  remains

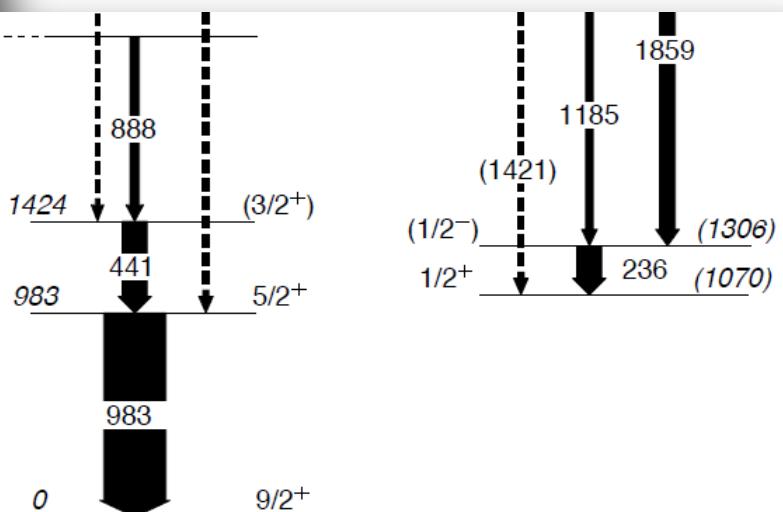
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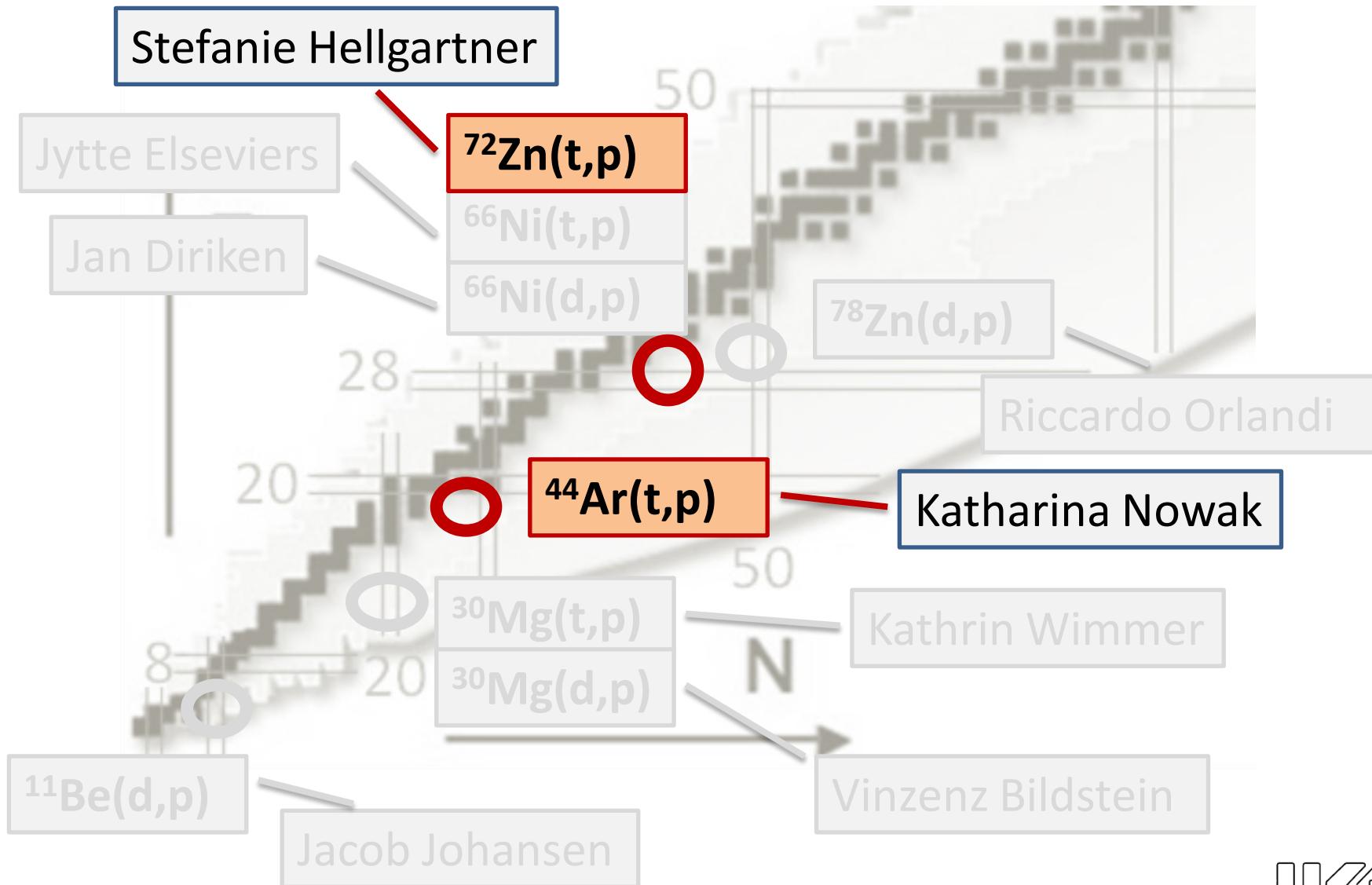


- N=50 gap larger than in Z=32
- Agreement with a strong N=50 closure in  $^{78}\text{Ni}$

- ...however the  $\ell$ -character is mixed ( $\ell = 0, 2$ )  
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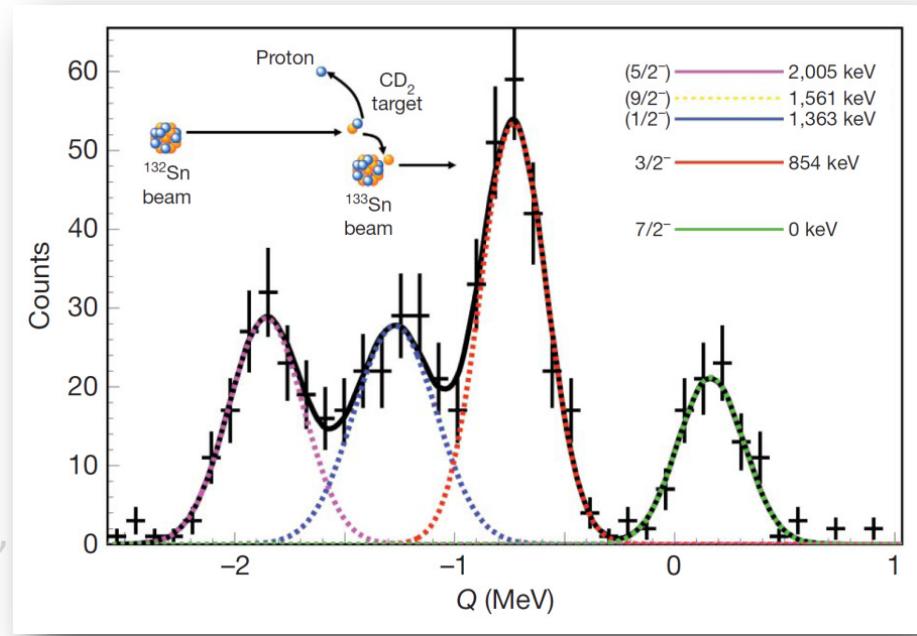


# Transfer reactions at REX



# Results at other facilities

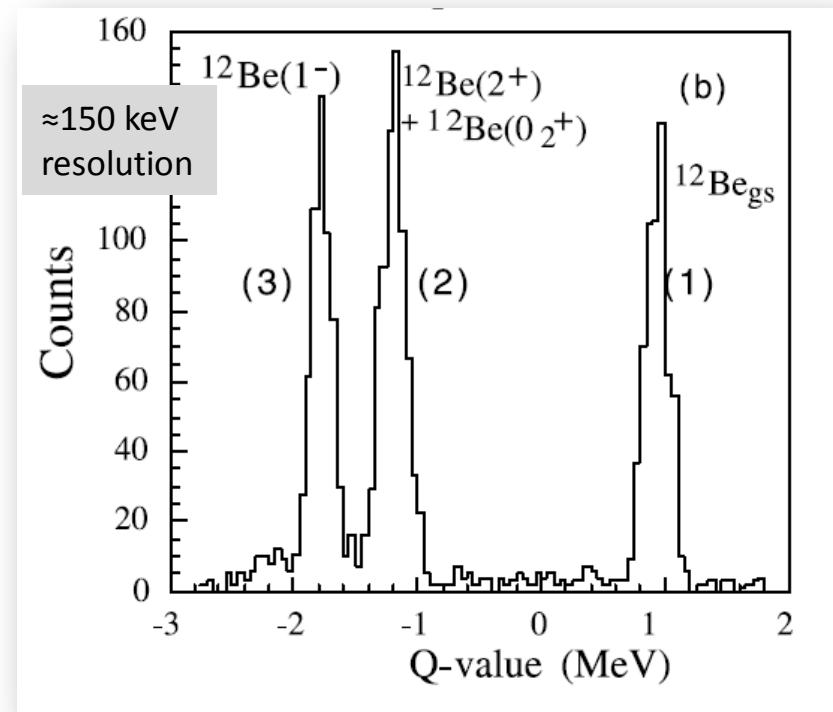
- HRIBF at ORNL  
 $^{82}\text{Ge}(\text{d},\text{p})$ ,  $^{132}\text{Sn}(\text{d},\text{p})$   
Si array
- ISAC-II at TRIUMF: light nuclei  
 $^{11}\text{Be}(\text{d},\text{p})$ ,  $^{11}\text{Li}(\text{p},\text{t})$ ,  $^{25}\text{Na}(\text{d},\text{p})$   
Si array (+Tigress) / Active target
- SPIRAL and LISE at GANIL  
 $^8\text{He}(\text{d},\text{p})$ ,  $^8\text{He}(\text{p},\text{t})$ ,  $^{14}\text{O}(\text{d},\text{t})$ ,  $^{20}\text{O}(\text{d},\text{p})$ ,  $^{24,26}\text{Ne}(\text{d},\text{p})$ ,  
 $^{14}\text{O}(\text{t},\text{p})$ ,  $^{68}\text{Ni}(\text{d},\text{p})$ ,  $^{34}\text{Si}(\text{d},\text{p})$ ,  $^{60}\text{Fe}(\text{d},\text{p})$   
ISOL and fragmentation beams  
Si array and Ge array, VAMOS
- Argonne (in-flight): HELIOS  
 $^{12}\text{B}(\text{d},\text{p})$ ,  $^{19}\text{O}(\text{d},\text{p})$ ,  $^{13}\text{B}(\text{d},\text{p})$



K.L. Jones et al., Nature 465 (2010) 454

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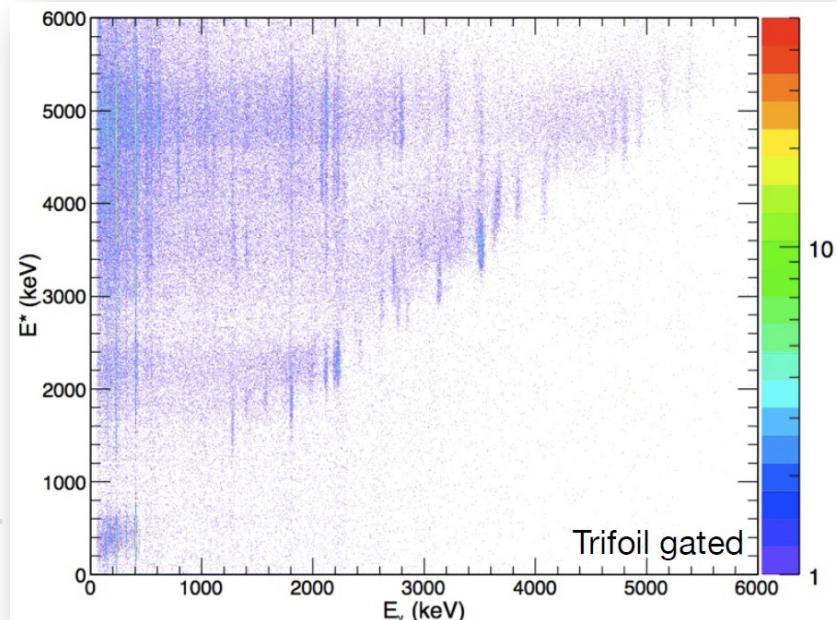
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R. Kanungo et al., PLB 682 (2010) 391

# Results at other facilities

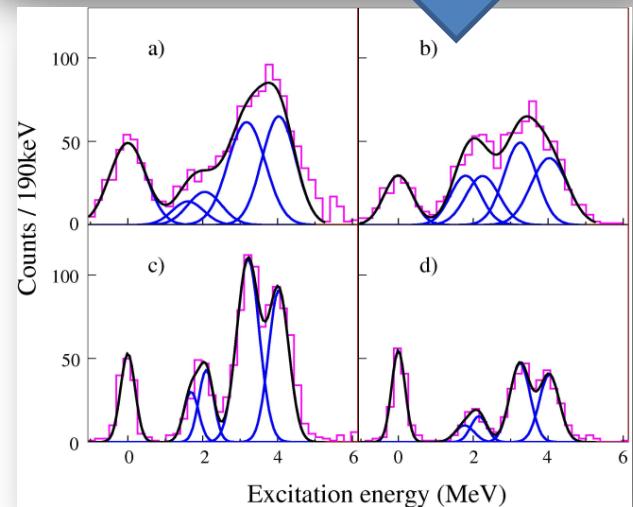
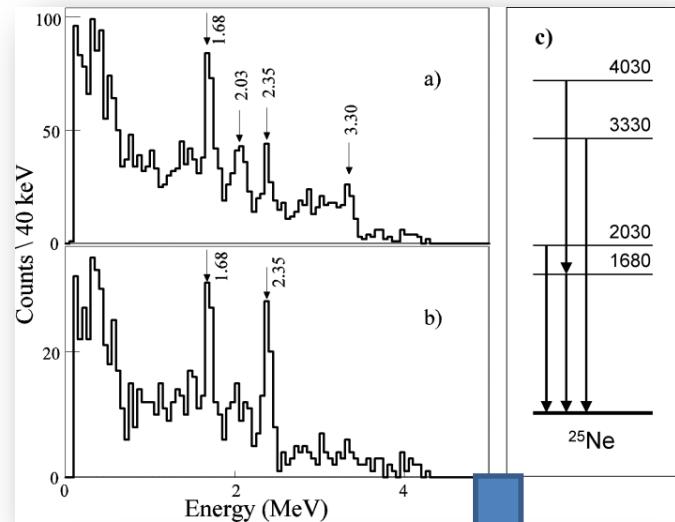
- HRIBF at ORNL  
 $^{82}\text{Ge}(\text{d},\text{p})$ ,  $^{132}\text{Sn}(\text{d},\text{p})$   
Si array
- ISAC-II at TRIUMF: light nuclei  
 $^{11}\text{Be}(\text{d},\text{p})$ ,  $^{11}\text{Li}(\text{p},\text{t})$ ,  $^{25}\text{Na}(\text{d},\text{p})$   
Si array (+Tigress) / Active target
- SPIRAL and LISE at GANIL  
 $^8\text{He}(\text{d},\text{p})$ ,  $^8\text{He}(\text{p},\text{t})$ ,  $^{14}\text{O}(\text{d},\text{t})$ ,  $^{20}\text{O}(\text{d},\text{p})$ ,  $^{24,26}\text{Ne}(\text{d},\text{p})\dots$   
 $^{14}\text{O}(\text{t},\text{p})$ ,  $^{68}\text{Ni}(\text{d},\text{p})$ ,  $^{34}\text{Si}(\text{d},\text{p})$ ,  $^{60}\text{Fe}(\text{d},\text{p})$   
ISOL and fragmentation beams  
Si array and Ge array, VAMOS
- Argonne (in-flight): HELIOS  
 $^{12}\text{B}(\text{d},\text{p})$ ,  $^{19}\text{O}(\text{d},\text{p})$ ,  $^{13}\text{B}(\text{d},\text{p})$



G. Wilson, IoP Nuclear Physics  
Group Conference, York 2013

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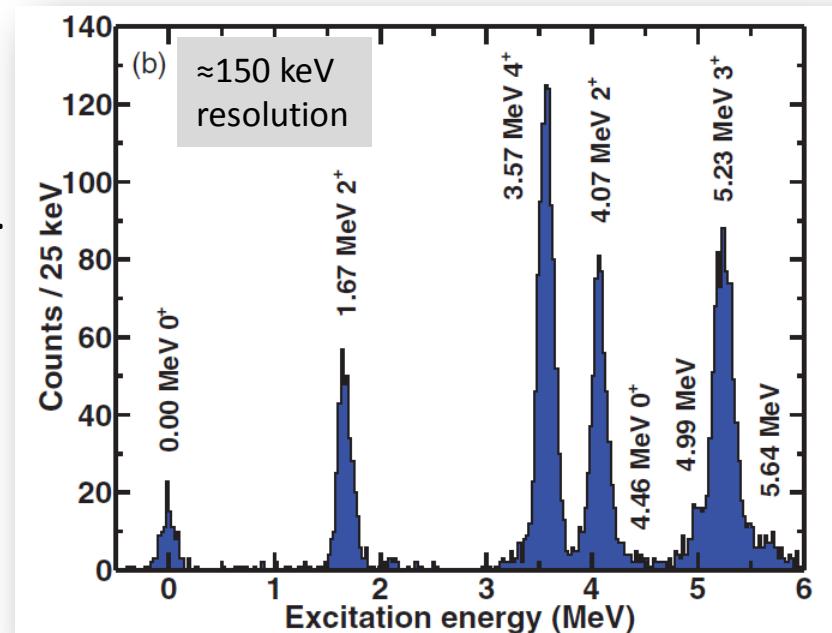
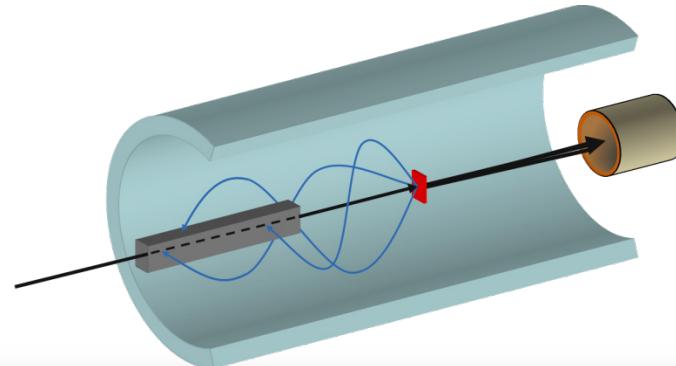
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W. Catford et al., PRL 104 (2010) 192501

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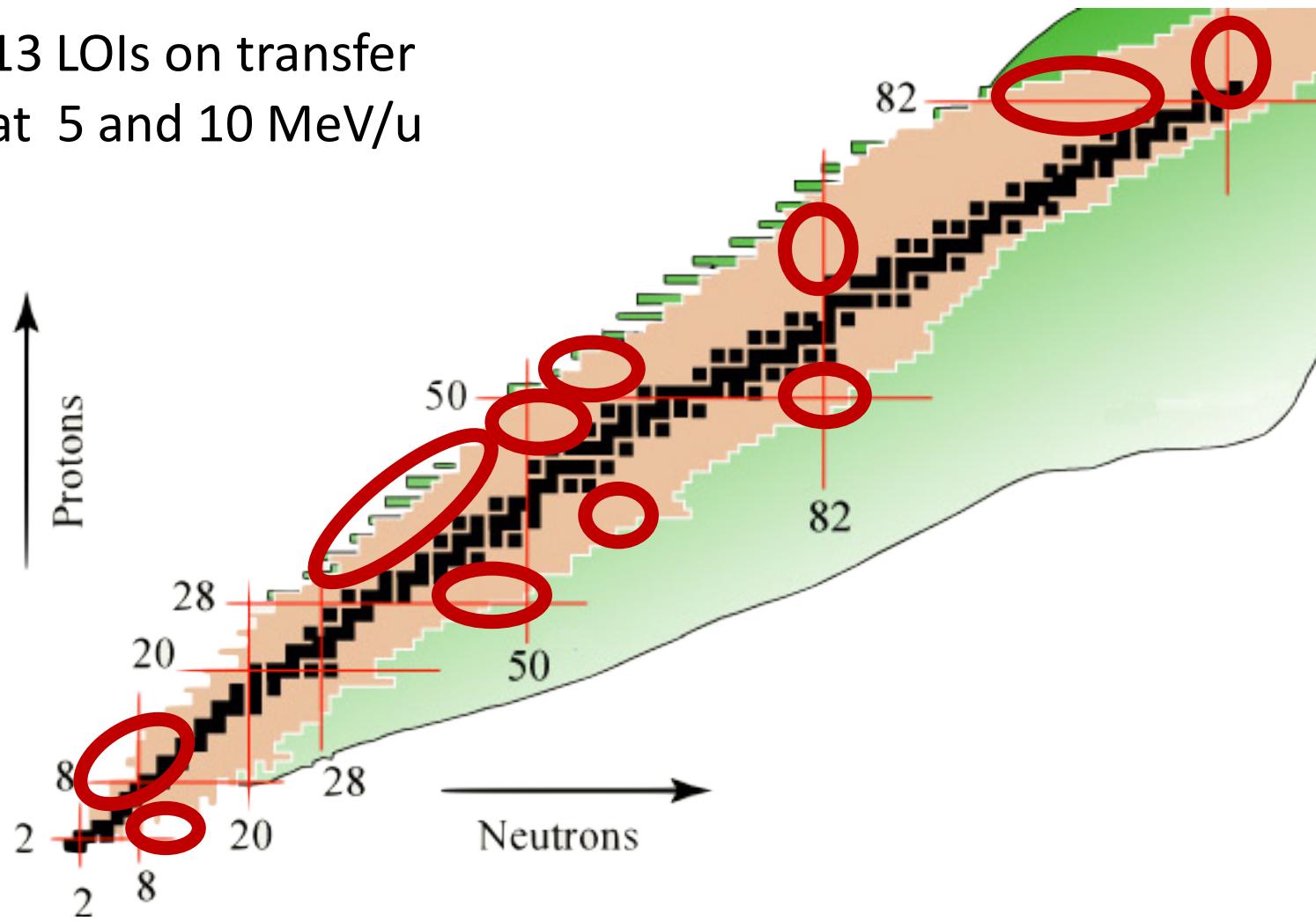
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C.R.Hoffman et al, PRC 85 (2012) 054318

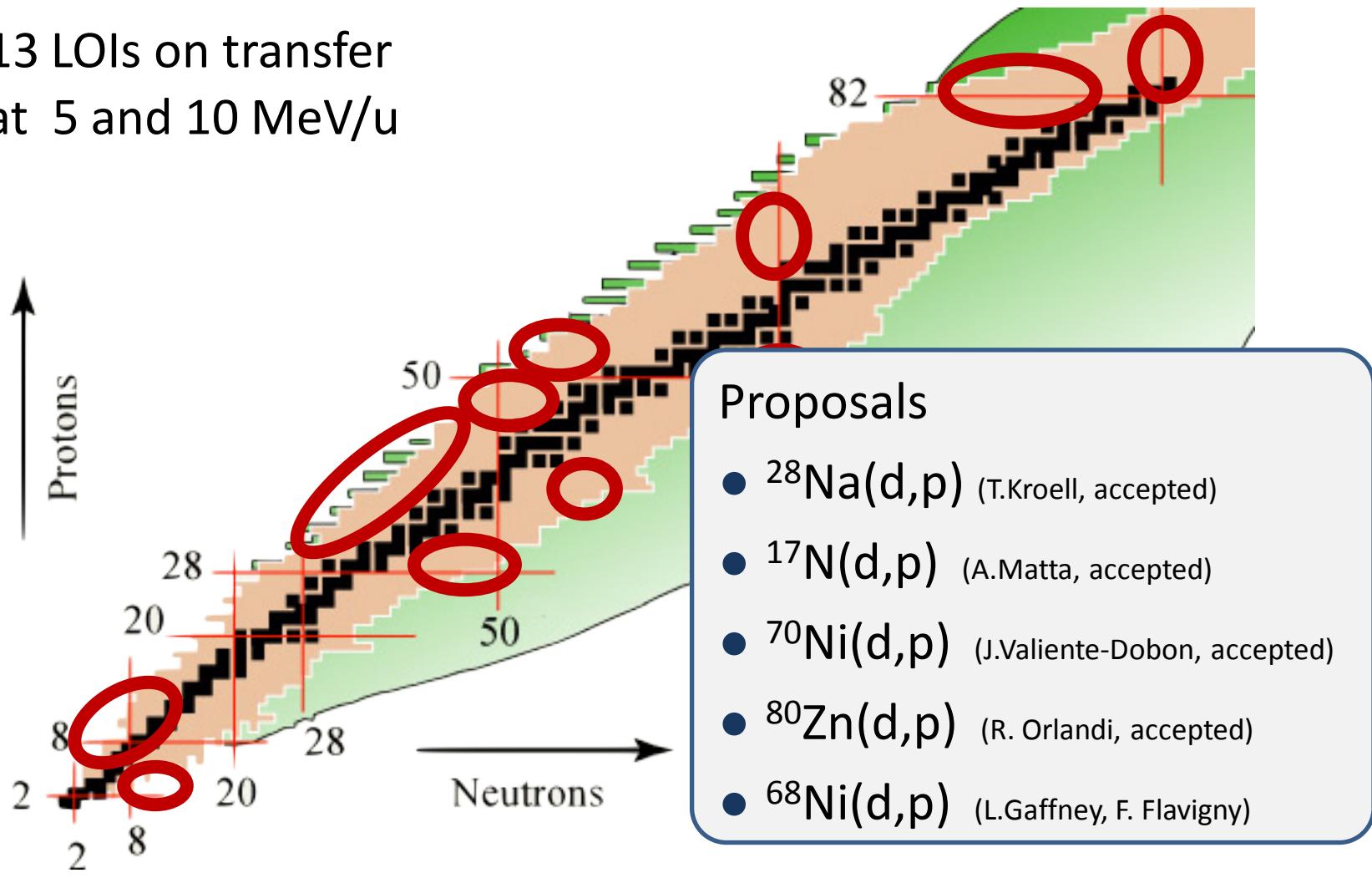
# HIE-ISOLDE

- 13 LOIs on transfer  
at 5 and 10 MeV/u



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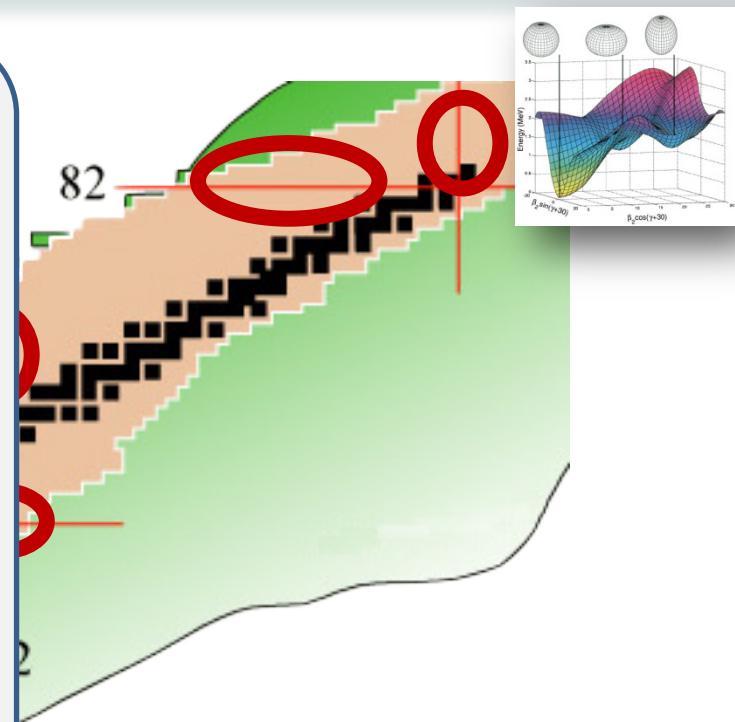
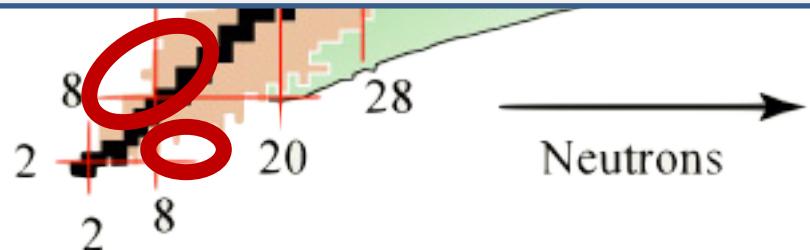
# Unique at HIE-ISOLDE

**Shape coexistence in neutron-deficient Z=82 region (LoI I-110):**

- (d,p) and (p,d) on even-even Hg to populate low-spin isomer or high-spin ground-state
- Isomeric beams (low-spin) in odd Hg to determine intruder contribution in low-spin states in even-even Hg

**Multiplets generated by two valence particles (or holes) around  $^{208}\text{Pb}$**

- Nucleon transfer on g.s. and isomer in  $^{206}\text{Tl}$



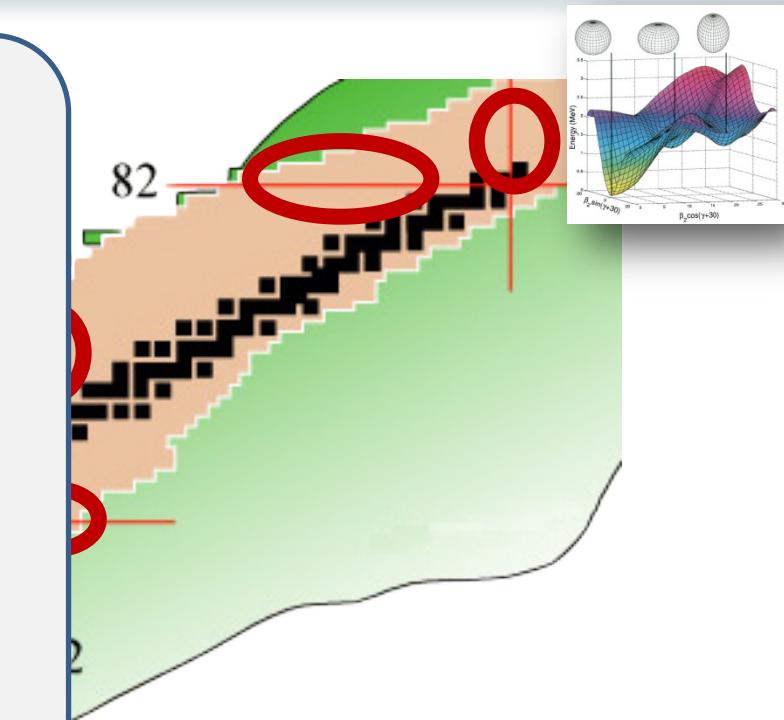
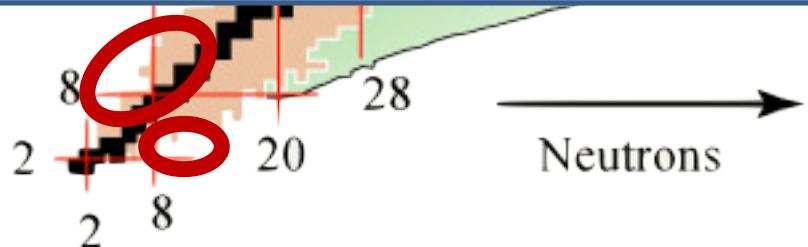
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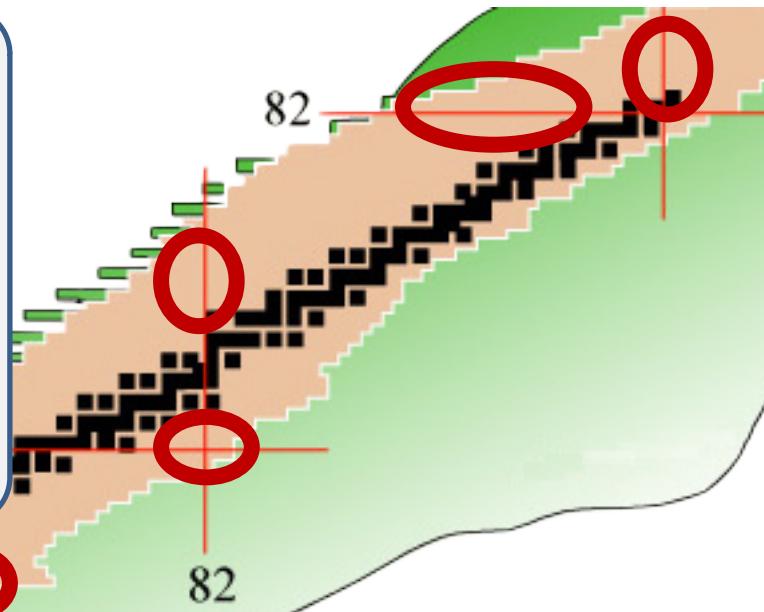
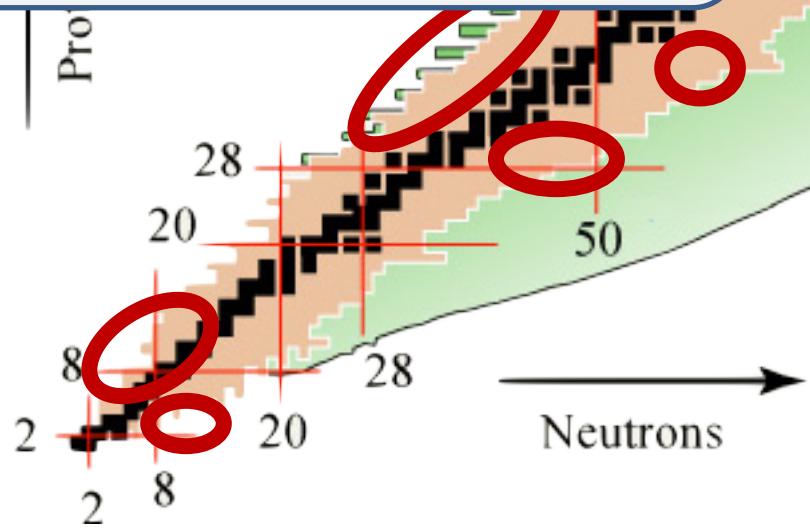


**5.5 MeV/nucleon  
is not sufficient!**

# Unique at HIE-ISOLDE

## Instrumentation

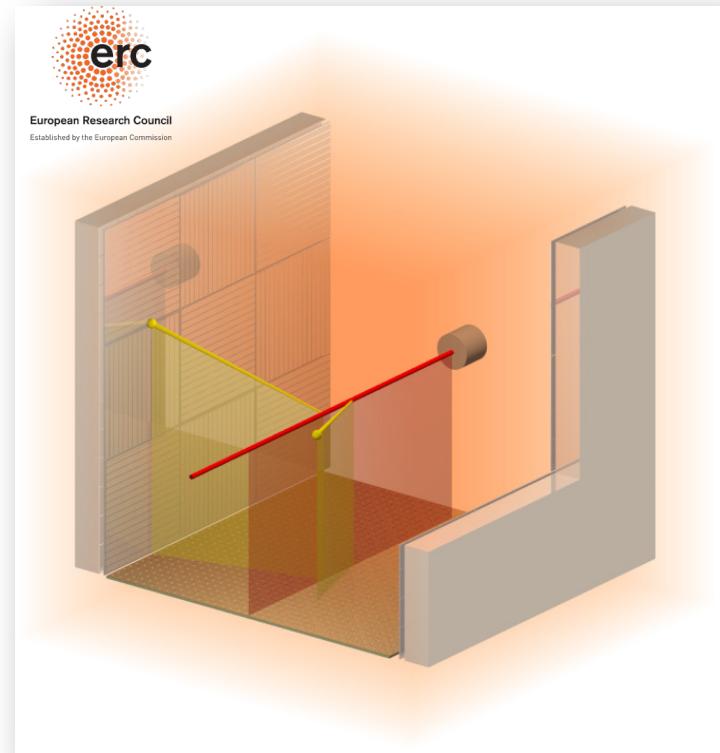
- Upgrade T-REX
  - Active target
  - Solenoid
  - Storage ring
- F. Wenander, tomorrow 9:50



# ACTAR TPC / SpecMAT

## Two ERC Grants!!

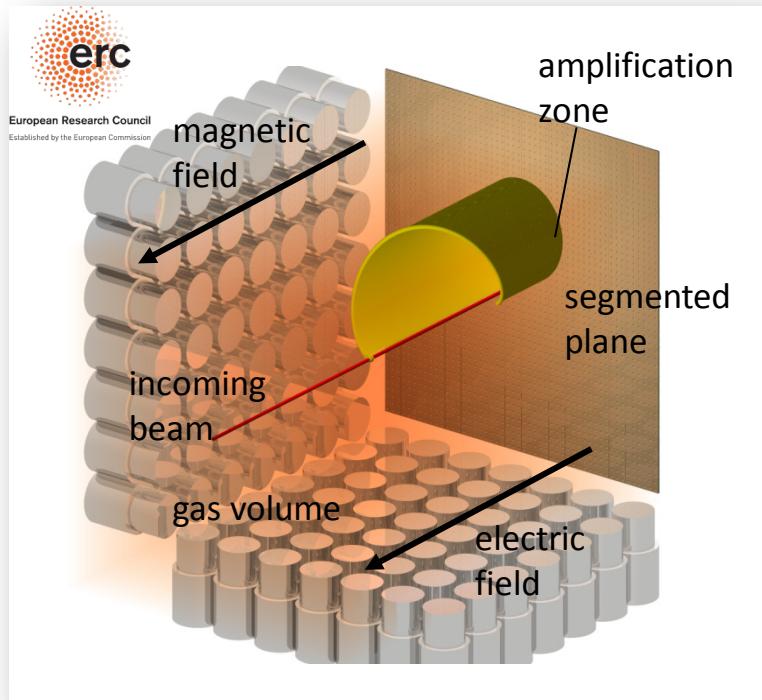
- Active target: Time-projection chamber where detection gas is the target
- Array of  $\gamma$ -ray detectors within the field  $\text{LaBr}_3$  preferred for best compromise efficiency/resolution
- Magnetic field parallel to beam direction to confine emitted particles



# ACTAR TPC / SpecMAT

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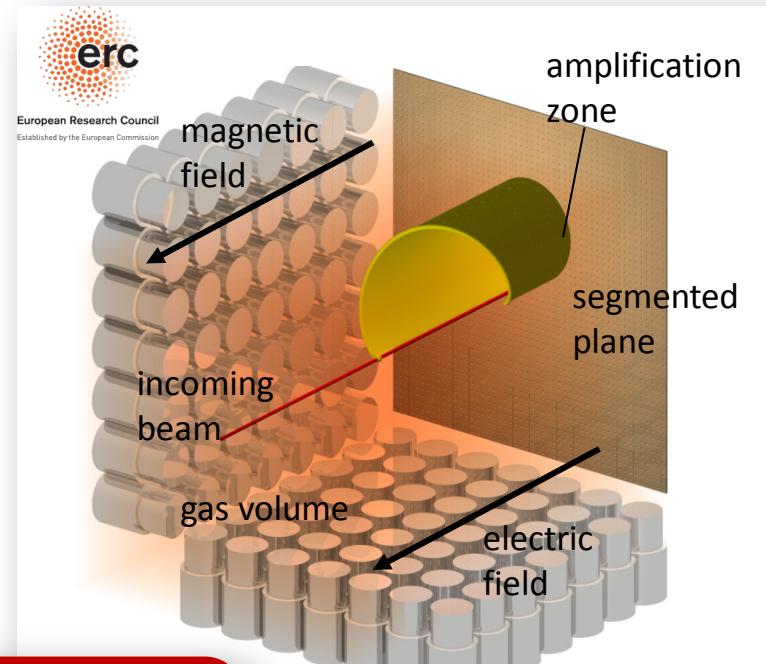
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- Particle detection: improved resolution + higher luminosity (30x)
- Gamma-ray detection in coincidence:
  - importance seen in  $^{66}\text{Ni}+\text{d}$
  - unique improvement of one order of magnitude in resolution

# Summary

## So far

- Successful measurements of transfer reactions with REX, T-REX and Miniball
- Importance of  $\gamma$ -ray detection
- From light nuclei up to Zn
- New results for N=40 and N=50 around  $^{68}\text{Ni}$  and  $^{78}\text{Ni}$

## HIE-ISOLDE

- Isomeric beams
- 5 MeV/nucelon  $\rightarrow$  Sn region, ( $d, ^3\text{He}$ )...
- 10 MeV/nucelon  $\rightarrow$  Pb region, unique for ISOLDE
- New instrumentation will also open new possibilities



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