

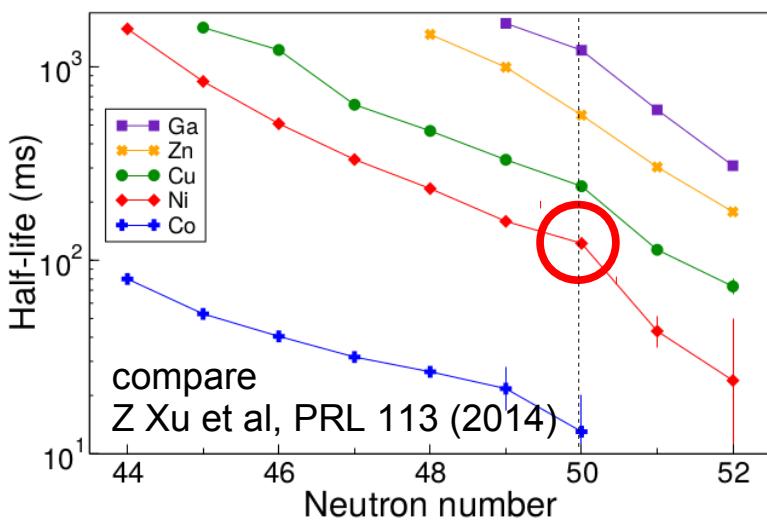
# Persistence of nuclear shell closures far from stability: $\gamma$ spectroscopy of $^{79}\text{Cu}$ at Riken

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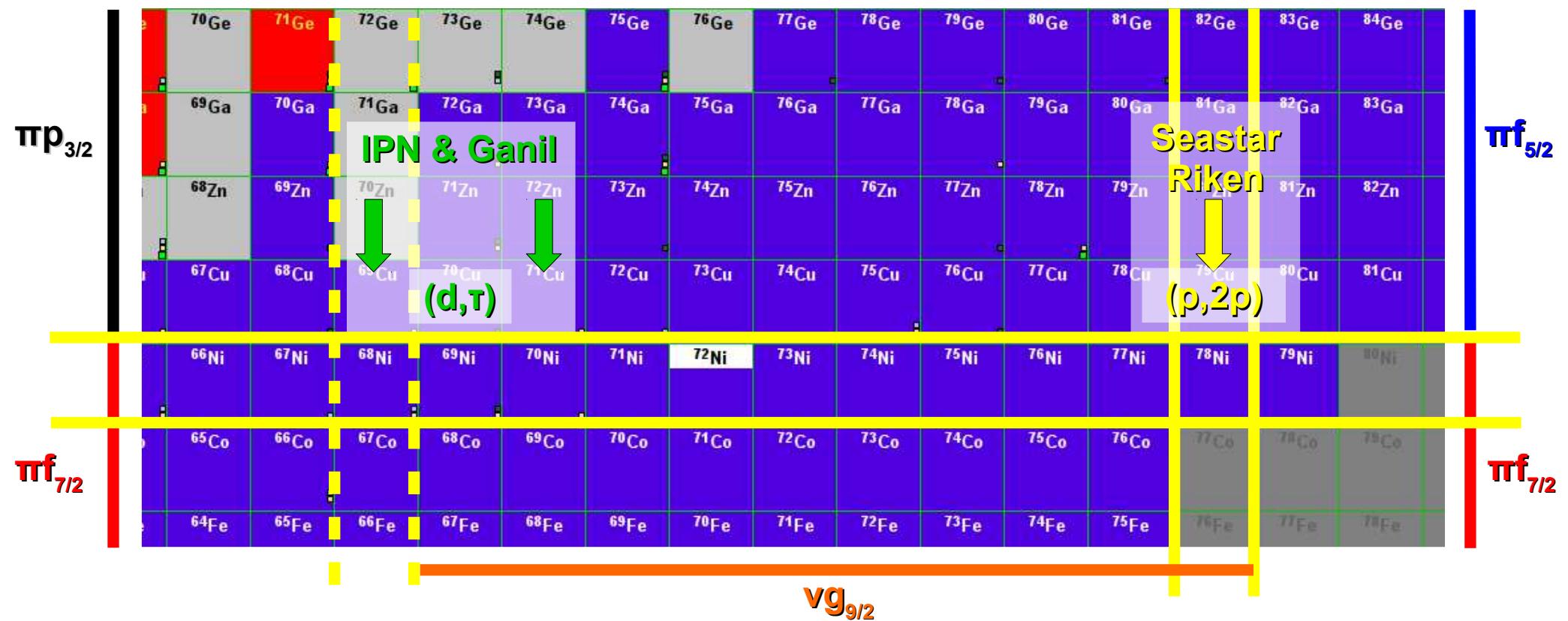
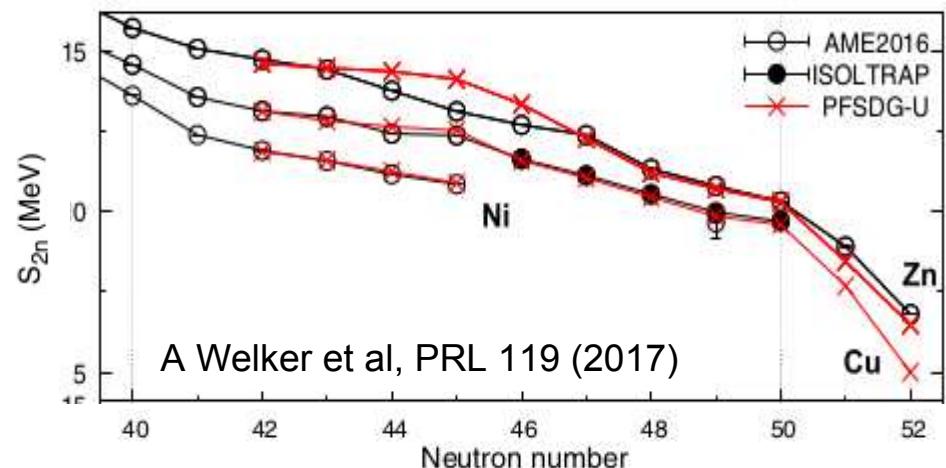
The Seastar collaboration: <sup>1</sup> IPN Orsay; <sup>2</sup> University of Tokyo; <sup>3</sup> Atomki Debrecen; <sup>4</sup> Riken Wakoshi;  
<sup>5</sup> Irfu Saclay; <sup>8</sup> Rikkyo University; <sup>9</sup> University of Brighton; <sup>10</sup> Vinatom Hanoi; <sup>11</sup> University of Oslo;  
<sup>12</sup> University of Hong Kong; <sup>13</sup> Technical University of Darmstadt; <sup>14</sup> IPHC Strasbourg; <sup>15</sup> University of  
Osaka; <sup>16</sup> University of Surrey; <sup>17</sup> Tohoku University; <sup>18</sup> University of Peking



# Towards doubly magic $^{78}\text{Ni}$

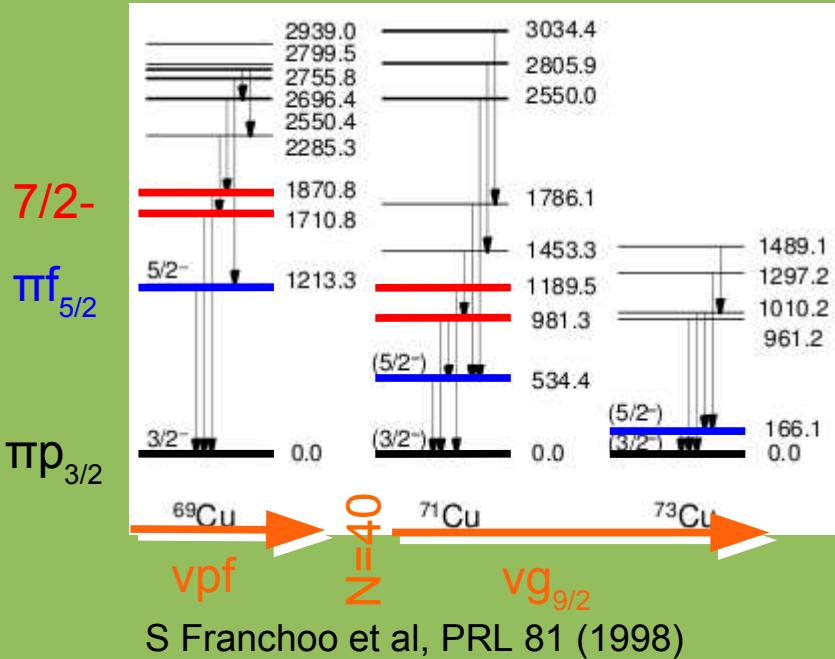


## $^{75-79}\text{Cu}$ mass measurement at Isoltrap

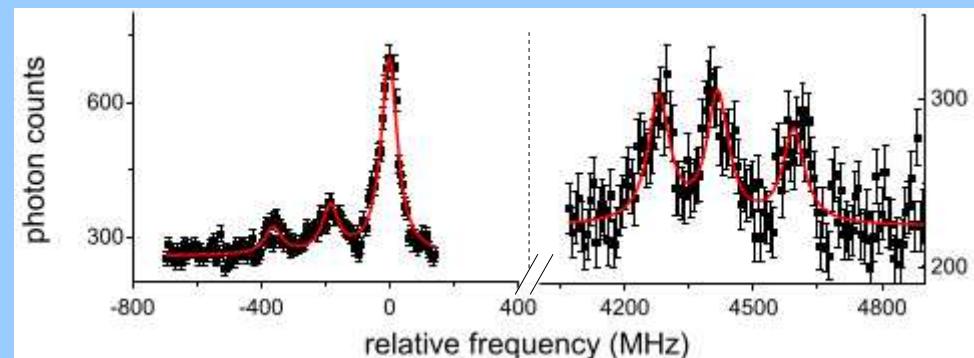
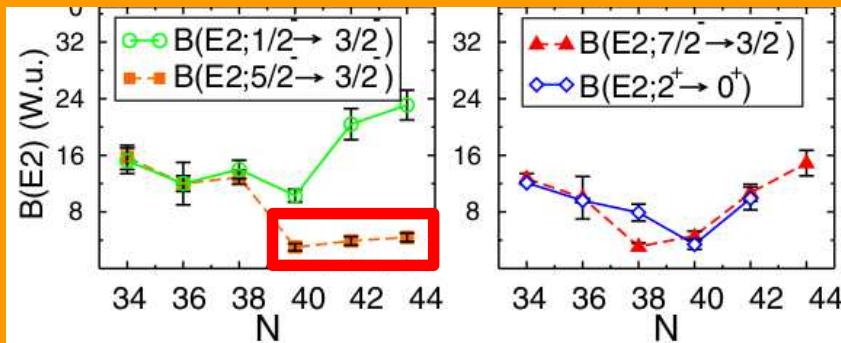


# Monopole migration in neutron-rich copper

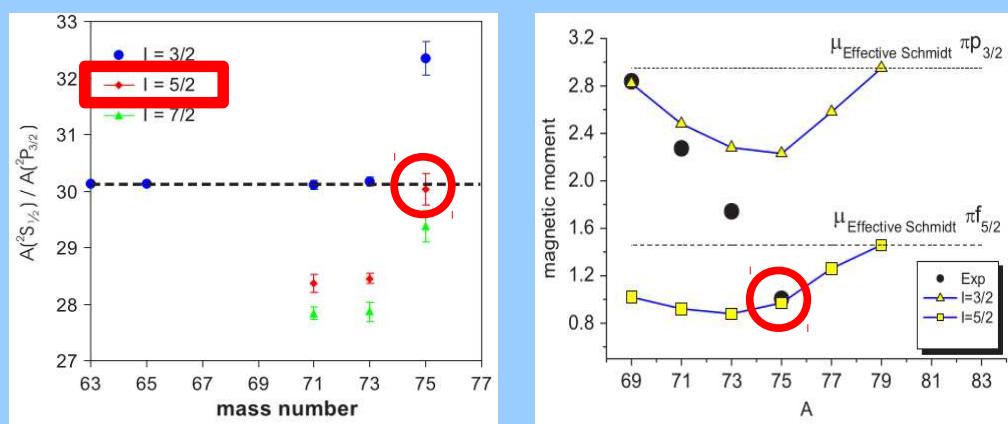
## $\beta$ decay into $^{69,71,73}\text{Cu}$ at Lisol



## Coulomb excitation at Rex Isolde



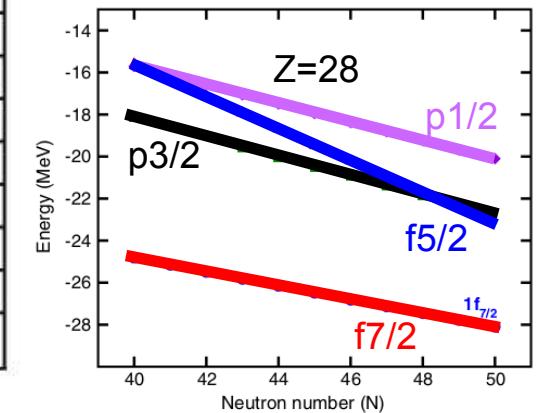
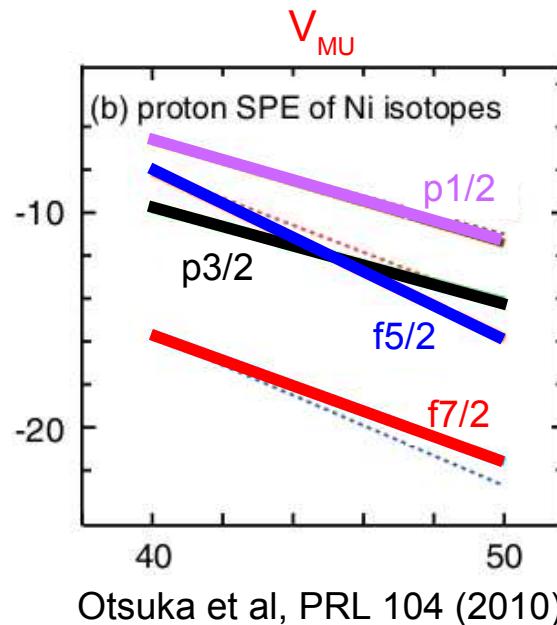
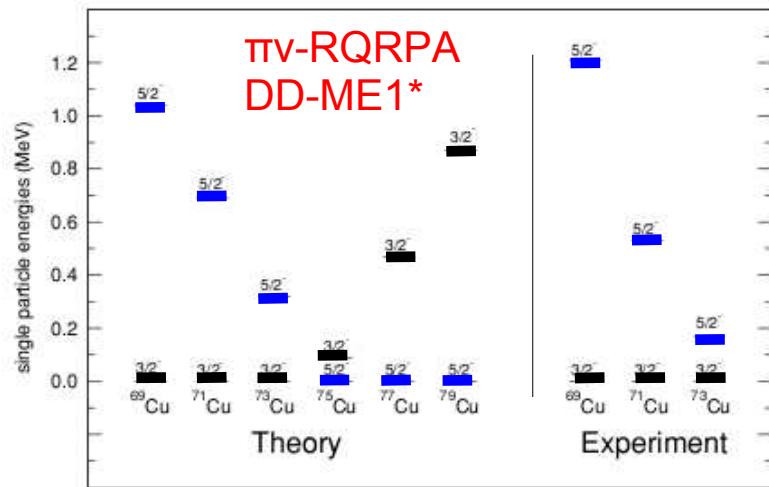
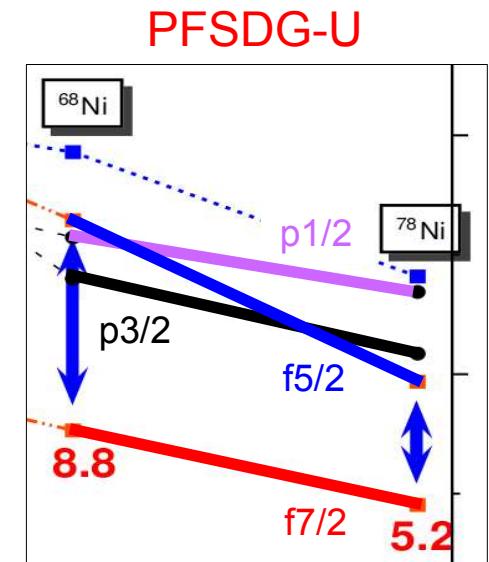
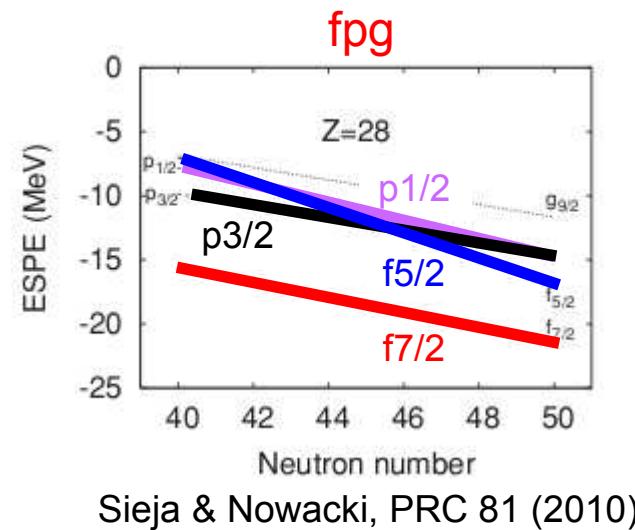
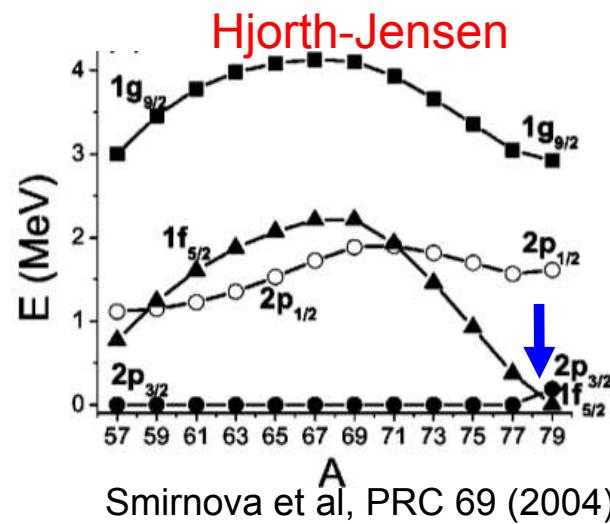
laser spectroscopy of  $^{75}\text{Cu}$  at Cris Isolde  
hyperfine parameters best agree for  $5/2^-$



K Flanagan et al, PRL 103 (2009)

- $\pi f_{5/2}$  becomes ground state in  $^{75}\text{Cu}$
- $\pi f_{5/2}$  single-particle nature from Coulex
- two (one?) candidates for  $\pi f_{7/2}$  in  $^{71}\text{Cu}$
- related to addition of  $l+\frac{1}{2}$  neutrons in  $g_{9/2}$ ?

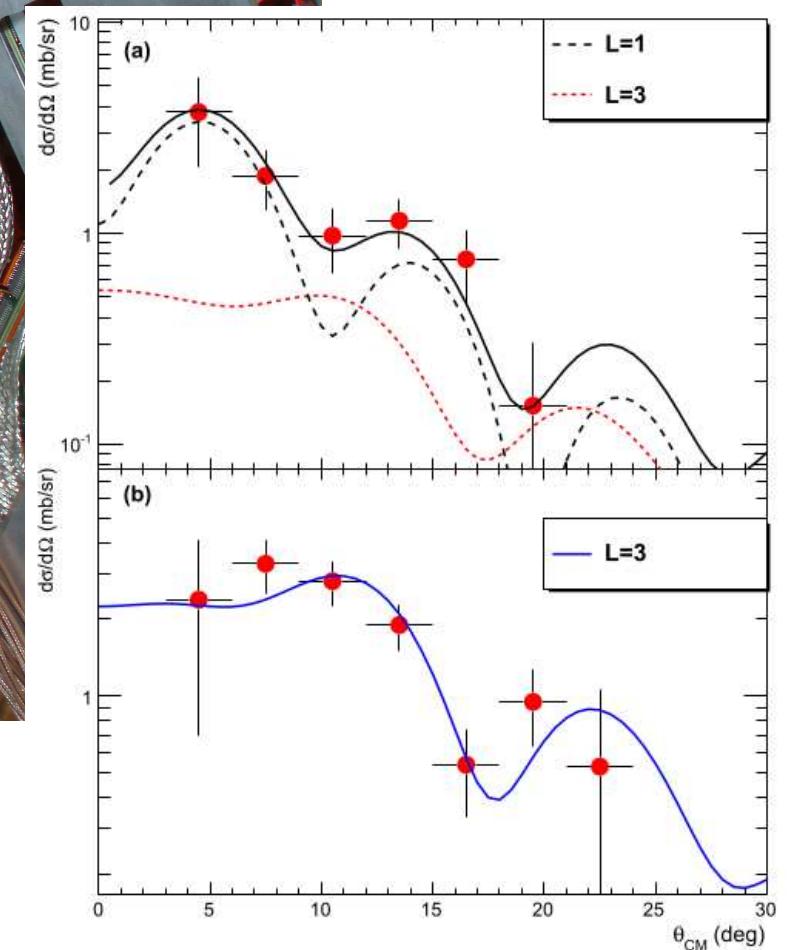
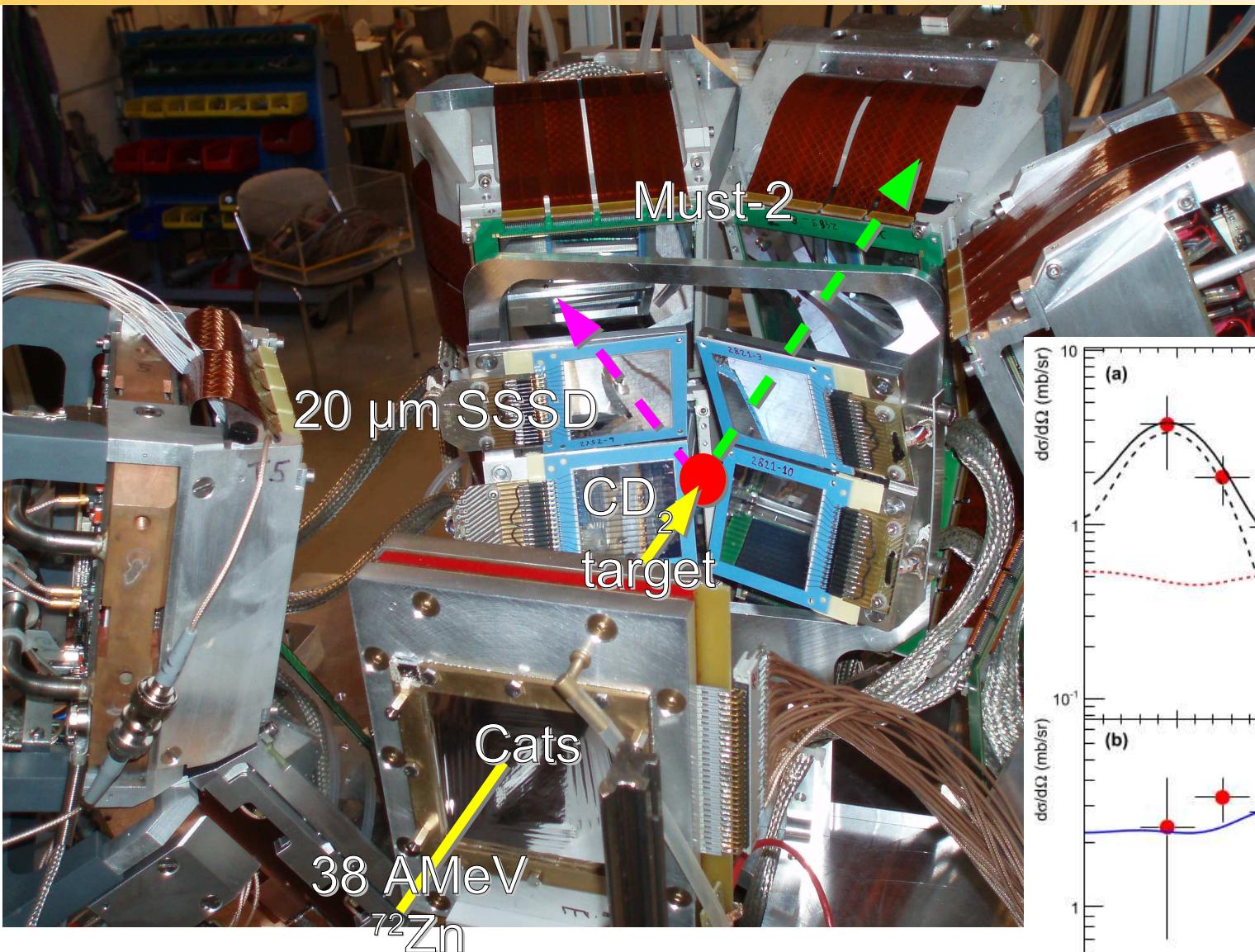
## Extensive theory landscape



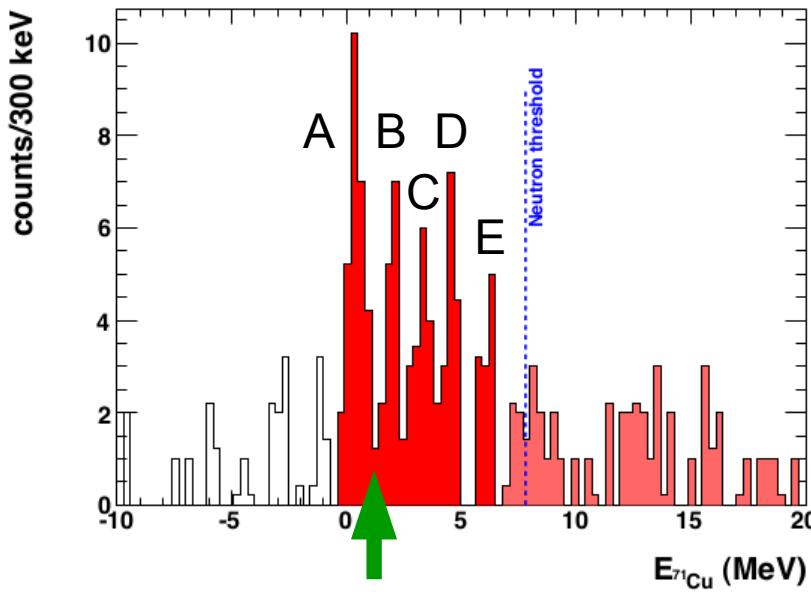
also Lisetskiy et al, PRC 70 (2004), Honma et al, PRC 80 (2009)...

$\pi\text{f}_{5/2}$  well described... what about its spin-orbit partner  $\pi\text{f}_{7/2}$ ?

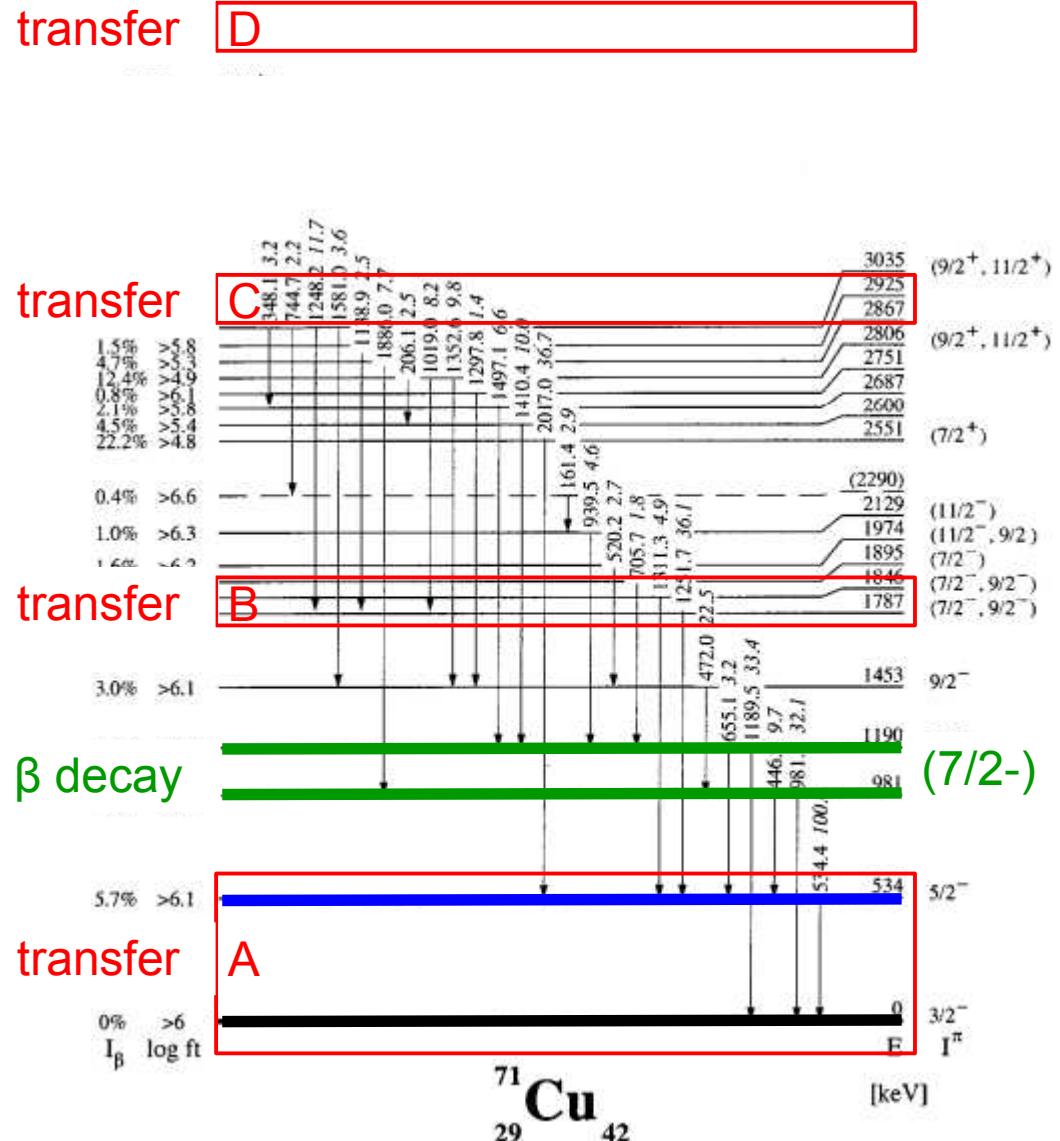
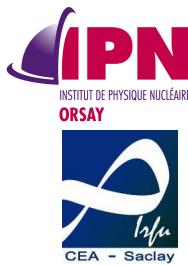
# proton pick-up into $^{71}\text{Cu}$ at Ganil



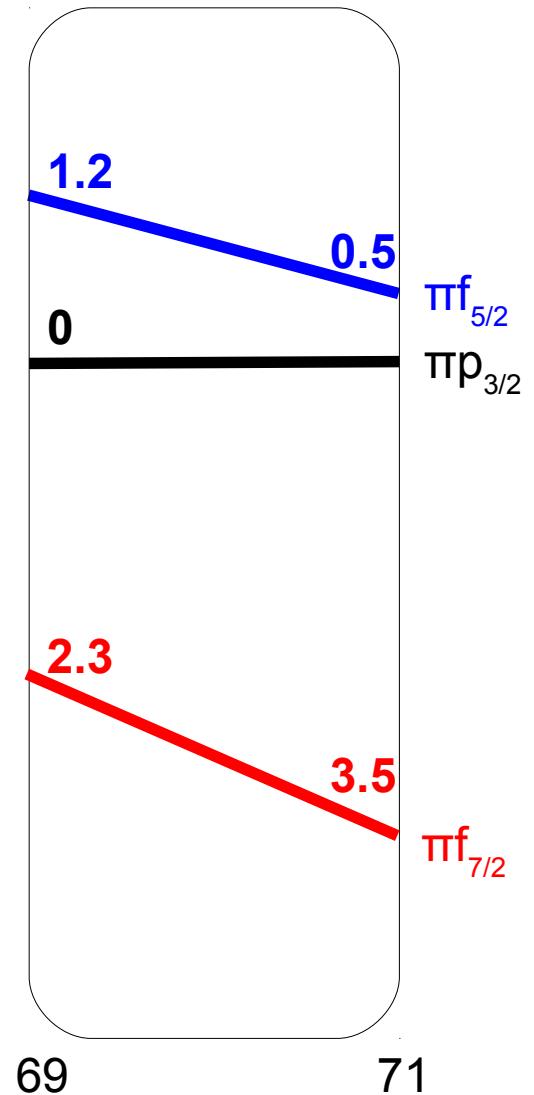
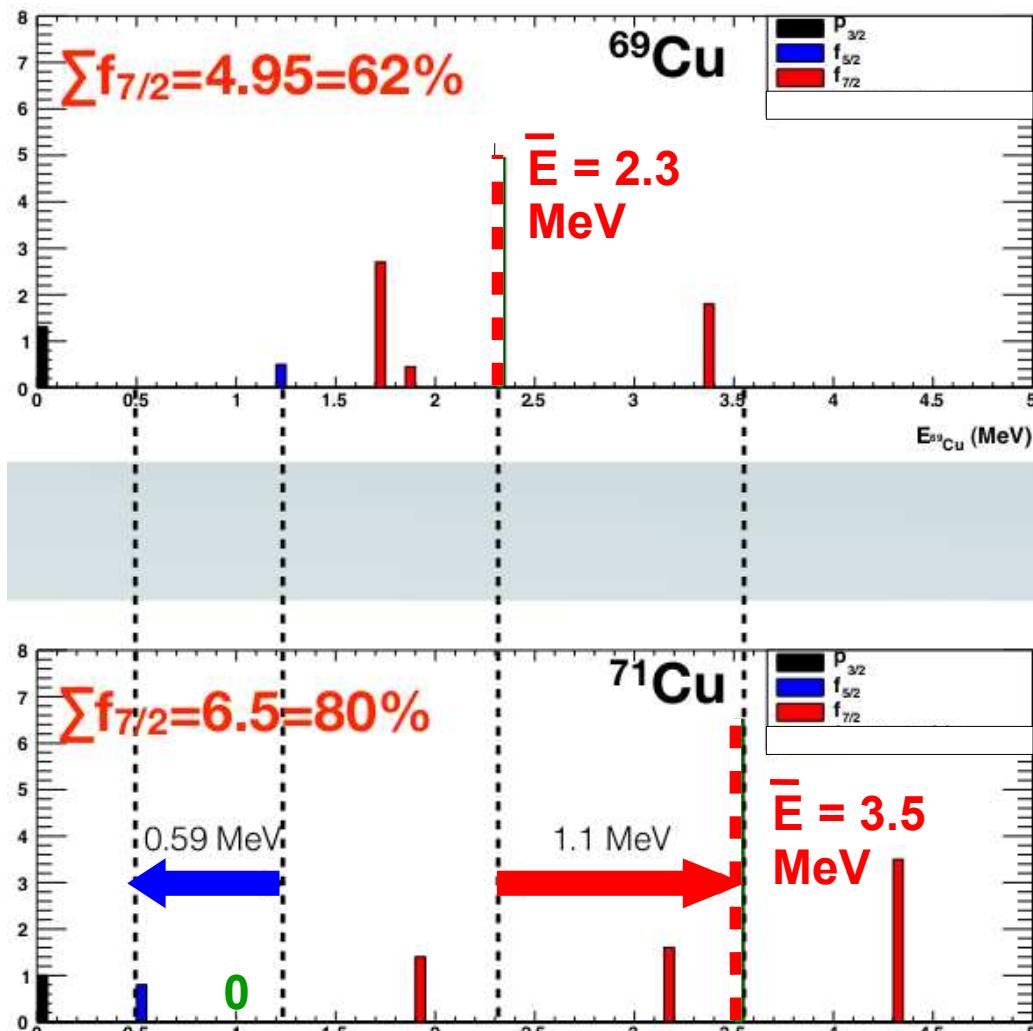
# proton pick-up into $^{71}\text{Cu}$ at Ganil



- $^{72}\text{Zn}(\text{d},\text{t})^{71}\text{Cu}$  proton transfer
- resolution  $\Delta E_x = 300 \text{ keV}$
- $\pi f_{7/2}$  centroid at 3.5 MeV (80%)
- no proton hole strength at 1 MeV:  
 $7/2^- = 2^+ \times \{\pi p_{3/2}, \pi f_{5/2}\}$

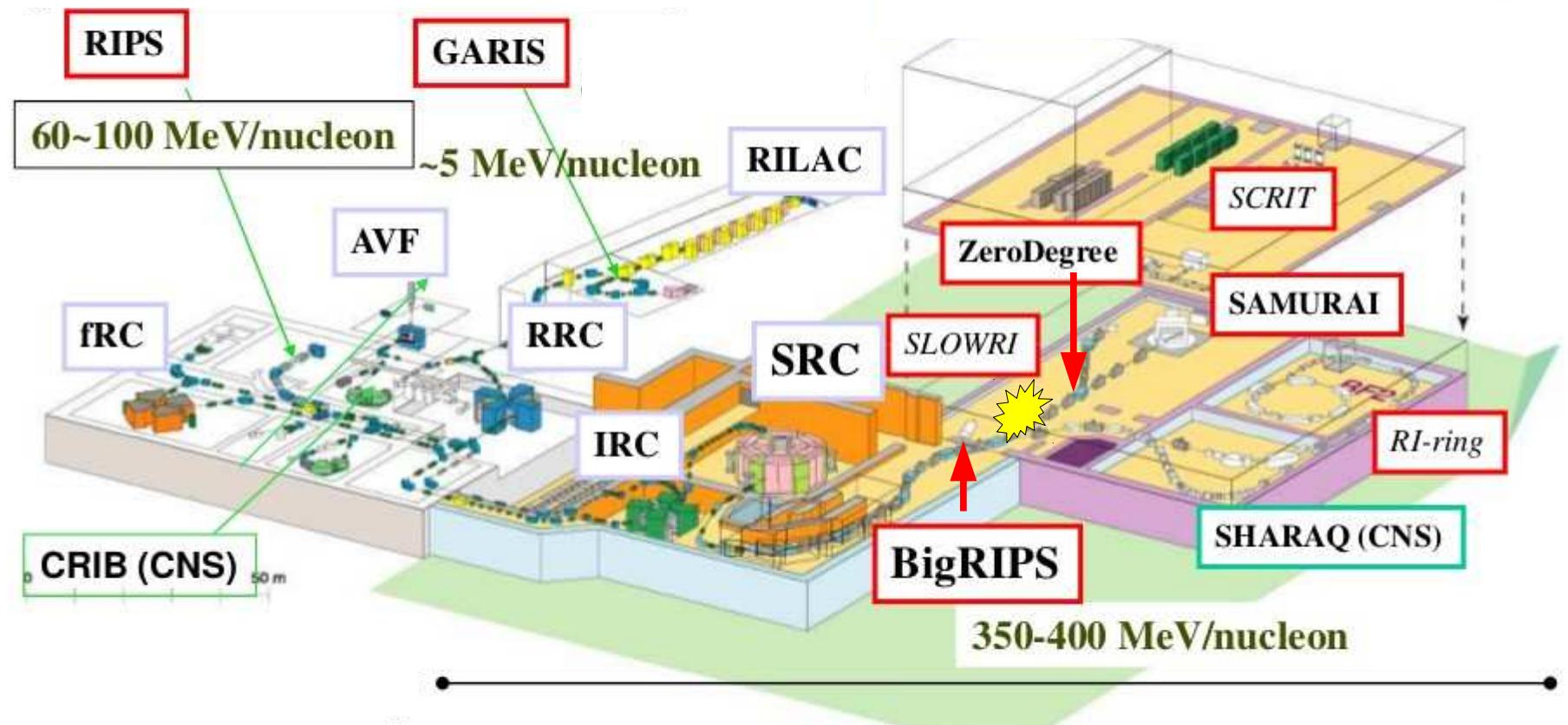


# proton pick-up into $^{71}\text{Cu}$ at Ganil



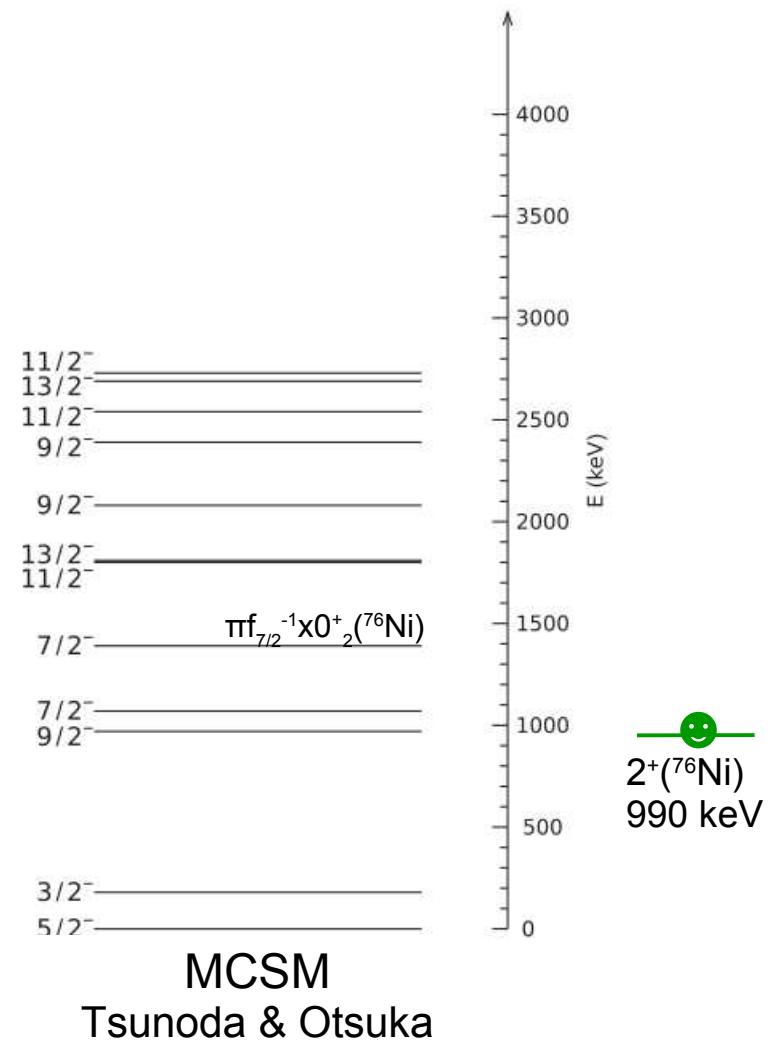
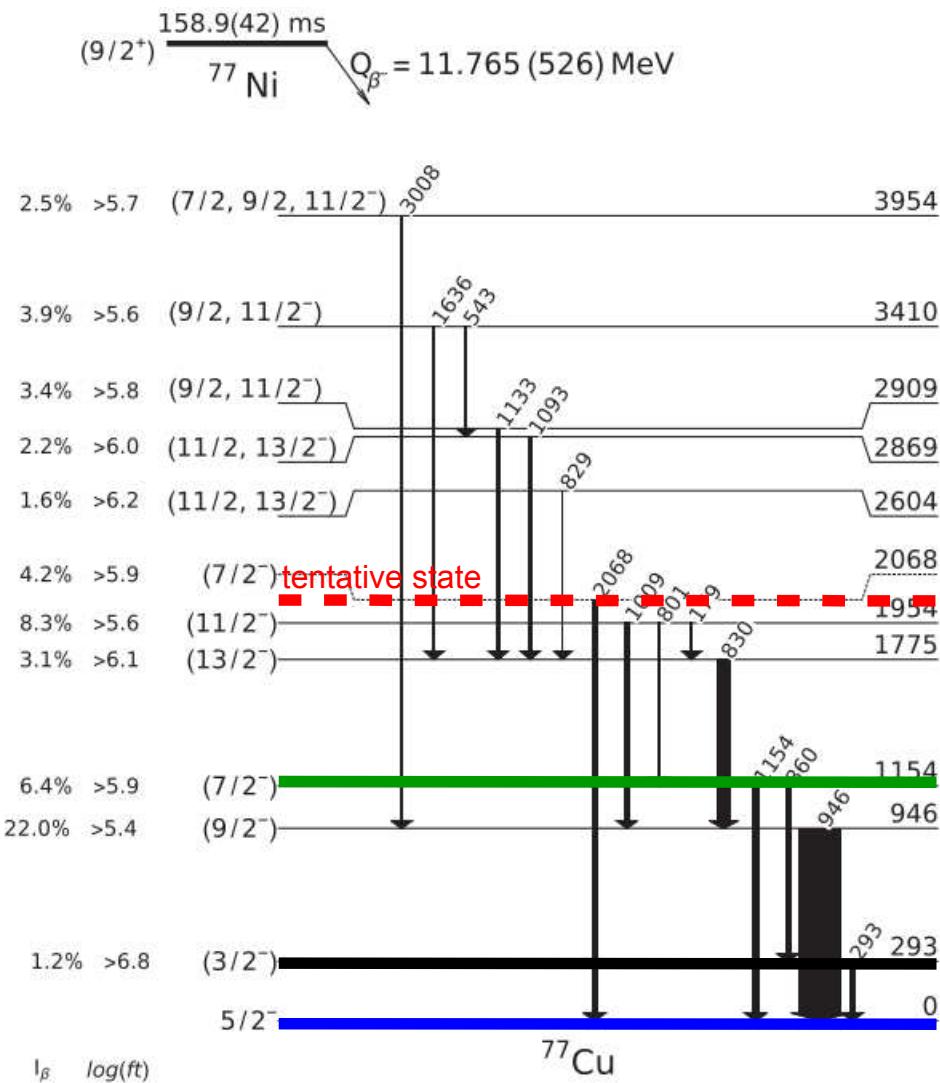
$\pi f_{7/2}$ - $\pi f_{5/2}$  spin-orbit splitting maintained in  $^{71}\text{Cu}$

# RIKEN RI Beam Factory (RIBF)



**Intense (80 kW max.) H.I. beams (up to U) of 345AMeV at SRC  
Fast RI beams by projectile fragmentation and U-fission at BigRIPS**

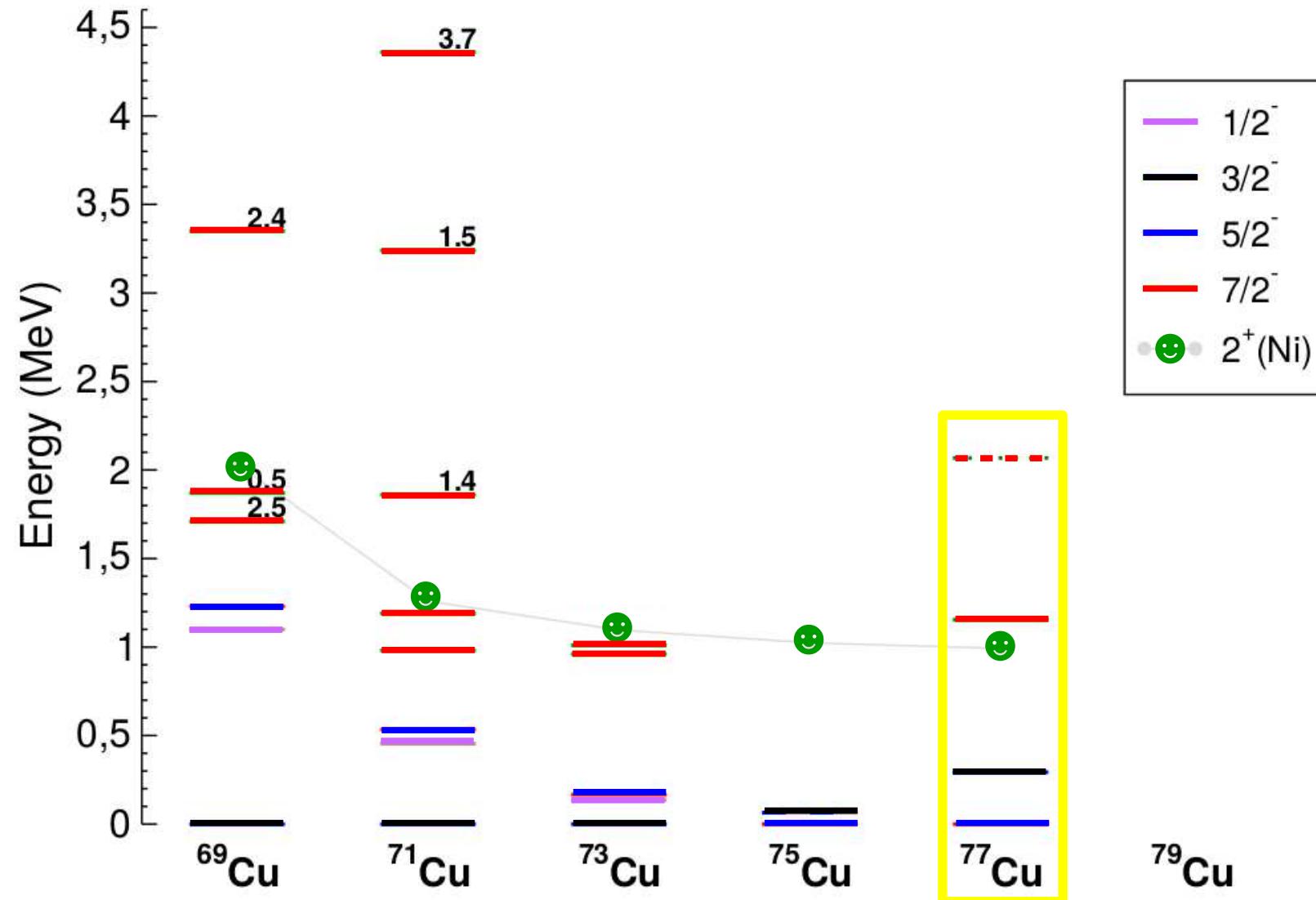
# $\beta\gamma$ spectroscopy of $^{77}\text{Cu}$ at Riken



- 10 pnA  $^{235}\text{U}$  at 345 AMeV on  $^9\text{Be}$
- fission fragments separated in Bigrips + Zerodegree
- Wasabi + Eurica

E Sahin et al, PRL 118, 242502 (2017)

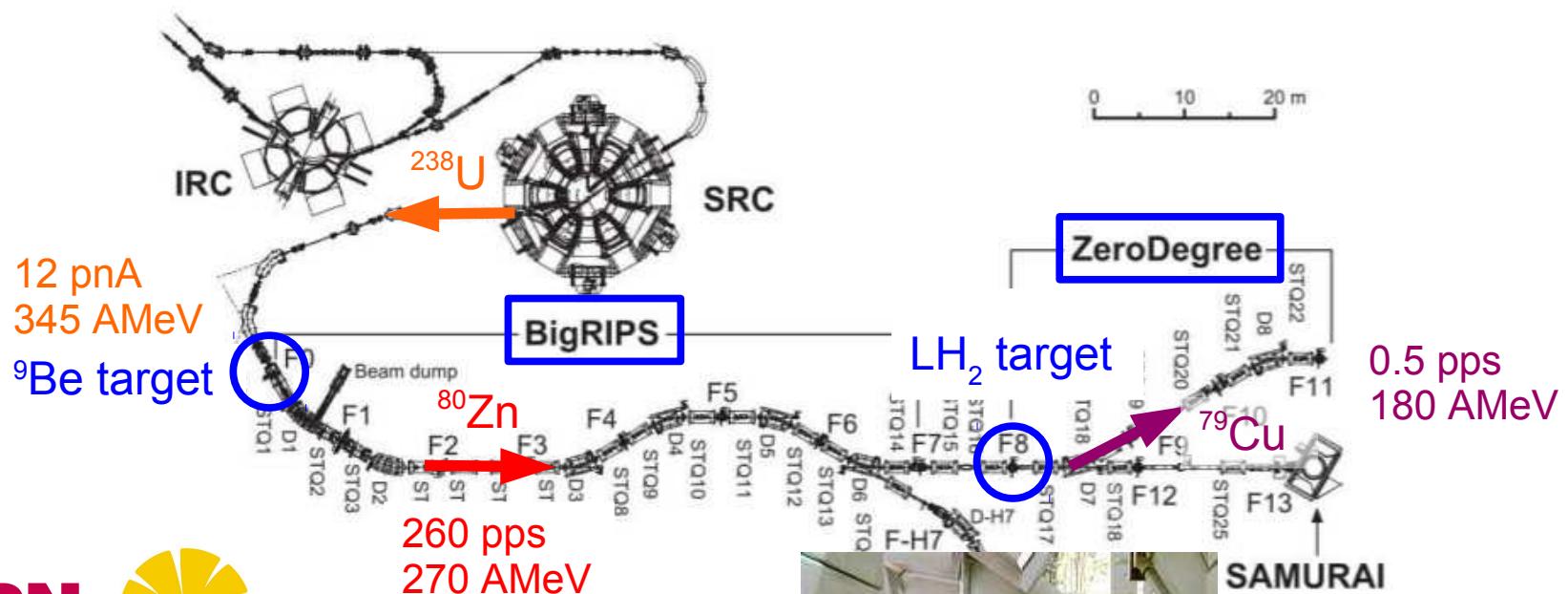
# $\beta\gamma$ spectroscopy of $^{77}\text{Cu}$ at Riken



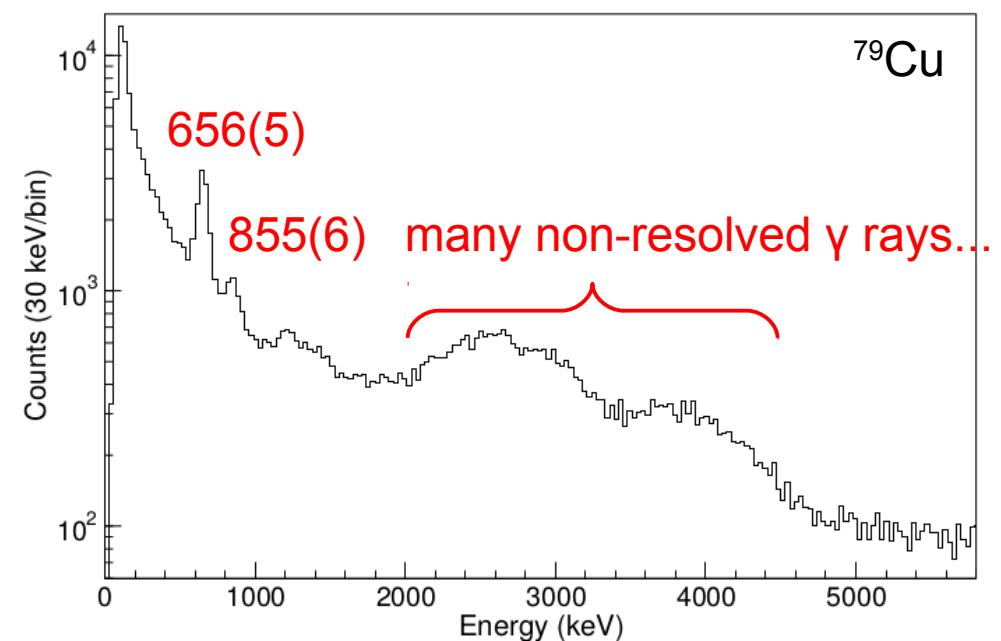
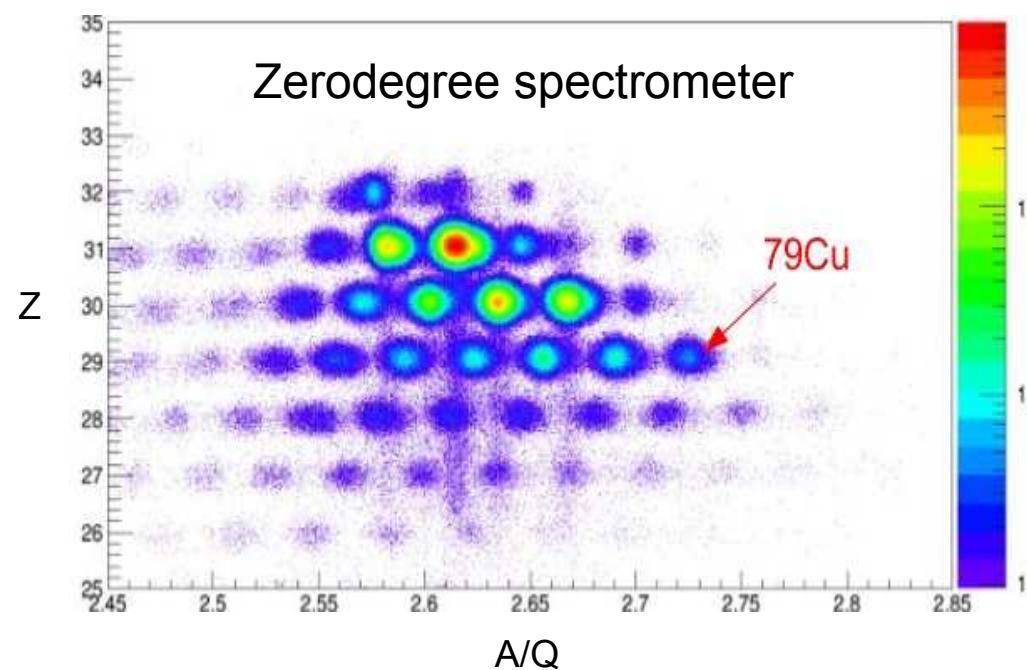
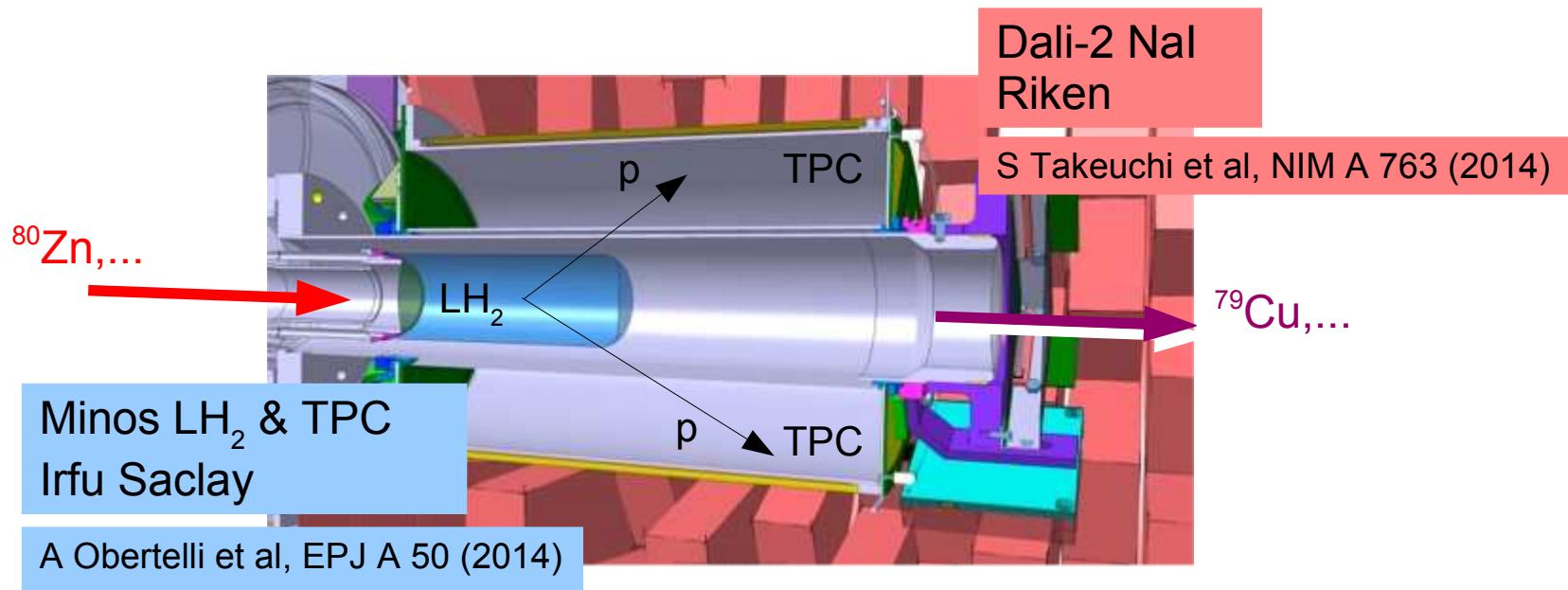
# $\gamma$ spectroscopy of $^{79}\text{Cu}$ at Riken

Seastar collaboration "Shell evolution and search for two-plus energies at RIBF"

- $^{80}\text{Zn}(\text{p},2\text{p})^{79}\text{Cu}$  proton knock-out at 270 AMeV in Minos
- identification before and after with Bigrips and Zerodegree
- in-beam  $\gamma$  spectroscopy with Dali-2
- E( $2^+$ ) from  $^{52}\text{Ar}$  to  $^{110}\text{Zn}$  including doubly magic  $^{78}\text{Ni}$  & single-particle states in  $^{79}\text{Cu}$



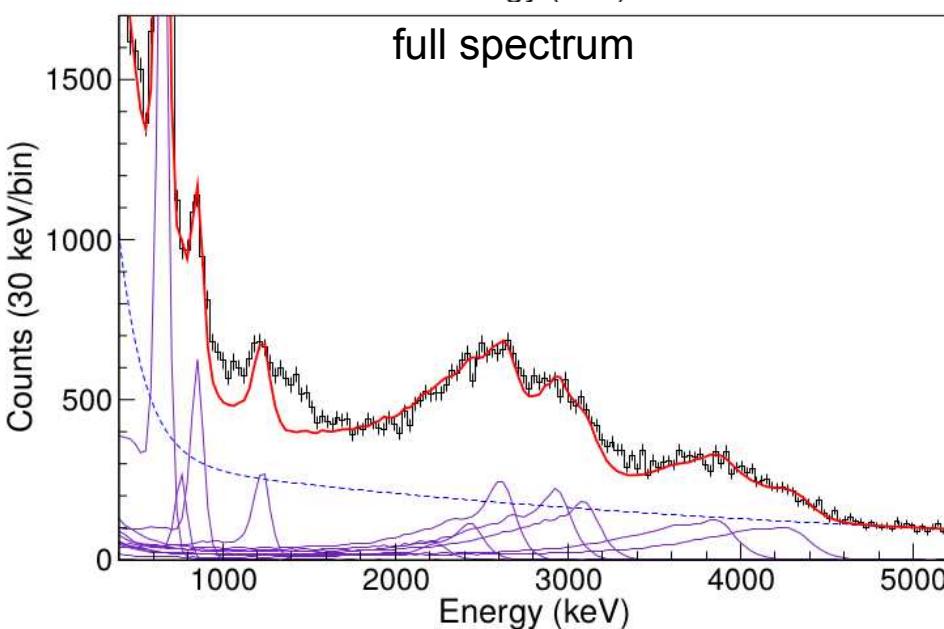
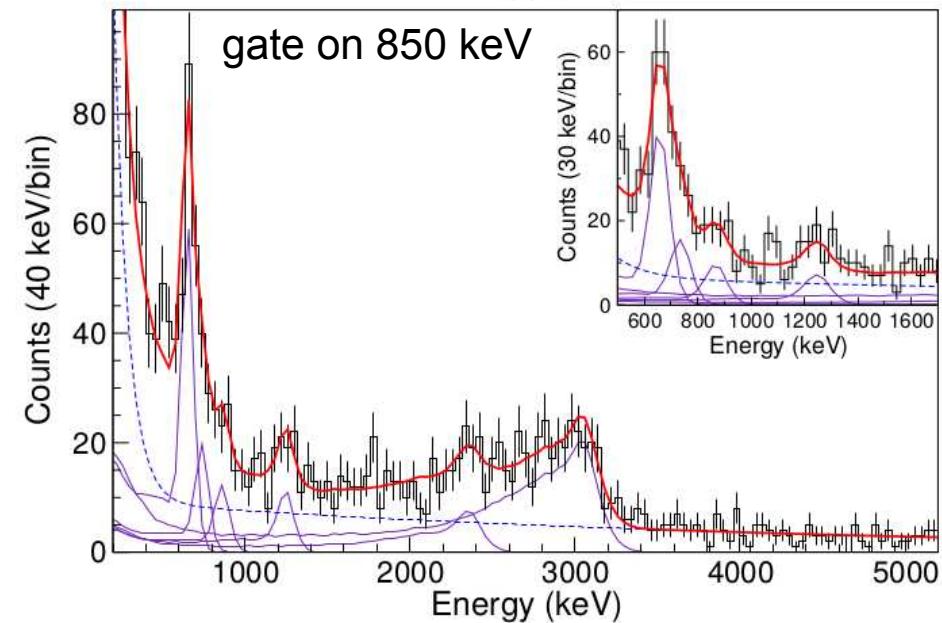
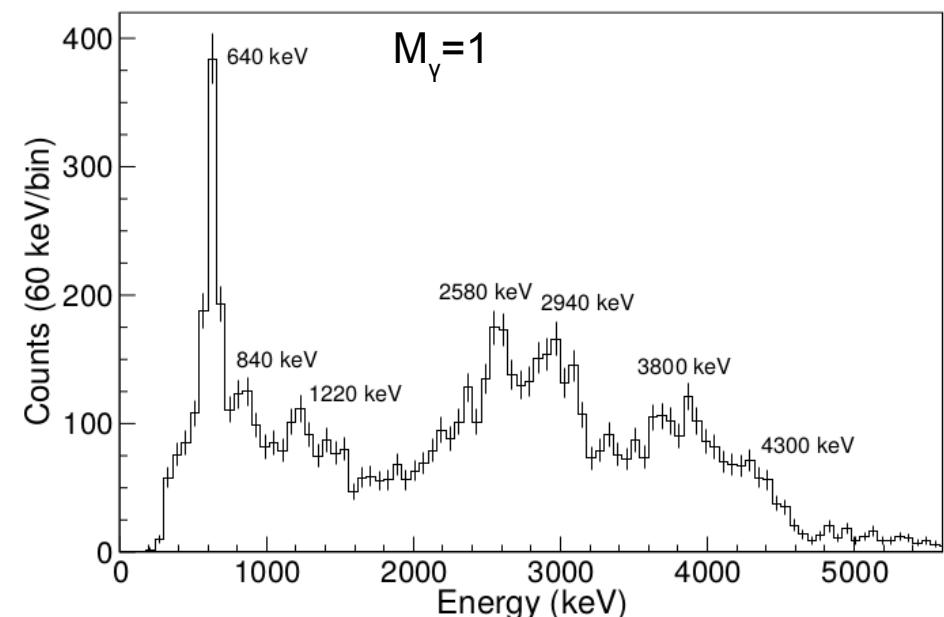
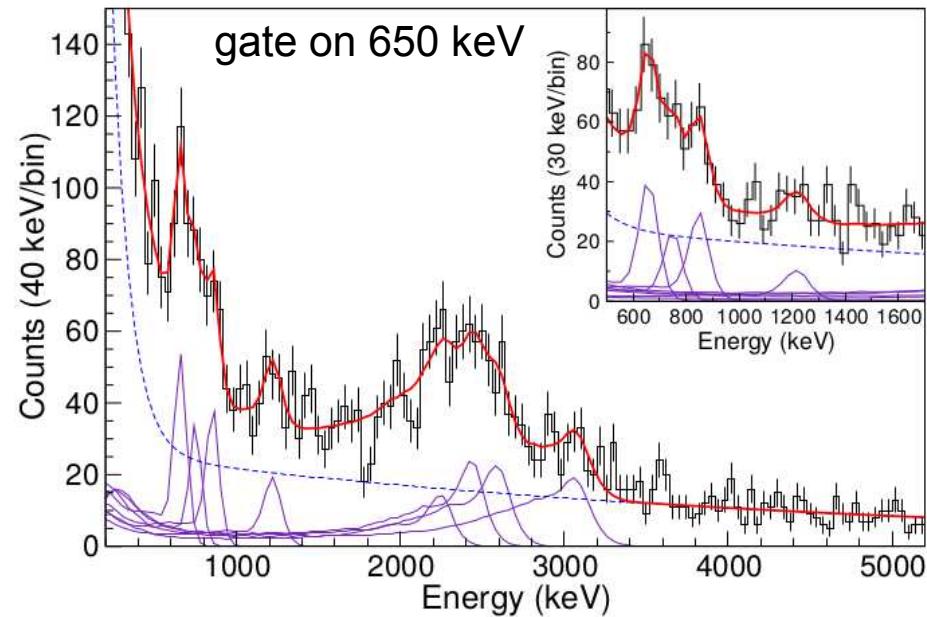
# $\gamma$ spectroscopy of $^{79}\text{Cu}$ at Riken



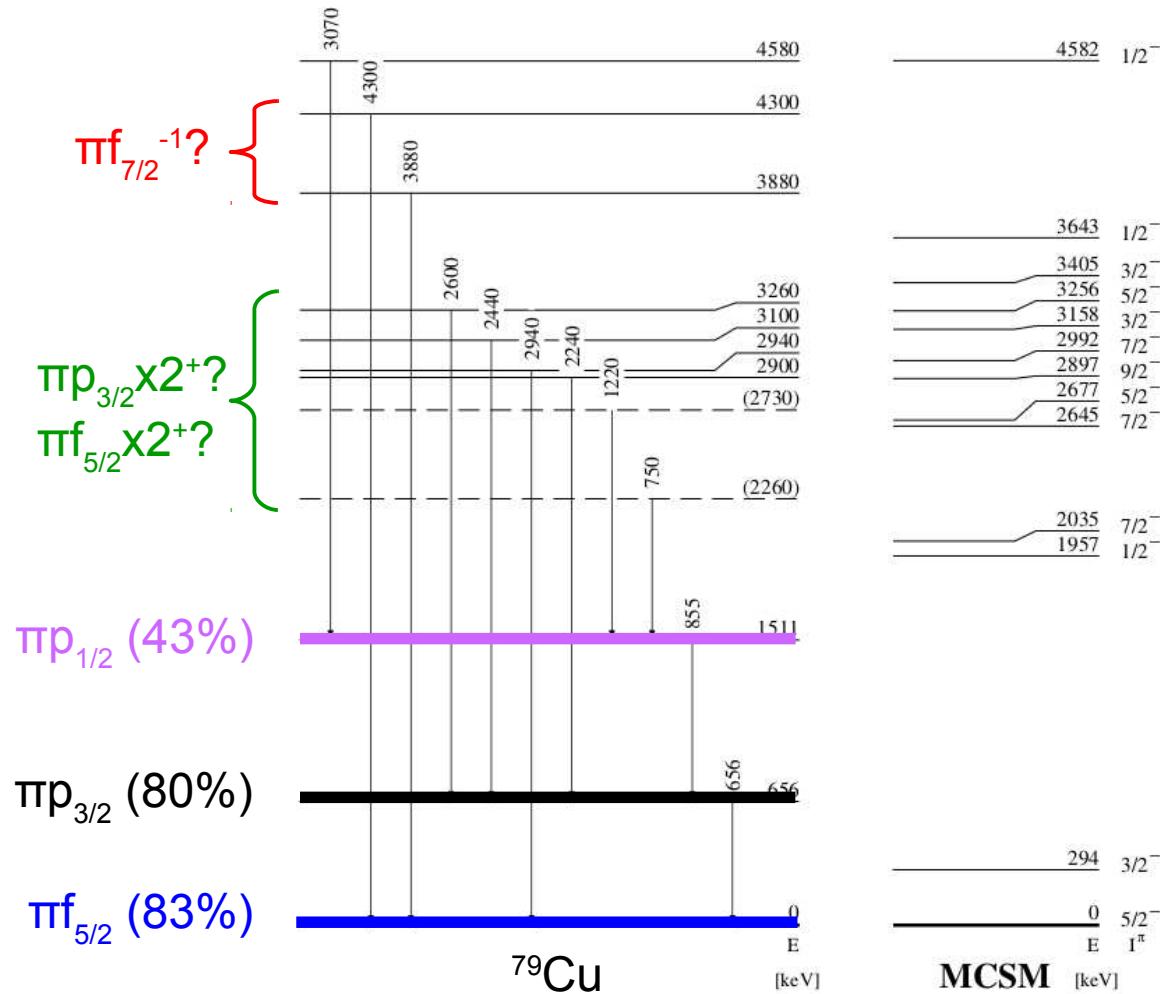
L Olivier et al, PRL 119, 192501 (2017)

# $\gamma$ spectroscopy of $^{79}\text{Cu}$ at Riken

## $\gamma\gamma$ coincidences

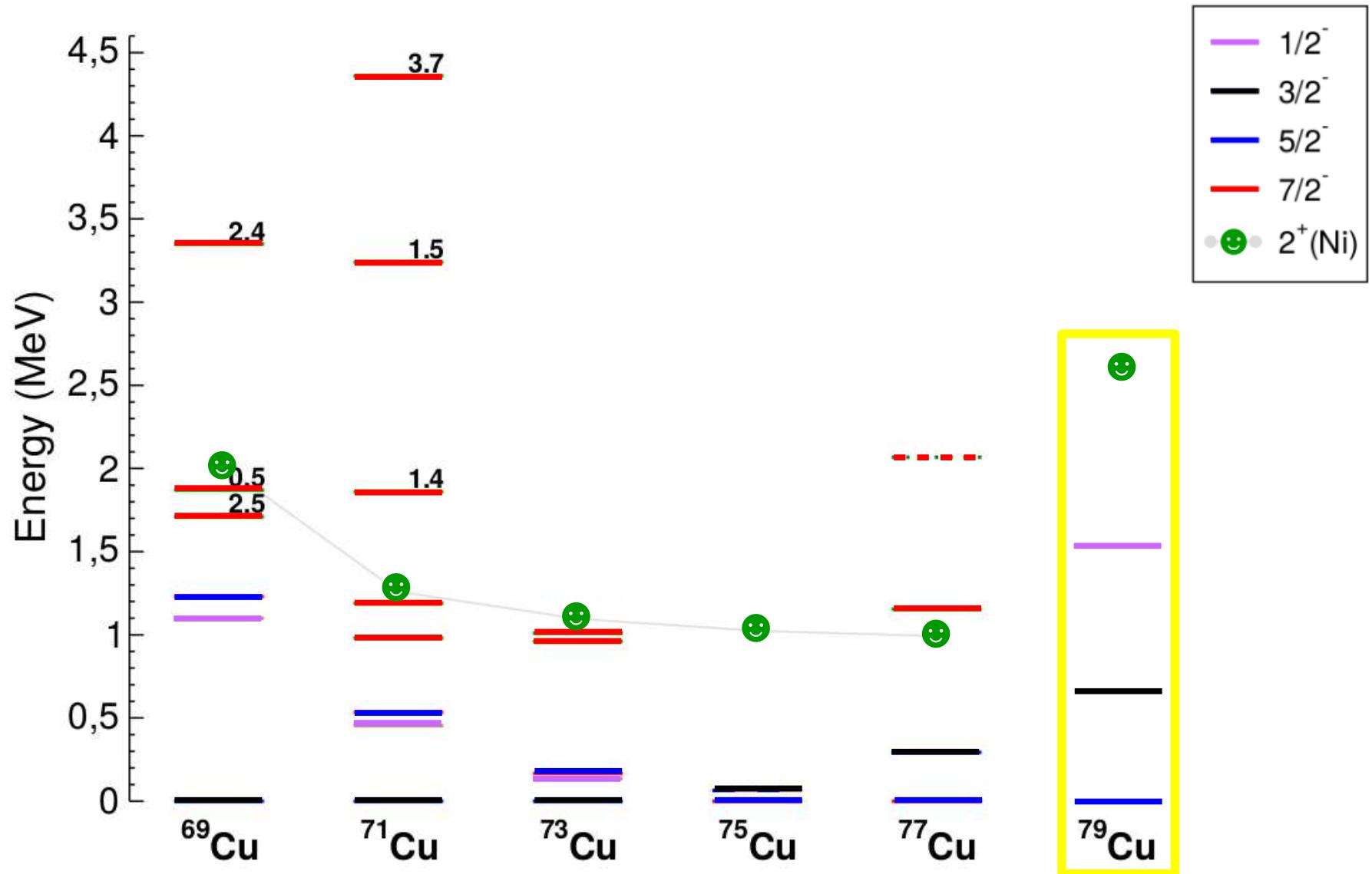


# $\gamma$ spectroscopy of $^{79}\text{Cu}$ at Riken

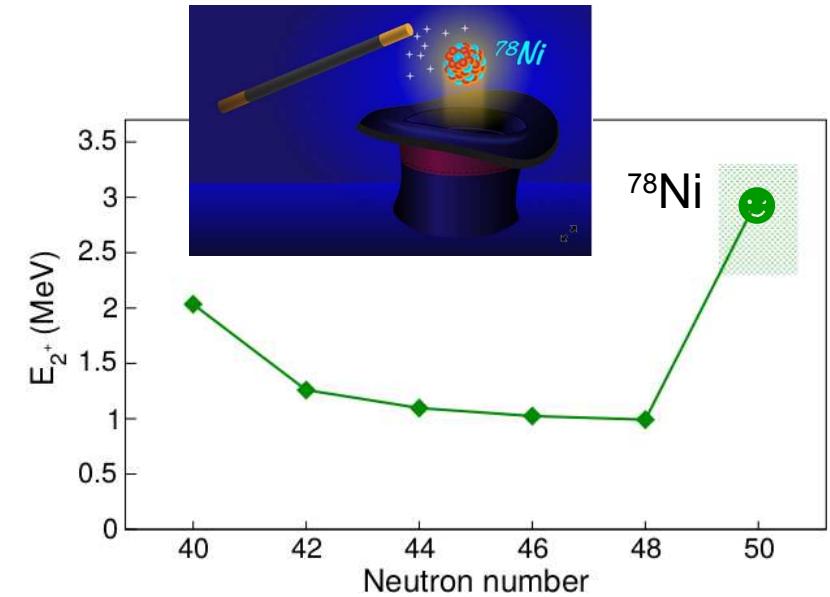
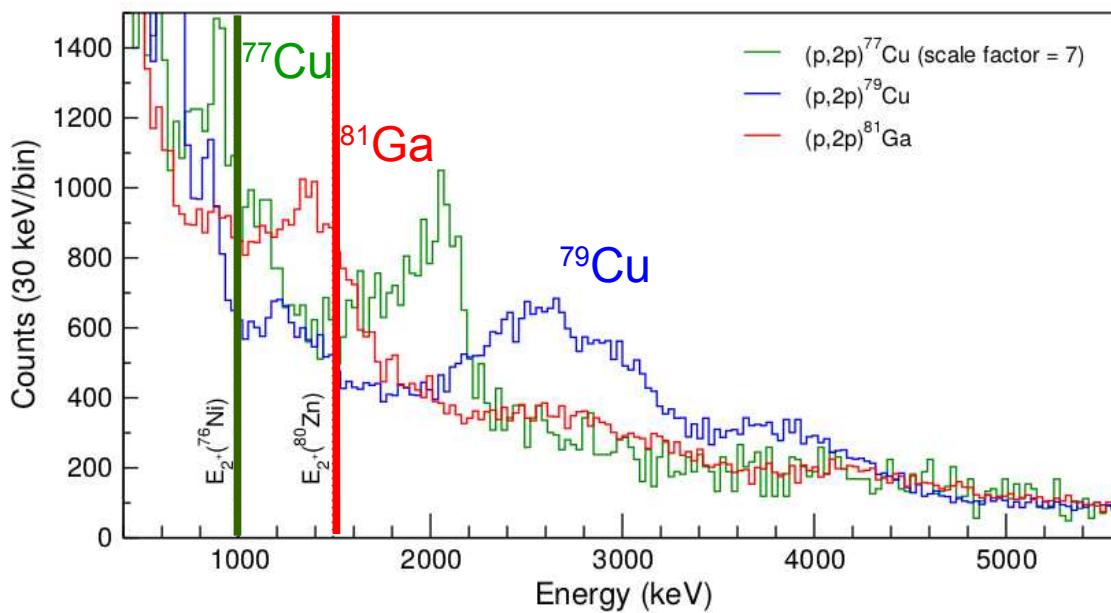


- good agreement with MCSM
- πp<sub>1/2</sub> at 1.5 MeV from absence of direct feeding
- multiplet allows for estimation of 2<sup>+</sup>( $^{78}\text{Ni}$ )
- πf<sub>7/2</sub> hole fragmented at 4 MeV ?

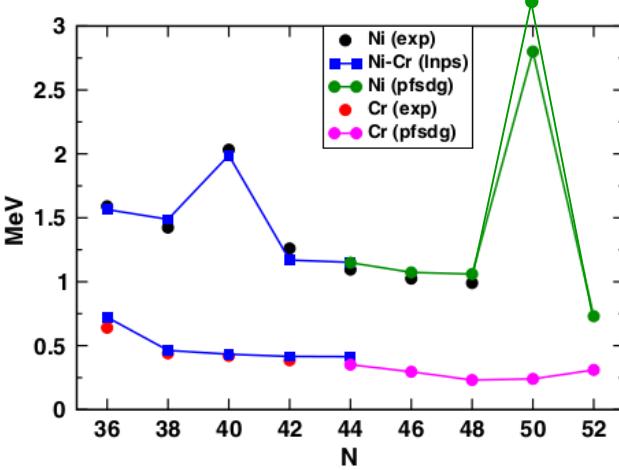
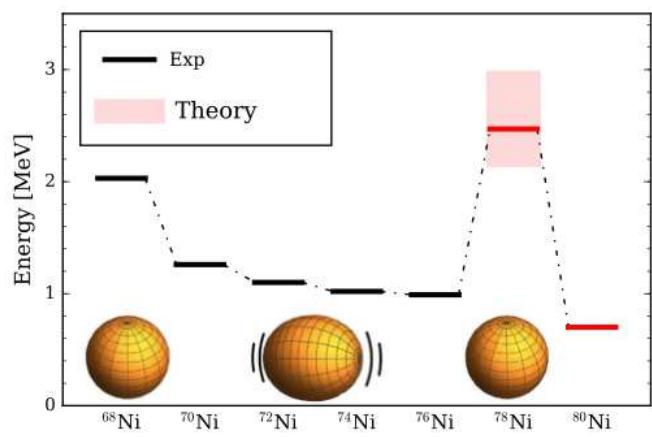
# $\gamma$ spectroscopy of $^{79}\text{Cu}$ at Riken



# $\gamma$ spectroscopy of $^{79}\text{Cu}$ at Riken

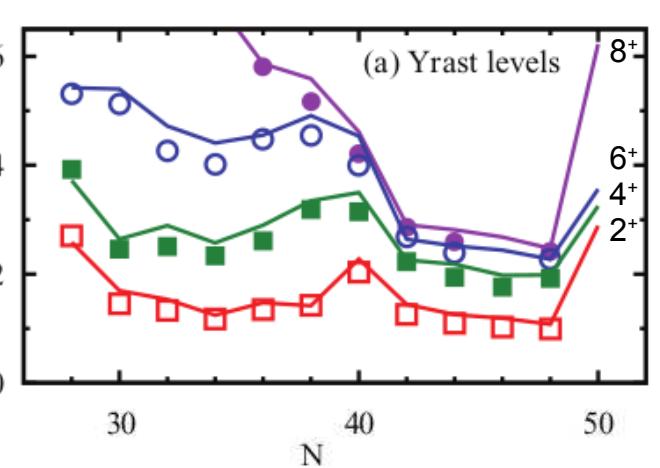


L Olivier et al, PRL 119, 192501 (2017)



Hagen, Jansen & Papenbrock,  
PRL 117 (2016)

Nowacki et al, PRL 117 (2016)



Tsunoda et al, PRC89 (2014)

# $\gamma$ spectroscopy of $^{79}\text{Cu}$ at Riken

inclusive DWIA cross section with SF from MCSM

$$\sigma_{\text{th}} = 9.2 \text{ mb}$$

$$\sigma_{\text{exp}} = 7.9(4) \text{ mb}$$

→ consistent with other Seastar results

exclusive cross sections

theory

	E (MeV)	$\sigma$ (mb)	SF	$\sigma \cdot \text{SF}$	
5/2-	0	1.04	1.33	1.38	
3/2-	0.29	1.31	0.57	0.75	
7/2-	2.04	1.14	5.58	6.36	
7/2-	2.65	1.14	0.15	0.17	
7/2-	2.99	1.14	0.43	0.49	
					7.02

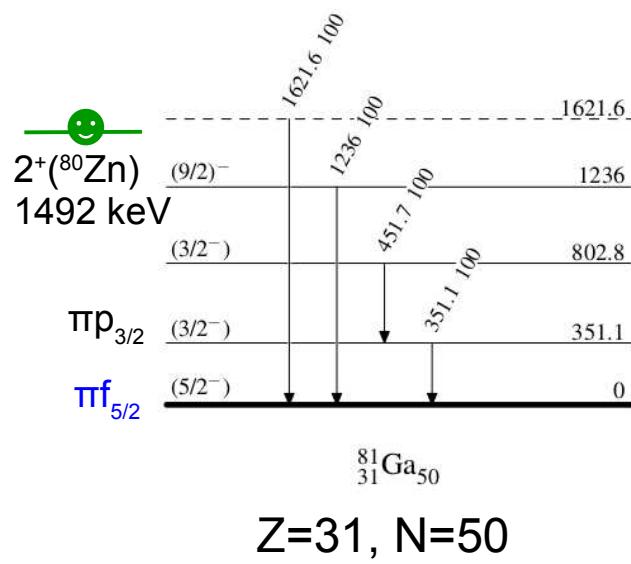
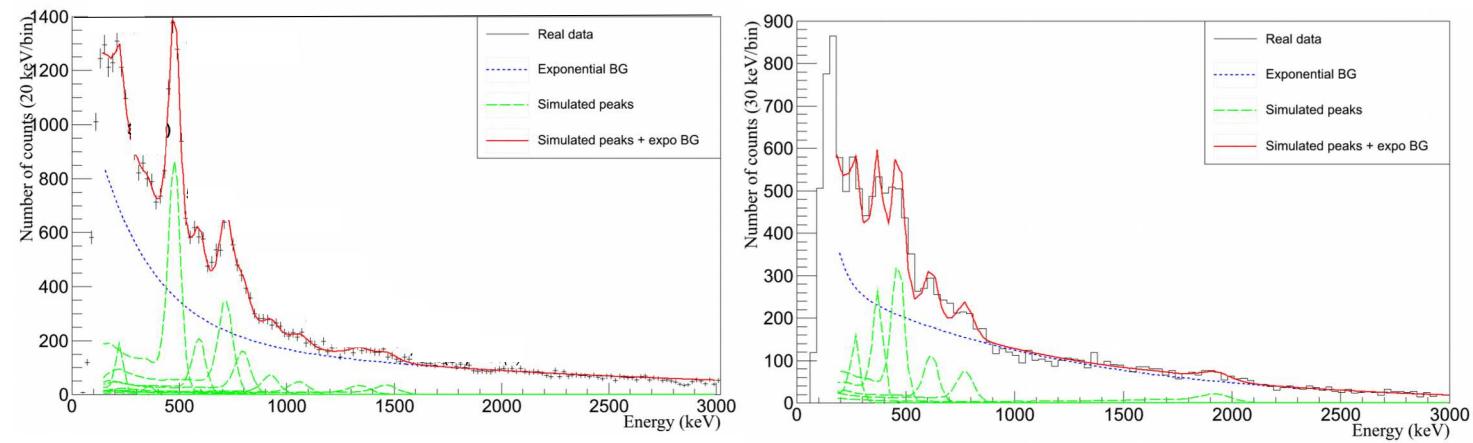
experiment

Energy levels (keV)	$\sigma_{\text{exc}}$ (mb)	
0	< 3.8(8)	
656(5)	0.04(29)	
1511(8)	0	
2260(20)	0.19(4)	
2730(30)	0.33(9)	
2900(40)	0.08(4)	
2940(60)	0.69(13)	
3100(40)	0.44(7)	
3260(40)	0.84(15)	
3880(40)	0.71(9)	
4300(40)	0.65(9)	
4580(30)	0.58(13)	
		> 4.1(9)

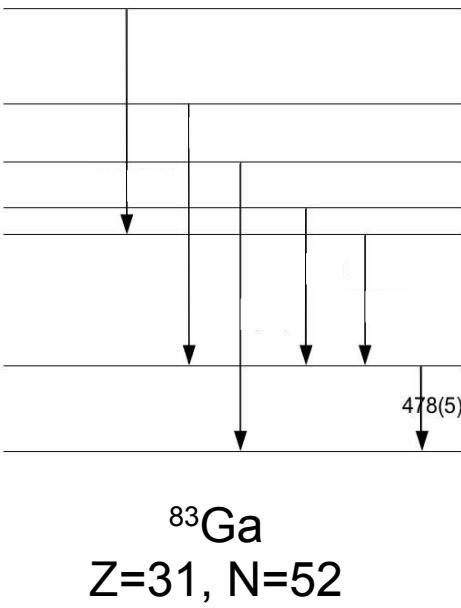
summed cross section is consistent with  $\pi f_{7/2}$  hole

experiment shows important fragmentation of spectroscopic strength

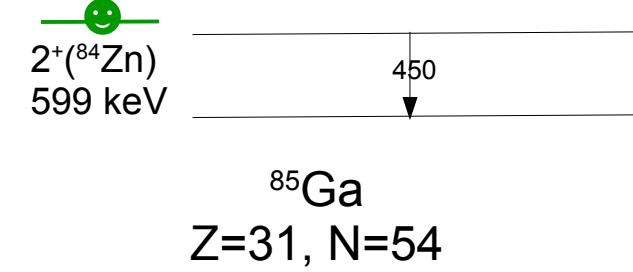
# $\gamma$ spectroscopy of $^{83,85}\text{Ga}$ at Riken



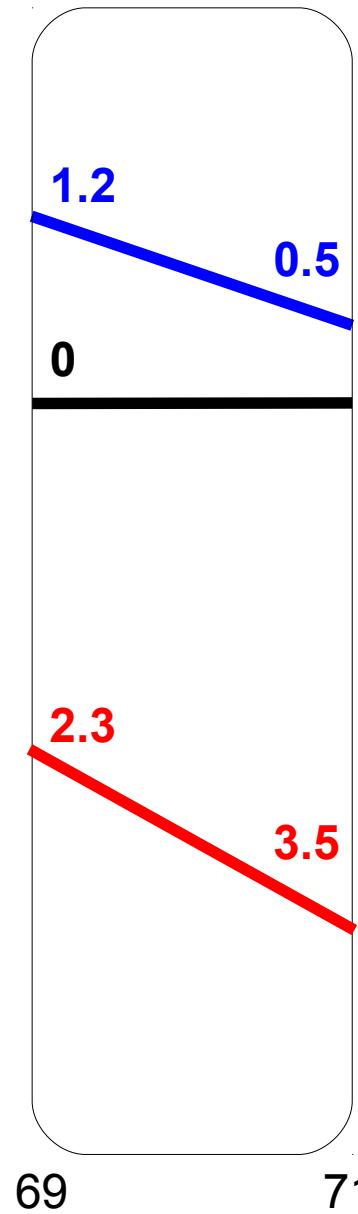
$^{81}\text{Ga}$ : D Verney et al, PRC 76 (2007)



Ga: L Olivier, PhD U Paris-Saclay (2017)  
Zn: C Shand et al, PLB 773 (2017)



## Conclusions

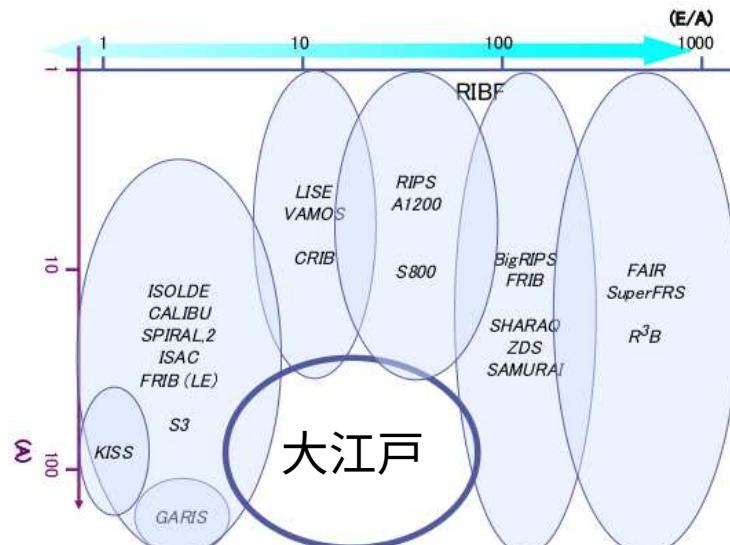


$\pi f_{7/2}$ - $\pi f_{5/2}$  spin-orbit force in neutron-rich copper

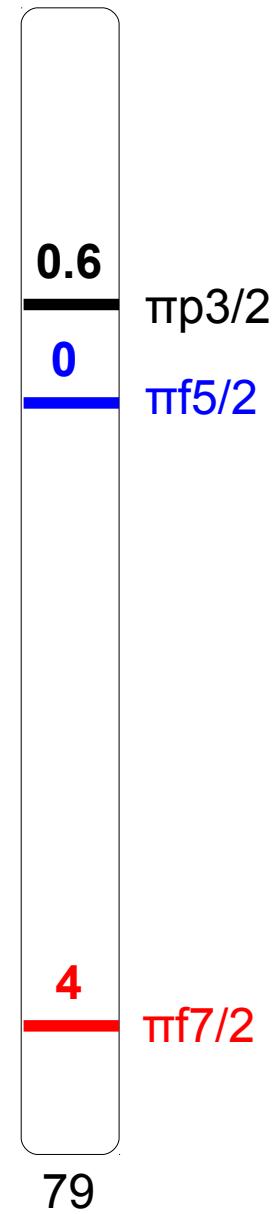
- (d, $^3$ He) $^{71}$ Cu transfer at Ganil  
spin-orbit splitting in  $^{71}$ Cu maintained
- (p,2p) $^{79}$ Cu knockout at Riken  
good agreement with MCSM  
 $\pi f_{7/2}$  hole strength fragmented at 4 MeV ?

single-particle character in  $^{79}$ Cu confirms magicity of  $^{78}$ Ni

new perspectives for transfer reactions at Oedo



Shimoura et al LOI, (2014)



proton pick-up into  $^{71}\text{Cu}$  at Ganil

