Search for intruder states in ^{66,67}Co and ^{68}Ni

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Motivation

- ^{68}Ni at Z=28 shell and N=40 subshell gaps
- Robustness of shell gaps called into question:
  - N≈40 not magic in neighbors, e.g. ^{66}Fe, ^{64}Cr, ^{67}Ni
  - Proposed proton intruder states important in the low-lying structure of ^{64,66}Mn, $^{65\text{-}68}$Co, ^{67,69,71}Cu

$\pi p_{3/2}$ from above Z=28

$\pi f_{7/2}$ from below Z=28

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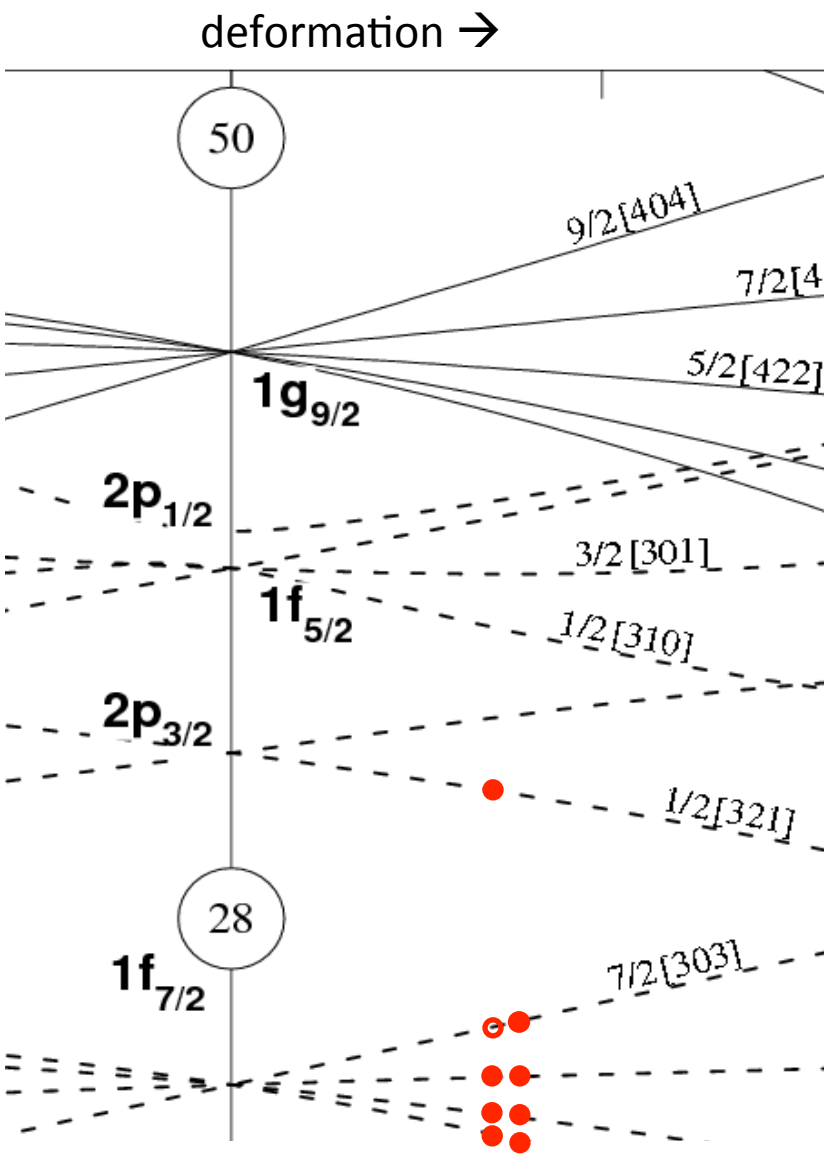
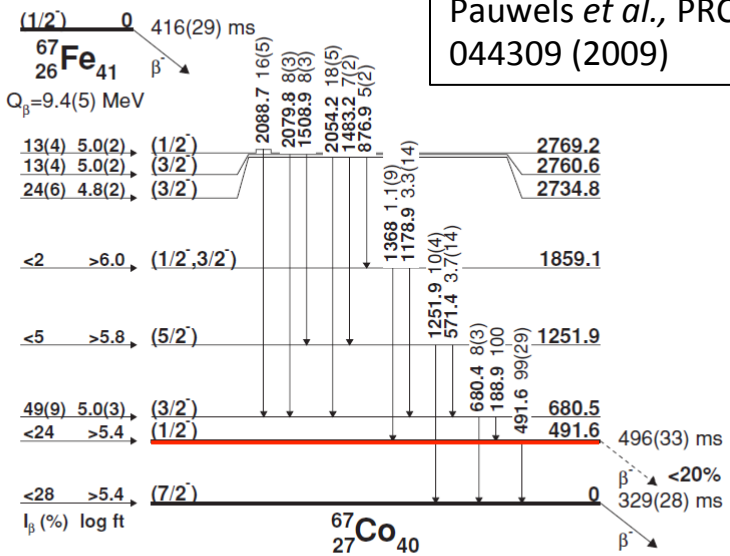
^{66}**Fe**: Hannawald *et al.,* PRL**82**, 1391 (1999)
^{64}**Cr**: Gade *et al.,* PRC**81**, 051304(R) (2010)
^{67}**Ni**: Zhu *et al.,* PRC**85**, 034336 (2012)
^{64,66}**Mn**: Liddick *et al.,* PRC**84**, 061305 (2011)
^{65}**Co**: Pauwels *et al.,* PRC**79**, 044309 (2009)
^{67}**Co**: Pauwels *et al.,* PRC**78**, 041307(R) (2008)
^{66,68}**Co**: Liddick *et al.,* PRC**85**, 014328 (2012)
^{67}**Cu**: Chiara *et al.,* PRC**85**, 024309 (2012)
^{69}**Cu**: Ishii *et al.,* PRL**84**, 39 (2000)
^{71}**Cu**: Oros-Peusquens and Mantica, NPA**669**, 81 (2000)

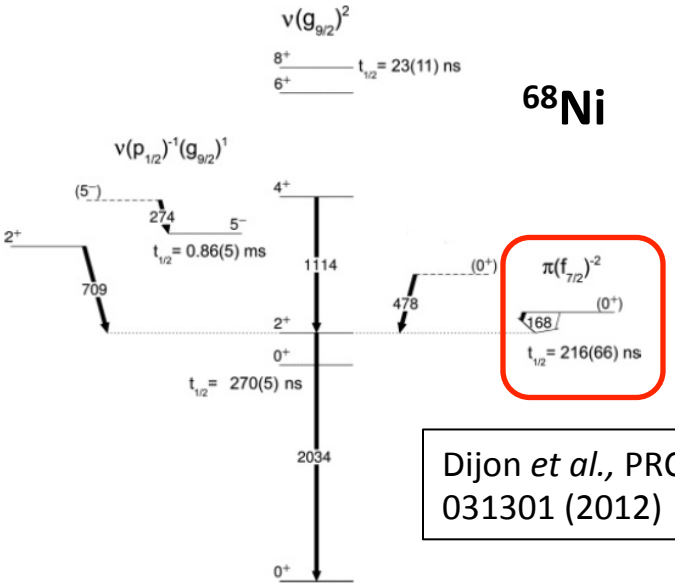


Nilsson diagram of region



Pauwels *et al.*, PRC**79**, 044309 (2009)

^{66}Co: see Liddick talk this afternoon, and Walters poster



Dijon *et al.*, PRC**85**, 031301 (2012)

Motivation

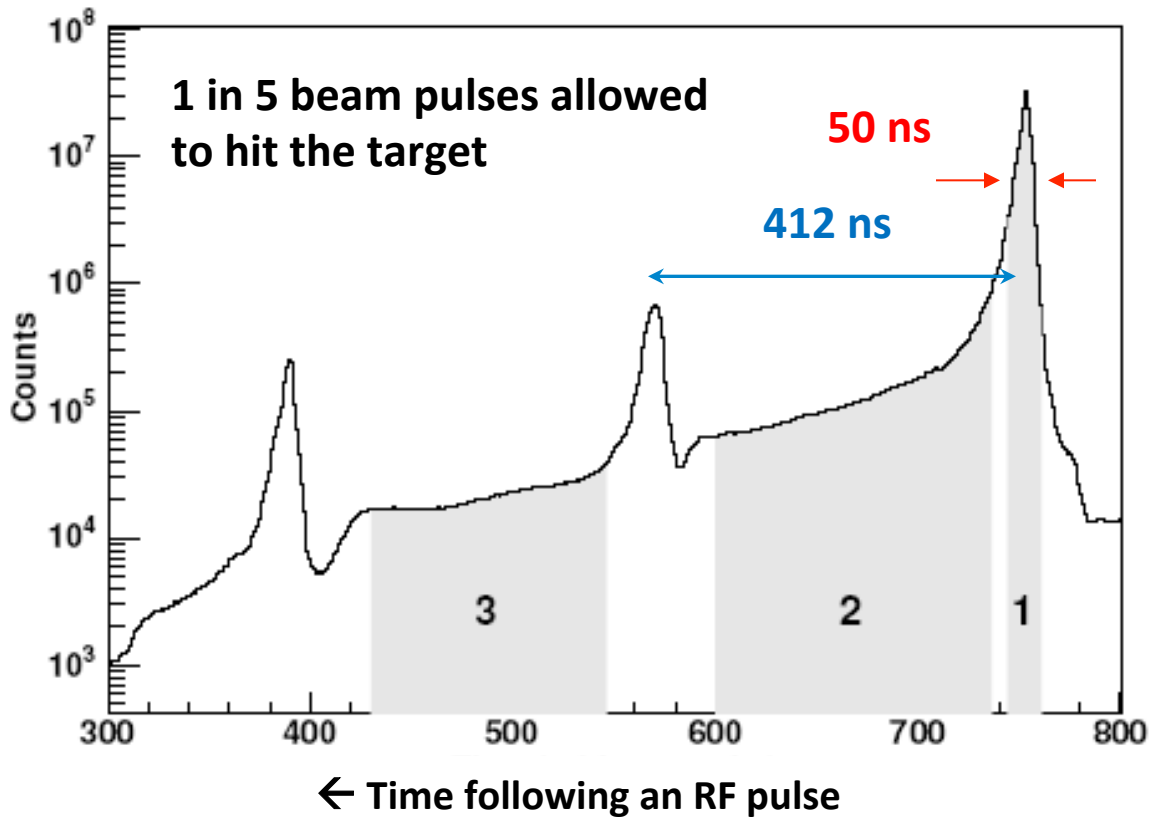
- Intruder states provide insight into size and robustness of shell gap and can test the interactions and single-particle energies
- Goal: extend knowledge of intruder configurations in the ^{68}Ni region

Experiment

- ^{70}Zn-induced (deep-)inelastic reactions at ATLAS
- Gammasphere array of 100 Compton-suppressed Ge
- Thick targets stop *all* reaction products
- Interested in ^{66,67}Co (-3pn,-3p) and ^{68}Ni (-2p)

E_{beam} [MeV]	target	trigger	duration [h]	# events
430	^{197}Au	$\gamma^{\geq 3}$	68	2.1×10^9
440	^{197}Au	$\gamma^{\geq 2}$	12	3.8×10^8
440	^{238}U	$\gamma^{\geq 2}$	8	4.1×10^8
440	^{208}Pb	$\gamma^{\geq 2}$	32	1.3×10^9
440	^{208}Pb	$\gamma^{\geq 3}$	64	2.2×10^9

Ge timing



Prompt: t(γ) in region 1

Delayed: t(γ) in region 2 or 3

Coincidence cubes:

PPP – all three γ's are prompt

PPD – two prompt, one delayed

PDD – one prompt, two delayed

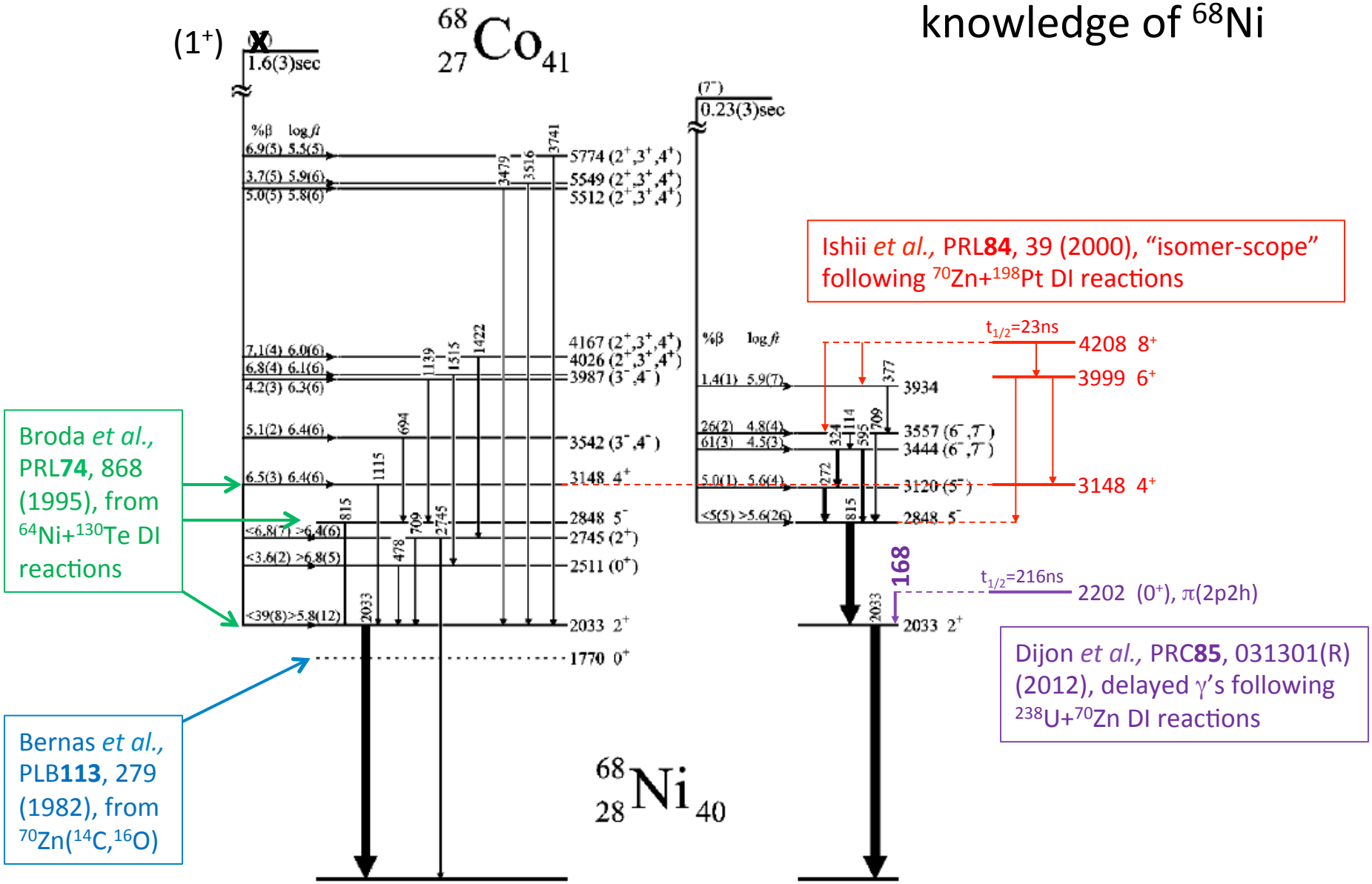
DDD – all three γ's are delayed

Prompt γ rays – emitted by excited states directly populated in the reaction

Delayed γ rays – emitted by isomeric states or by β-decay daughters

Previous state of knowledge of ^{68}Ni

Mueller *et al.*, PRC**61**, 054308 (2000), from beta decay



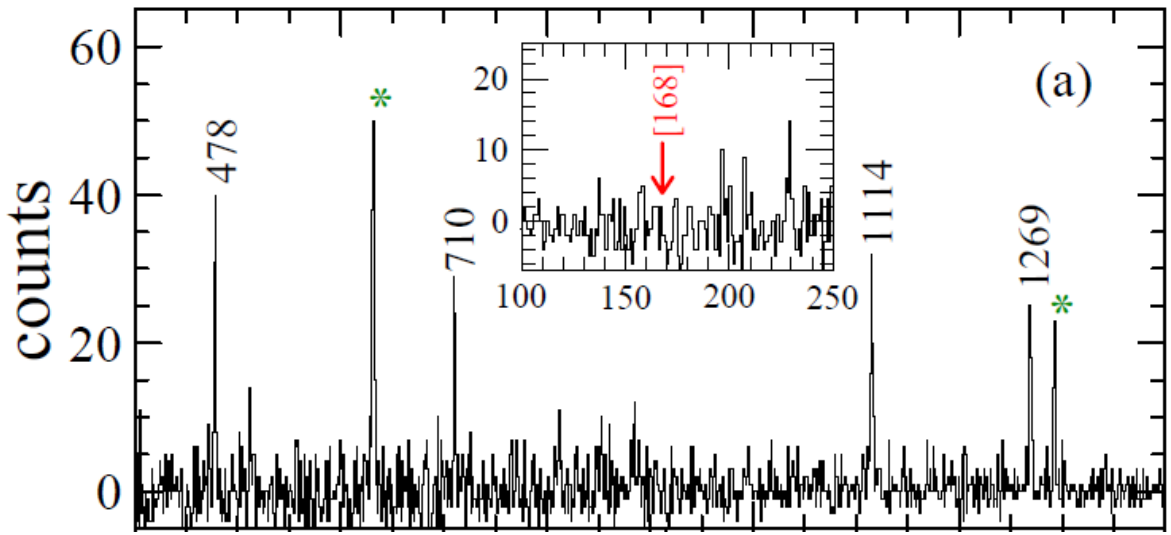
Ishii *et al.*, PRL**84**, 39 (2000), "isomer-scope" following ^{70}Zn+^{198}Pt DI reactions

Broda *et al.*, PRL**74**, 868 (1995), from ^{64}Ni+^{130}Te DI reactions

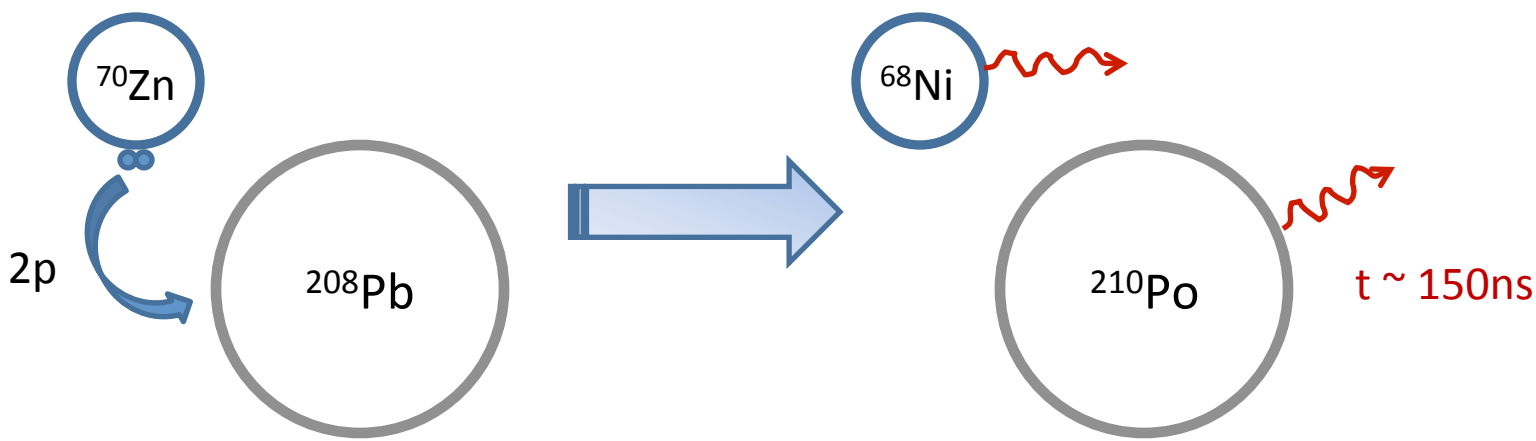
Bernas *et al.*, PLB**113**, 279 (1982), from ^{70}Zn(^{14}C,^{16}O)

Dijon *et al.*, PRC**85**, 031301(R) (2012), delayed γ's following ^{238}U+^{70}Zn DI reactions

Double-gated spectra from ^{70}Zn + ^{208}Pb reaction



From PPD cube: gate on prompt 2033 in ^{68}Ni and delayed 1182 and 245 in ^{210}Po.



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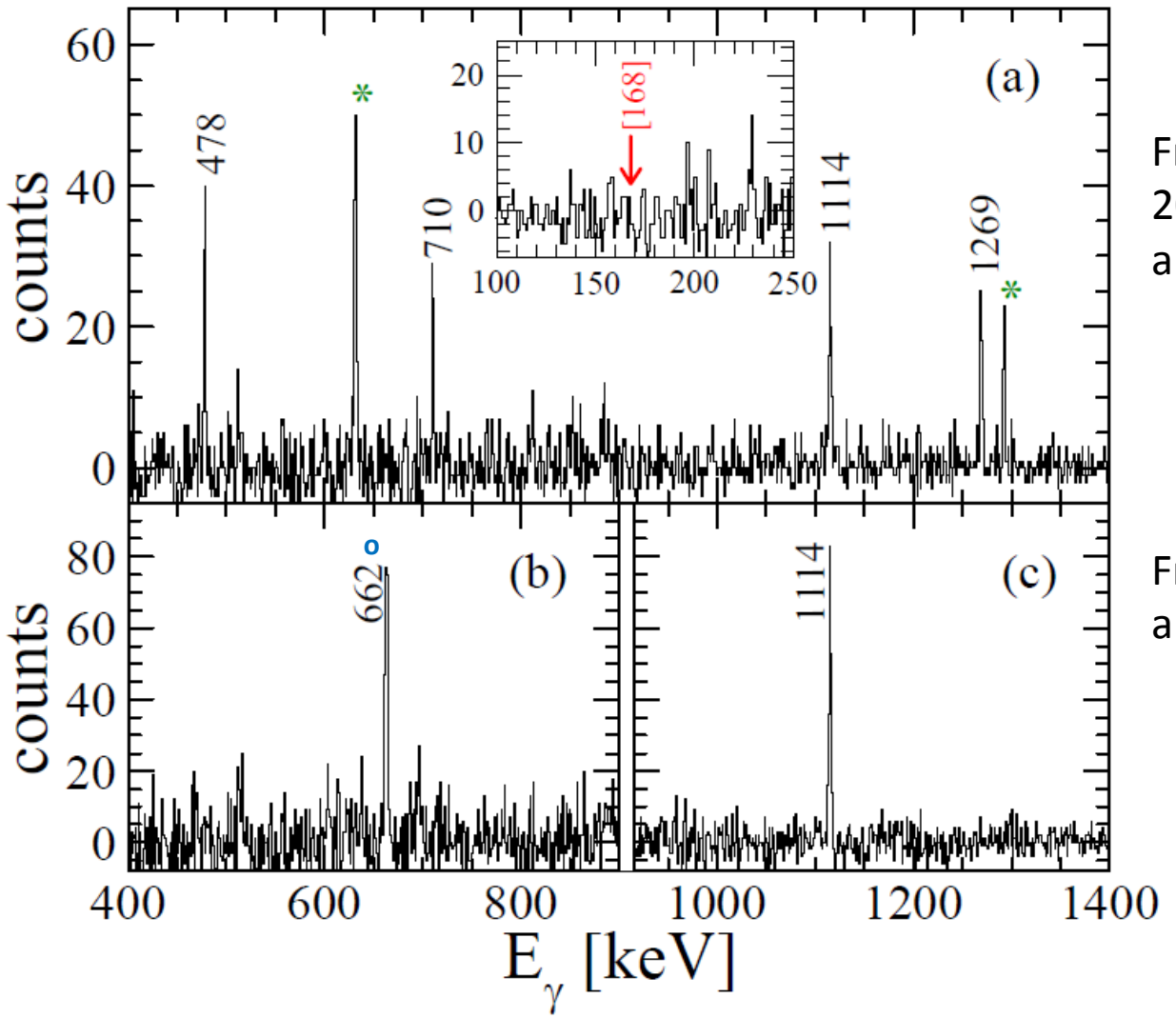
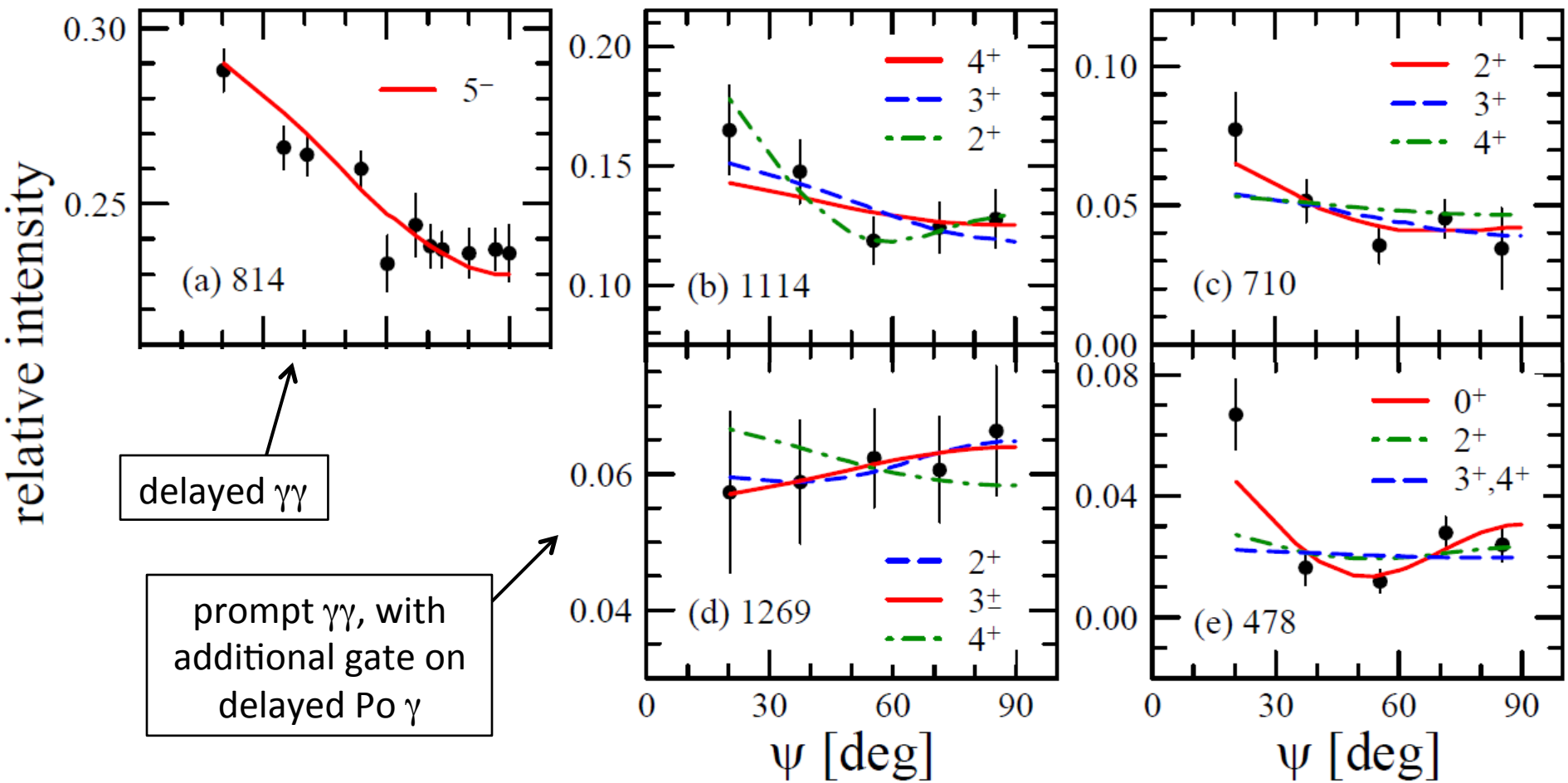


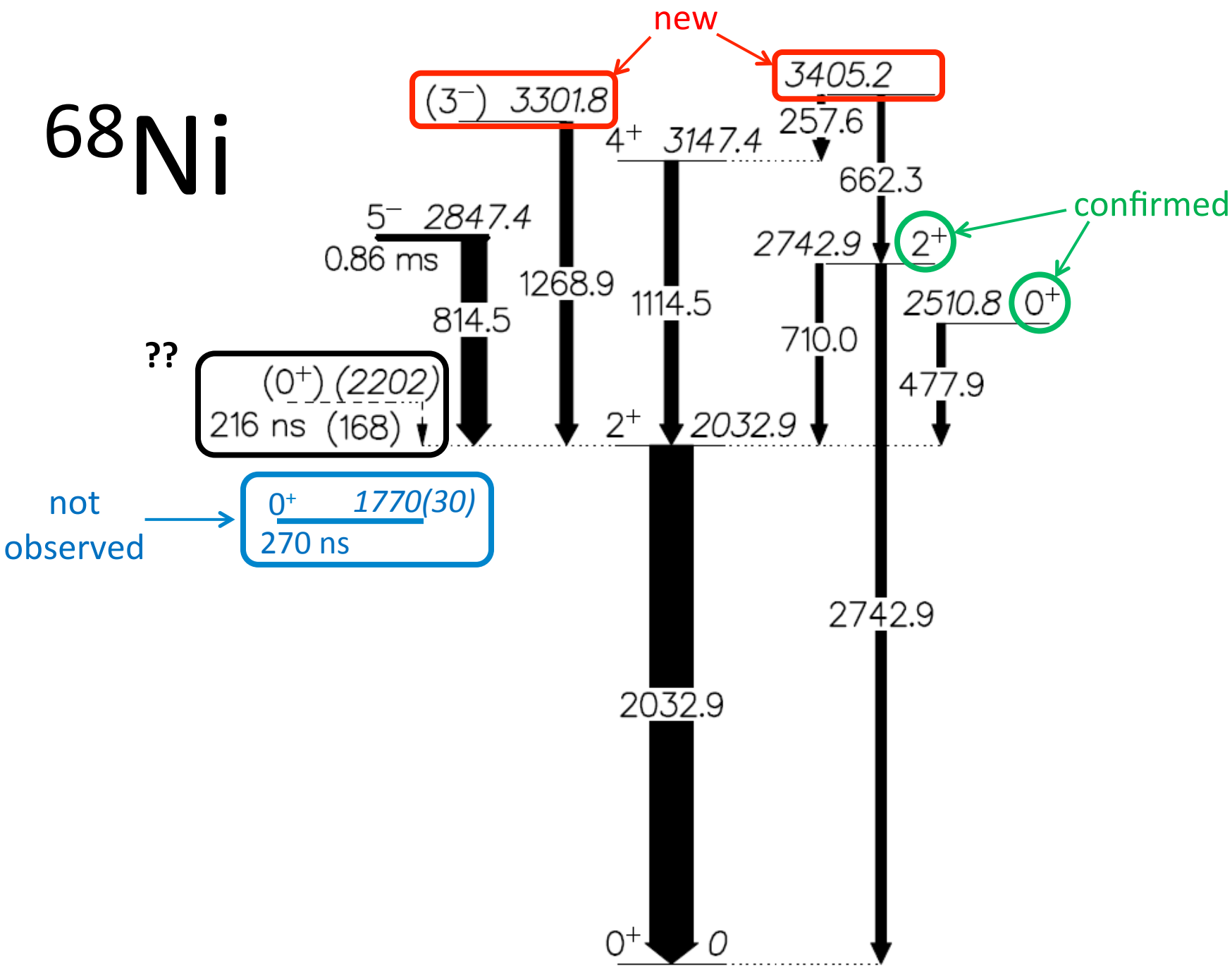
From PPD cube: gate on prompt 2033 in ^{68}Ni and delayed 1182 and 245 in ^{210}Po.

From PPP cube: gate on 2033 and either (b) 710 or (c) 258.

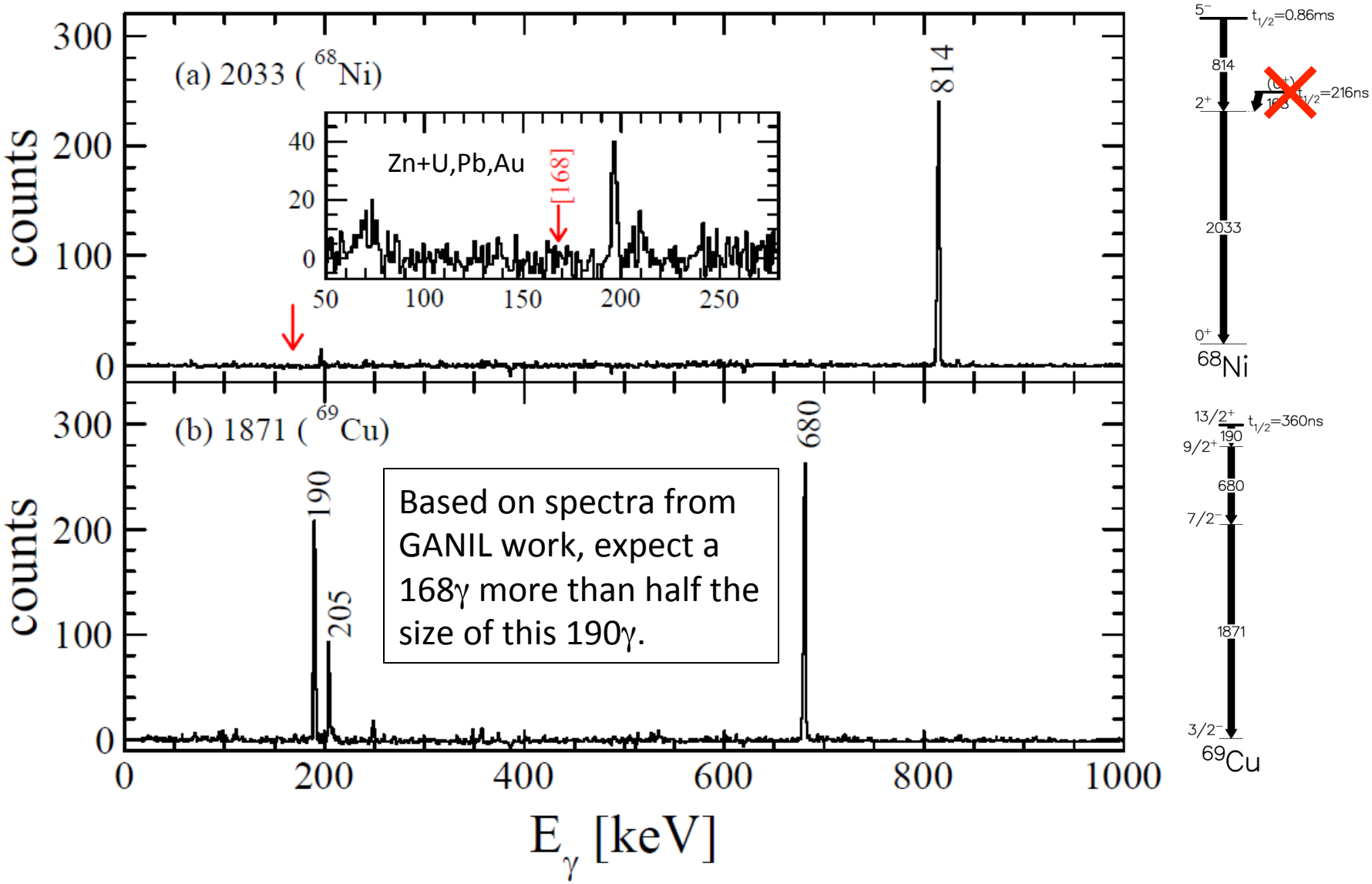
o [Seen, but not placed, by Mueller *et al.*?]

Angular correlations in ^{68}Ni, relative to the 2033-keV $2^+ \rightarrow 0+$ gating transition




68Ni
new
(3⁻) 3301.8
3405.2
257.6
4⁺ 3147.4
662.3
5⁻ 2847.4
0.86 ms
814.5
1268.9
1114.5
2742.9
2⁺
confirmed
2510.8
0⁺
710.0
477.9
??
(0⁺) (2202)
216 ns (168)
2⁺ 2032.9
not observed
0⁺ 1770(30)
270 ns
2742.9
2032.9
0⁺ 0

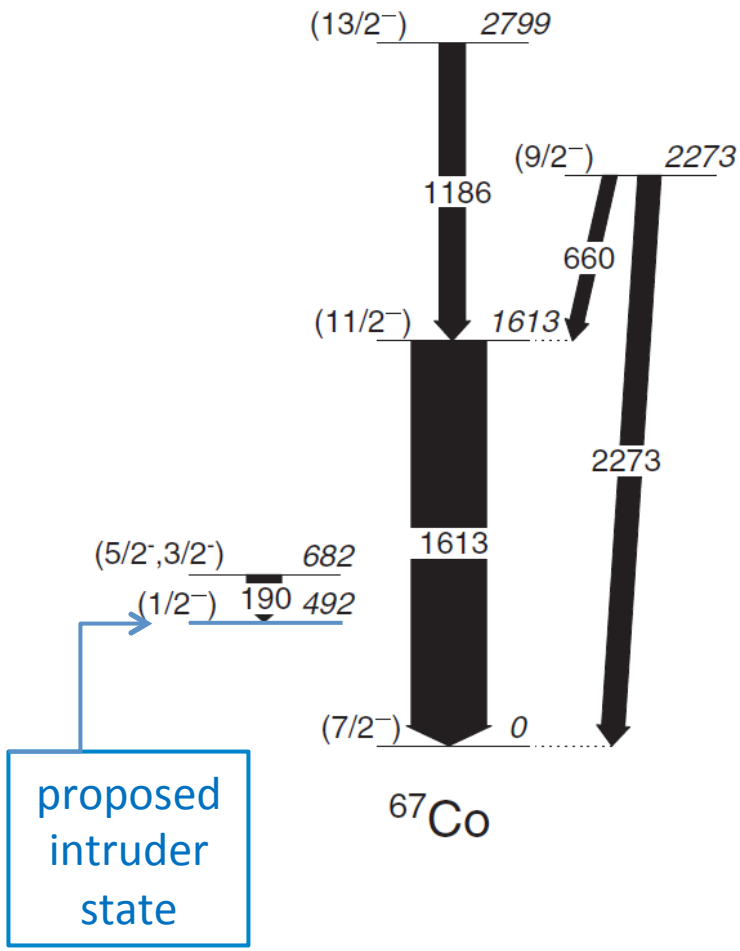
Single-gated spectra from ^{70}Zn + ^{238}U reaction (DD)



Based on spectra from GANIL work, expect a 168γ more than half the size of this 190γ.

Levels in ^{67}Co

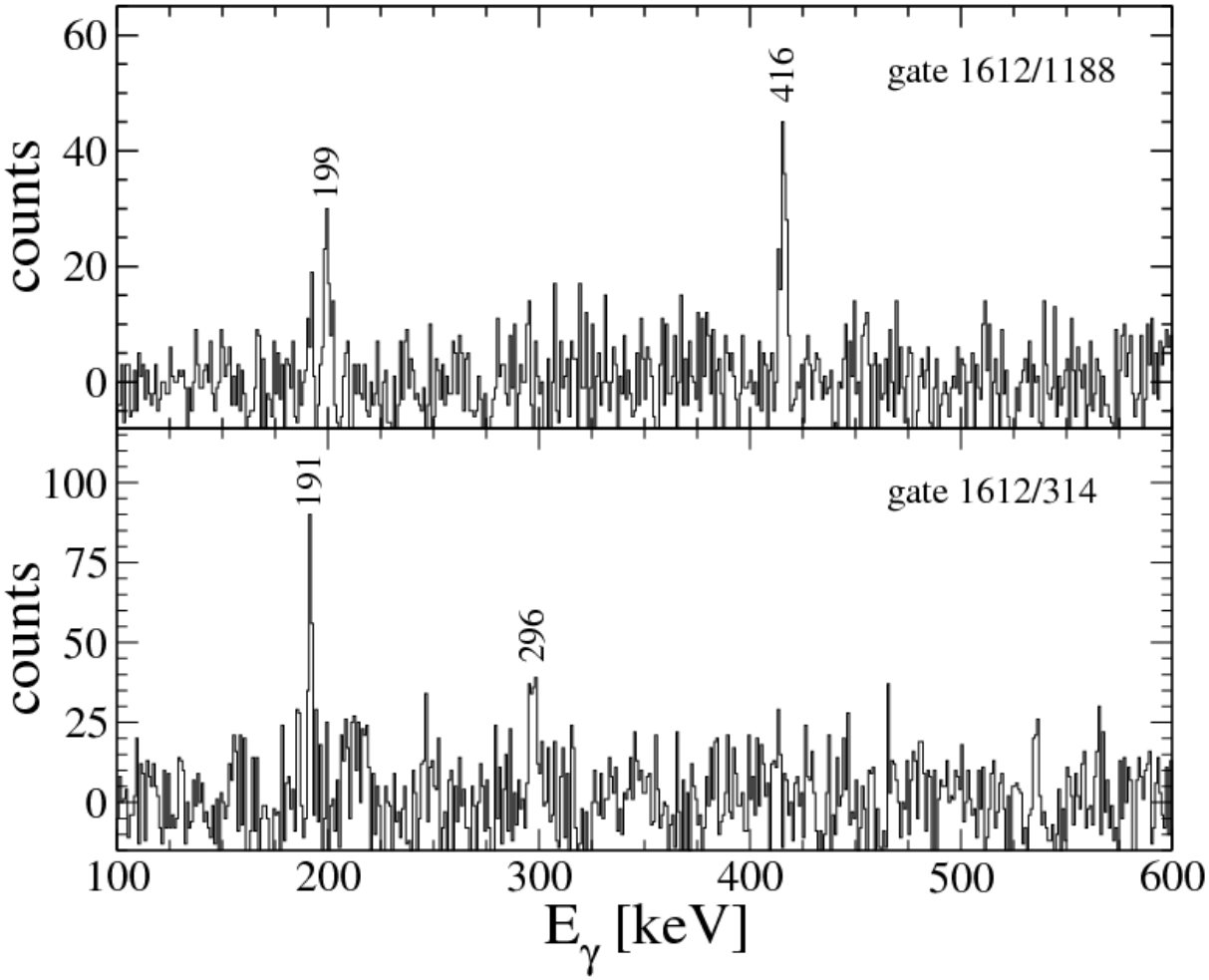
- 460-MeV ^{70}Zn + ^{238}U at LNL [Recchia *et al.*, PRC**85**, 064305 (2012)]
- γ – recoil coincidences with CLARA – PRISMA; no γγ



		^{67}Co	
172.9(6)*	10(3)		
190.2(4)	46(4)	1.15(34)	$(5/2^-, 3/2^-) \rightarrow (1/2^-)$
199.1(3)*	13(3)		
295.9(9)*	11(4)		
314.0(7)*	19(4)		
415.8(5)*	17(4)		
659.7(7)*	19(6)		$(9/2^-) \rightarrow (11/2^-)$
797.9(5)*	22(5)		
1186.2(12)*	35(7)		$(13/2^-) \rightarrow (11/2^-)$
1612.7(7)*	100(10)	1.77(43)	$(11/2^-) \rightarrow (7/2^-)$
2273.1(20)*	31(6)		$(9/2^-) \rightarrow (7/2^-)$

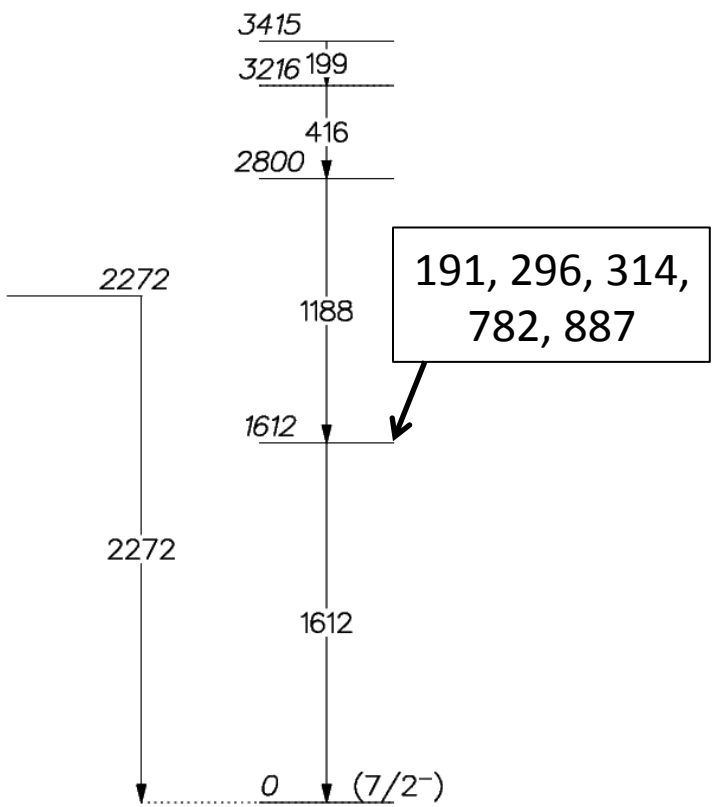
Levels in ^{67}Co

- Our work: 440-MeV ^{70}Zn + ^{208}Pb at ANL (also in 430-MeV ^{64}Ni + ^{238}U)
- $\gamma\gamma(\gamma)$ coincidences with Gammasphere



Levels in ^{67}Co

- Coincidences observed between several lines identified by LNL (•)
- Could not confirm 660-keV transition placed parallel to 2272
- Could not (yet??) build upon the intruder state



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797.9(5)*	22(5)		
• 1186.2(12)*	35(7)		$(13/2^-) \rightarrow (11/2^-)$
• 1612.7(7)*	100(10)	1.77(43)	$(11/2^-) \rightarrow (7/2^-)$
• 2273.1(20)*	31(6)		$(9/2^-) \rightarrow (7/2^-)$

Conclusions

- ^{68}Ni:
  - Two new states below 3.5 MeV have been added
  - 0^+ assignment confirmed for the 2511-keV state
  - Sensitivity to both isomers *and* 0^+ states ➔ 2202-keV 0^+ isomer (and the 168γ) ruled out by our data
- ^{67}Co:
  - Several γ's identified by LNL now placed via $\gamma\gamma$ coinc.
  - Additional states related to intruder yet to be identified
- ^{66}Co:
  - Discrepancies between Leuven and Legnaro works regarding isomeric transitions that we can address…

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Side-by-side comparison of the two experiments:

GANIL

- 6.33-MeV/A ^{238}U beam
- 1.3 mg/cm^2 ^{70}Zn target
- VAMOS separator + focal plane detectors (Z, A, q selection)
- Prompt gammas with EXOGAM (11 Clovers), delayed gammas with focal plane array (4 HPGe)
- Sensitive to isomers in ~100 ns to ~10 μs range
- Duration: ??

- 168-keV line seen in spectrum nominally gated on Z=28, A=68; no coincident gammas identified

ATLAS

- 6.29-MeV/A (440-MeV) ^{70}Zn beam
- ~55 mg/cm^2 ^{238}U target
- no separator – use brute-force gamma-ray coincidences
- Both prompt and delayed gammas with Gammasphere (100 Ge)

- Sensitive to all time scales; delayed time window ~700 ns wide
- Duration: ~8h of Zn+U with γγ trigger; also have, in total, several days with Pb and Au targets with either γγ or γγγ triggers

- No evidence of a 168-keV gamma ray in ^{68}Ni in either prompt or delayed coincidence spectra