Structure of ^{68}Ni :

New insights on the low-lying 0^+ and 2^+ states from two-neutron transfer on ^{66}Ni and β-decay of ^{68}Co

IS467 and IS504 collaborations

Freddy Flavigny

KU Leuven, Instituut voor Kern- en Stralingsfysica, Belgium

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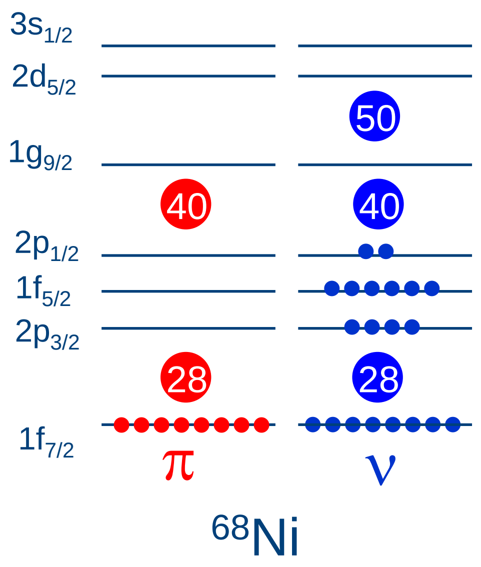
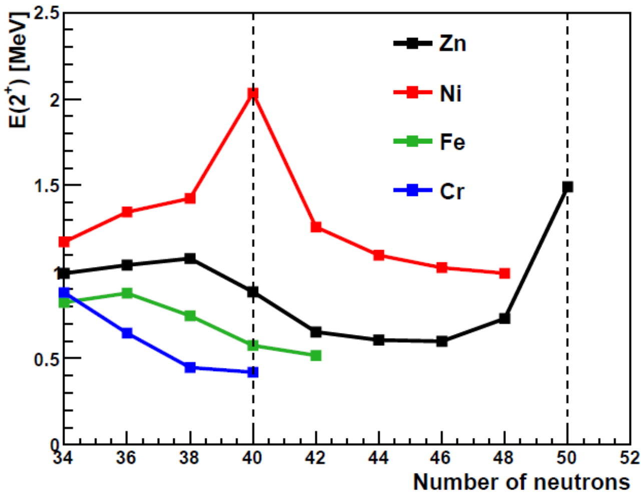
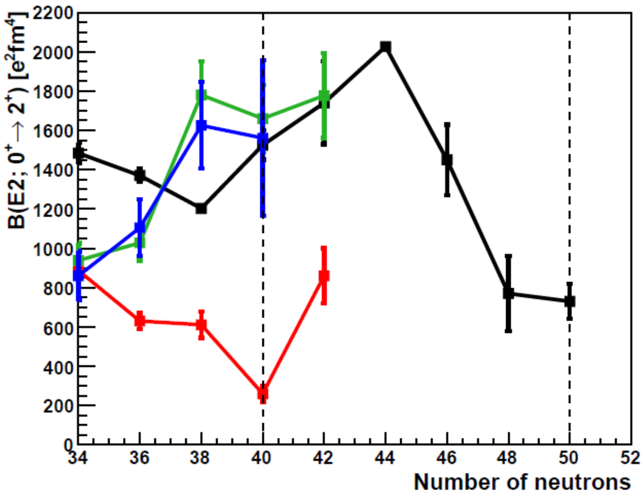
Motivation: Shell structure at Z=28 and N=40







(See also K. Wimmer's talk on Friday, session 4A)

Motivation: Shell structure at Z=28 and N=40

Recent experimental work:

- J. Elseviers et al., to be submitted.
- F. Flavigny et al., to be submitted.
- S. Suchyta et al., PRC **89**, 021301R (2013)
- 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)
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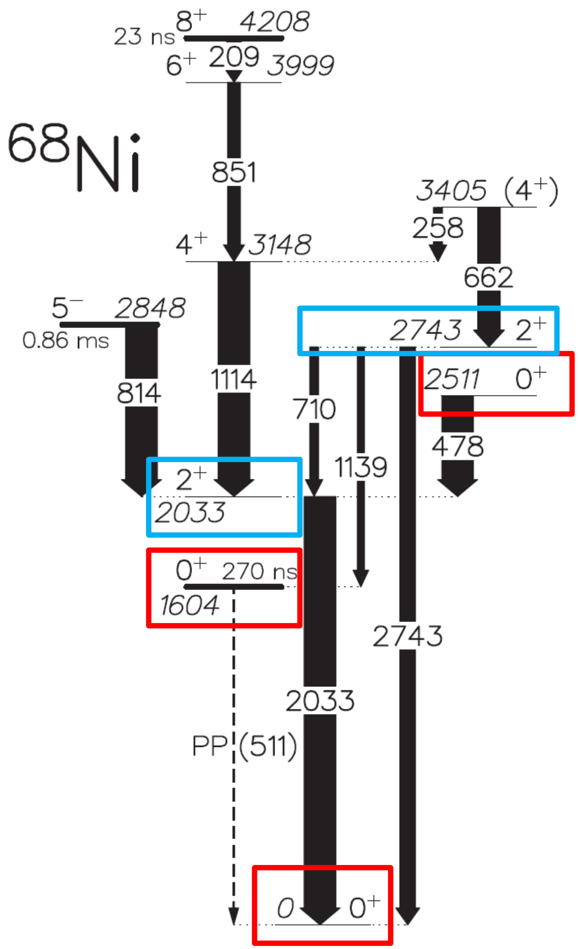
- *Precise position and firm spin/parity assignment:*

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



Level scheme from F. Recchia et al. PRC80, 041302R (2013)

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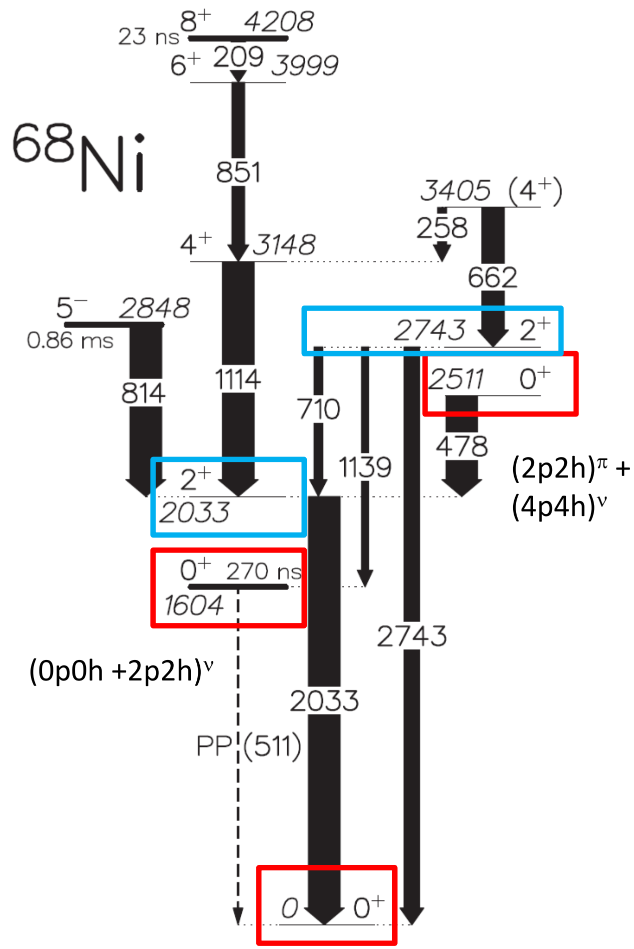

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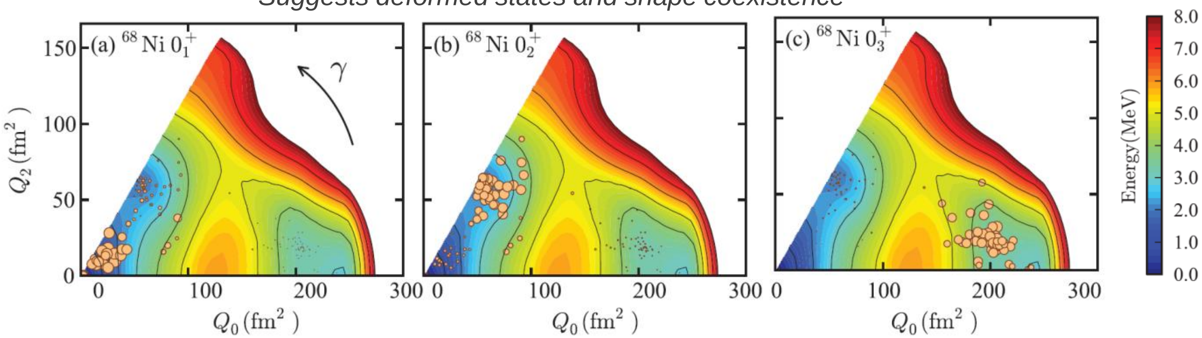
State of the art shell model calculations (MCSM [1], SM [2],)

Suggests deformed states and shape coexistence



→ **New picture : need to characterize these states**

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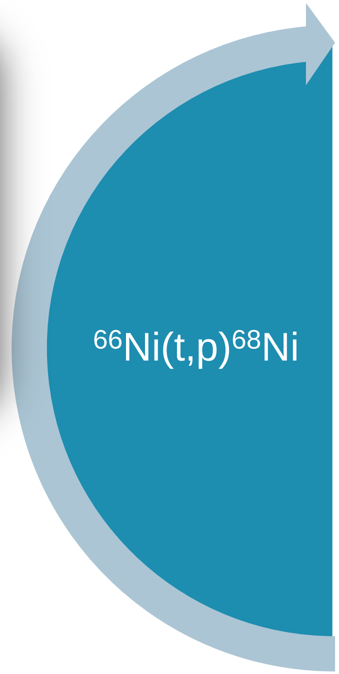
[1] Y. Tsunoda et al., PRC89 031301R (2014) [2] S. Lenzi et al., PRC82 054301 (2010)

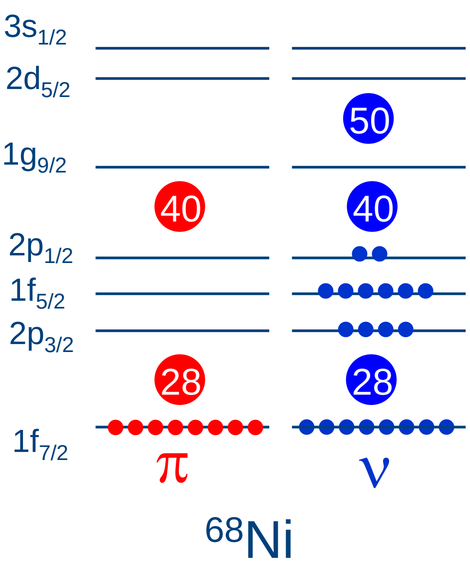
Experimental approach: 2 complementary data sets

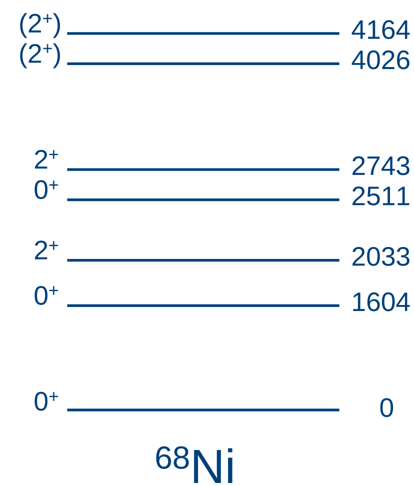
IS504

- Nature of **0^+ states** in ^{68}Ni
  → 2ν-2h
- Conf. Mixing of 0^+_1 and 0^+_2

PhD thesis, J. Elseviers







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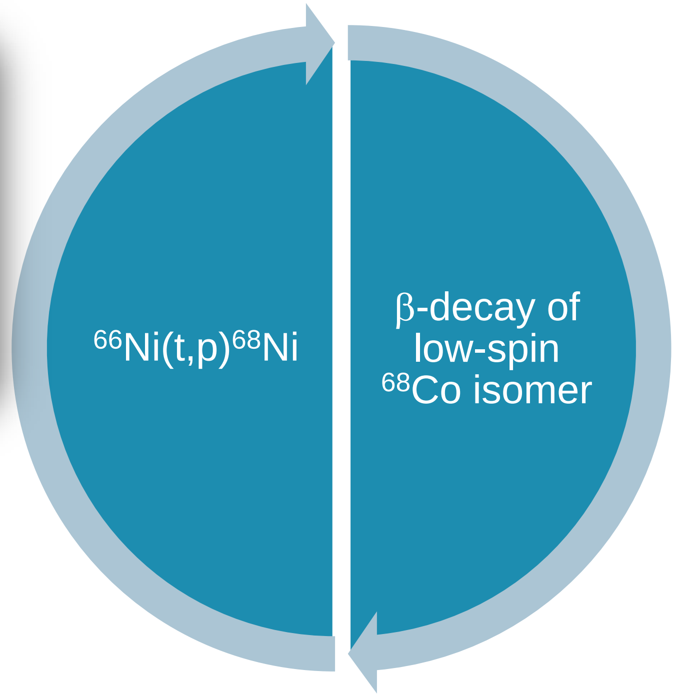
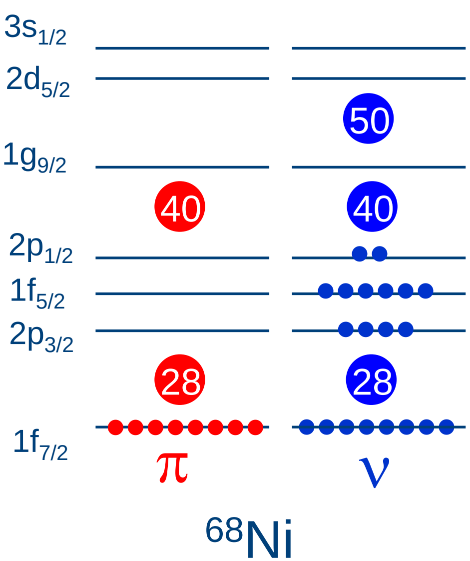
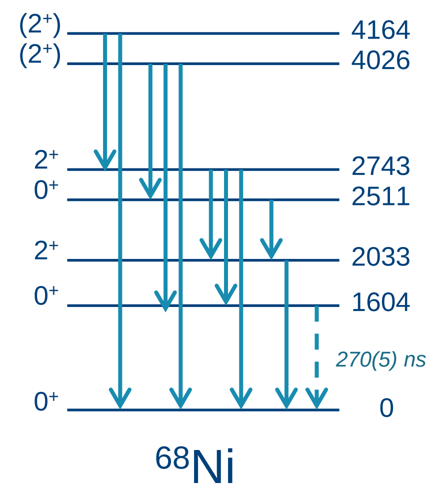


IS467 (A=68)

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





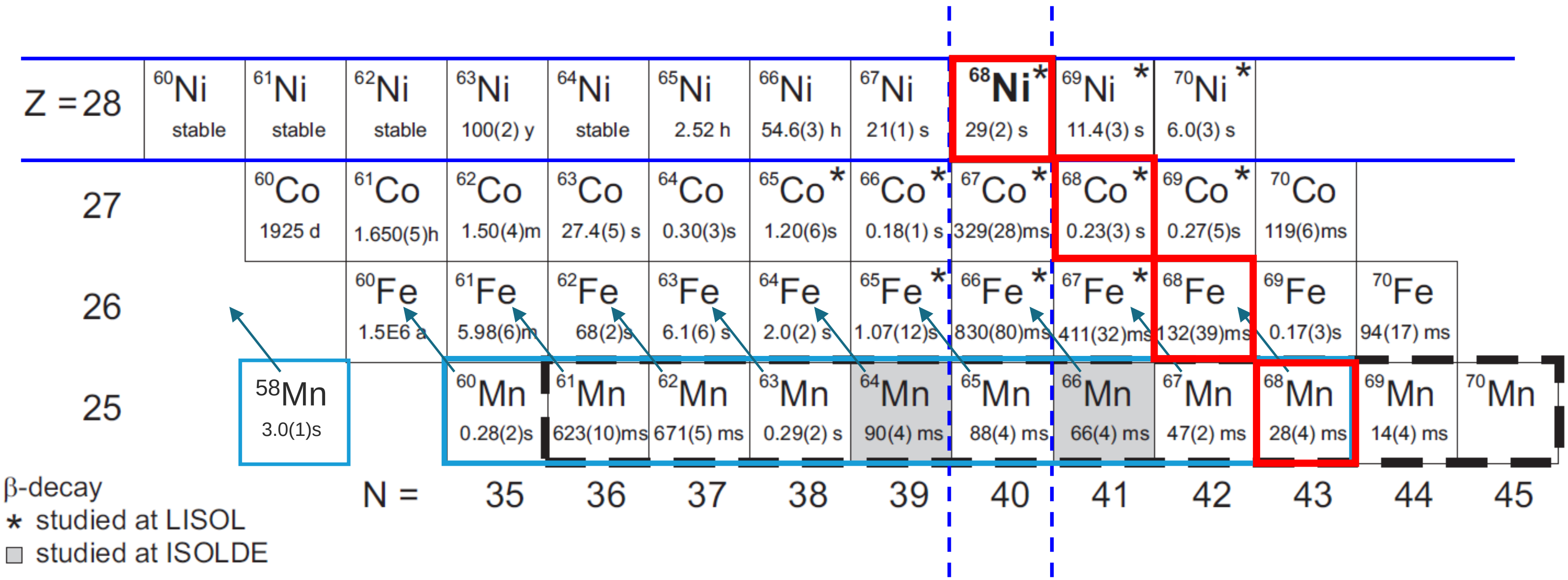
β-decay studies in the ^{68}Ni region using resonant laser ionization

Facility: ISOLDE (p (1.4GeV) → UC_x)

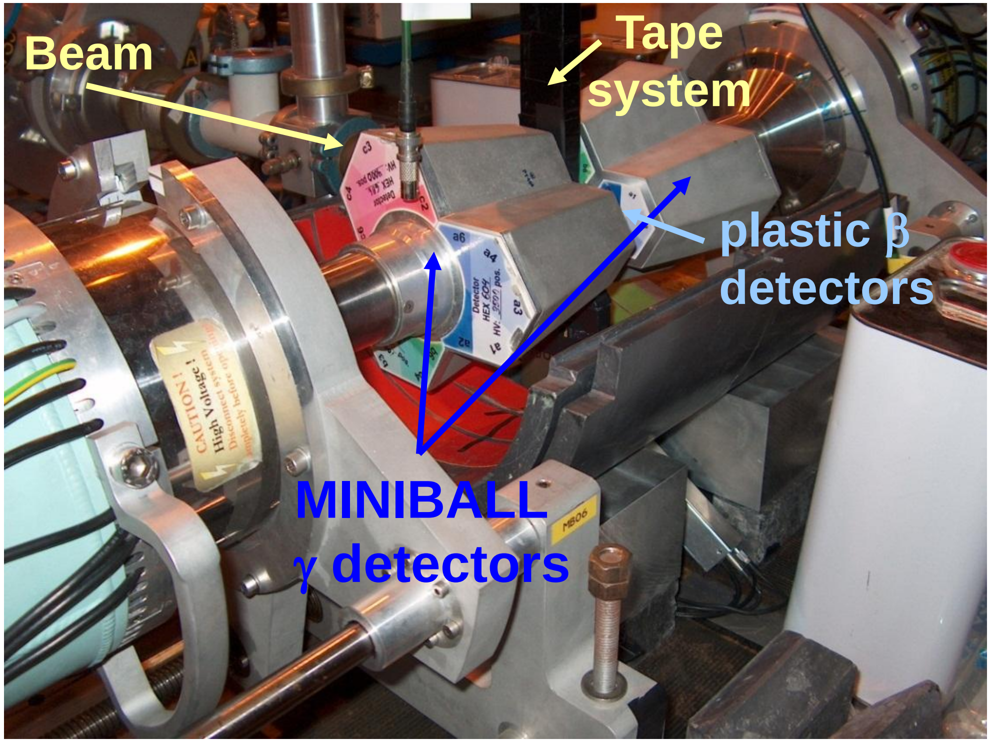
thick & hot target

- **Pure Mn sources**
  - Z selection: Laser ionisation (RILIS)
  - A/Q selection: Spectrometer (HRS)

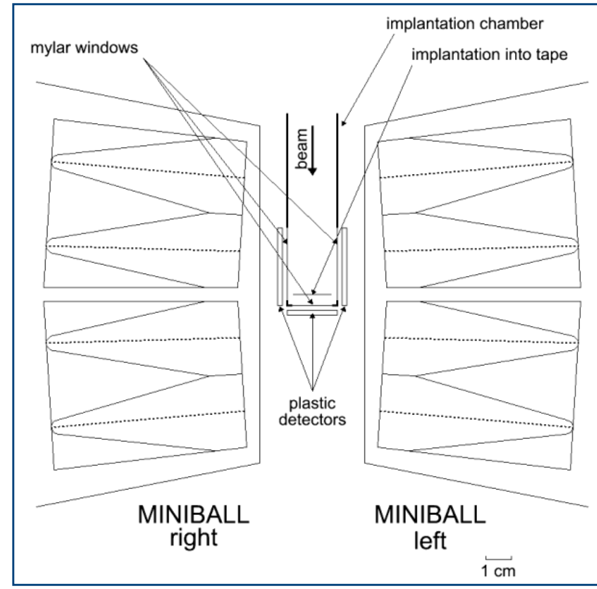
- **A=68**
  - Previous exp. : 2 isomers in ^{68}Co
    - (7^-) $T_{1/2}$= 0,23(3) s
    - **(1^+,3^+) $T_{1/2}$ = 1,6(3) s**
  - ISOLDE: **Selectivity of $^{68}Fe_{gs}$ (0^+) decay**



LISOL β-γ detection setup at ISOLDE



Top view

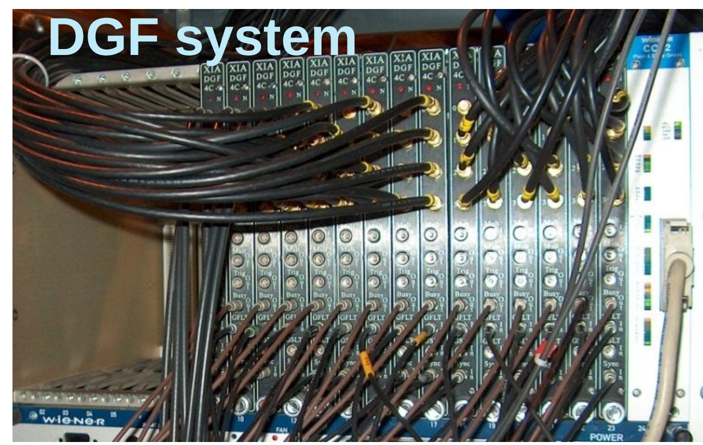


MINIBALL: 5.8% photo-peak efficiency at 1.332 MeV

3 plastic detectors: 50% beta efficiency

DGF system: digital read-out on event-by-event basis

Polyethylene-borax-lead-brass shielding



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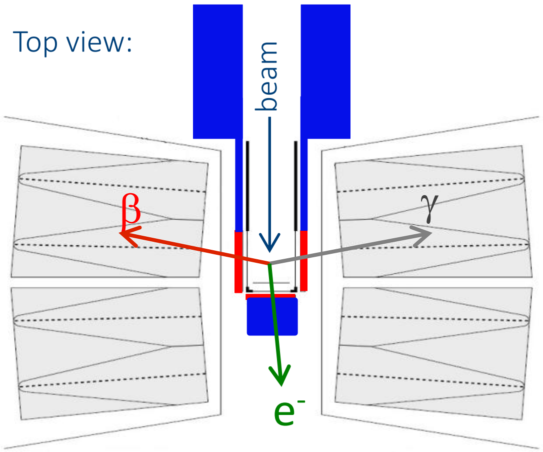
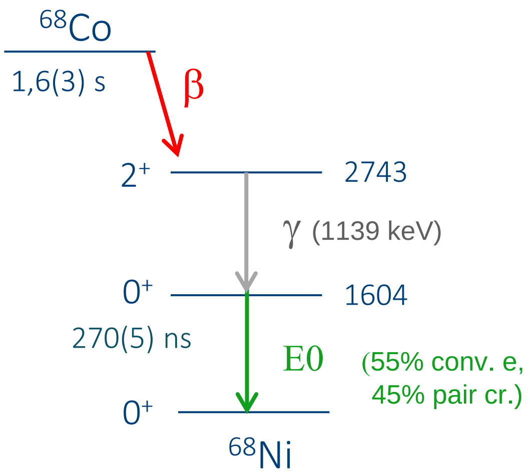
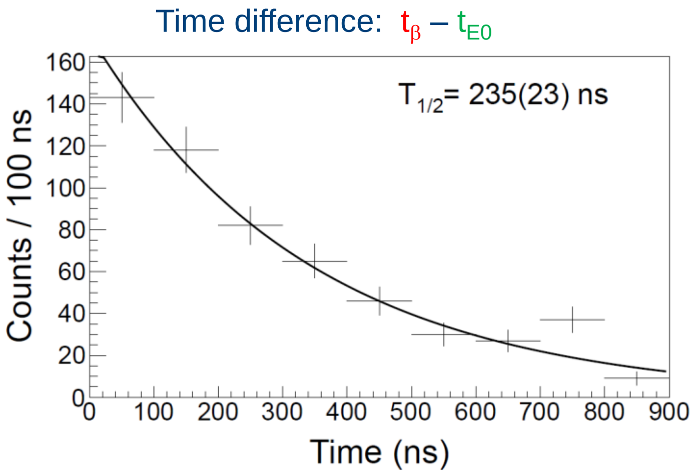
Feeding of 0^+_2 state in ^{68}Ni : β-γ-E0 coincidences







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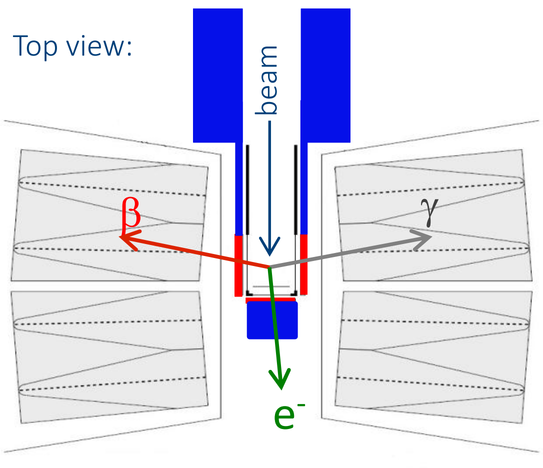

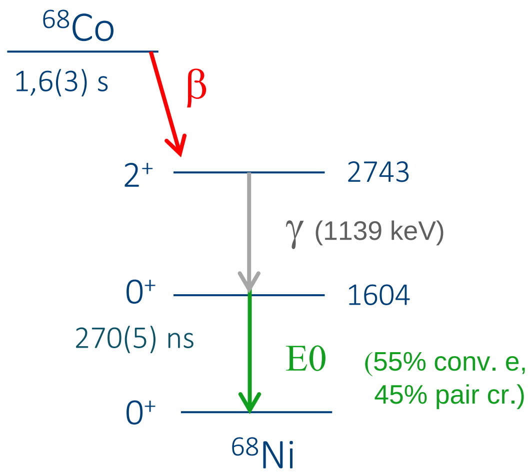

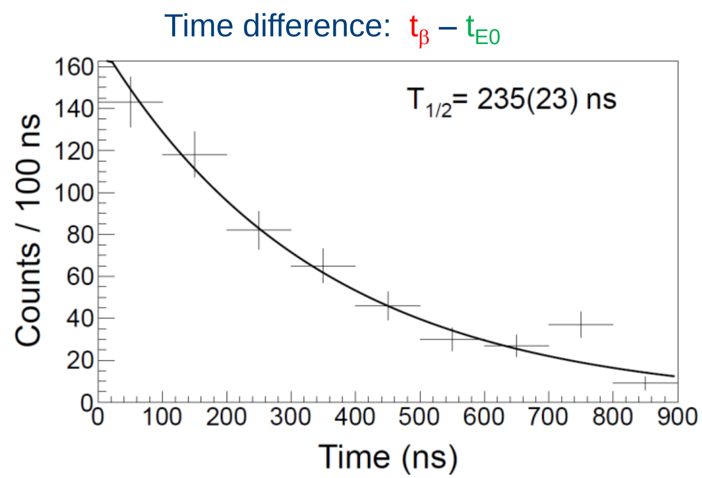

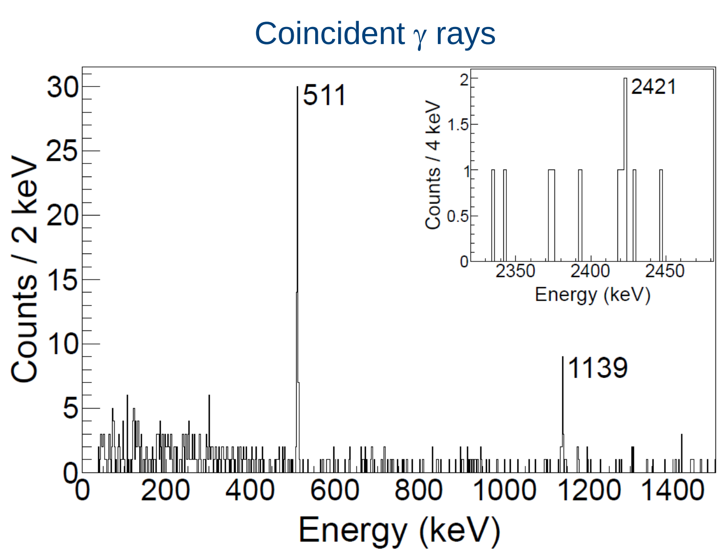

β-γ-E0 coincidences (590 events) :

- Highly selective signal
- 1139 and 2421 keV feeding 0^+_2
- $E(0^+_2)$ = 1603,6(6) keV in agreement

  1603,5(3) in [1].
  1605(3) in [2]
- $I_{rel}(0^+_2 \rightarrow 0^+_1)$ = 19(8) %

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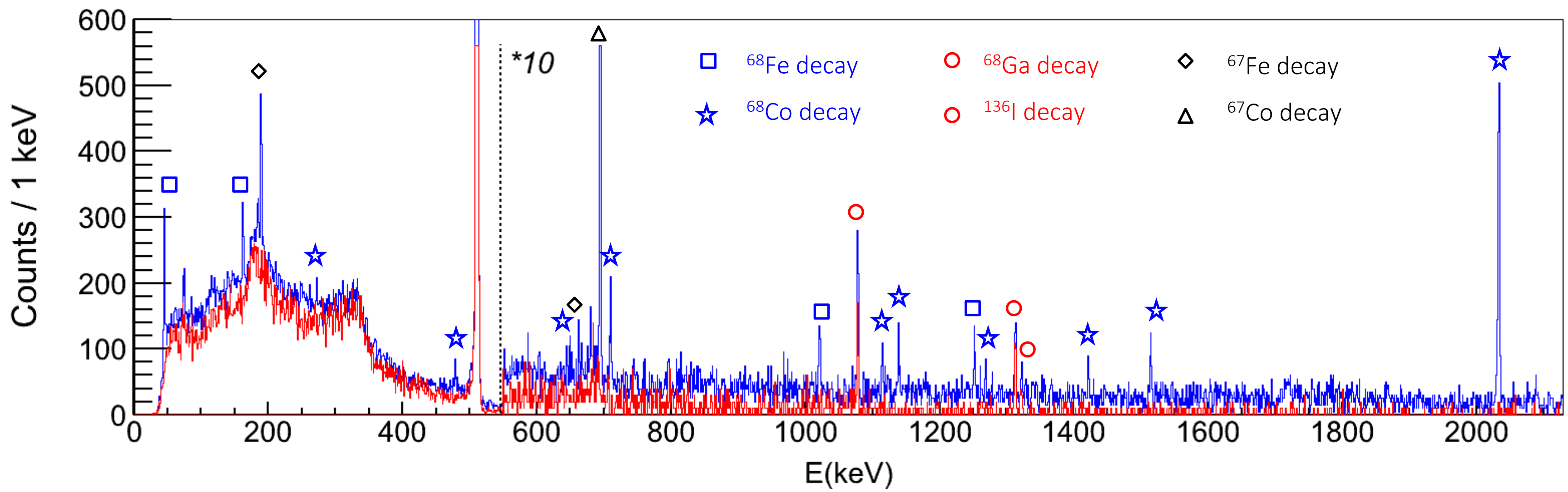
[1] F. Recchia et al., PRC88 041302 (2013) [2] S. Suchyta et al., PRC89 021301R (2013)

β-γ coincidences

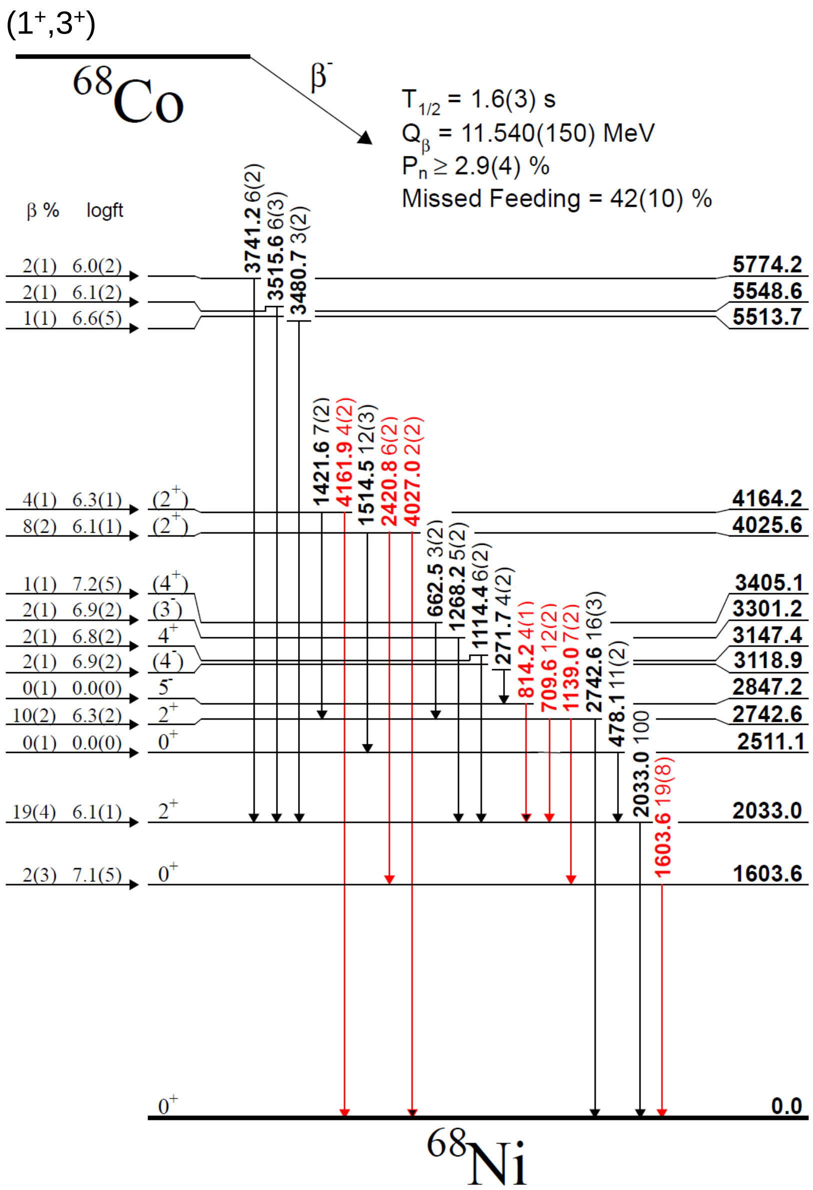
- Time condition: $t_\beta - t_{PP}$ in [350,2200] ms

  → to avoid ^{68}Mn decay ($T_{1/2}$ =28(3) ms)

- Clean ^{68}Co low-spin spectrum
  - Low bkg (shielding)
  - Laser ionisation (RILIS)
  - Mass separation (HRS)
  - Selectivity of the $^{68}Fe_{gs}$ (0+) decay
- Grand daughter decay
  - 1/3 statistics previous LISOL studies [1]
- Beta-delayed n branches



Revised decay scheme



- **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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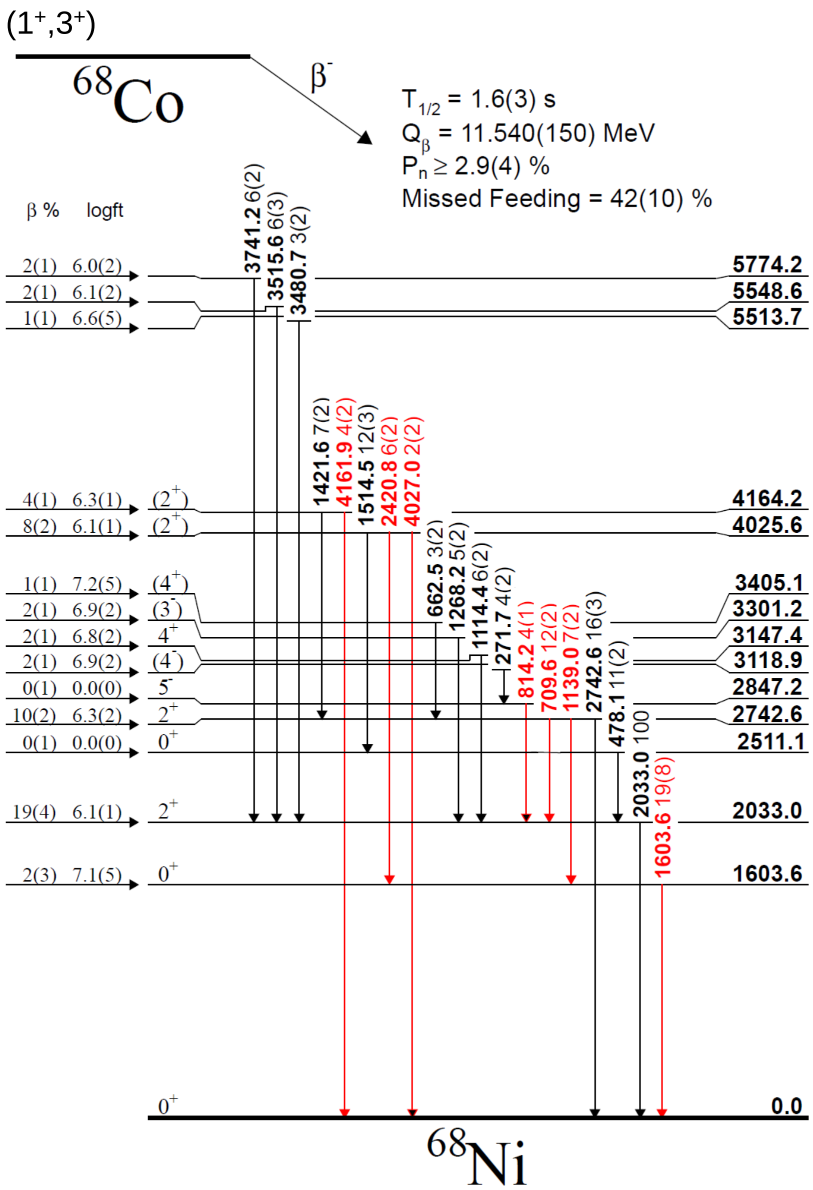

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- **Int. balance: test of completeness in the full A=68 chain**
  - Determination of missed feeding:
    - Direct β feeding of gs
    - Direct β-del.n feeding to gs or isomeric state
    - Missed E0 decay
    - Missed γ ray feeding to gs or isomeric states

Missed feeding: 42(10)%

-> No conclusion on spin assignment from β-feeding

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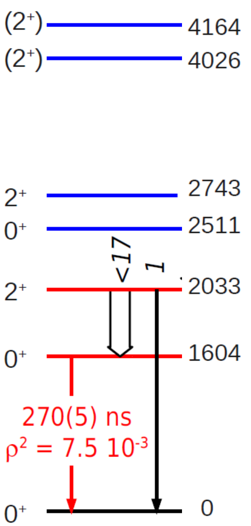
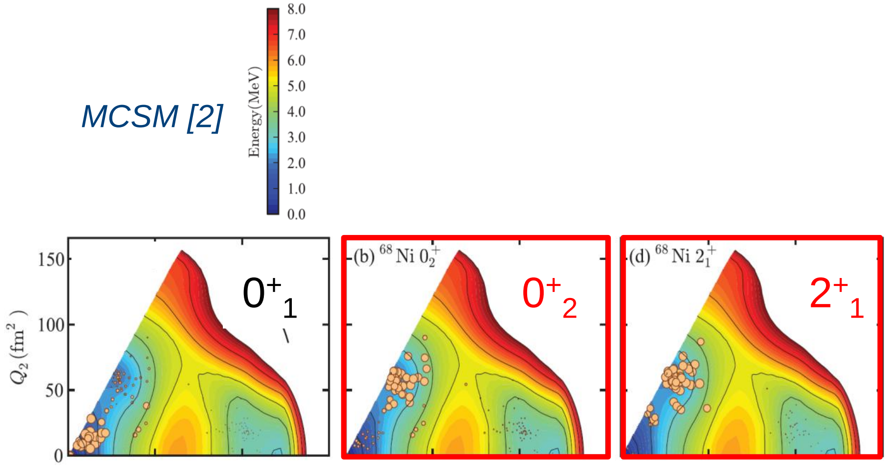
B(E2) ratios

From experiment:



^{68}Ni

MCSM [2]



- **Exp. VS SM calculations:**

  1 – Using the LNPS interaction [1]

  2 – Monte-Carlo shell model calculations [2]

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

- **Main results:**
  - **$2^+_1 \rightarrow 0^+_2$**

    $I_{rel} < 0.7(2)$ % → **R < 17** Th: R=12 (MSCM), 4 (LNPS)

[1] S. Lenzi et al., PRC82 054301 (2010) [2] Y. Tsunoda et al., PRC89 031301R (2014)

[3] $\delta(E2/M1) = -1.5^{+0.9}_{-1.2}$ from C.J. Chiara et al, PRC86 041304R (2012)

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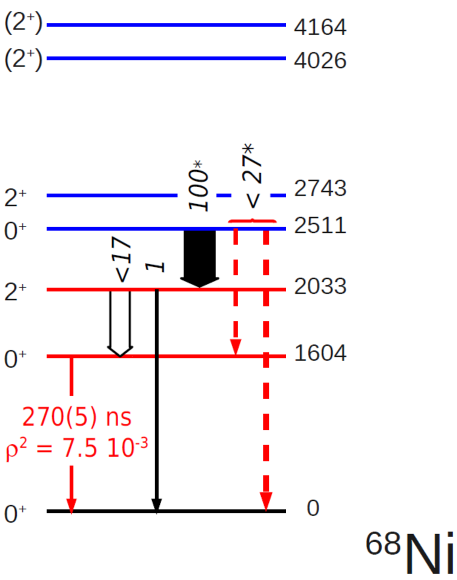

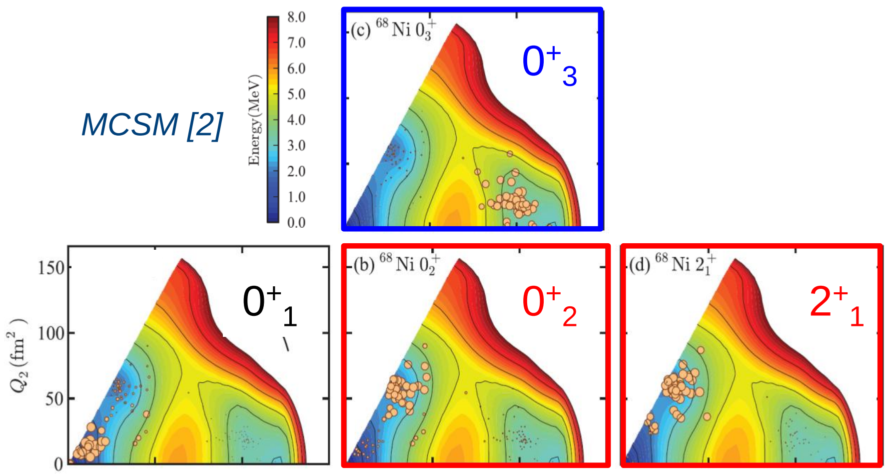

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  - **$0^+_3 \rightarrow 2^+_1$**
    Th. partial $T_{1/2}$ of **108 and 1.5 ns** (MCSM,LNPS)
    Big difference : lifetime measurement needed.

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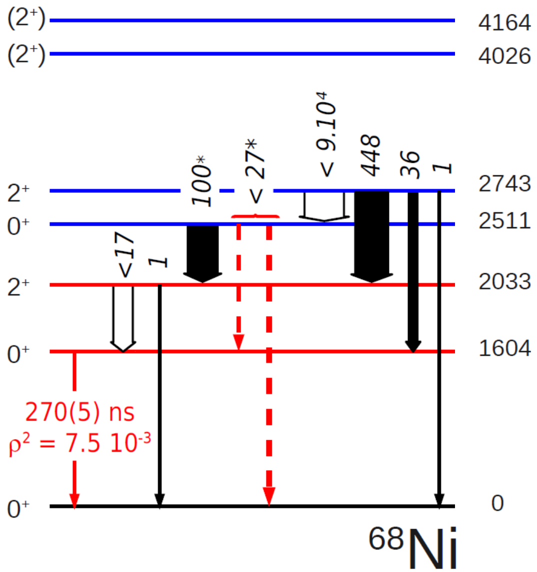

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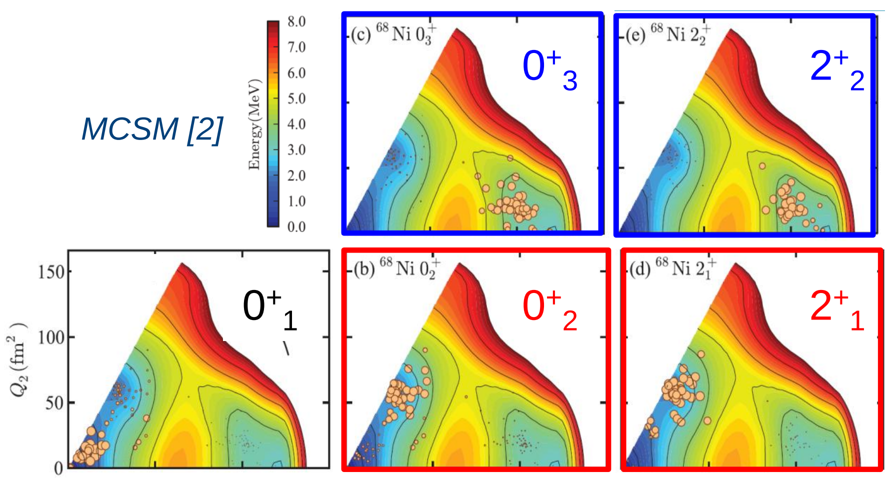

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  - **$2^+_2 \rightarrow 2^+_1$**

    I_{rel}= 11(2)% → **$R = 448^{+185}_{-311}$** using [3]

    Higher than published values [4]

    R = 29 and 278 (MCSM,LNPS)

[1] S. Lenzi et al., PRC82 054301 (2010)
[2] Y. Tsunoda et al., PRC89 031301R (2014)
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B(E2) ratios

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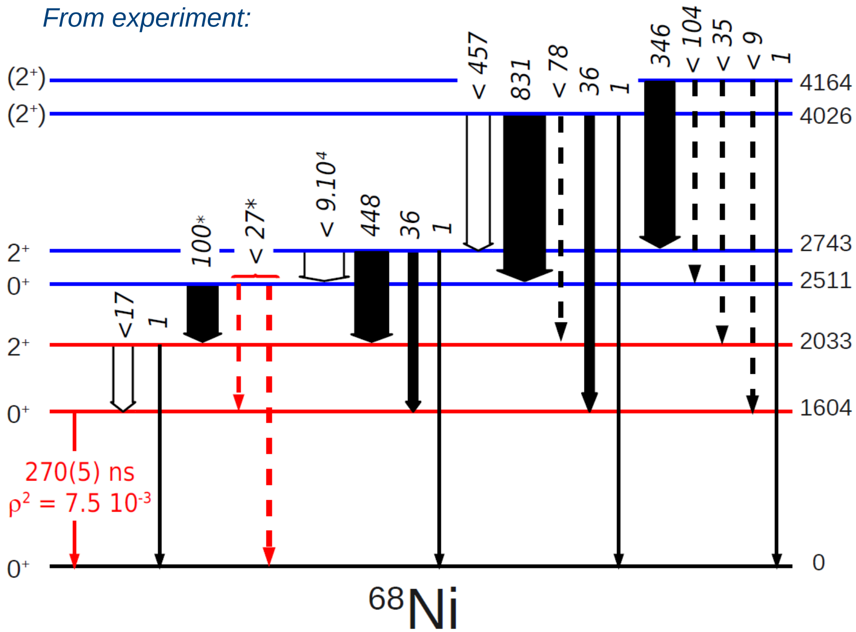

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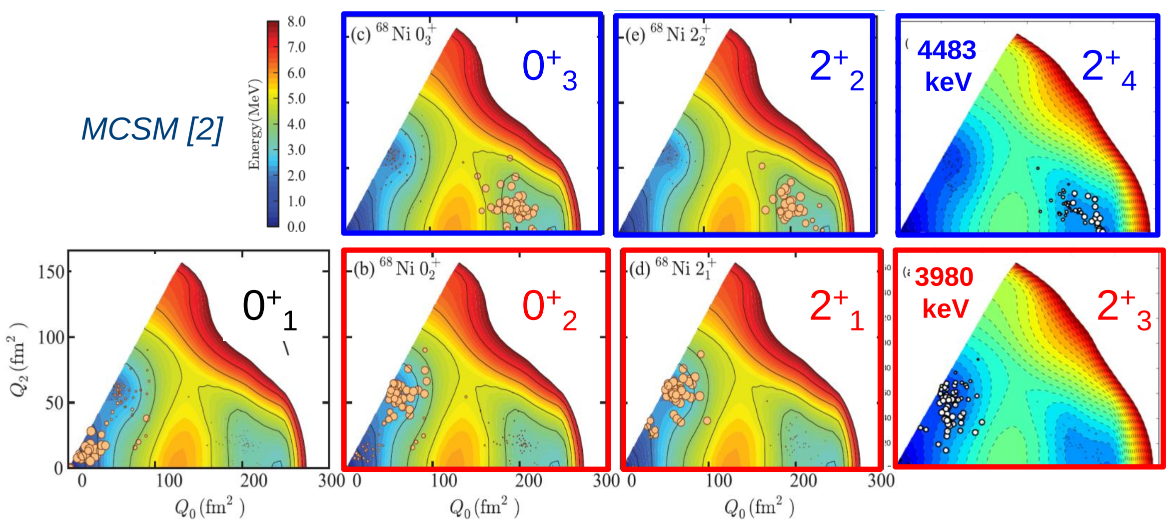
MCSM [2]



- **$2^+_2 \rightarrow 2^+_1$**
  I_{rel}= 11(2)% → **$R = 448^{+185}_{-311}$** using [3]
  Higher than published values [4]
  R = 29 and 278 (MCSM,LNPS)
- **2^+_3 and 2^+_4**
  Qualitative **agreement** for (2^+_4)
  Significant **discrepancies** for (2^+_3)

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[1] S. Lenzi et al., PRC82 054301 (2010)   [2] Y. Tsunoda et al., PRC89 031301R (2014)

Two-neutron transfer reaction: $^{66}Ni(t,p)^{68}Ni$

^{66}Ni(t,p)^{68}Ni : Experimental Setup

Resonant Laser Ion Source
- Z-selectivity

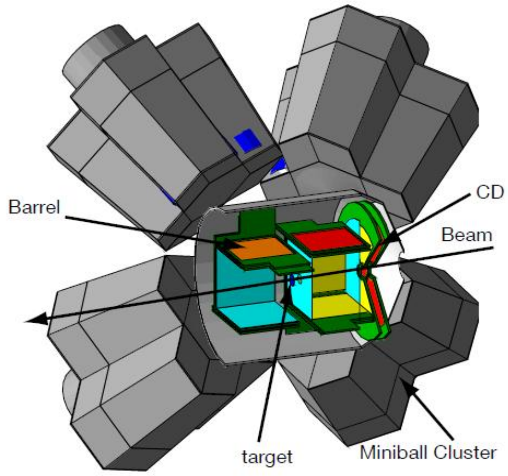
Mass separation
- A/Q-selectivity

Post-acceleration (REX-ISOLDE)

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

- Beam energy: 2.6 MeV/u
- Intensity ~2.0 x 10^6 pps
- Beam purity >86%
- Target : 500 mg/cm²
  ^{3}H loaded Ti (40 mg/cm² ^{3}H)
- Measurement time: ~ 100h

- Proton detection in T-REX:
  - Identification
  - Energy
  - Angular distribution
- γ detection in Miniball:
  - Energy
  - Angular distribution (Doppler correction)



- 8 DE-E_{rest} Barrel det.
- 1 DE-E_{rest} CD detectors

- 8 Miniball triple (HPGe) clusters
- Crystals: 6-fold segmented
- 5% efficiency at 1.33 MeV

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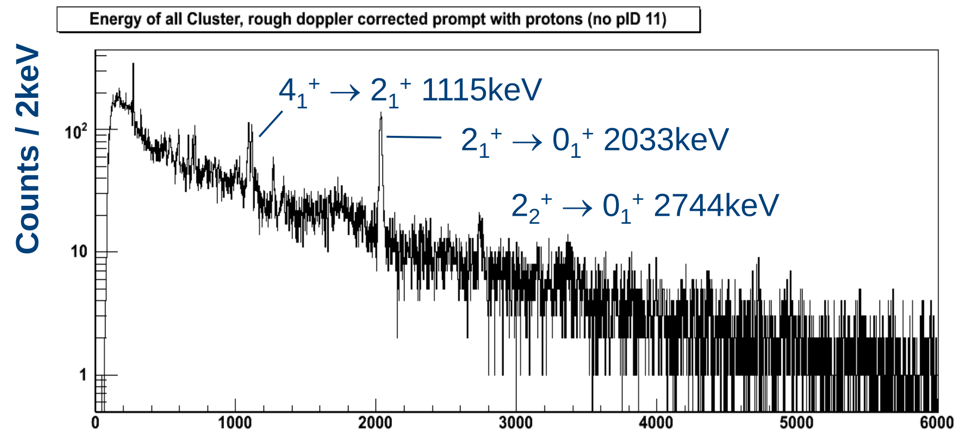
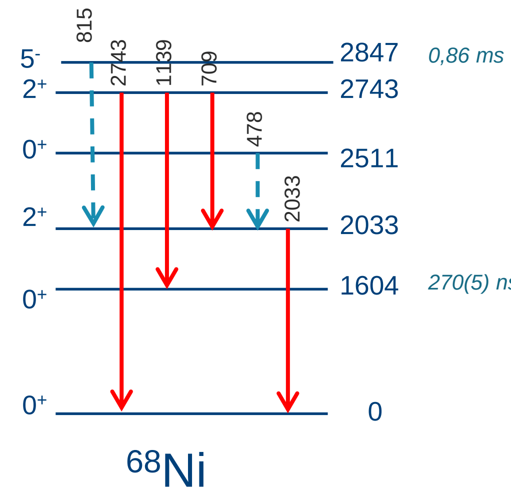
$^{3}H(^{66}Ni,p)^{68}Ni$: Results

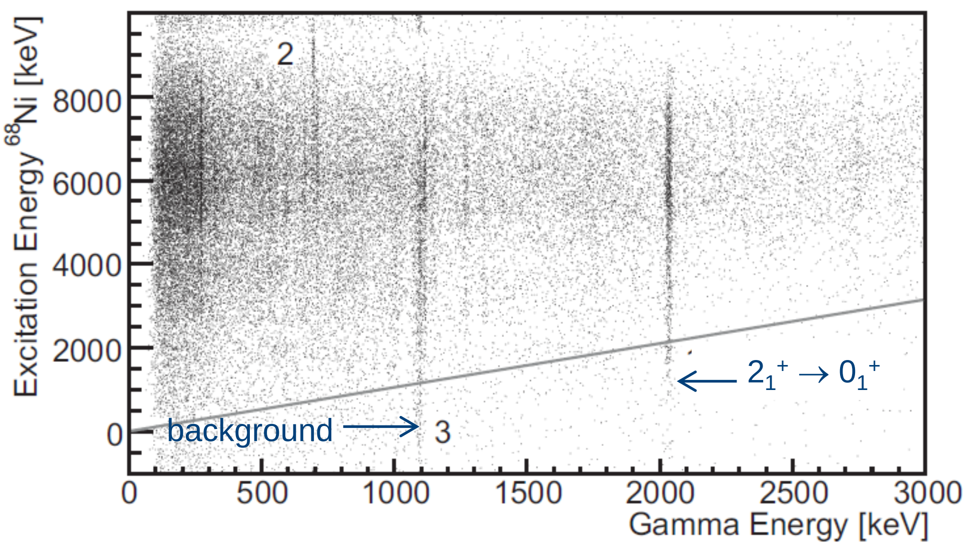
$^{66}Ni(^{3}H,^{1}H)\,^{68}Ni$

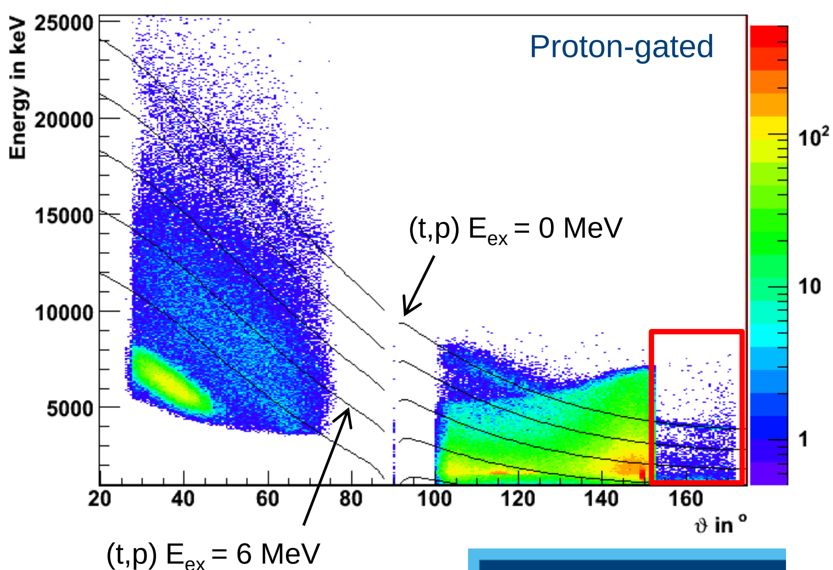
Q = 5.12 MeV

Proton - gamma coincidences









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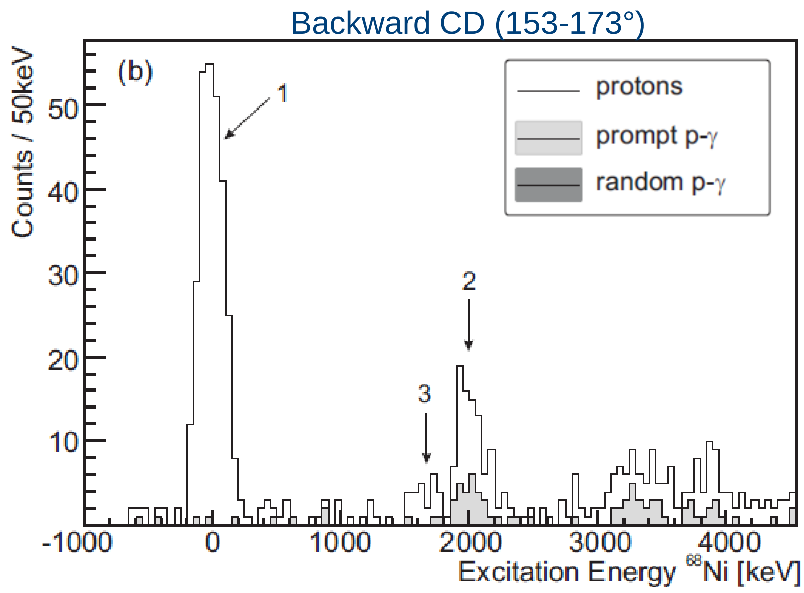
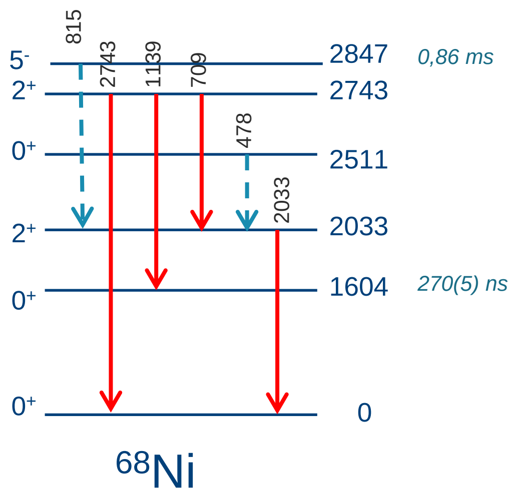
$^{3}H(^{66}Ni,p)^{68}Ni$: Backward CD





CD data only

- **Population of 0_2^+ and 2^+_1 states**

  E = 1621(28) keV - **4.8(16) % of gs**
  E = 2033(10) keV - **28(4) % of gs**

- Non-observed direct population of 0_3^+ , 2_2^+ and 2^+_3 states

0^+_3 (2512 keV) < 2%	based on 478 keV transition
2^+_2 (2744 keV) < 4%	based on 709 keV transition
2^+_3 (4026 keV) < 3%	based on 1515 keV transition

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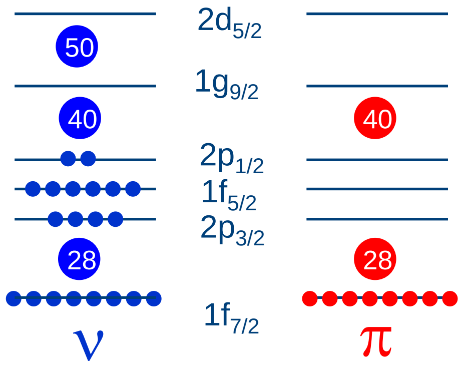
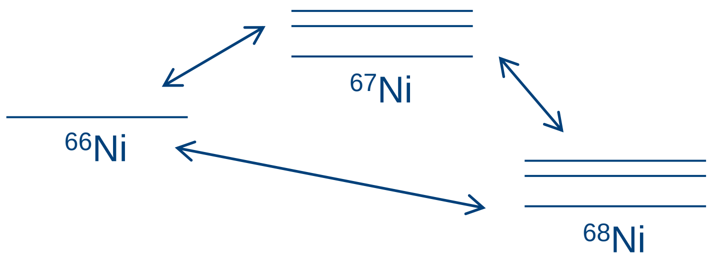
Reaction + Structure model



Two-neutron transfer :

Direct + Sequential



Parameters of our calculations:

- Finite-range DWBA (code FRESCO[1])
- Glob. Pot. : ^{3}H+^{66}Ni and ^{1}H+^{68}Ni
- Two nucleon overlap amplitudes (TNA's)
  - Code: NUSHELL (A. Brown, MSU) [2]
  - Interaction jj44pna from [3]
  - Model space: $f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2}$
  - Calculated ^{68}Ni energies

E(0^+_2) = 1593 kev, E(2^+_1) = 2077 keV)

[1] www.fresco.org.uk [2] B. A. Brown and W. D. M. Rae, Nushell@MSU 2007 [3] A. F. Lisetskiy et al., PRC 70, 044314 (2004)

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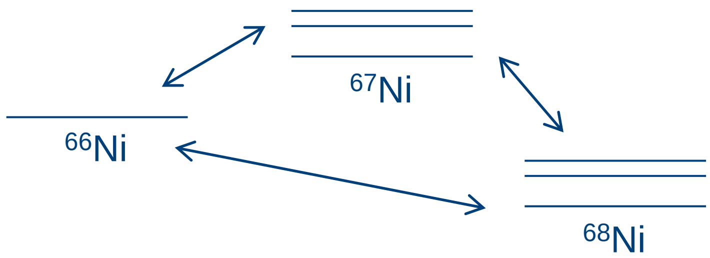

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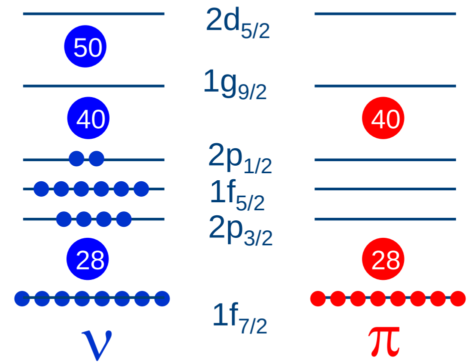

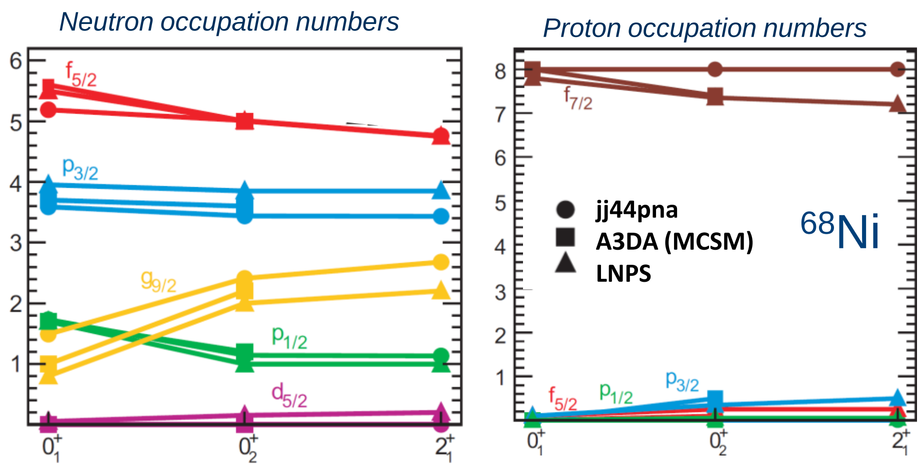

Average number of neutrons in a given state:

jj44pna	$f_{5/2}$		$p_{3/2}$		$p_{1/2}$		$g_{9/2}$	
^{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**

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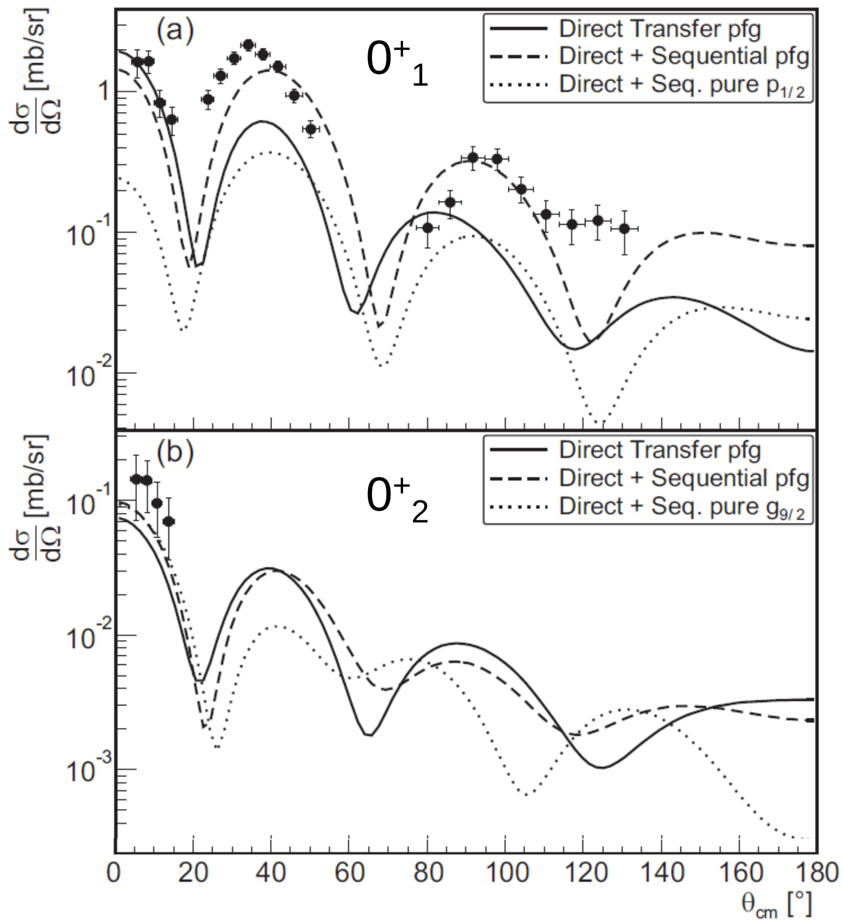
$^{66}Ni(^{3}H,p)^{68}Ni$: Angular distributions



Conclusions:

- Reasonable agreement th/exp for $0^+_{1,2}$ states

Small CM angles

Th:	$\sigma(0^+_2) / \sigma(0^+_1)$ in [3 ; 7] %
Exp:	$\sigma(0^+_2) / \sigma(0^+_1)$ = 4.8(16) %

→ **Validation of structure input**

- No scaling of theory to experiment

- Shape very sensitive to intermediate state properties

- **First exp. evidence that 0^+_2 in ^{68}Ni is a neutron excitation above N=40**

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Outlook

- Future experiments at HIE-ISOLDE in the region of ^{68}Ni:
  - ^{80}Zn(d,p)^{81}Zn, [R. Orlandi *et al.*, INTC-2012-051 P-352]
  - ^{70}Ni(d,p)^{71}Ni, [J.J Valiente Dobon *et al.*, INTC-2012-050 P-351]
  - ^{68}Ni(d,p)^{69}Ni, [accepted]
    - $d_{5/2}$ single particle strength above N=50
  - Coulomb excitation of ^{68}Ni, ^{70}Ni
    - Absolute B(E2) values
  - Decay of ^{68}Mn with the new ISOLDE Decay Station [accepted]
    - Lifetime of $0^+_3 \rightarrow 2^+_1$ transition (478 keV)