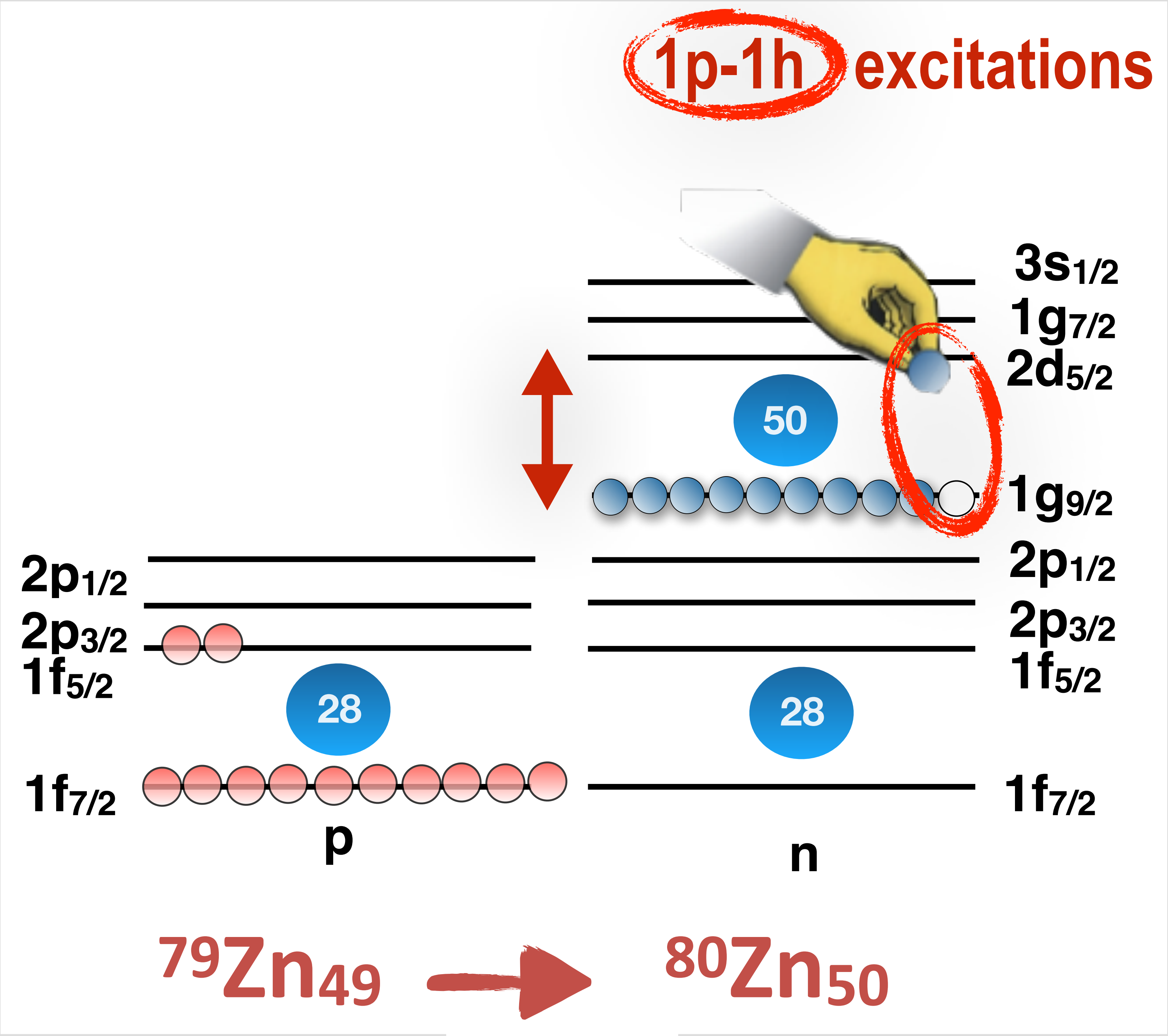
Evolution of N = 50 shell and neutron single-particle states towards ^{78}Ni: ^{79}Zn(d,pγ)^{80}Zn



^{79}Zn(n,γ) cross section and r-process around A = 80 mass region

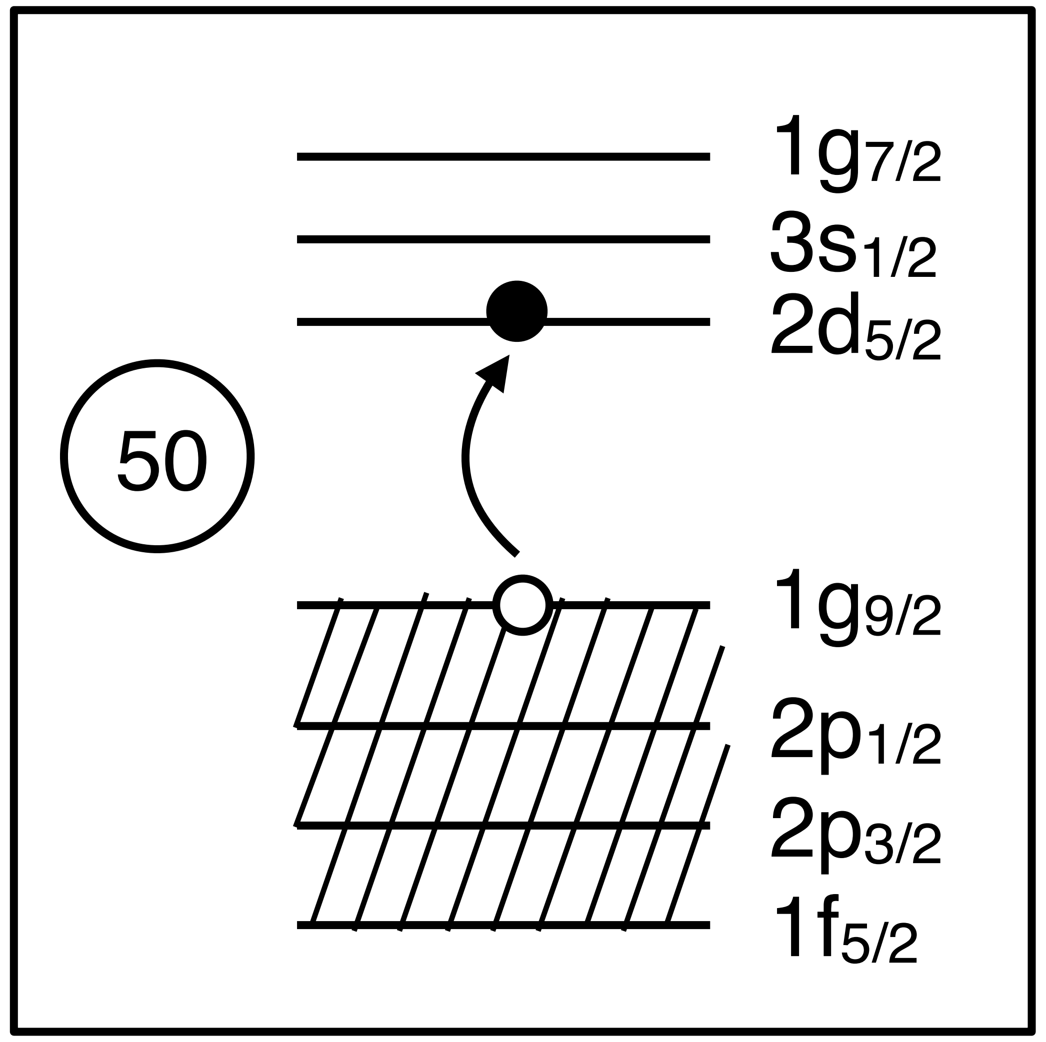
Spokesperson: E. Sahin,
University of Oslo, Oslo, Norway

- Location of the neutron single particle orbitals
- Size of the N=50 gap at Z=30 near ^{78}Ni (Z=28)

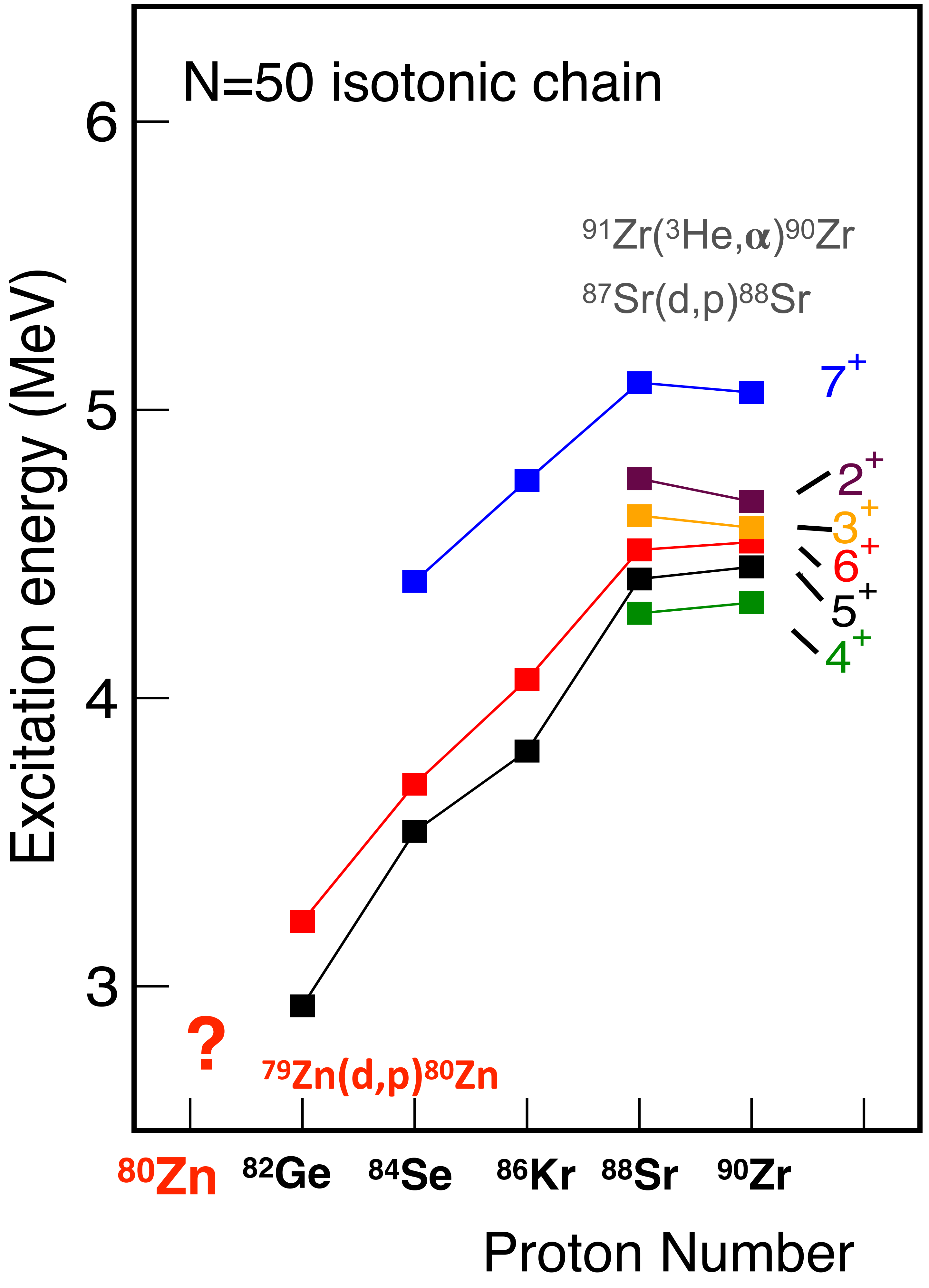
$\nu 1g_{9/2}^{-1} \otimes \nu 2d_{5/2}^{1}$ States

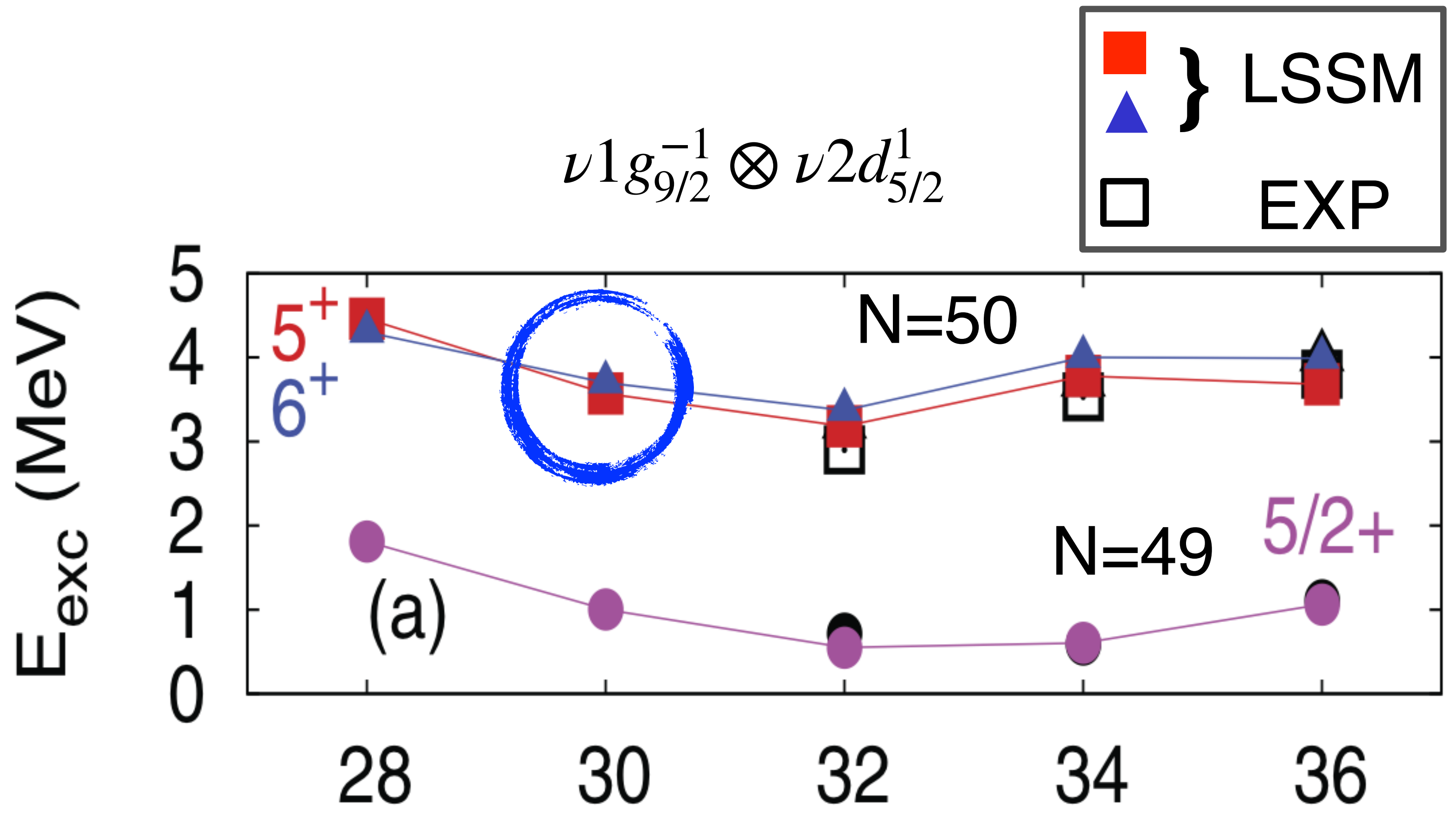
- $l=2$ transfer ($2^+, 3^+, \ldots, 7^+$) from the g.s. ^{79}Zn, $9/2^+$
- Sensitive to changes in the N=50 shell gap due to monopole interaction
- SM calculations exist only for 5^+ and 6^+ from Z=28 to Z=36

1p-1h excitations



States from 1p-1h excitations





K. Sieja and F. Nowacki , PRC85 051301(R) (2012)

$\nu 1g_{9/2}^{-1} \otimes \nu 2d_{5/2}^{1}$ States

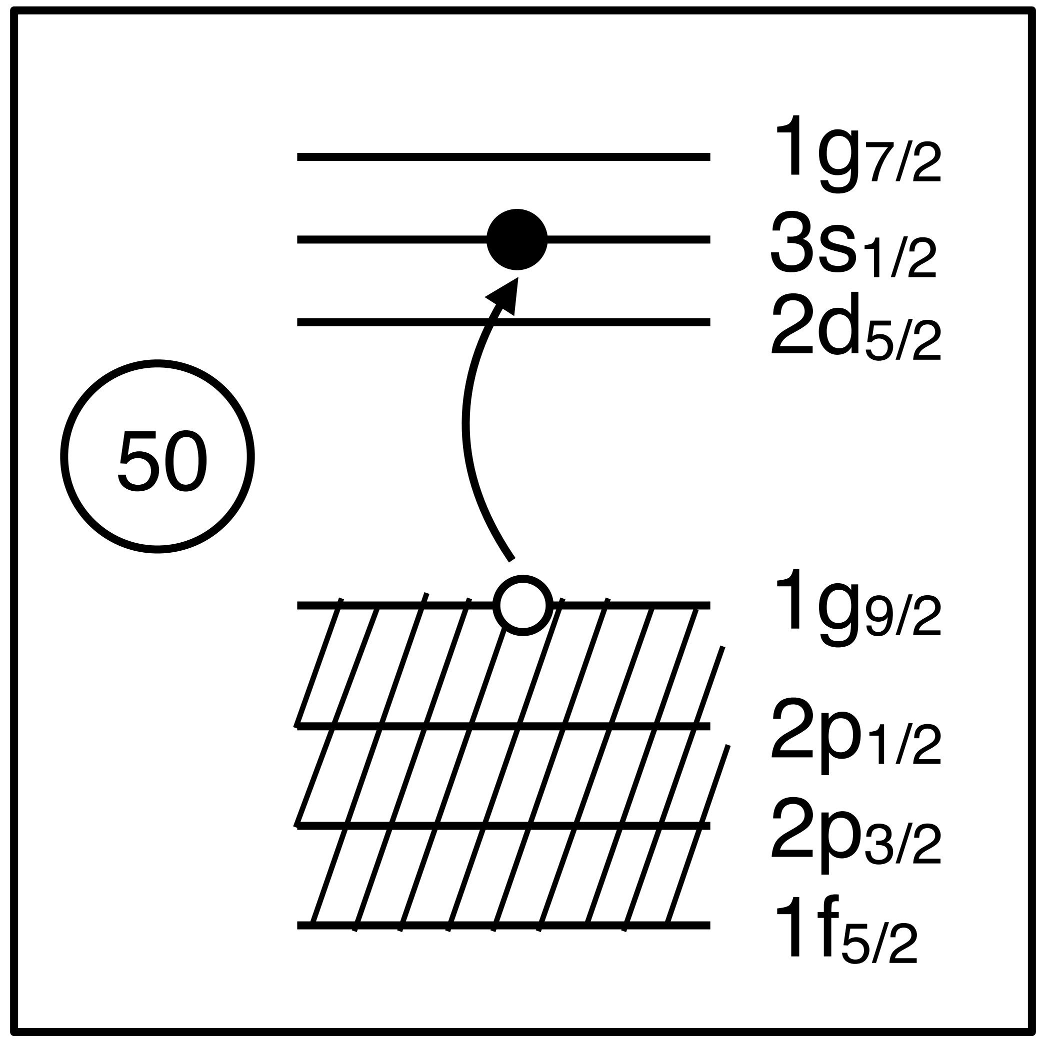
- l=2 transfer ($2^+,3^+,\ldots,7^+$) from the g.s. ^{79}Zn, $9/2^+$
- Sensitive to the N=50 shell gap due to monopole interaction
- SM calculations exist only for 5^+ and 6^+

$\nu 1g_{9/2}^{-1} \otimes \nu 3s_{1/2}^{1}$ States

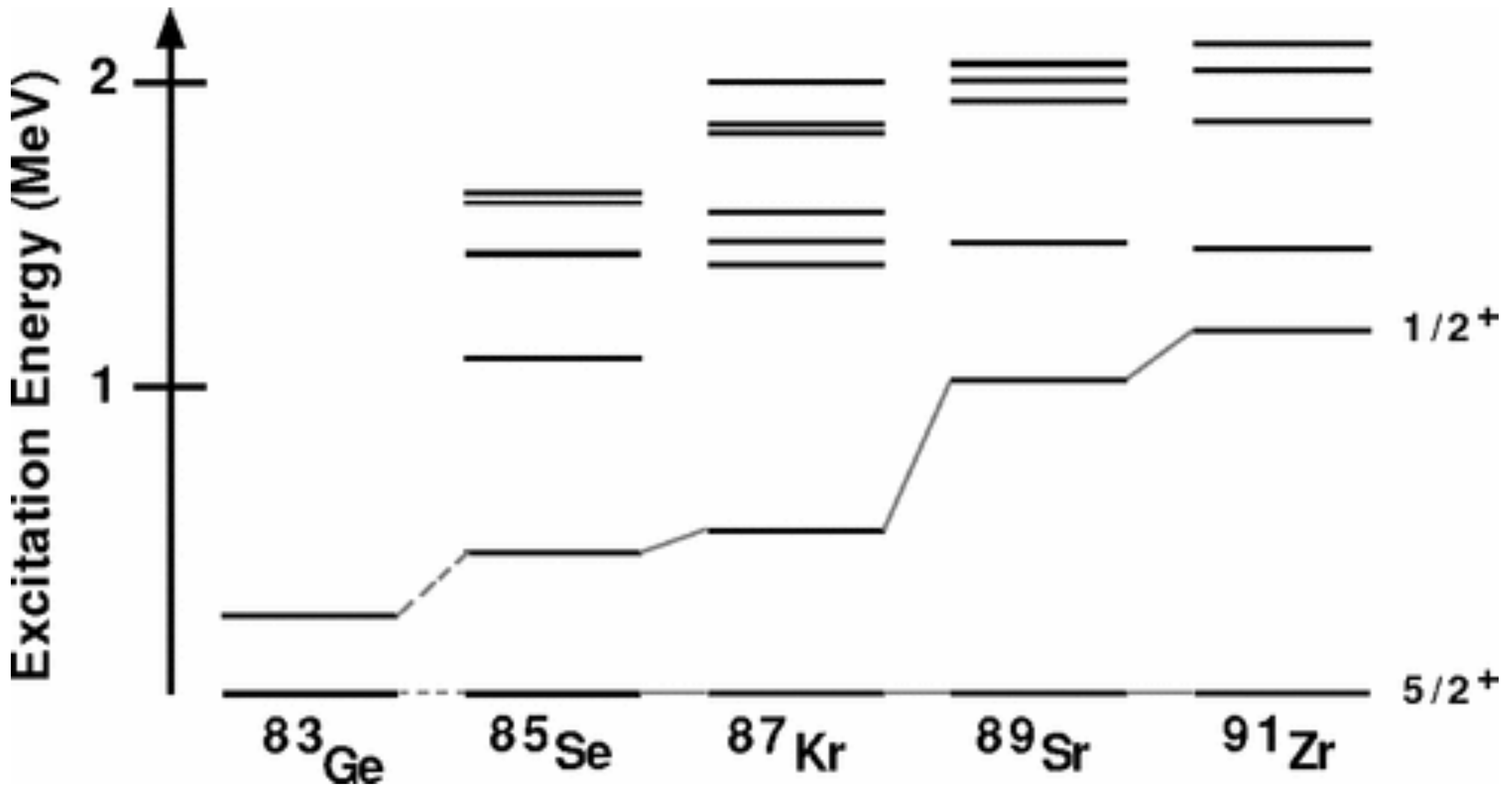
- l=0 transfer ($4^+,5^+$) from the g.s.
- Location information, $3s_{1/2}$
- No SM calculations
- **Estimated to be few hundreds keV higher than the l=2 states**

J.S. Thomas et al., Phys. Rev. C 71, 021302R (2005)

^{80}Zn $\boldsymbol{\nu}$(1p-1h)



Location of the $s_{1/2}$ and $d_{5/2}$ states in the N=51 isotones



$\nu 1g_{9/2}^{-1} \otimes \nu 2d_{5/2}^{1}$ States

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- Sensitive to the N=50 shell gap due to monopole interaction
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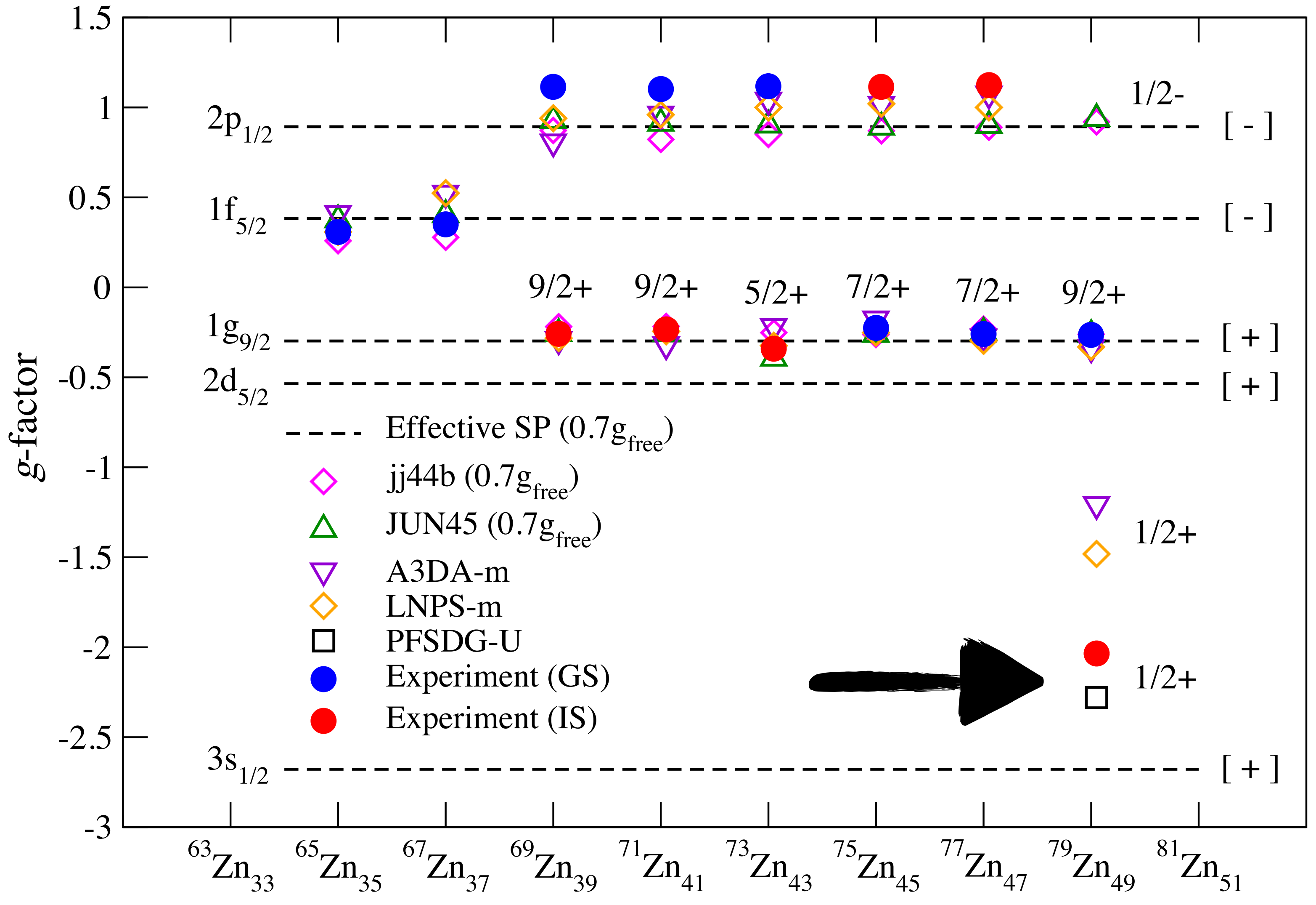
$\nu 1g_{9/2}^{-1} \otimes \nu 3s_{1/2}^{1}$ States

- l=0 transfer ($4^+,5^+$) from the g.s.
- Location i calculations nformation, $3s_{1/2}$
- No SM
- Estimated to be few hundreds keV higher than the l=2 states

$\nu 1g_{9/2}^{-2} \otimes \nu 3s_{1/2}^{2}$ States

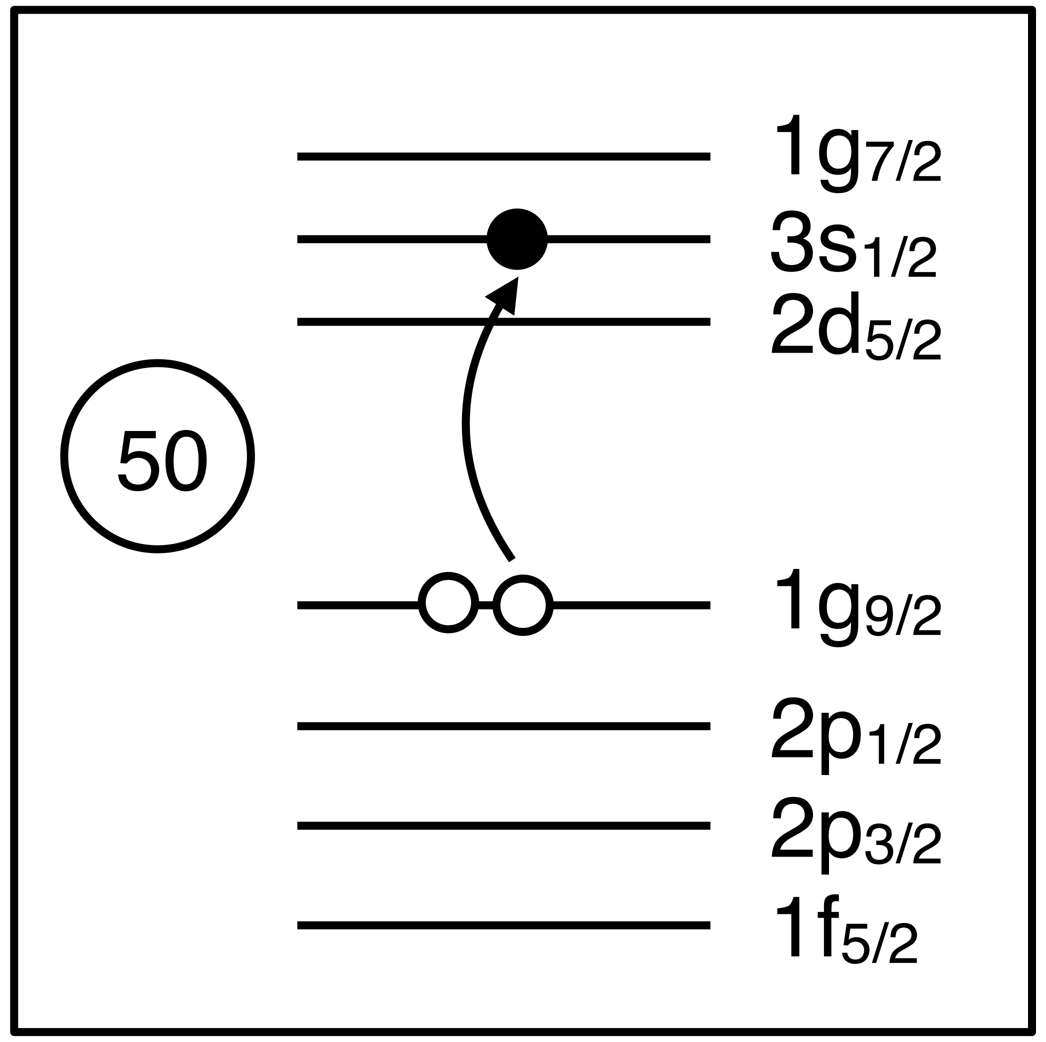
- l=0 transfer from the isomeric state in ^{79}Zn
- $E_{1/2+}$= 1.05 MeV & $t_{1/2} \geq 200$ ms
- Possible assignment as (1p-2h) excitations across N=50 (PFSDG-U int.)
- Evidence for a 0^+ intruder state



ISOLDE: X. F. Yang et al., PRL 116, 182502 (2016).

ISOLDE: R.Orlandi et al., Phys. Letts. B 740, 298 (2015).

^{79}Zn $\boldsymbol{\nu}$(1p-2h)



$\nu 1g_{9/2}^{-1} \otimes \nu 2d_{5/2}^{1}$ States

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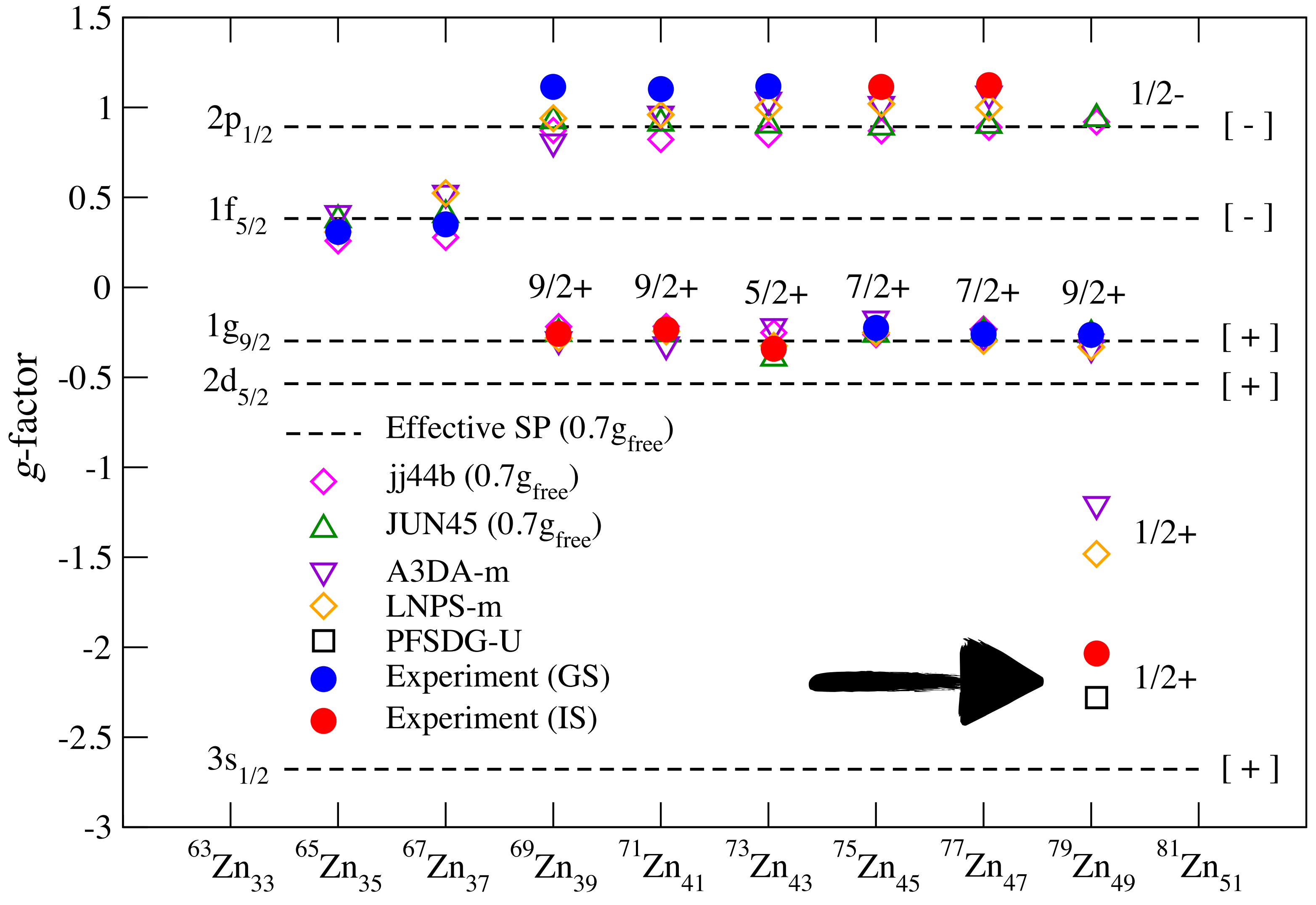
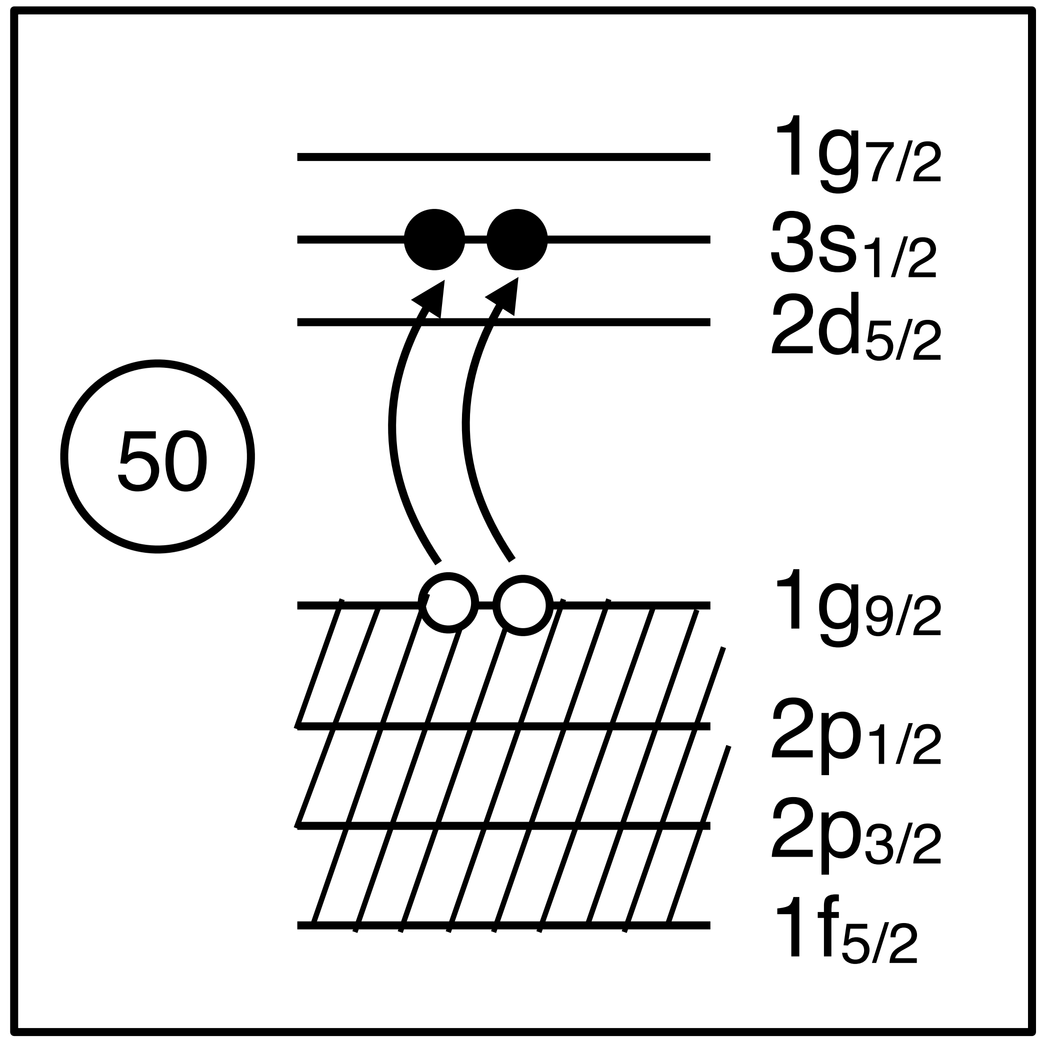


ISOLDE: X. F. Yang et al., PRL 116, 182502 (2016).

ISOLDE: R.Orlandi et al., Phys. Letts. B 740, 298 (2015).

$E(0^+) \cong 2$ MeV $\boldsymbol{\nu}$(2p-2h)

^{80}Zn $\boldsymbol{\nu}$(2p-2h)



$\nu 1g_{9/2}^{-1} \otimes \nu 2d_{5/2}^{1}$ States

- l=2 transfer ($2^+,3^+,\ldots,7^+$) from the g.s., $9/2^+$
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$\nu 1g_{9/2}^{-1} \otimes \nu 3s_{1/2}^{1}$ States

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- Location i calculations nformation, $3s_{1/2}$
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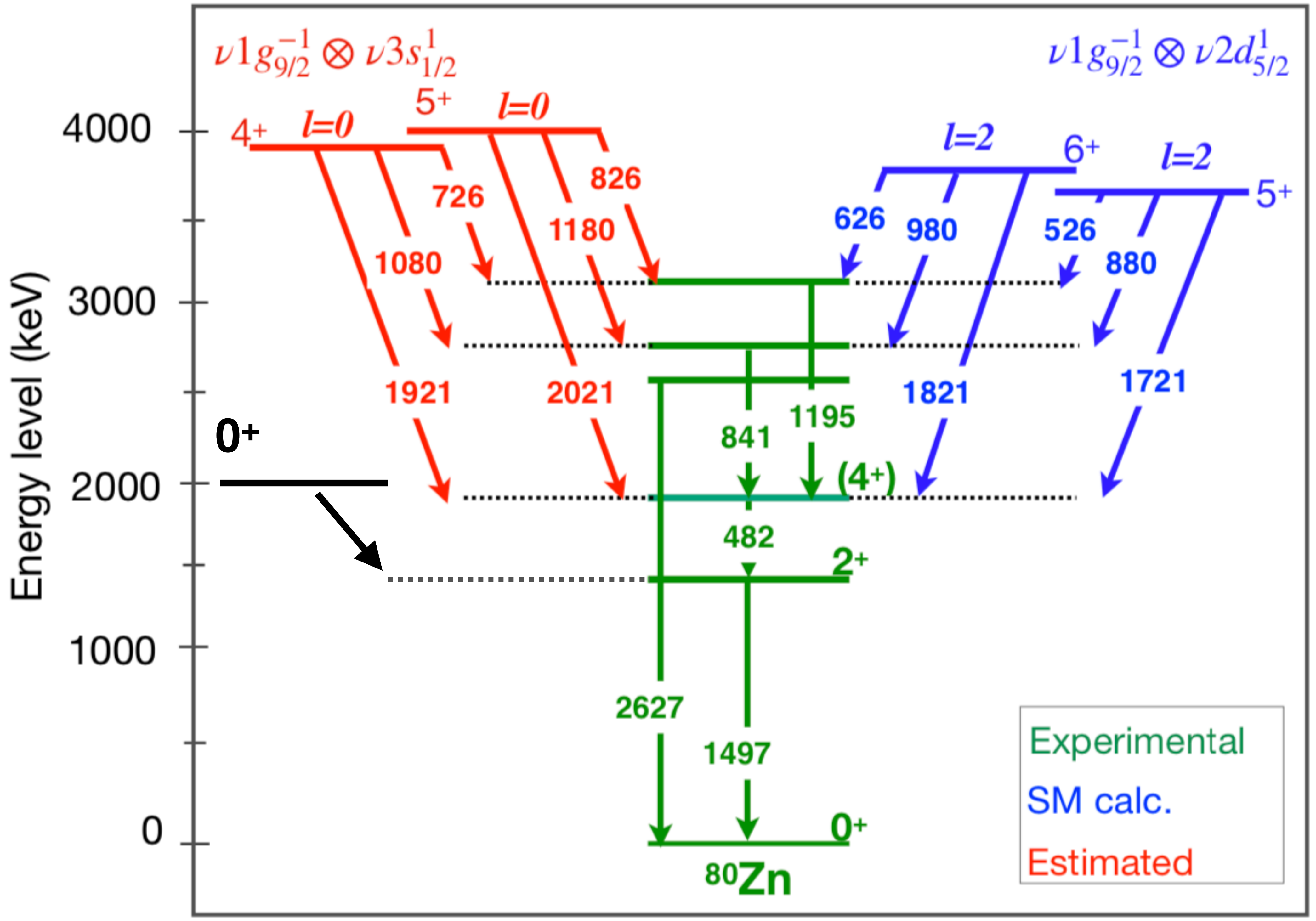
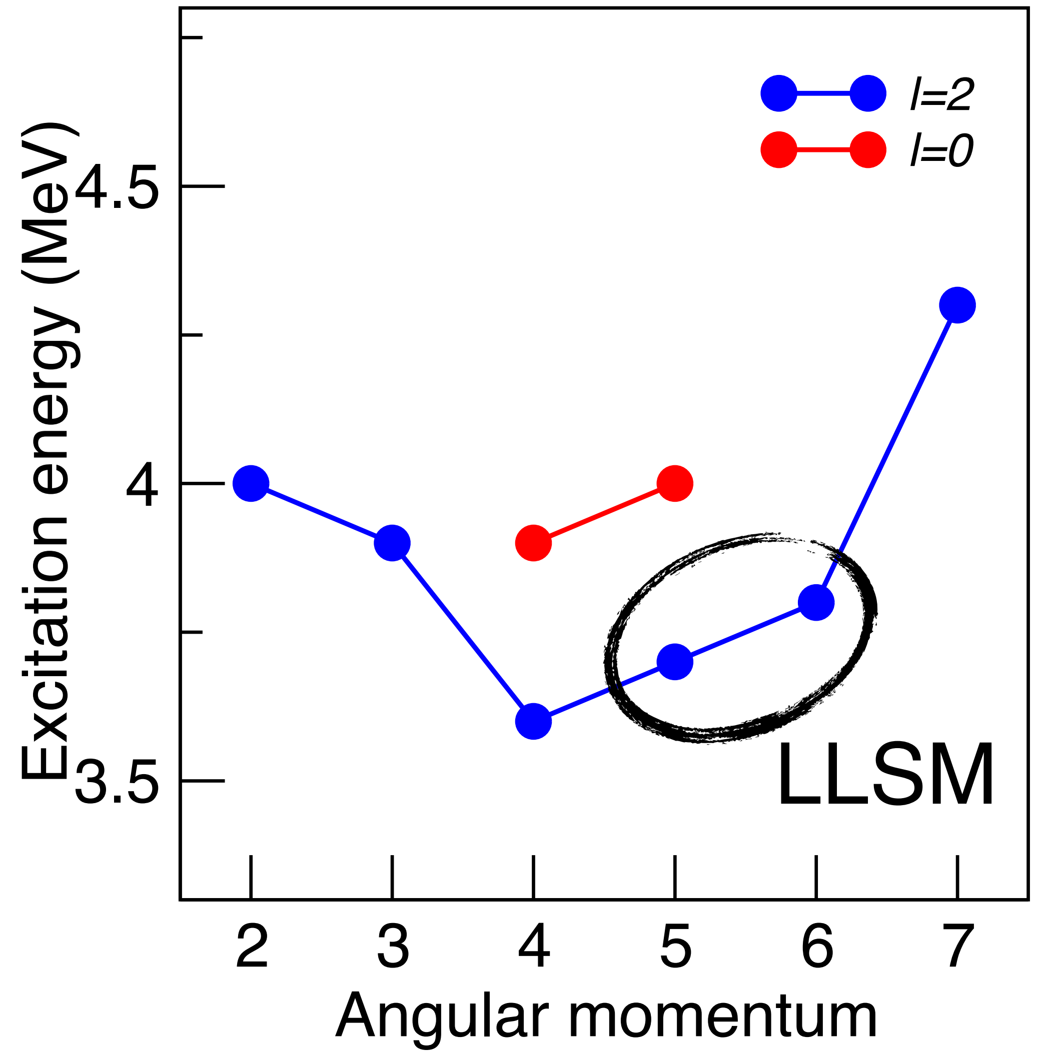


2^+ state at ISOLDE Coulomb excitation : J. Van de Walle et al., PRL 99, 142501 (2007).

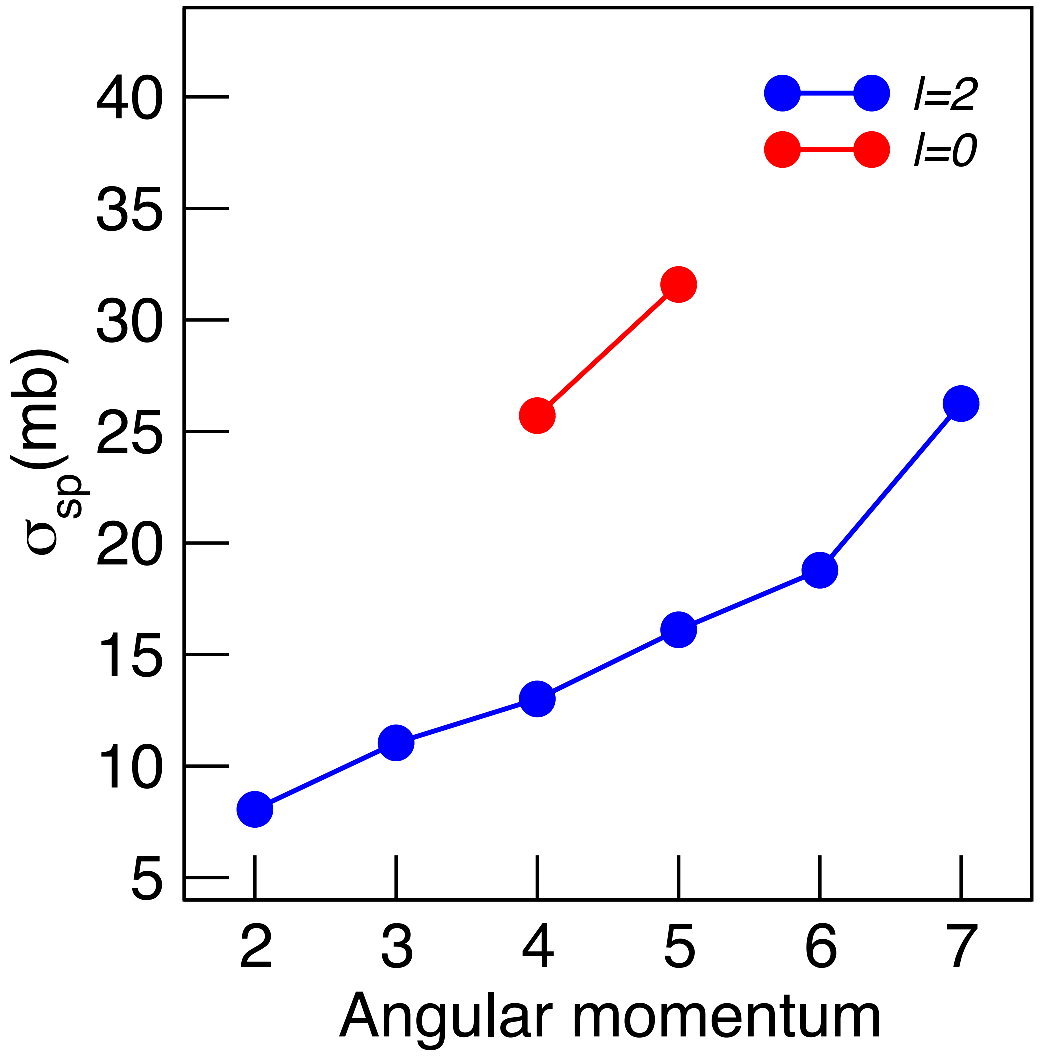
RIKEN inelastic scattering and proton removal: ^{9}Be(^{80}Zn,^{80}Zn) and ^{9}Be(^{81}Ga,^{80}Zn) :
Y. Shiga et al., PRC 93 024320 (2016).

5^+,6^+ : K. Sieja and F. Nowacki , PRC85 051301(R) (2012)

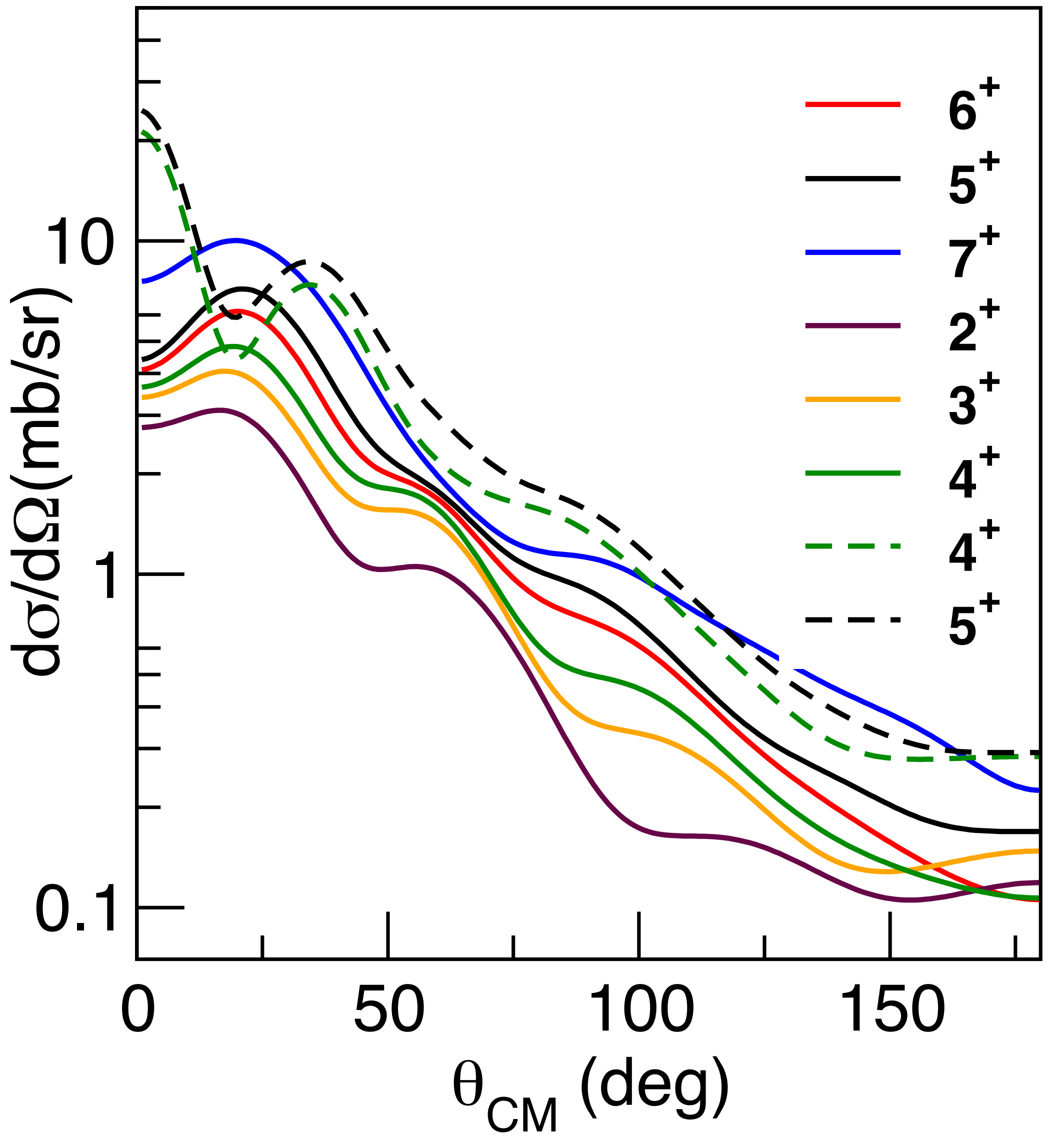
DWBA Calculations via FRESCO



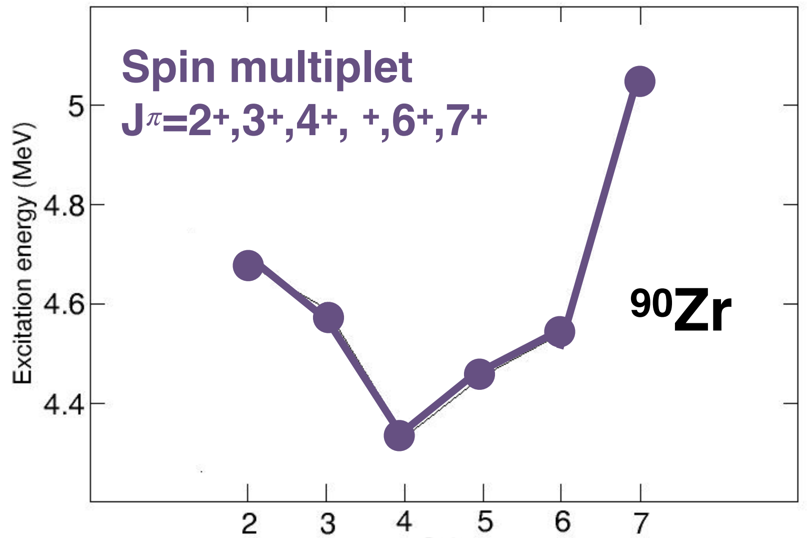
s.p. cross sections



Differential cross sections

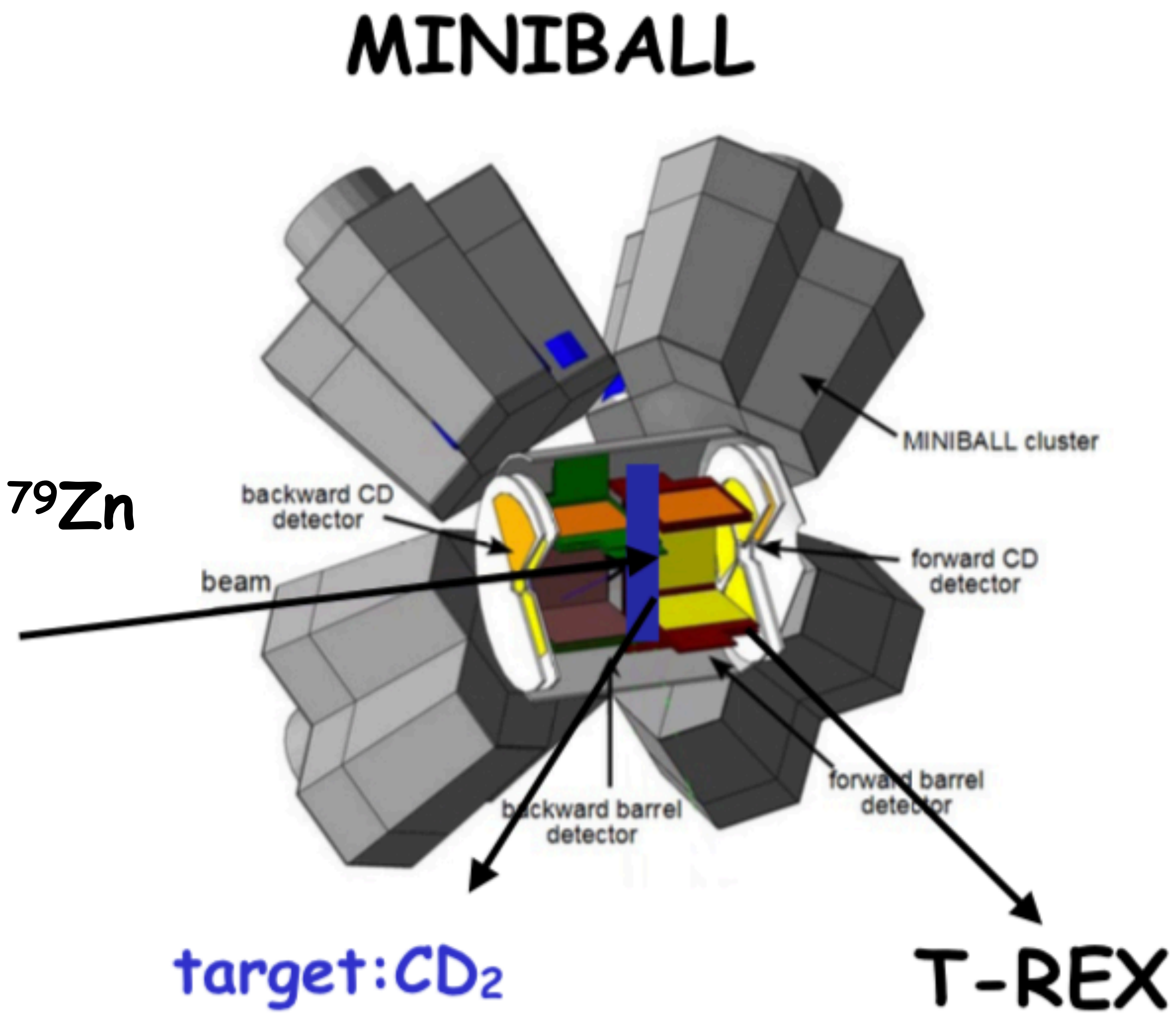


Parabola similar to ^{90}Zr & ^{88}Sr



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

Setup and Experiment



$^{79}\mathrm{Zn}(d,p\gamma)^{80}\mathrm{Zn}$ inverse kinematics

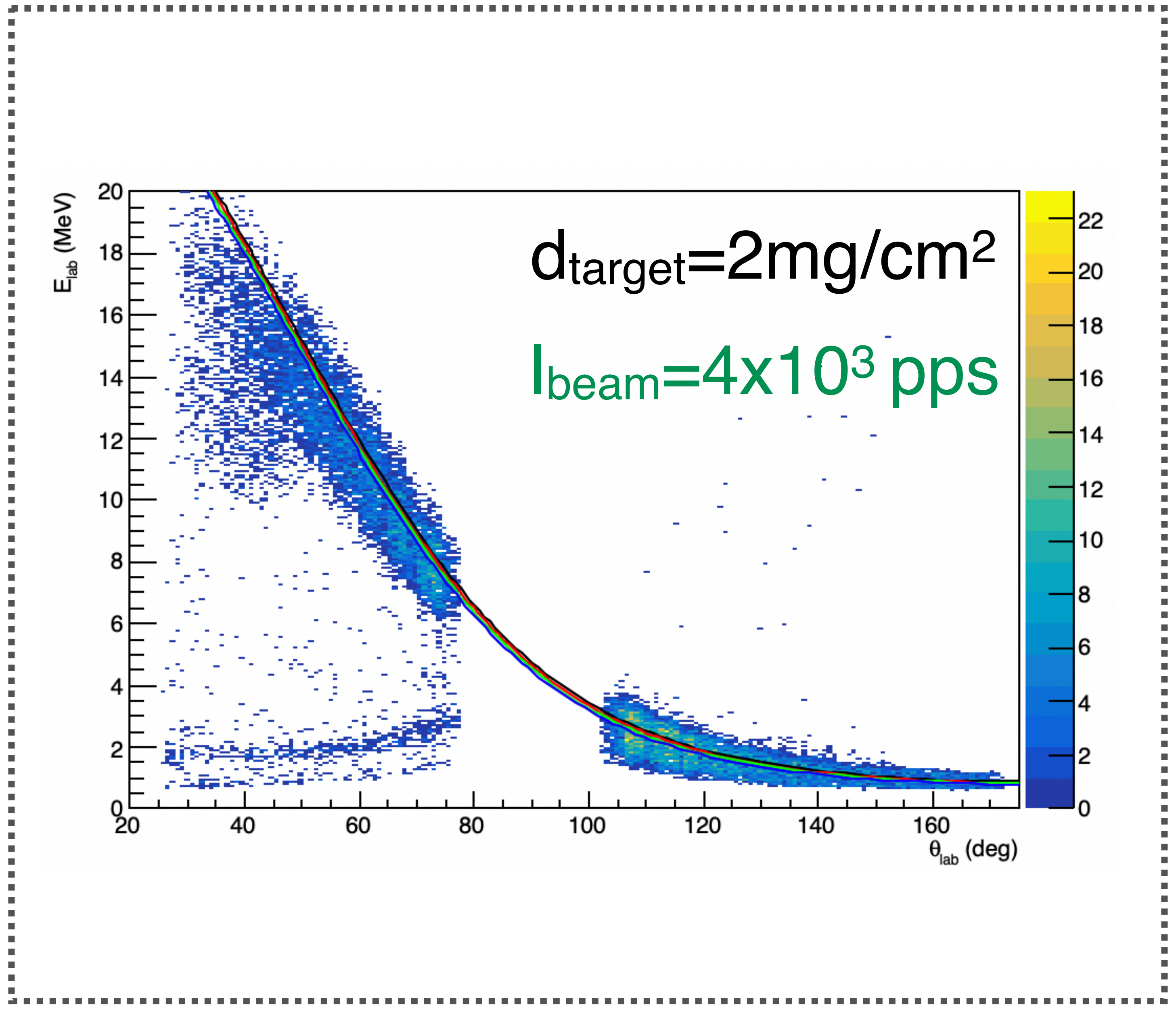
Beam energy (^{79}Zn)	395 MeV (5 MeV/nuc)
Beam intensity on MINIBALL	**~~$4\mathrm{x}10^4$ pps~~** —> **$4\mathrm{x}10^3$ pps**
Target thickness (CD_2)	**~~1 mg/cm^2~~ —> 2 mg/cm^2**
Cross sections	DWBA via FRESCO

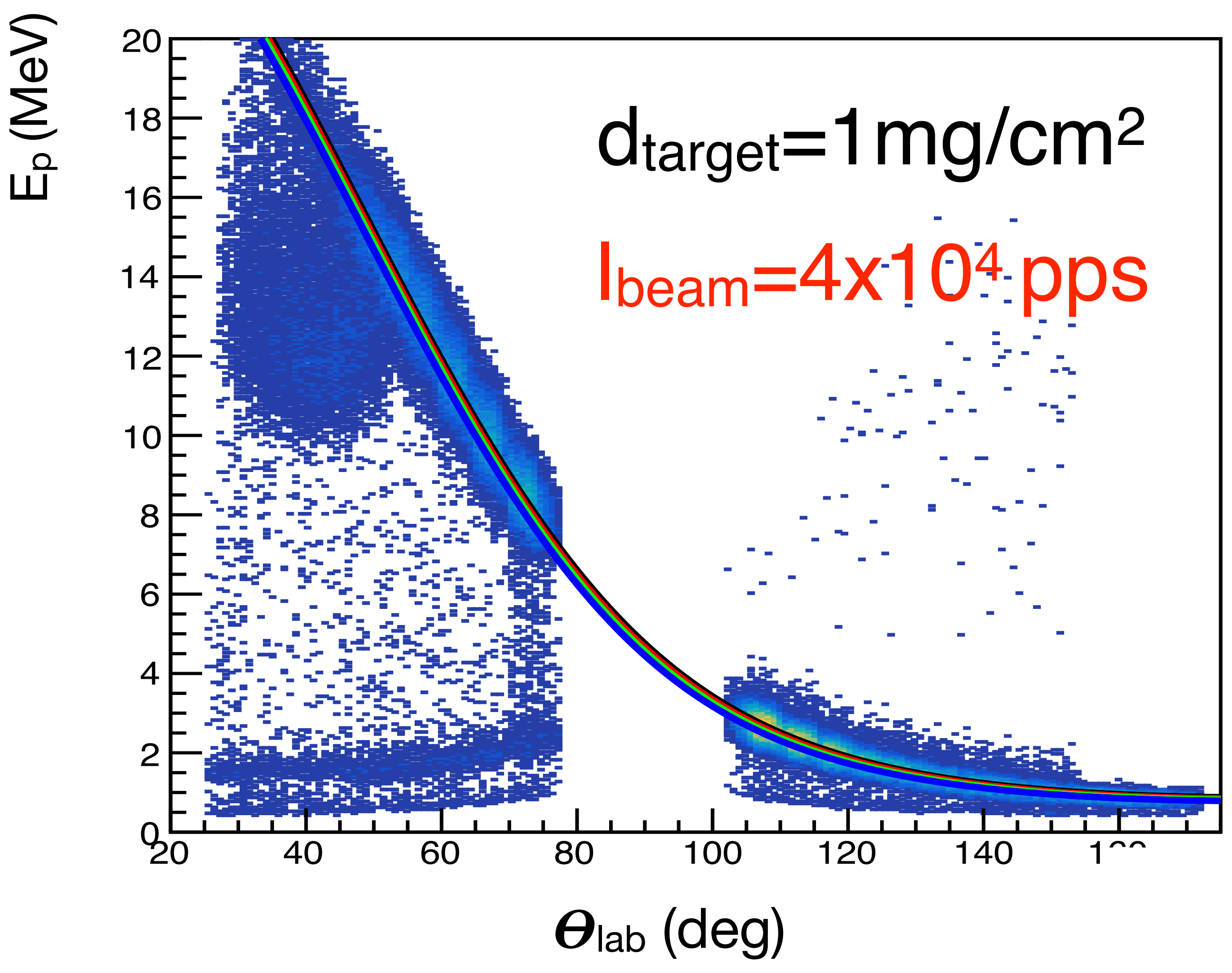
Isolde Database: 10^6 pps/μC UCx

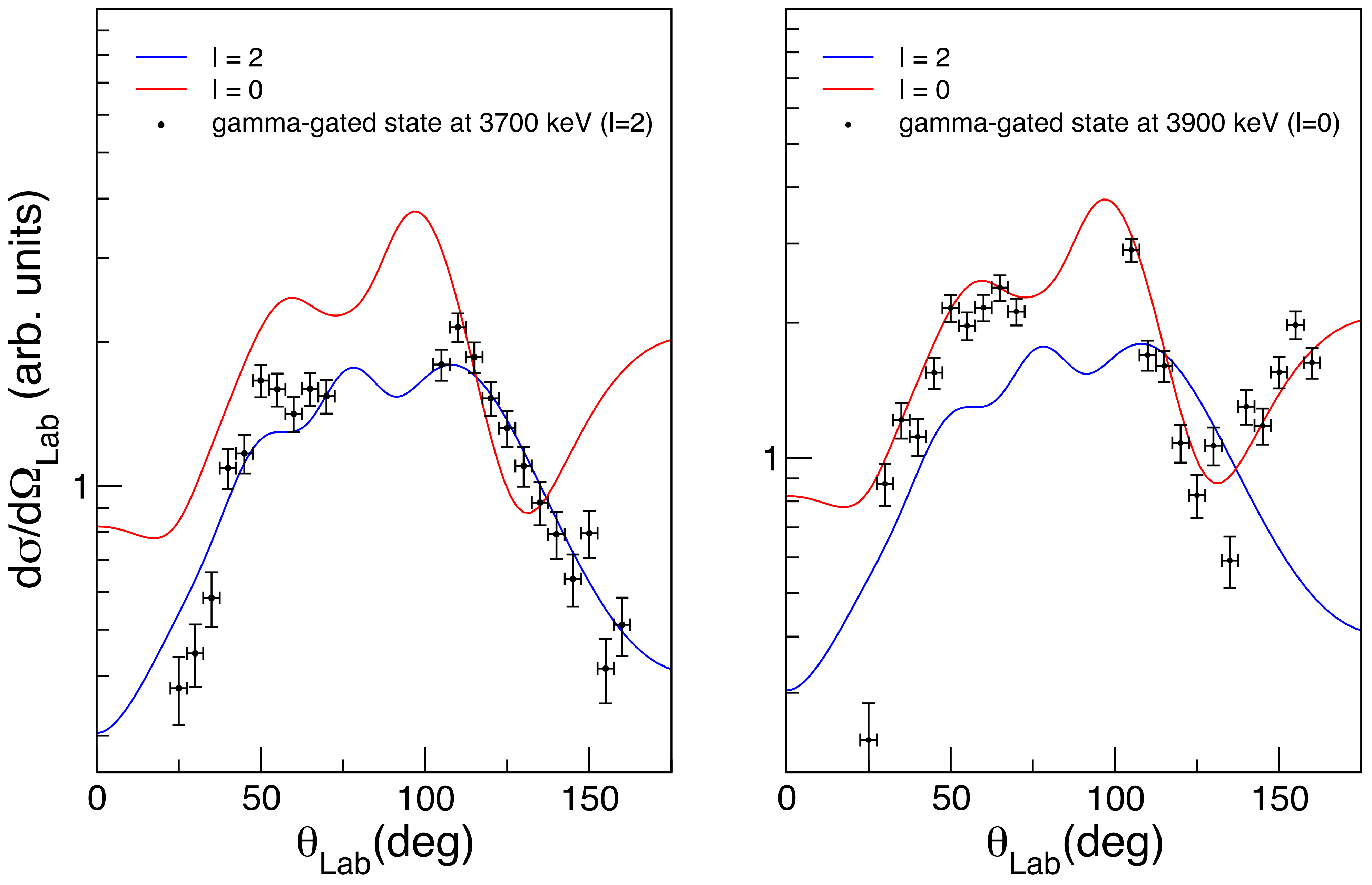
Suggested value from the earlier records: ~5.10^5 pps/μC UCx

1.6 μC total proton intensity + 5% transmission eff. ==> **$4\mathrm{x}10^4$ pps** at MINIBALL

Rb/Ga contamination: **$4\mathrm{x}10^3$ pps** recommended by TAC .





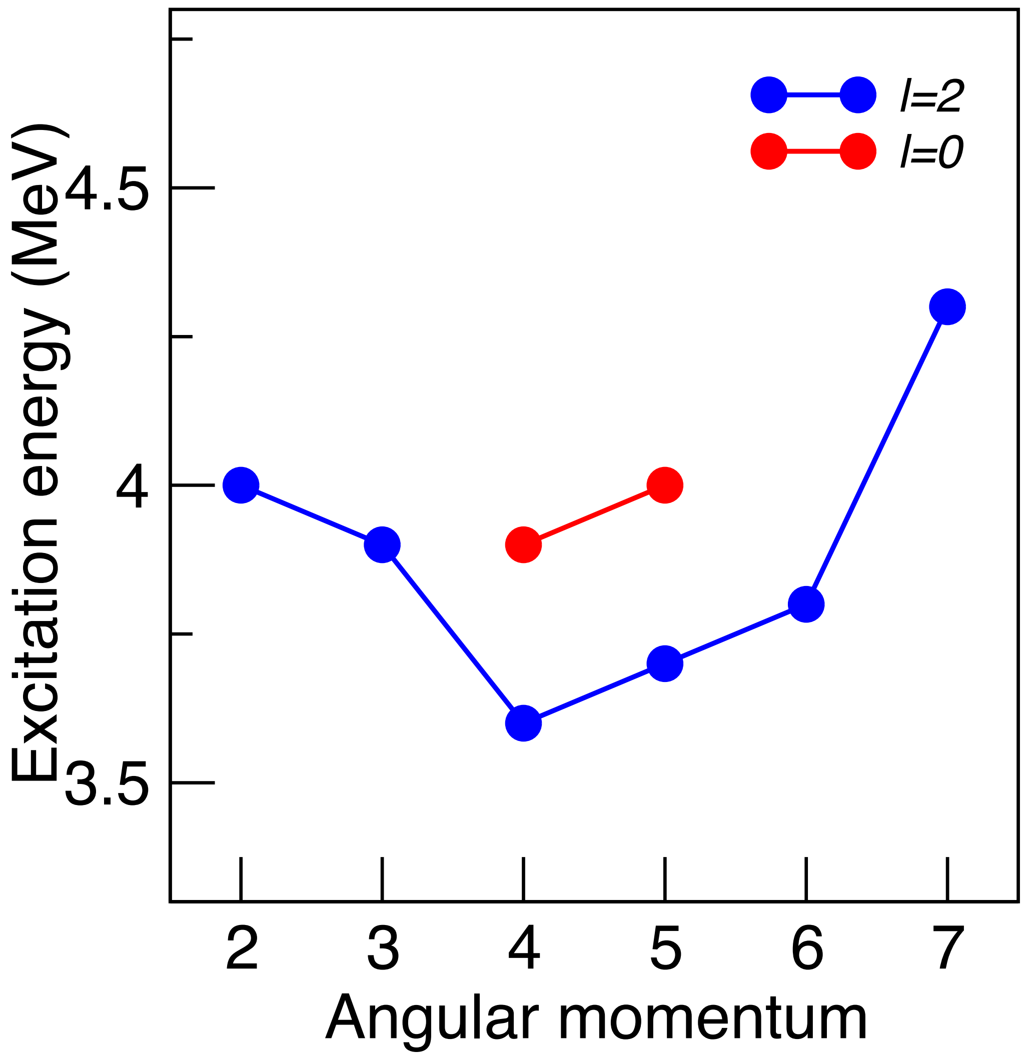


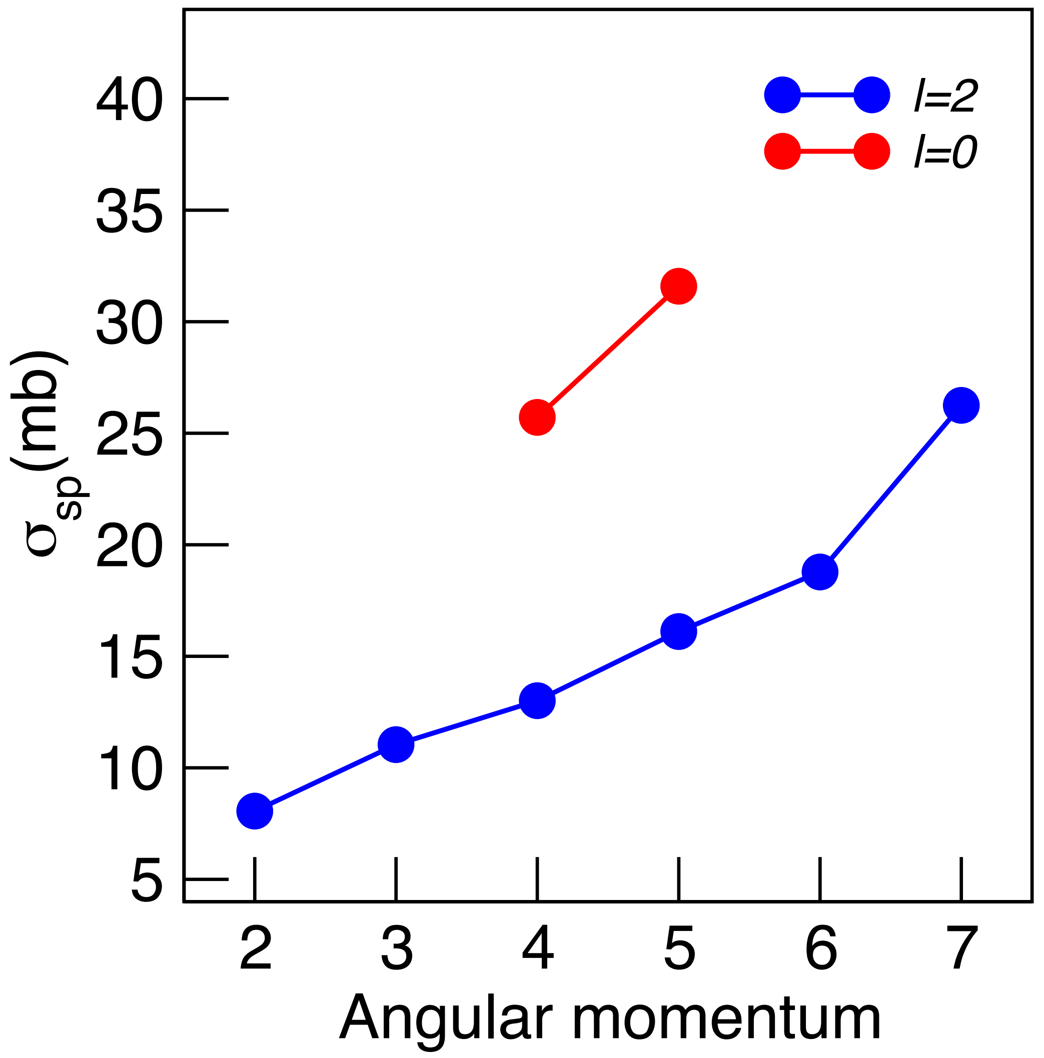
- TREX angular coverage: 60%
- MINIBALL efficiency on average 6% at 1MeV

	(particle-γ)	(particle-$\gamma\gamma$)
Average cross section for $\nu 1g_{9/2}^{-1} \otimes \nu 2d_{5/2}^{1}$ states : 20 mb	300	30
Average cross section for $\nu 1g_{9/2}^{-1} \otimes \nu 3s_{1/2}^{1}$ states : 28 mb	400	40

Beam time request

TOTAL: 21 shifts for physical runs + 3 shifts for beam preparation





Identification of states in the worst scenario:

Low-spin states have lower cross section and energy behaviour also follows a certain trend (parabola) .

One can use gamma-tagged proton angular distributions and see how this compares with the expected trends of the excitation energy and the s.p. cross sections.

Plus shell model calculations might be helpful.

	This proposal $^{79}Zn(d,p\gamma)^{80}Zn$	Accepted proposal Spokesperson: R. Orlandi IS556 $^{80}Zn(d,p\gamma)^{81}Zn$
Beam intensity	5×10^4 pps/μC at UCx 4×10^3 pps at MINIBALL	3×10^4 pps/μC at UCx 2.3×10^3 pps at MINIBALL
Target thickness	2 mg/cm^2	2 mg/cm^2
Required beam time	7 days	7 days
Expected yield	300 pγ / 30 pγγ events for one l=2 state 400 pγ /40 pγγ events for one l=0 state	350 pγ events for the l=0 state, $1/2^+$

Future perspective: New neutron converter will increase expected yield as indicated in IS556.
Test has been done Ref: J.P. Ramos et al., NIMB 463, 357 (2020).

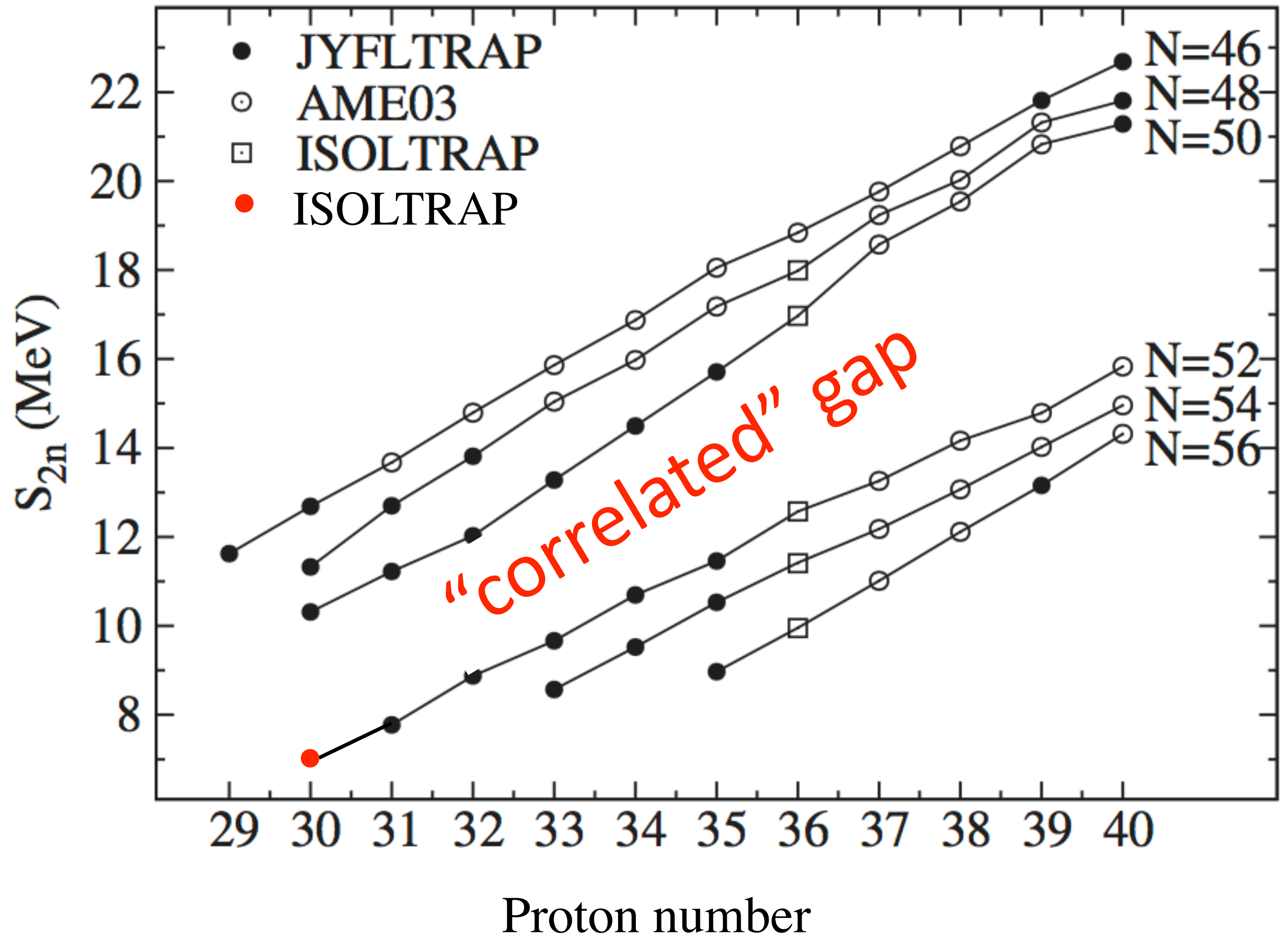
Alternative solution could be dropping the neutron converter
(UCx + neutron converter + quartz line + RILIS)

Special thanks to Sebastian Rothe

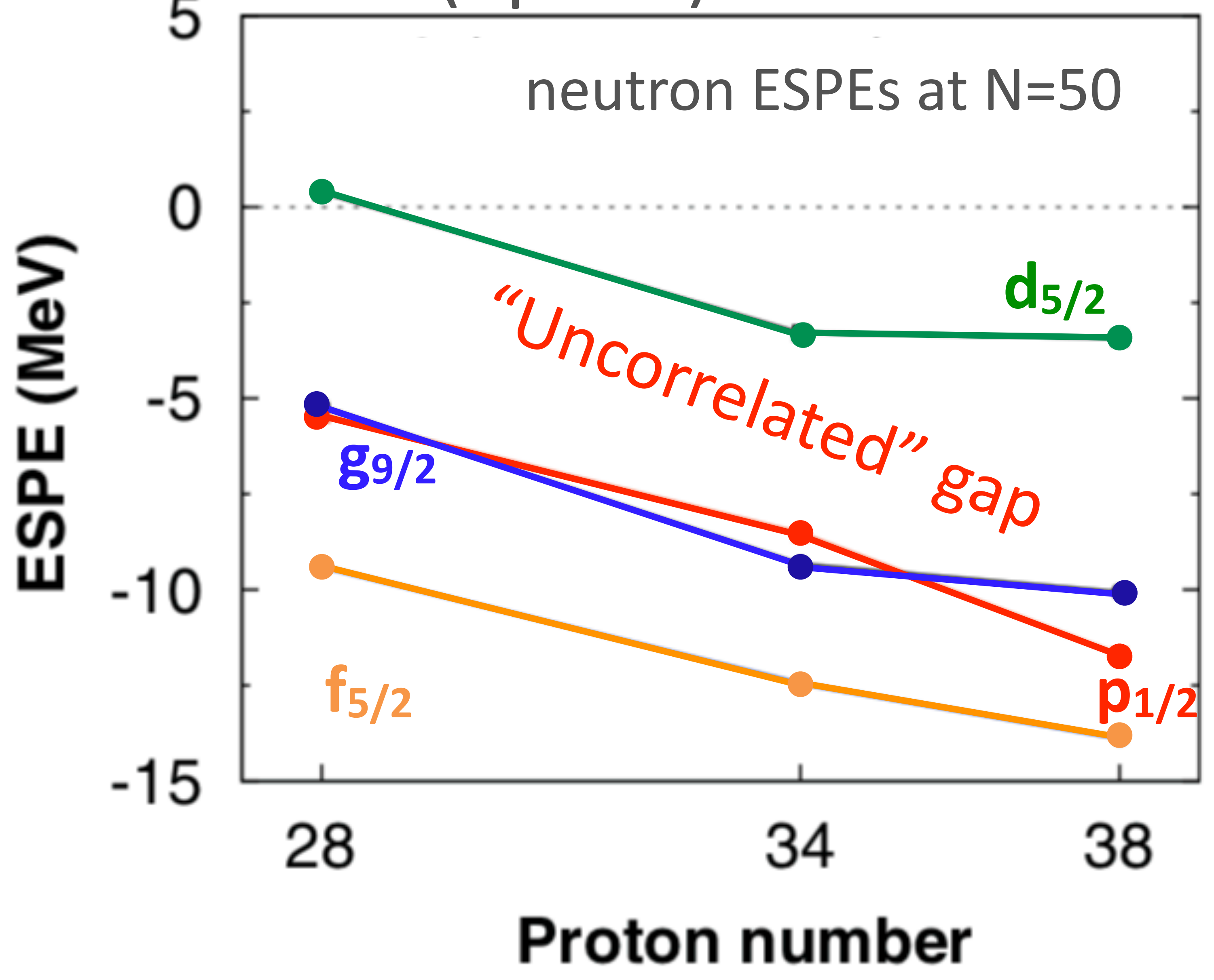
Thank you

Additional slides

N=50 gap from mass measurements



(1p-1h) states



Shell gap from mass is correlated.

SM approach:
K. Sieja and F. Nowacki , PRC85 051301(R) (2012)
F. Nowacki et al., PRL 117, 272501 (2016)
A. Welker et al., PRL 119, 192502 (2017).

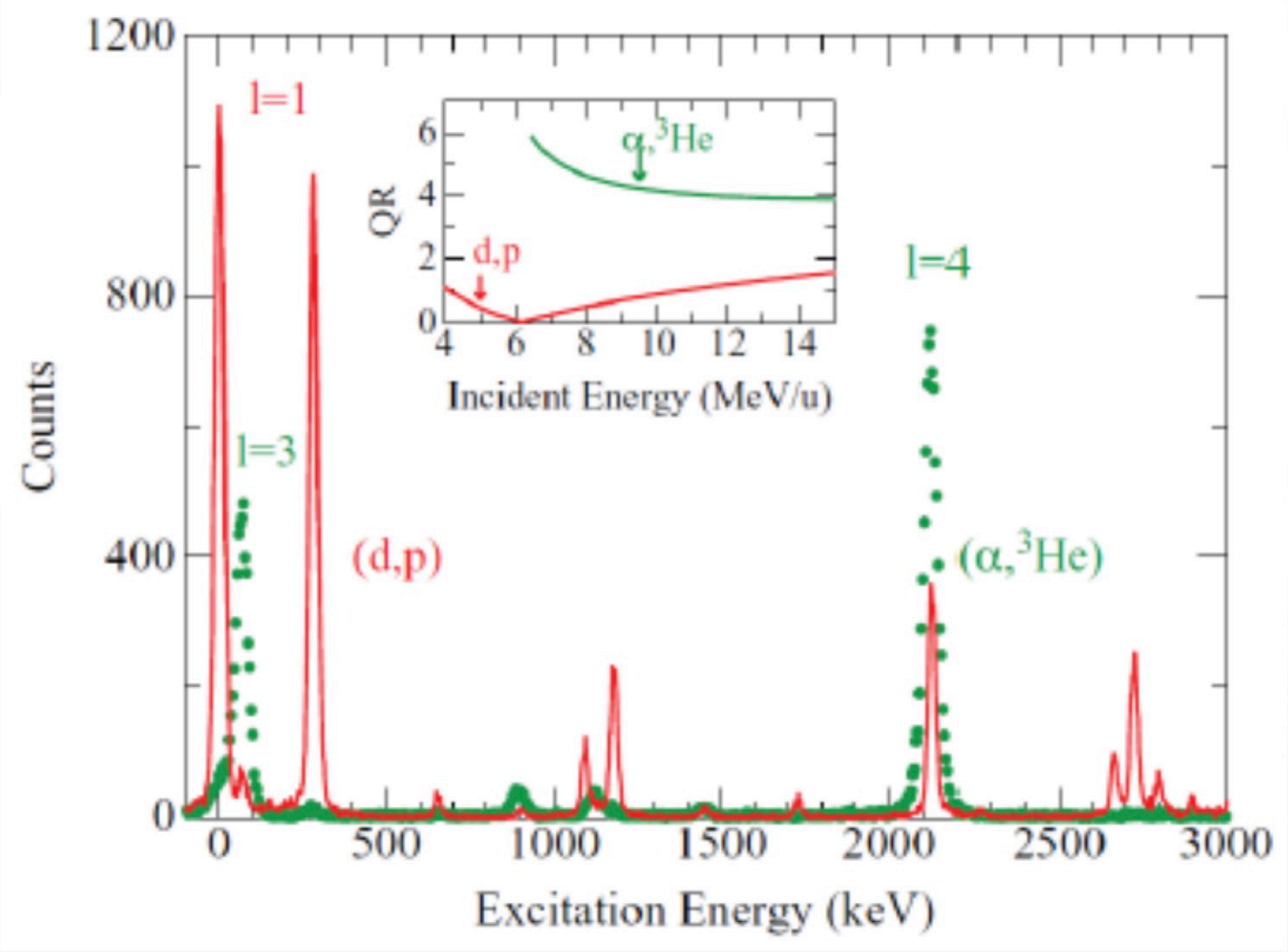
Mean-field approach:
M. Bender et al. PRC78, 054312 (2008)

- **Correlation effects can be explored and help theory**

Momentum matching in transfer reactions

^{60}Ni(α,^{3}He): $Q_{g.s.}$= -12.8 MeV -> high momentum transfers

^{60}Ni(d,p): $Q_{g.s.}$= 5.6 MeV -> low momentum transfers



^{79}Zn(d,p)^{80}Zn

$Q_{g.s.}$=4.064 MeV

(example borrowed from C. Hoffman)

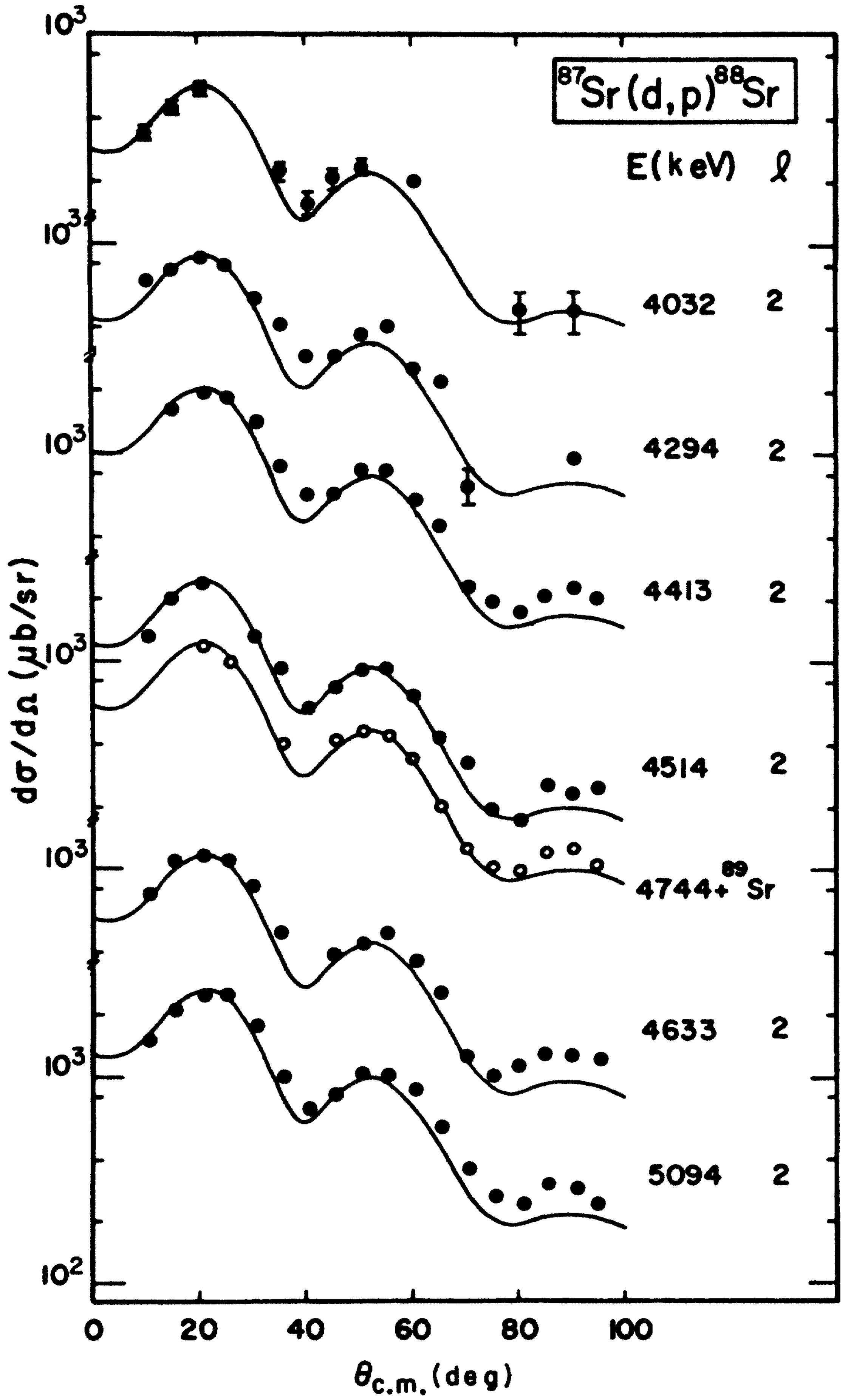
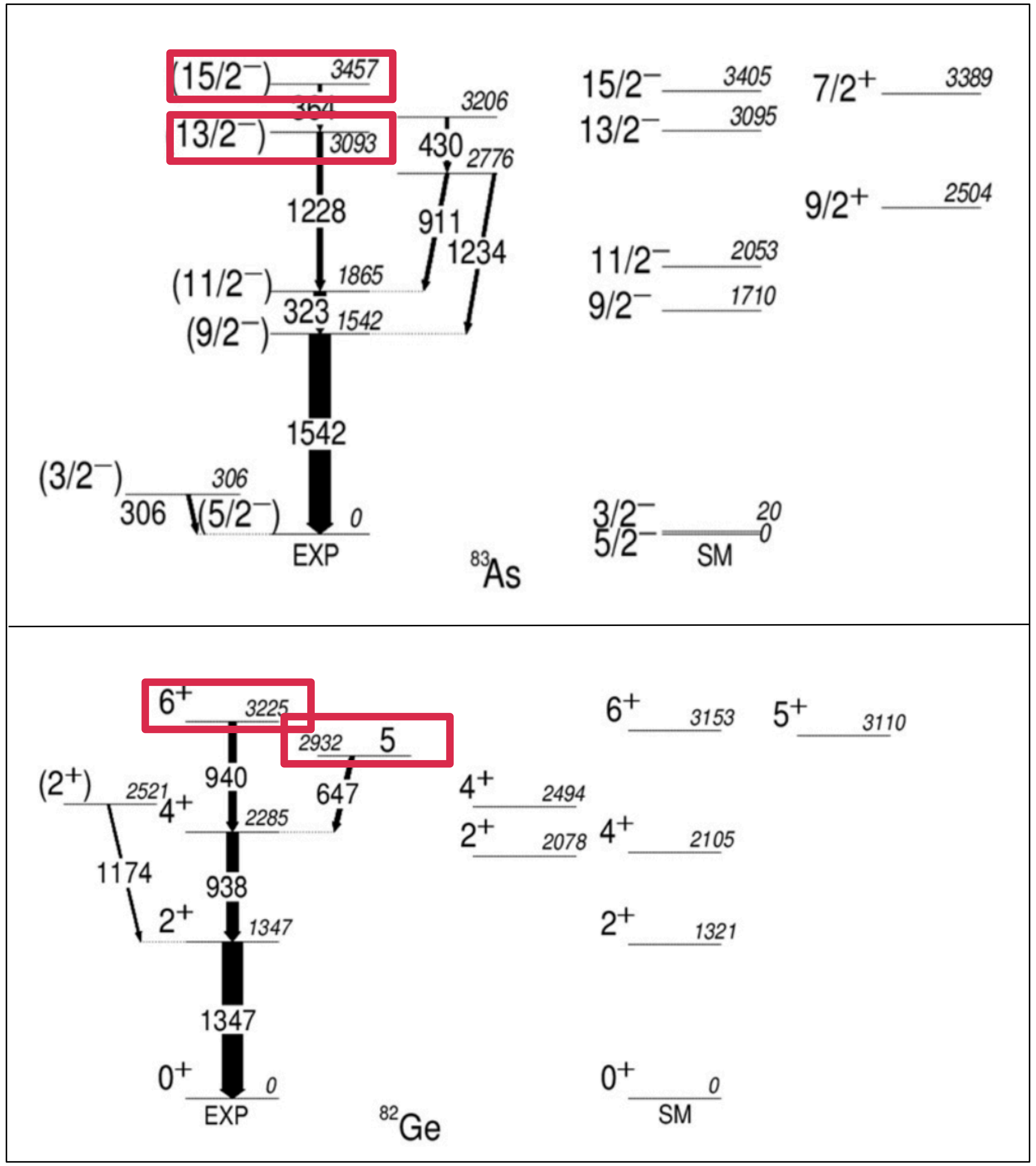


FIG. 8. Measured differential cross sections and DWBA fits for $l = 2$ transitions. All fits are based on NLFR calculations using L/B parameters.

TABLE V. Summary of (d,p) results for levels in ^{88}Sr.

Level No.[a]	E^* (keV)	Cosman and Slater[a] l	Cosman and Slater[a] G_{lJ}[c]	This experiment[b] l	This experiment[b] G^{88}_{lj}	This experiment[b] G^{89}_{lj}	This experiment[b] J^π (assumed)[d]	This experiment[b] S^{88}_{lj}
1	(1836)	2	0.126	2	(0.13)		2^+	0.25
5	4032	2	0.279	2	0.35		2^+	0.71
6	4294	2	0.376	2	0.53		4^+	0.59
7	4413	2	0.875	2	1.18		$[5]^+$	1.07
8	(4450)	2	0.083	(2)	(~0.10)		$[4]^+$	(0.11)
10	4514	2	1.080	2	1.31		$[6]^+$	1.00
12	4633	2	0.564	2	0.68		$[3]^+$	0.97
13	4744	2	0.805	2	0.14	5.86	$[4]^+$	0.28(0.16)
17	5094	2	1.040	2	1.33		$[7]^+$	0.89
			5.228		5.75	5.86		
15	4873[e]	0	0.230	0	0.24[e]		$[4]^+$	0.26[e]
21	5416	0	0.105	0	0.13		$[5]^+$	0.12
22	5466	0	0.563	0	0.61		4^+	0.67
23	(5506)	0	0.027	(0)	<0.01			
25	5729	0	0.789	0	0.94		$[5]^+$	0.85
26	(5780)	0	0.405	0	0(±0.03)	1.92		
32	(6214)	0	0.031	(0)	(~0.03)			
			2.150		1.95	1.92		

Equivalent of $5^+, 6^+$ states in ^{82}Ge
is found to be $13/2^-$, $15/2^-$ in ^{83}As



SM Calculations:

A.F. Lisetskiy, B.A. Brown, M. Horoi, H. Grawe,
Phys. Rev. C 70 (2004) 044314.

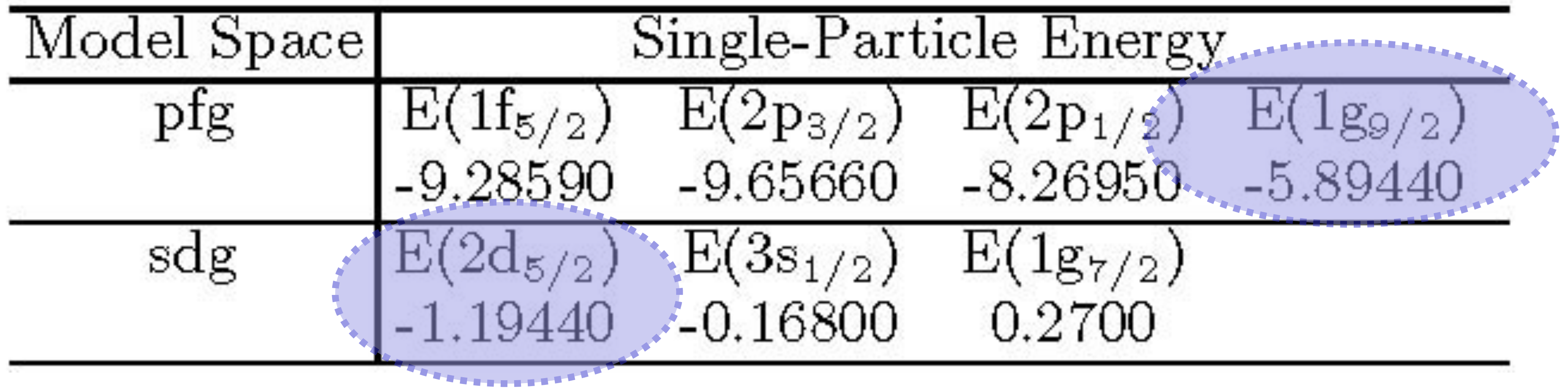
Interaction: JJ4B + SDI

Model spaces: *pfg9+sdg*

Inert Core nucleus: ^{56}Ni

Tensor interactions are included

The SPEs relative to the ^{56}Ni core have been derived from the SPEs with respect to the doubly-magic ^{78}Ni core.



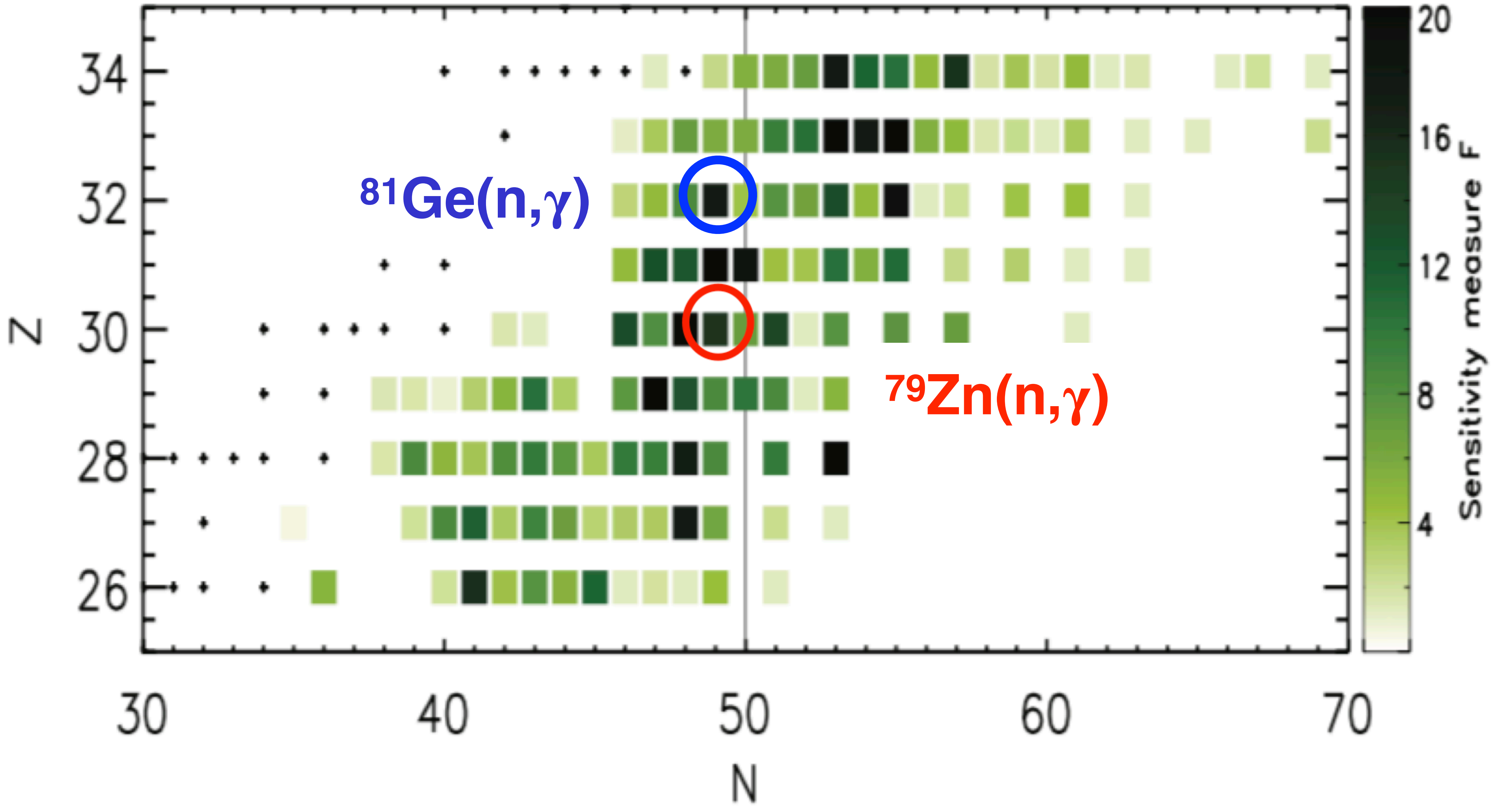
Model Space	Single-Particle Energy			
pfg	$E(1f_{5/2})$ -9.28590	$E(2p_{3/2})$ -9.65660	$E(2p_{1/2})$ -8.26950	$E(1g_{9/2})$ -5.89440
sdg	$E(2d_{5/2})$ -1.19440	$E(3s_{1/2})$ -0.16800	$E(1g_{7/2})$ 0.2700	

$$\mathbf{E(\nu d_{5/2} - \nu g_{9/2}) = parameter}$$

ES et al.,Nucl. Phys. A 893, 1-12 (2012)

Weak r-process

Sensitivity study to the n-capture process in the context of neutron-rich supernova and collapsar accretion disk winds.



weak *r* process—a rapid neutron capture process that forms a solar-type *A* ~ 80 *r*-process peak and potentially nuclei up to the *A* ~ 130 peak.

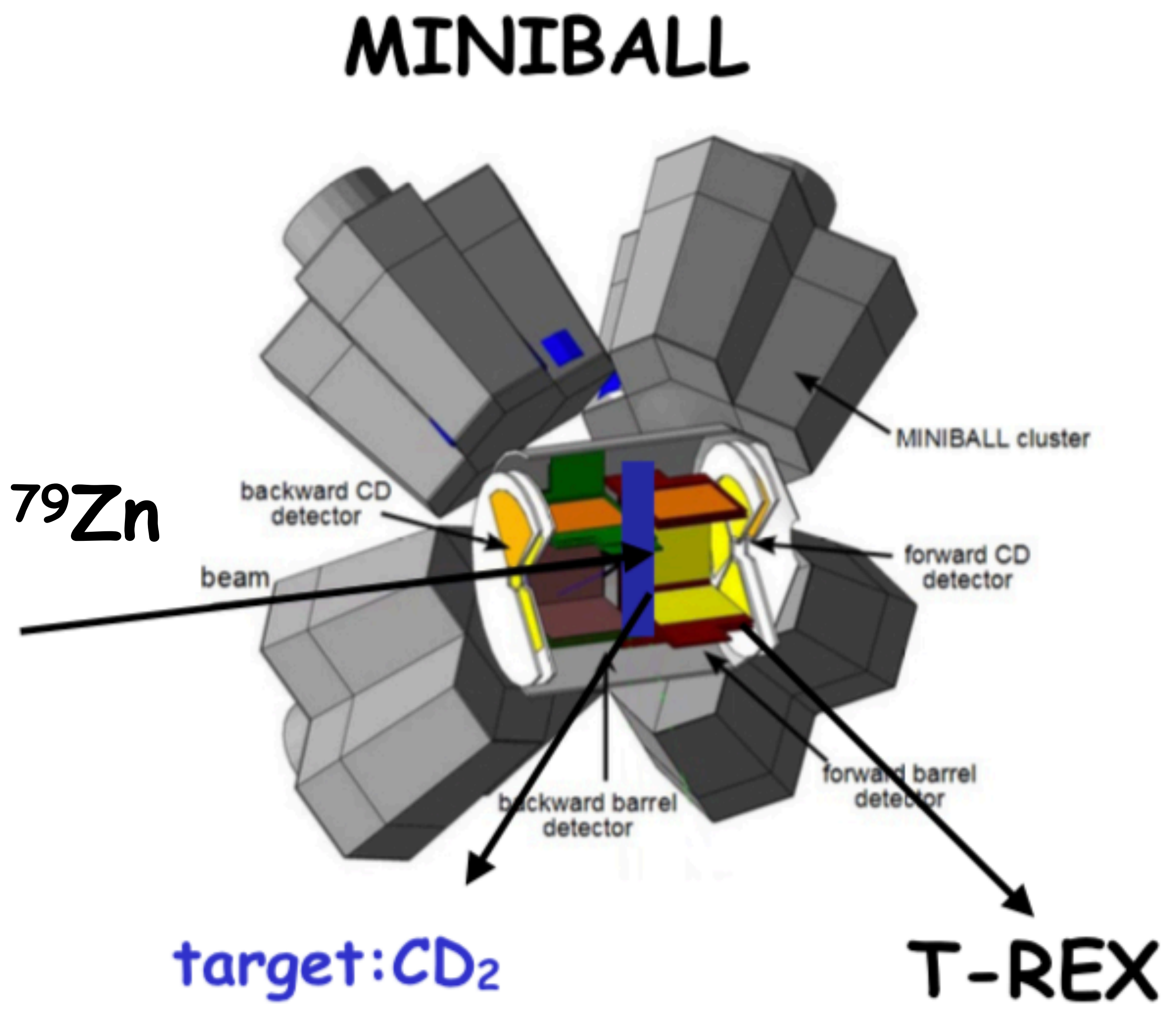
Nuclear data relevant to r-process calculations are (pin-parity assignments, excitation energies, spectroscopic factors and can be extracted from transfer reactions, such as (d, p).

R. Surman et al., AIP Advances 4, 041008 (2014)

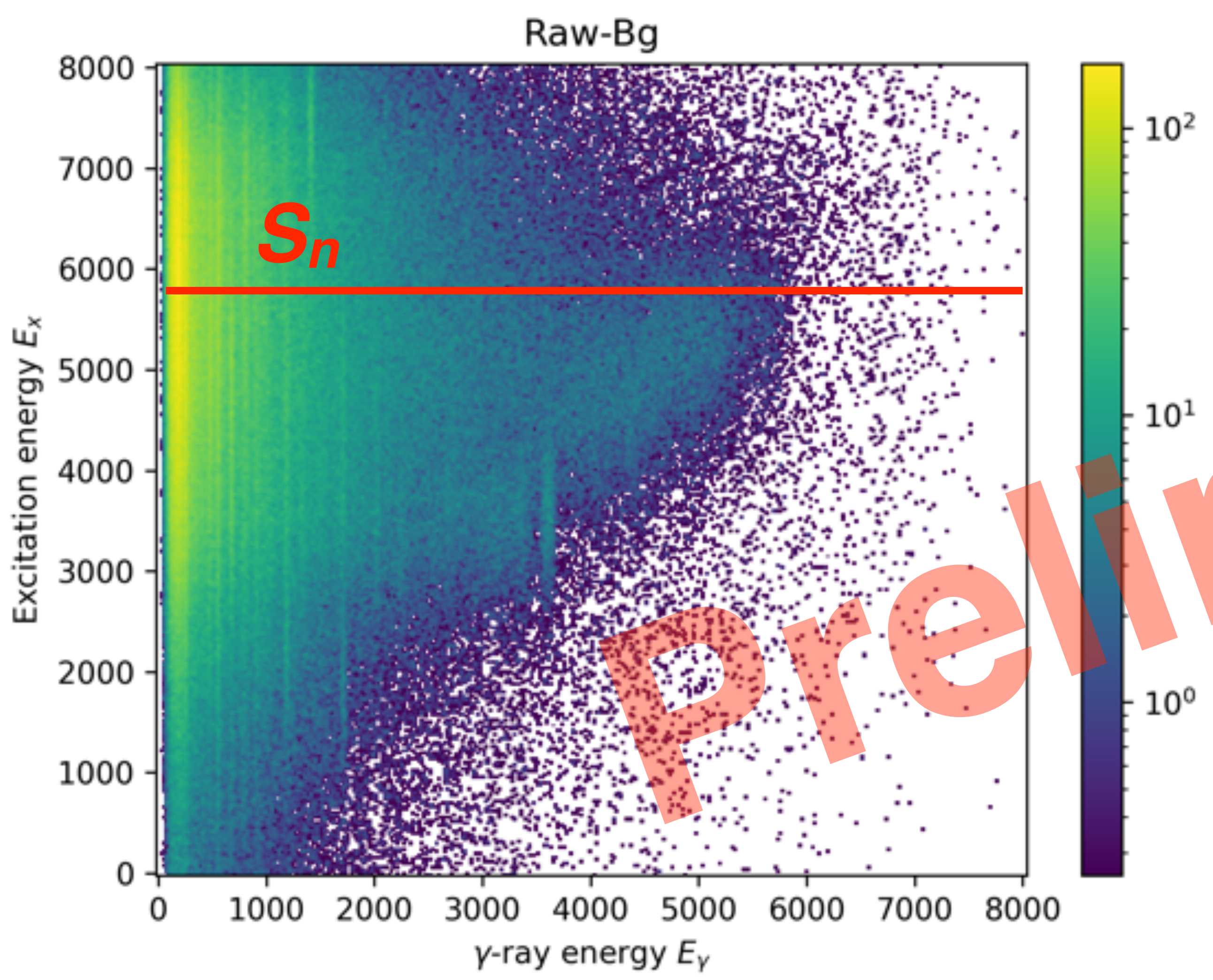
Oslo method in inverse kinematics

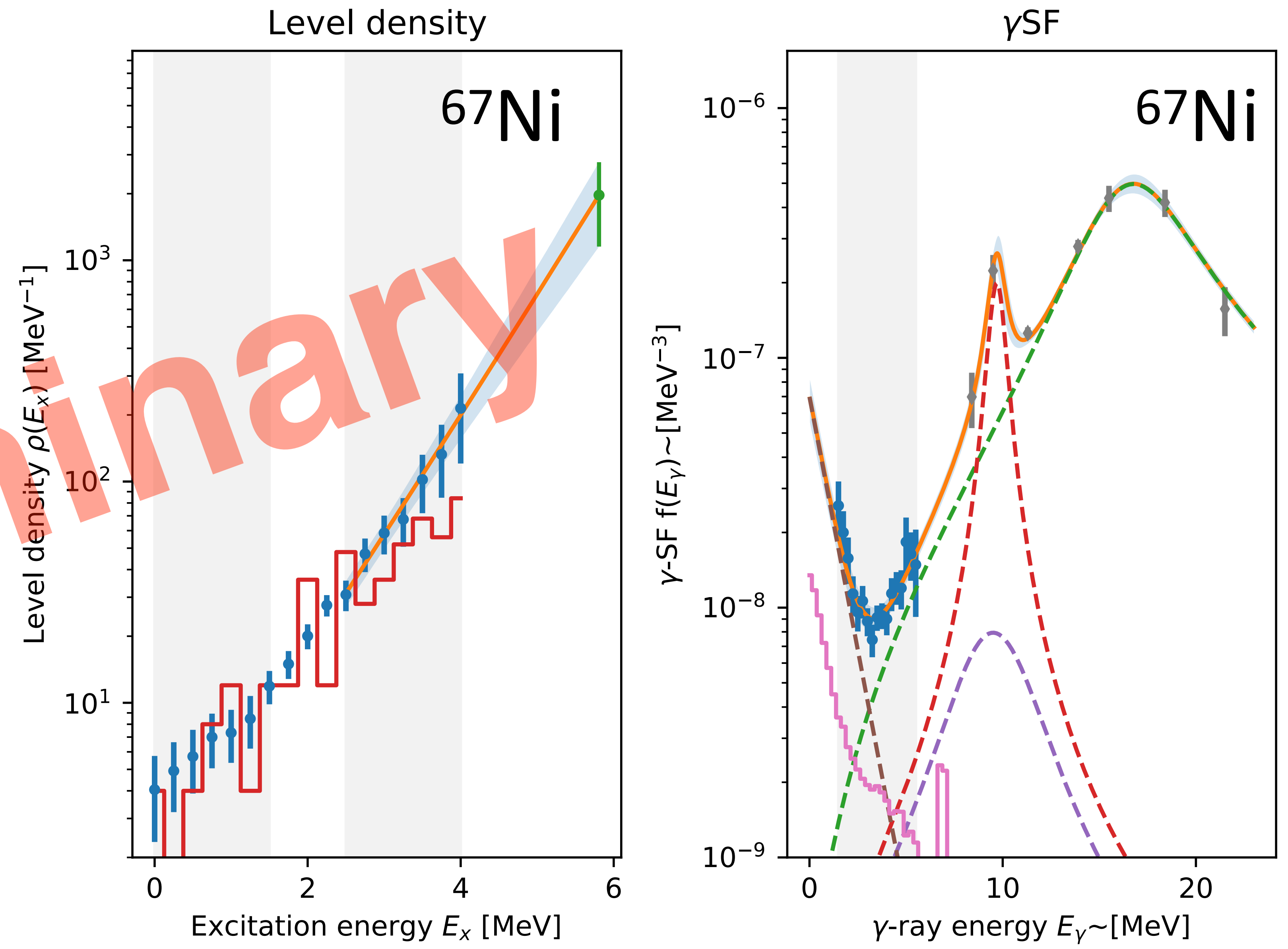
^{86}Kr(d,p)^{87}Kr iThemba
V. W. Ingeberg, Master thesis 2016
V.W.Ingeberg et al. Eur. Phys. J. A (2020) 56:68.

Experiment at ISOLDE (IS559): ^{66}Ni(d,p)^{67}Ni



+6 LaBr$_3$

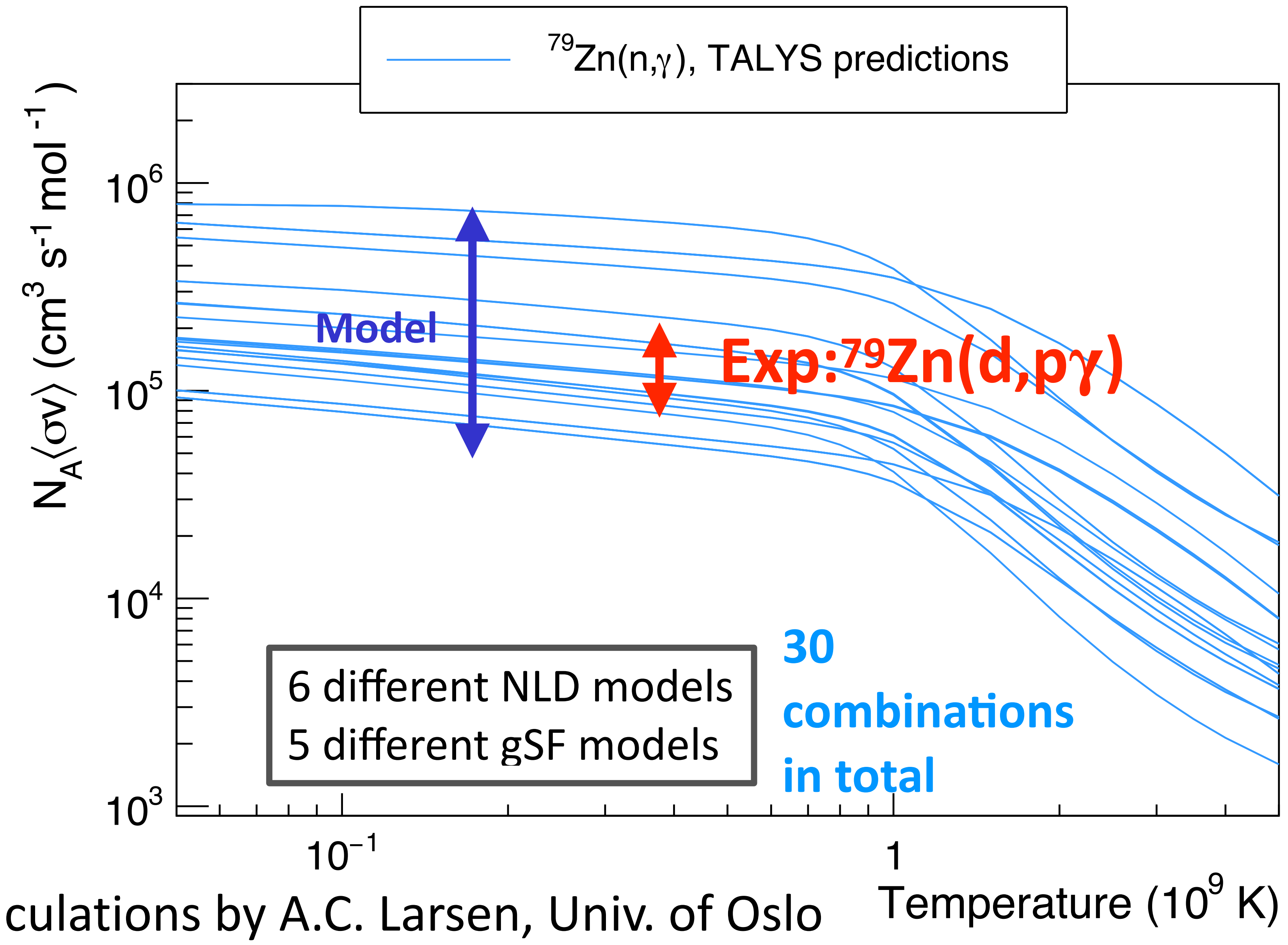




$$P(E_\gamma, E_x) \propto \underbrace{\rho(E_f)}_{\text{NLD}}\underbrace{\mathscr{T}(E_\gamma)}_{\text{gSF}}$$

V. Ingeberg, to be submitted to PRC, Feb 2022.
V. Ingeberg, PhD thesis to be submitted, Feb 2022

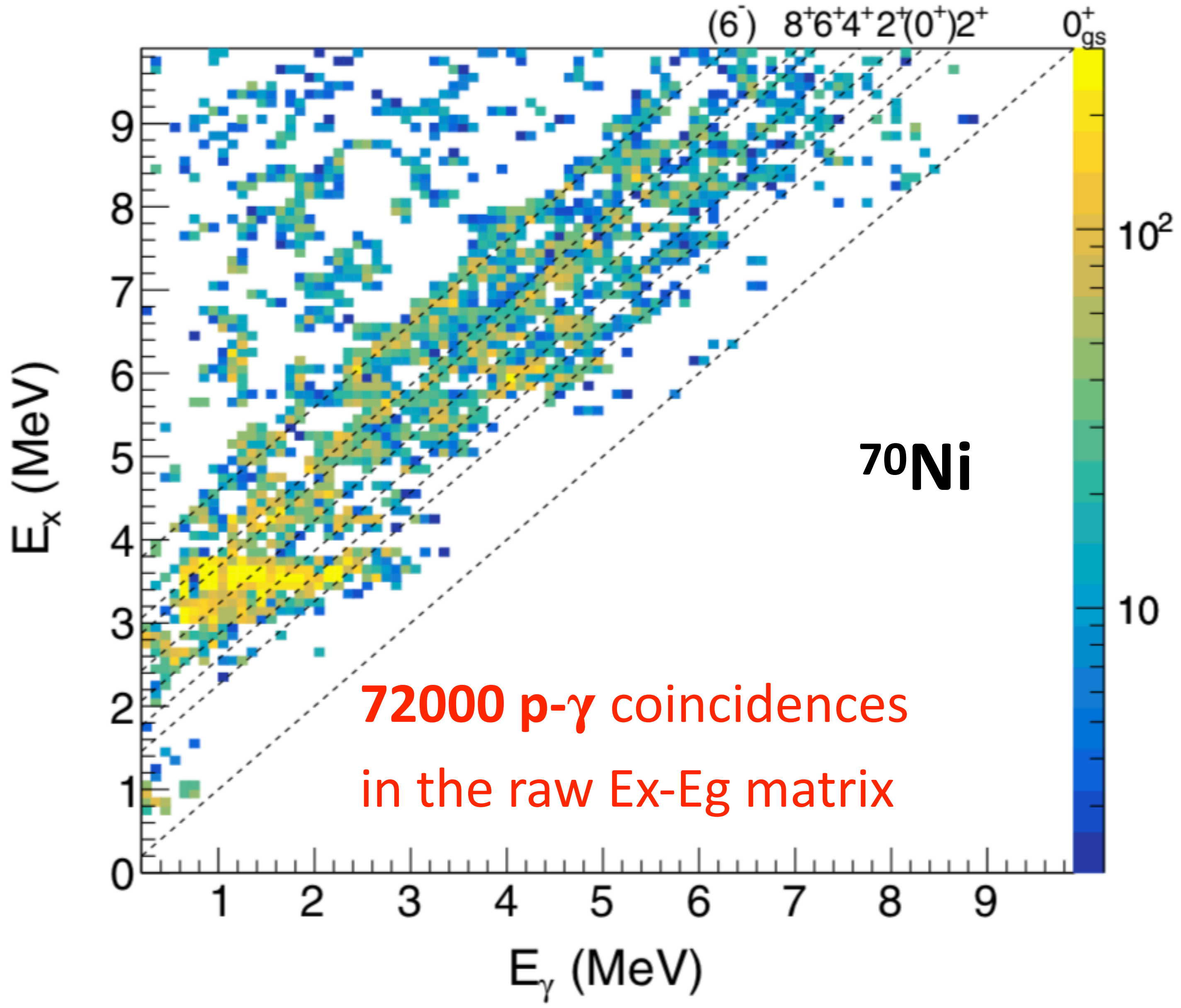
Aim: (n,γ) cross section for ^{79}Zn(d,pγ)



6 different NLD models
5 different gSF models

30 combinations in total

Calculations by A.C. Larsen, Univ. of Oslo



72000 p-γ coincidences
in the raw Ex-Eg matrix

A.C. Larsen et al., PRC **97**, 054329 (2018)