High resolution γ-ray spectroscopy at GANIL

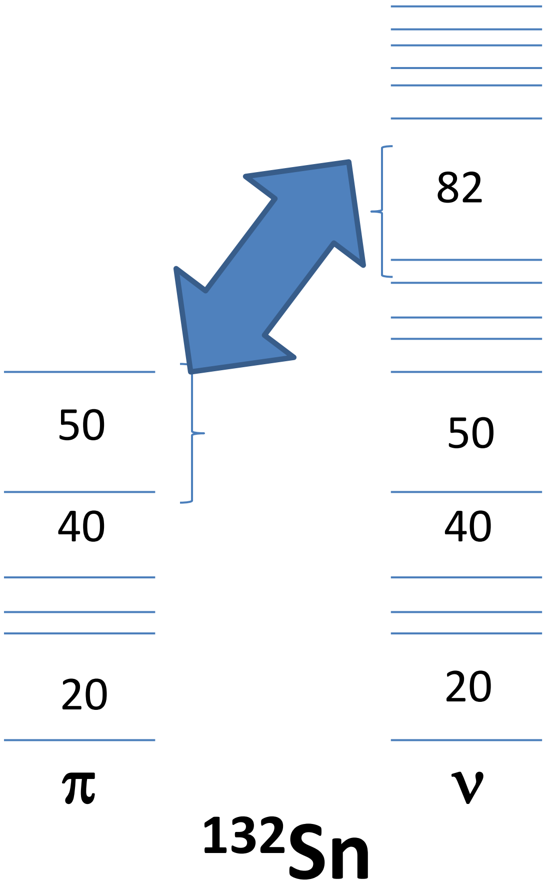
NSP13, Padova , June 10-12, 2013

- Pairing in self-conjugate nuclei
- EXOGAM as a polarimeter and ^{91}Ru
- Lifetime measurements
- Conclusions and perspectives

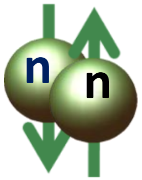
G. de France, GANIL

Pairing in self-conjugate nuclei

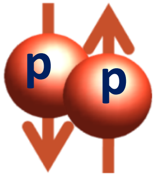
Different kind of pairing



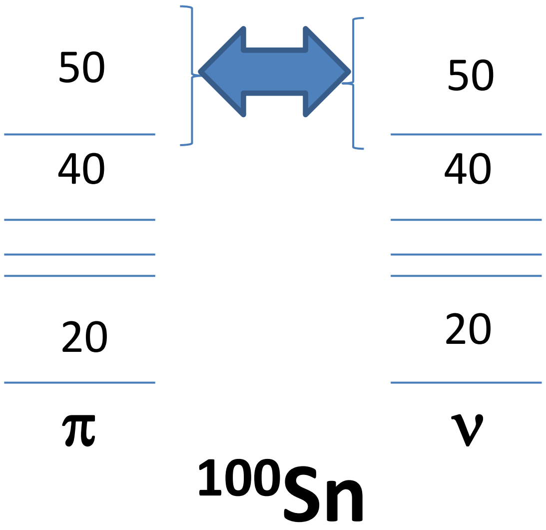
- In nuclei far from N=Z, protons and neutrons occupy very different orbitals: the valence nucleons do not interact
- For a pair of nucleon: T≤A/2=1 ➔ T=0,1
- Only nn and pp pairing: **identical** particles in **time reversed orbits (J=0)** ➔ **T=1 (Pauli)**. This is the **isovector** pairing involving nn and pp Cooper pairs



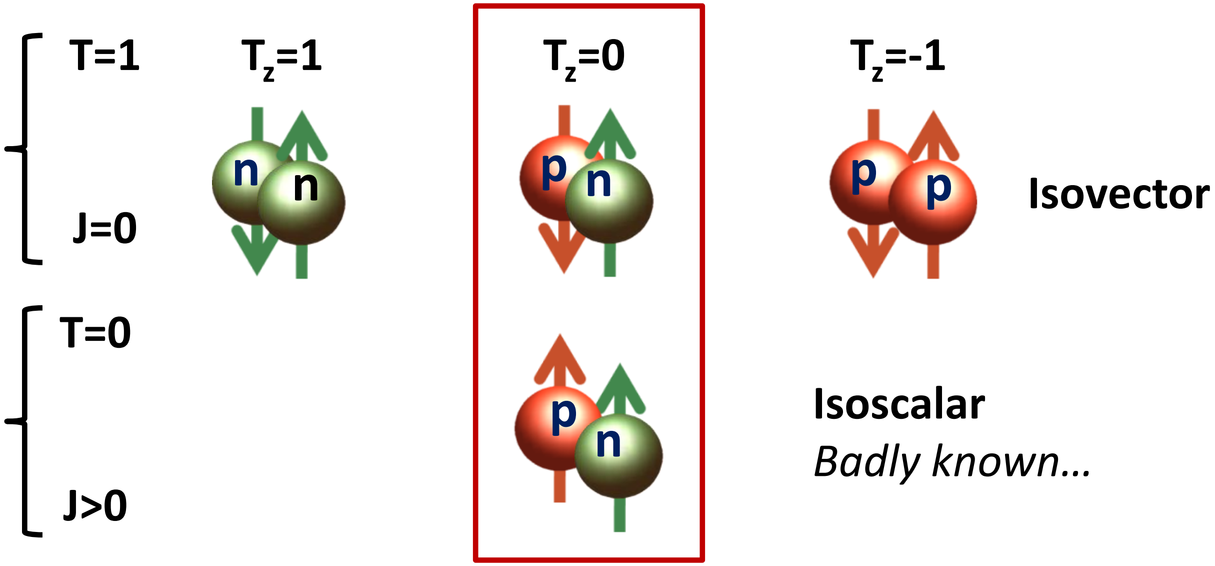
Like nucleon pairs:
T=1, J=0



Different kind of pairing: along N=Z



- Not anymore true along the N=Z line: protons and neutrons occupy the same orbitals ➔np pairs
- Pauli principle: « *The w.f. of 2 nucleon system must be antisymmetric in the exchange of all the coordinates i.e. space-spin-isospin* »

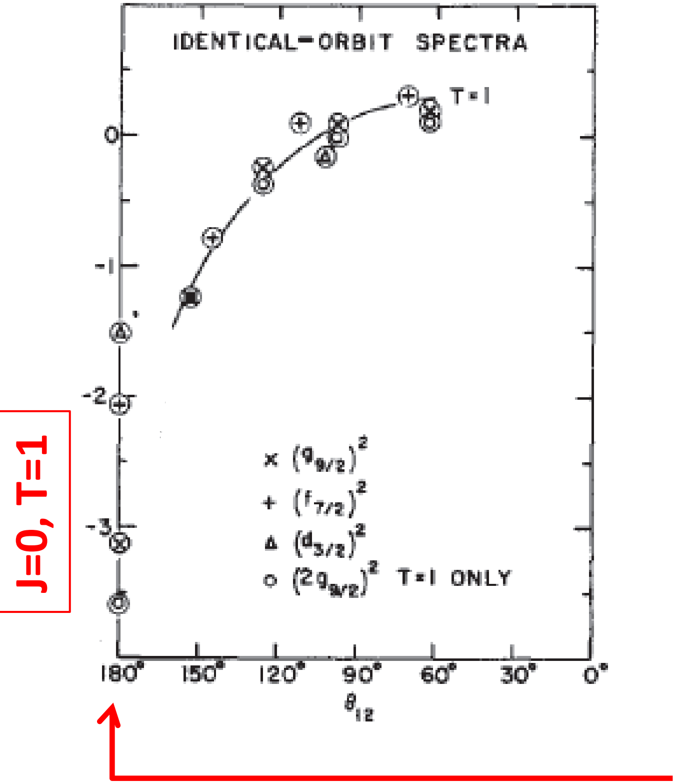


Isovector

Isoscalar
Badly known…

T=0 vs T=1 strength

Matrix elements particle-particle of magic nuclei+2 nucleons in the same orbit (from E*) as a function of coupling angle (➔ independent of the considered orbit)

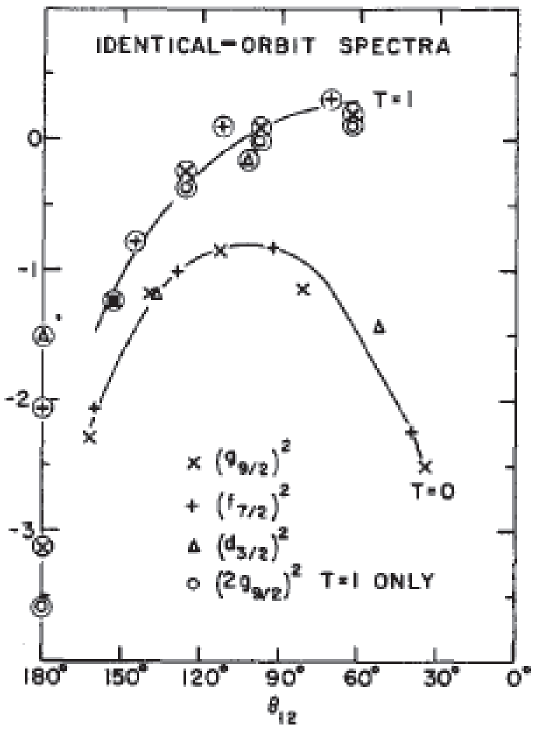


N. Anantaraman and J.P. Schiffer PLB37 (1971) 229

- **2 « universal » curves** for all the orbits: one for T=1 and one for T=0 (except for J=0, T=1)
- For T=1, strength concentrates in **J=0** i.e. (j,m)(j,-m)
- When spin increases: pairs are less bound; and less and less

  this justifies the description of like nucleon pairs (T=1) by a seniority pairing (i.e. considering only J=0)
- The dispersion of the points on the y-axis points however to limitations of this model

T=0 vs T=1 strength



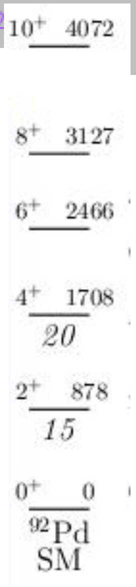
- For T=0, different situation:
  - the pair with **J=2j is as bound as J=1**
    - ➔ not correct to consider only the J=1 pair
  - Intermediate spins might play a role
- Except T=1, J=0, the **T=0 channel has a larger strength** compared to T=1 for two nucleons in the same orbit
  - →No reason to neglect T=0 (a fortiori in N=Z nuclei)…
- How to probe T=0 pairing experimentally?...

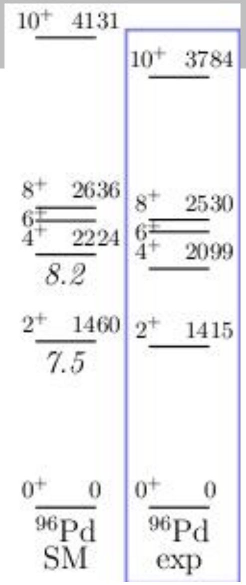
Search for seniority violation in an N=Z nucleus

Seniority violation

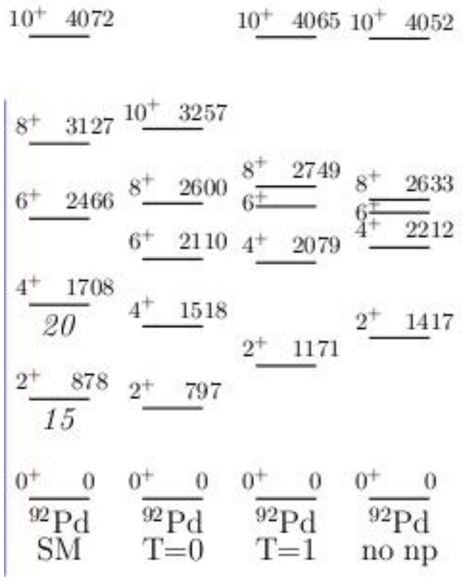
- ❑ Profound modification of the level scheme:

Regular spacing →





← **Seniority type**



- ❑ Predicted effect of the T=0 and T=1 channels
- ❑ **The major influence of T=0**

J. Blomqvist et al

EXOGAM-NWall-DIAMANT:
The power of the coupling

^{36}Ar (111 MeV) + ^{58}Ni → ^{94}Pd* → ^{91}Tc + 3p

^{91}Ru + 2p1n

^{90}Mo + 4p

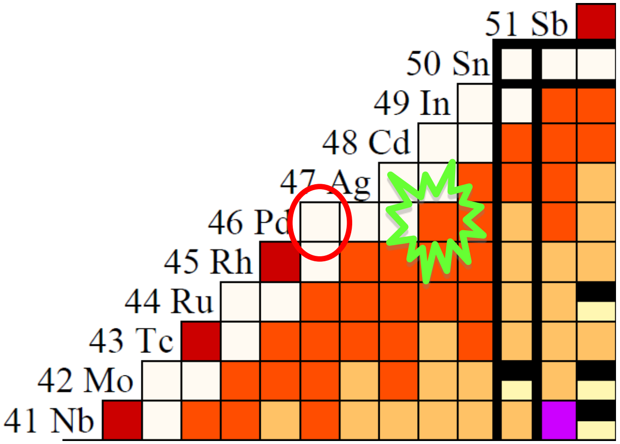
^{88}Mo + 4p2n

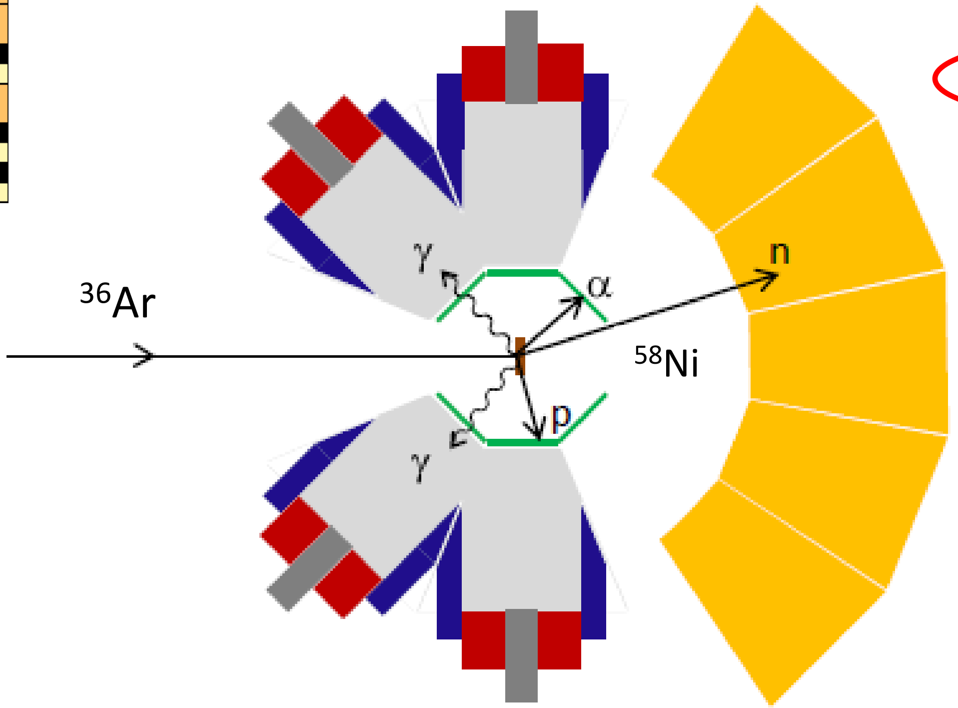
^{90}Tc + 3p1n

^{92}Rh + 2p

…

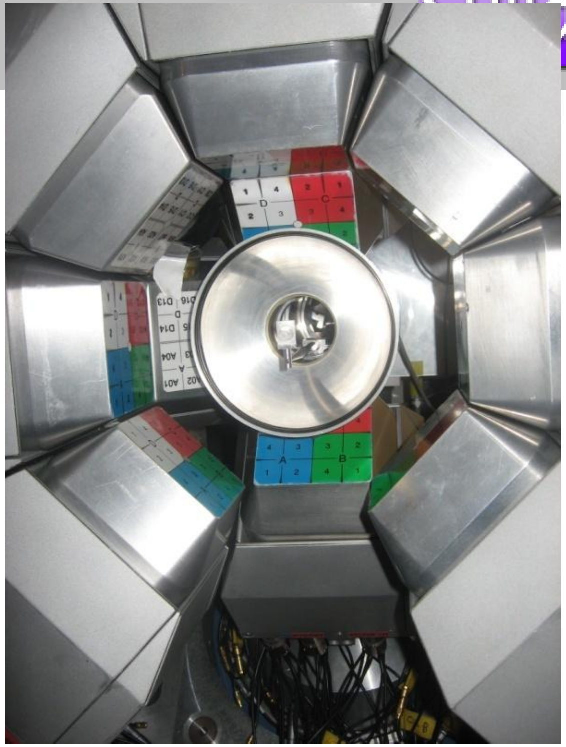
^{92}Pd + 2n



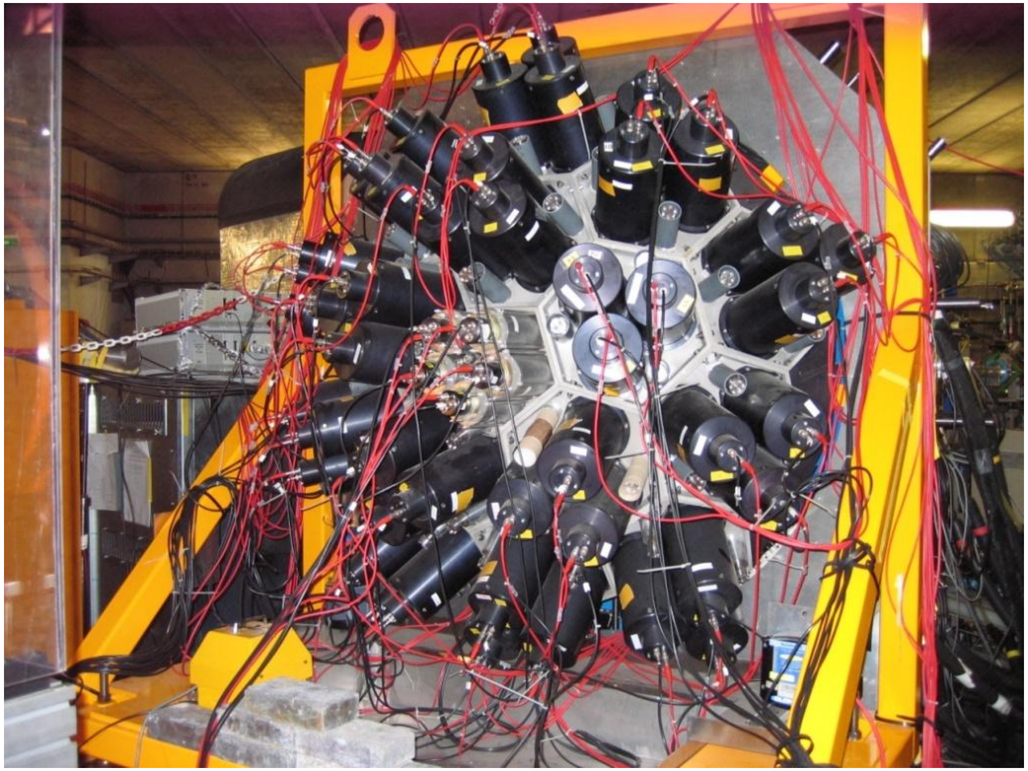


EXOGAM-NWall-DIAMANT:

The power of the coupling

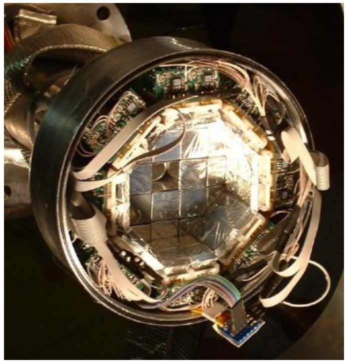


- EXOGAM: 11 Clovers with partial shield. $\varepsilon_p\omega$ ~ 10% for E_γ=1.3 MeV



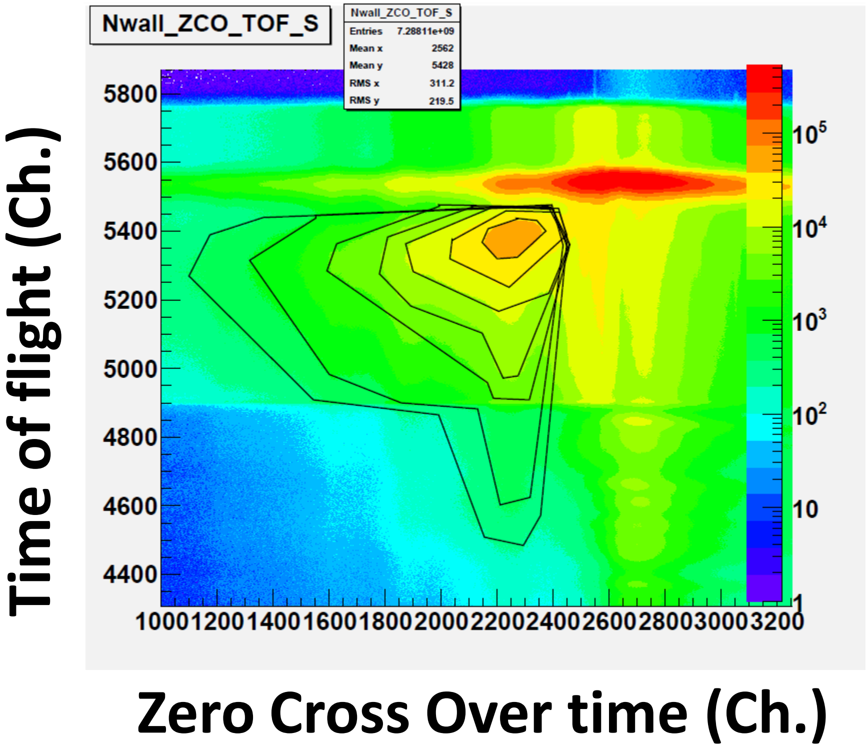
- The Neutron Wall: 50 liquid scintillator detectors. ε_{1n} ~ 23%

- DIAMANT: 80 CsI(Tl) dets. $\varepsilon_{p\text{ or }\alpha}$ ~ 66%

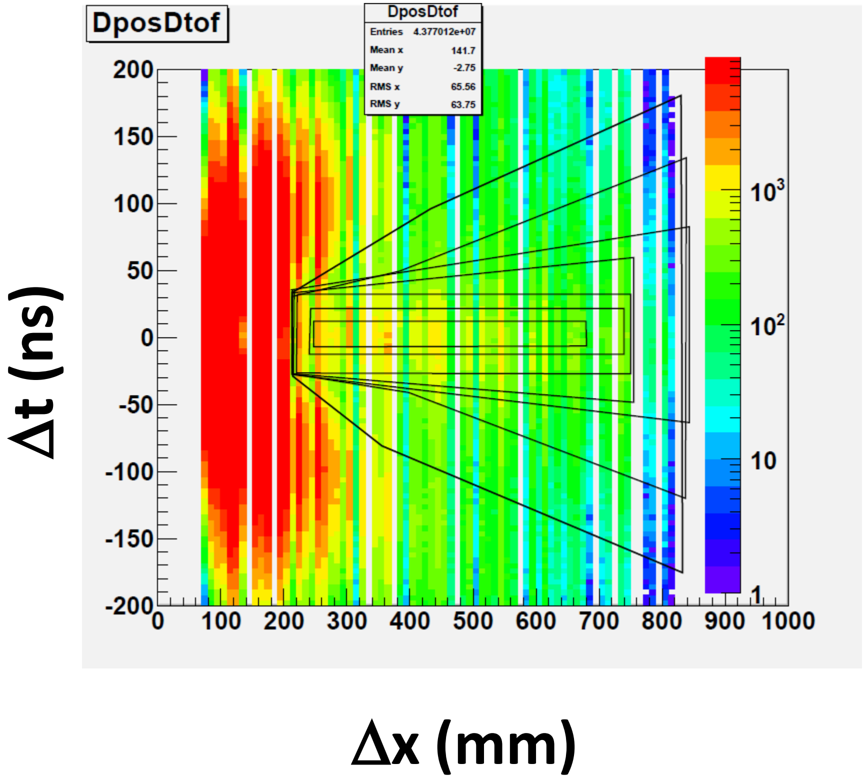


Neutron Wall performance

n-γ Separation



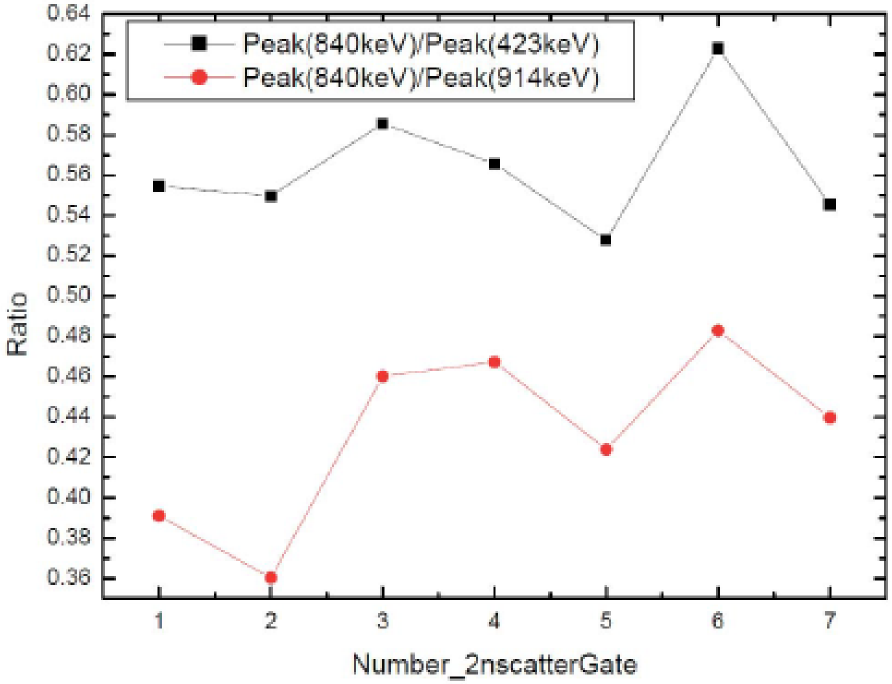
Rejection of n scattering

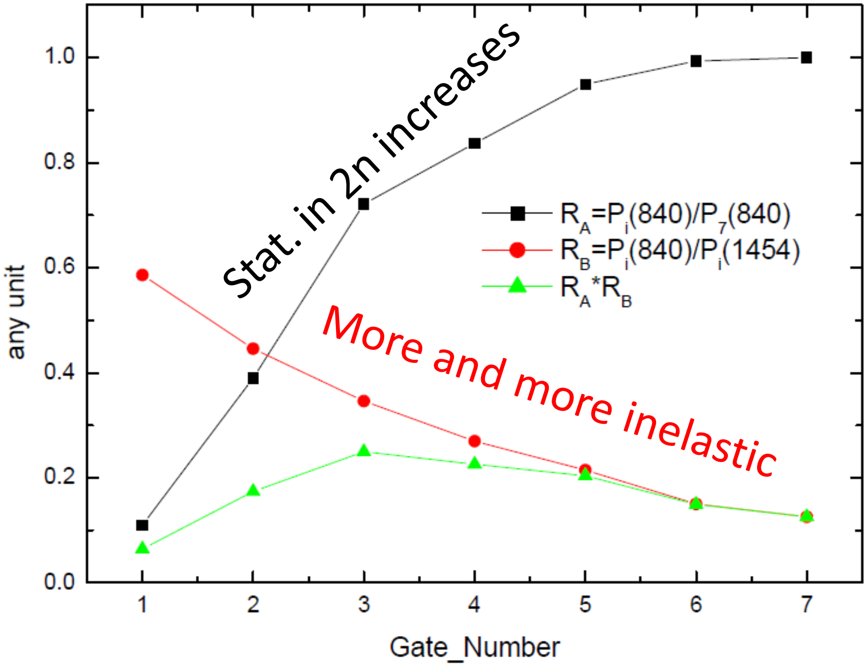


Neutron Wall performance

- Optimization of the n-selection and n-scattering gates:

  Maximize known γ–rays in ^{91}Rh (1p2n channel) at 840 keV while minimizing known γ-rays in contaminant (^{46}V) and inelastic of ^{58}Ni (1454 keV)

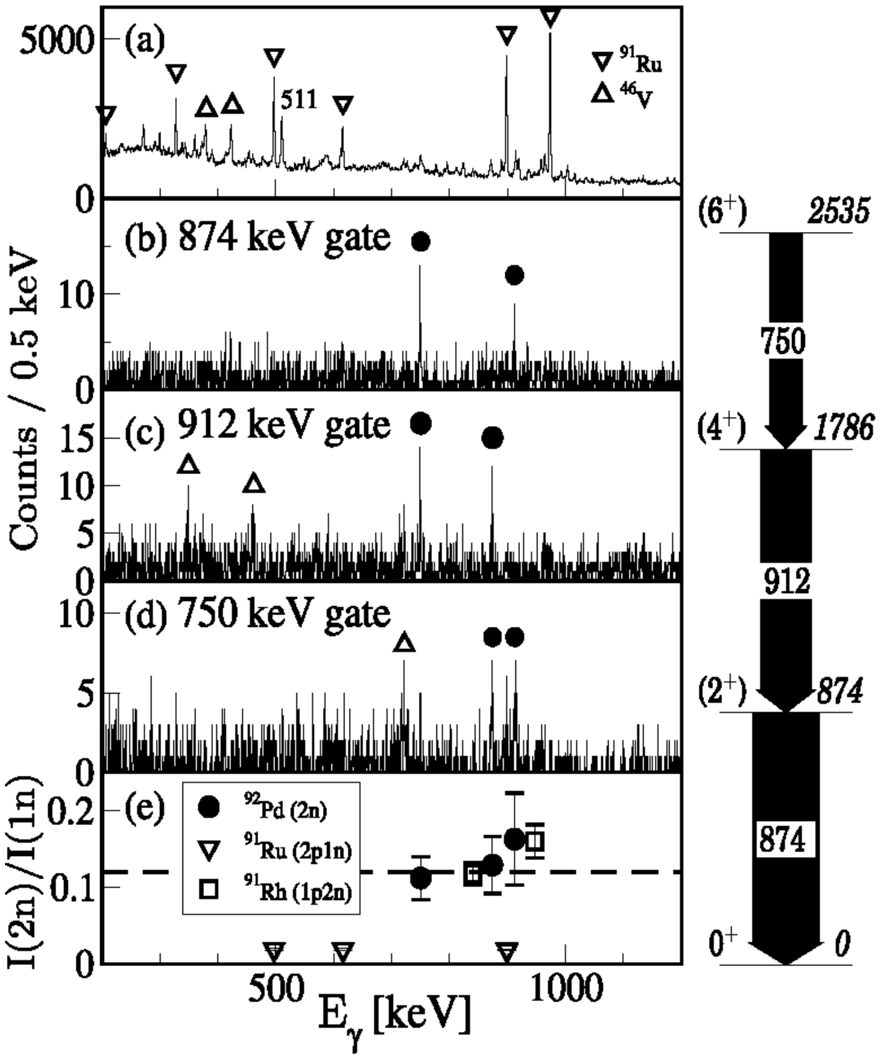




Stat. in 2n increases

More and more inelastic

EXOGAM:
First identification of γ-rays in ^{92}Pd



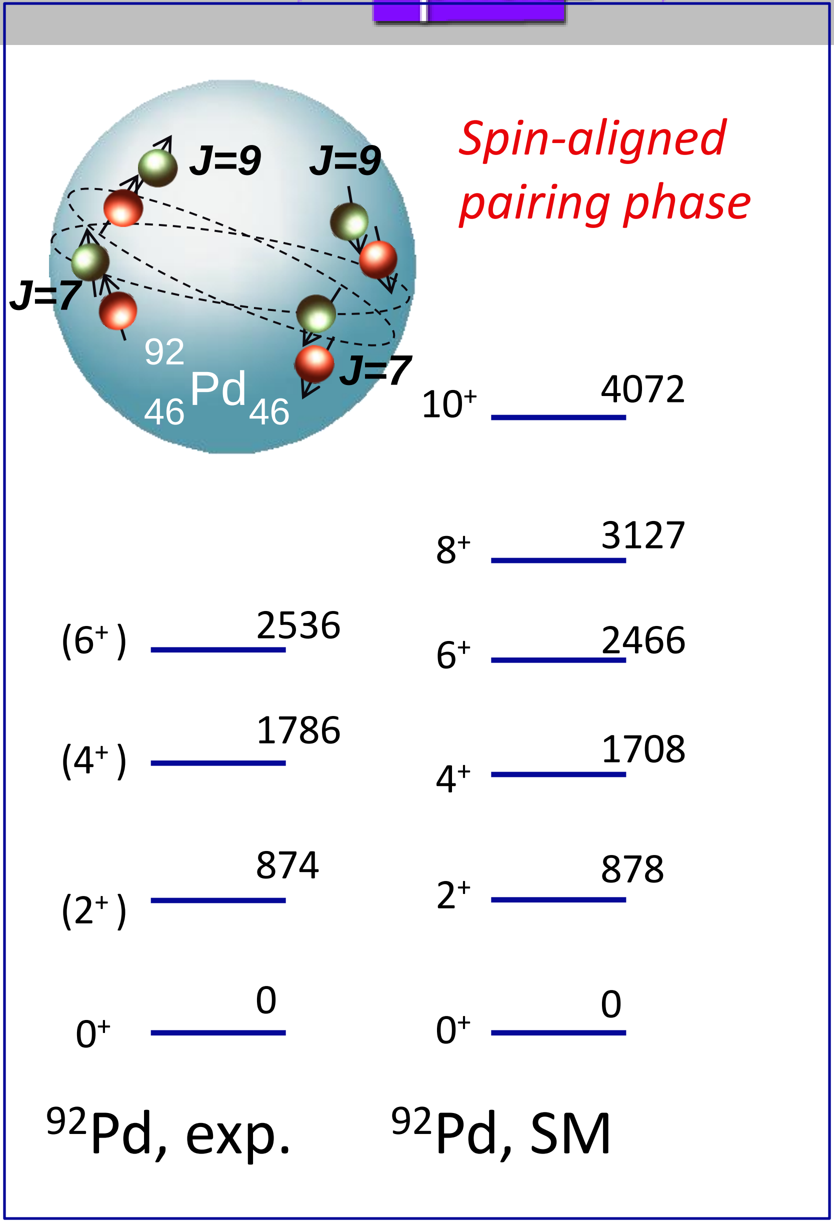
- ❑ Three γ-rays firmly identified
- ❑ In coincidence with 2n
- ❑ Not in coincidence with charged particles
- ❑ Mutually coincident
- ❑ All possible contaminants excluded
- ➔ Unambiguously assigned to ^{92}Pd

Production cross section ~ 0.5 μb

B Cederwall, F. Ghazi-Moradi, T Back, A Johnson,
J. Blomqvist, E Clément, G. de France,
R Wadsworth et al,

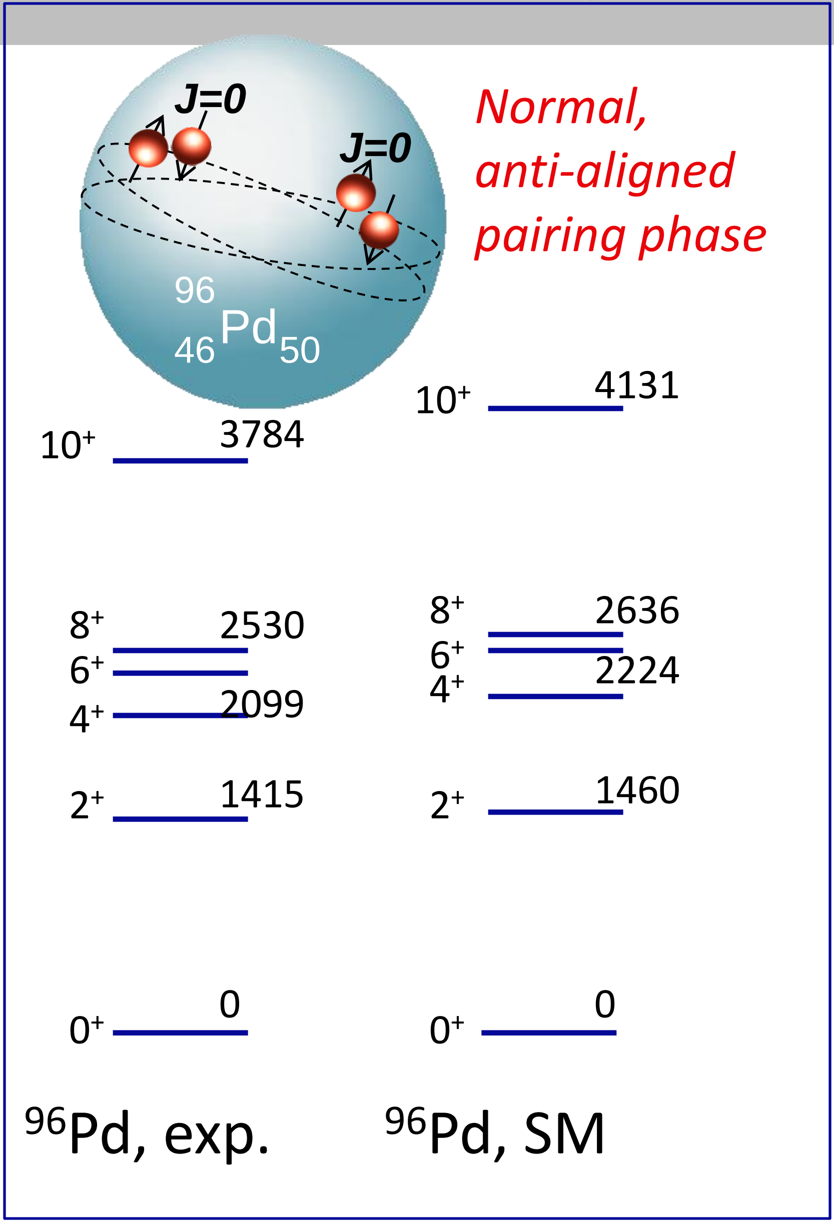
Nature 469, 68-71 (2011)

^{92}Pd: A new spin aligned np coupling scheme



Spin-aligned pairing phase

^{92}Pd, exp. ^{92}Pd, SM

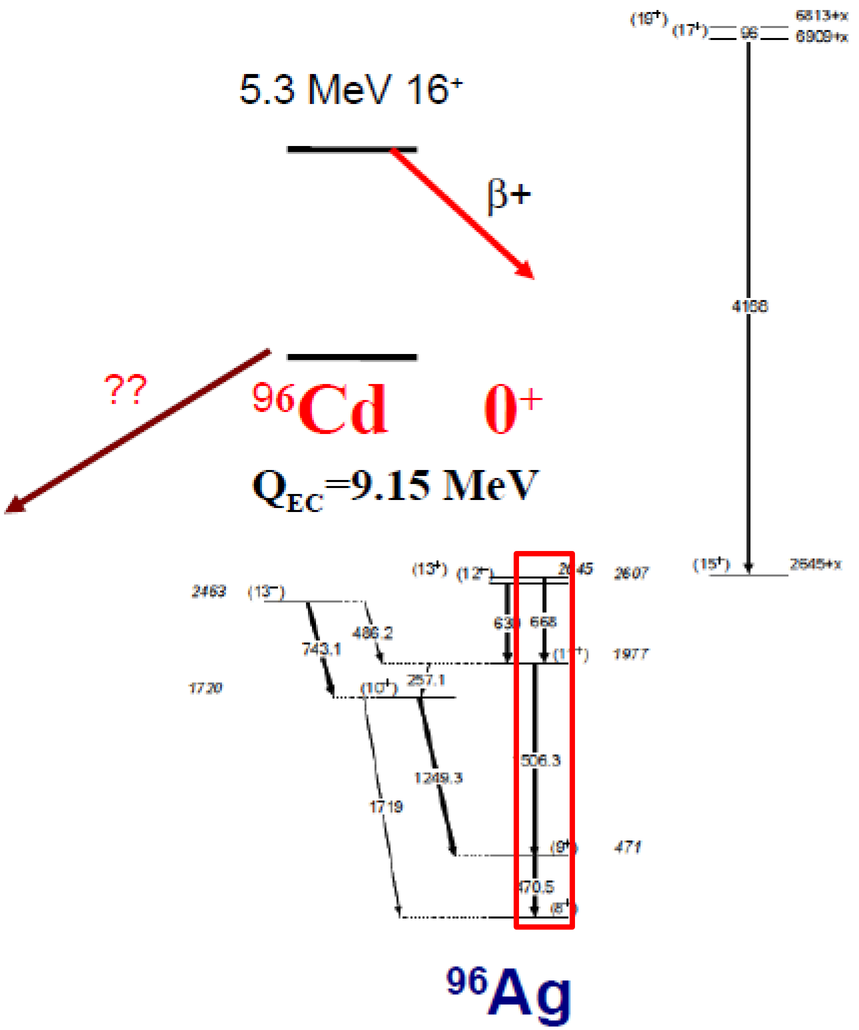


Normal, anti-aligned pairing phase

^{96}Pd, exp. ^{96}Pd, SM

^{96}Cd GSI results

- Observe the decay of identified ^{96}Cd to an 15+ isomer in ^{96}Ag



5.3 MeV 16^{+}

β+

??

^{96}Cd 0^{+}

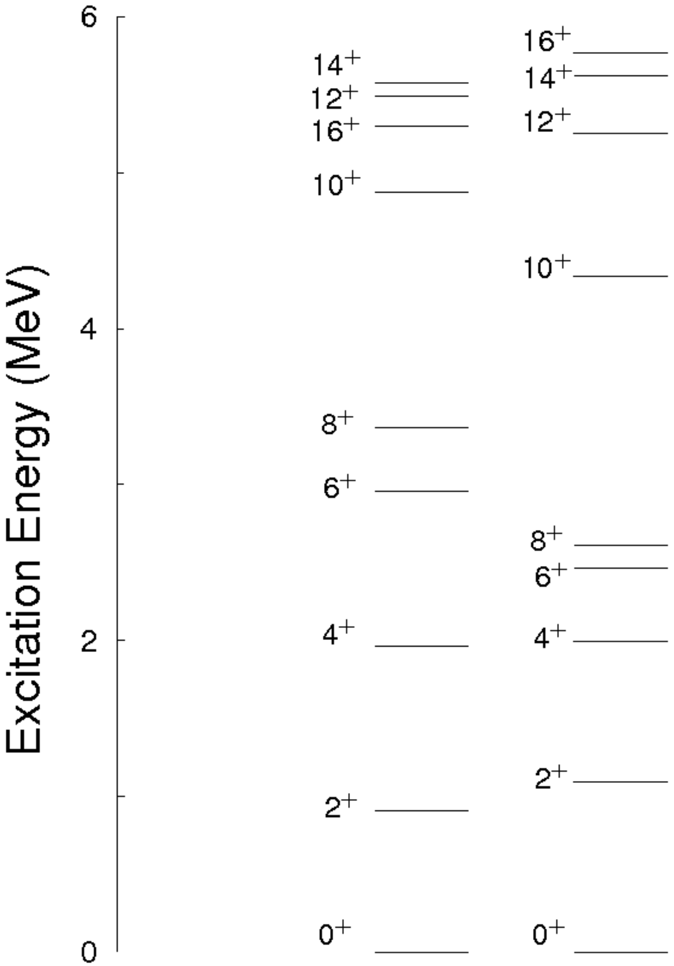
Q_{EC}=9.15 MeV

^{96}Ag

B.S. Nara-Singh et al 107, 172502 (2011)

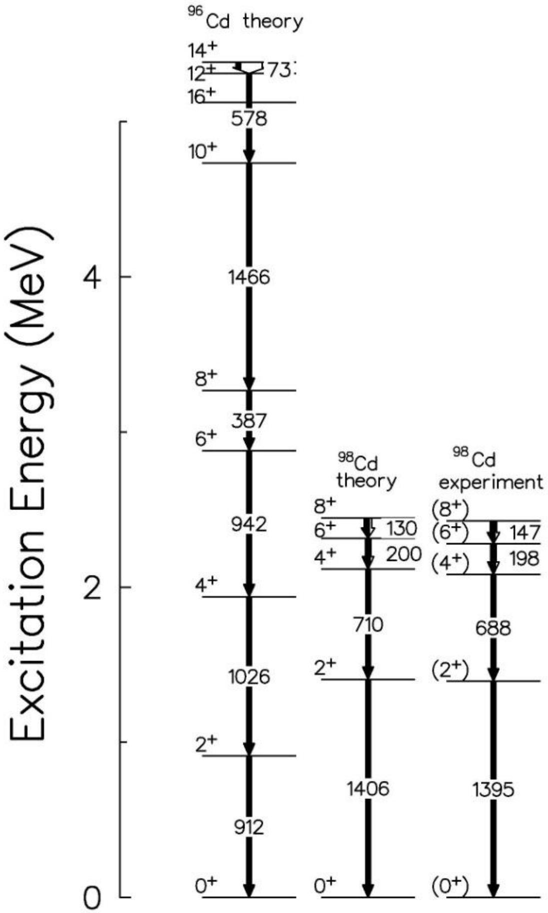
^{96}Cd GSI results

- Compatible with our interpretation:



No T=0

H. Grawe



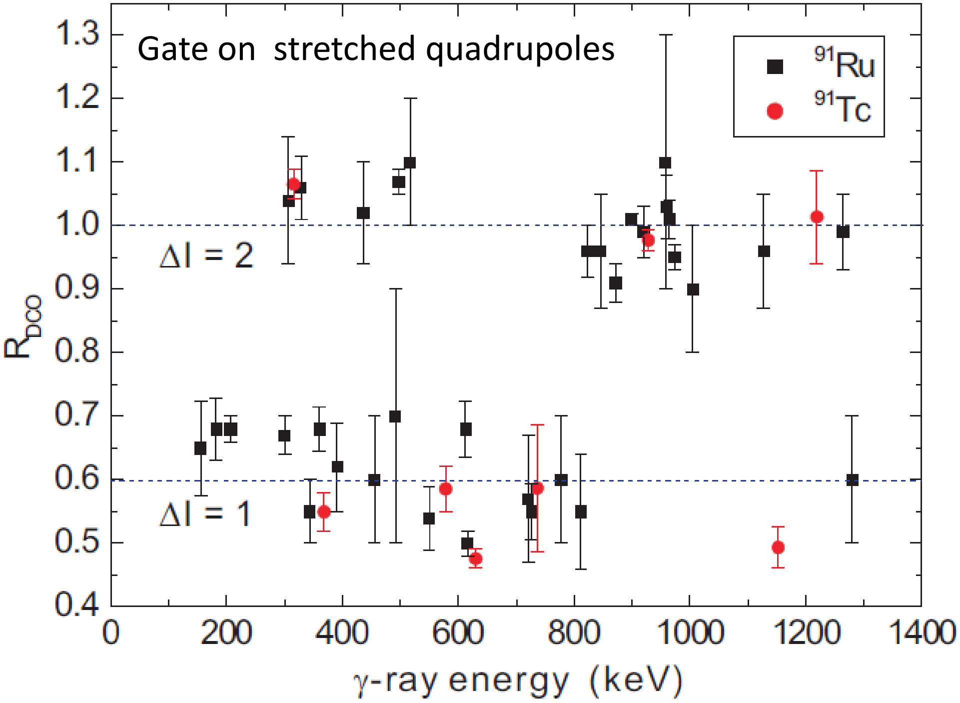
J. Blomqvist (2007)

EXOGAM as a polarimeter application to ^{91}Ru

- To fully characterize the nature of a transition need to measure the DCO ratios (multipolarity) and the linear polarization (electromagnetic nature)
- DCO ratio measurements (multipolarity) in ^{91}Ru (2p1n) and ^{91}Tc (3p)

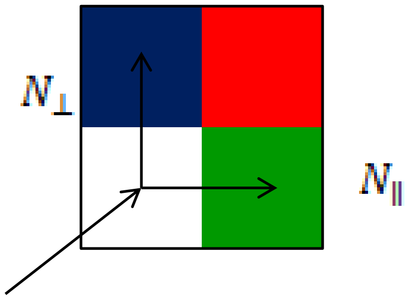
$$R_{DCO} = \frac{I(\gamma_1 at\ 135°\ gated\ by\ \gamma_2 at\ 90°)}{I(\gamma_1 at\ 90°\ gated\ by\ \gamma_2 at\ 135°)}$$

R_{DCO}	Gate on quadrupole	Gate on dipole
Quadrupole	1	1.6
Dipole	0.6	1



Y. Zheng et al., PRC87, 044328 (2013)

EXOGAM as a Compton polarimeter



- Polarization asymmetry: $$A = \frac{[a(E_\gamma)N_\perp] - N_\parallel}{[a(E_\gamma)N_\perp] + N_\parallel}$$

  With $a(E_\gamma) = \frac{N_\parallel(unpolarized)}{N_\perp(unpolarized)}$ (a(Eγ)= normalization factor)

- Polarization sensitivity Q: A=QP , P=linear polarization
- For a point-like polarimeter: $Q_{point} = \frac{1+\alpha}{1+\alpha+\alpha^2}$, $\alpha = \frac{E_\gamma}{m_e c^2}$
- Realistic polarimeter (integrate over scattering angles): $Q = Q_{point}(p_0 + p_1 E_\gamma)$
  with Q, p0 and p1 determined using using g-rays whose linear polarization is known
- Theoretical linear polarization of γ-rays detected at 90°: $$P(90°) = \frac{12A_2 + 5A_4}{8 - 4A_2 + 3A_4}$$
- Figure of merit: F=Qε_c , $$\varepsilon_c = \frac{N_\perp + N_\parallel}{2N_{clo}}\varepsilon_{clo}(E_\gamma)$$

Polarization sensitivity of EXOGAM

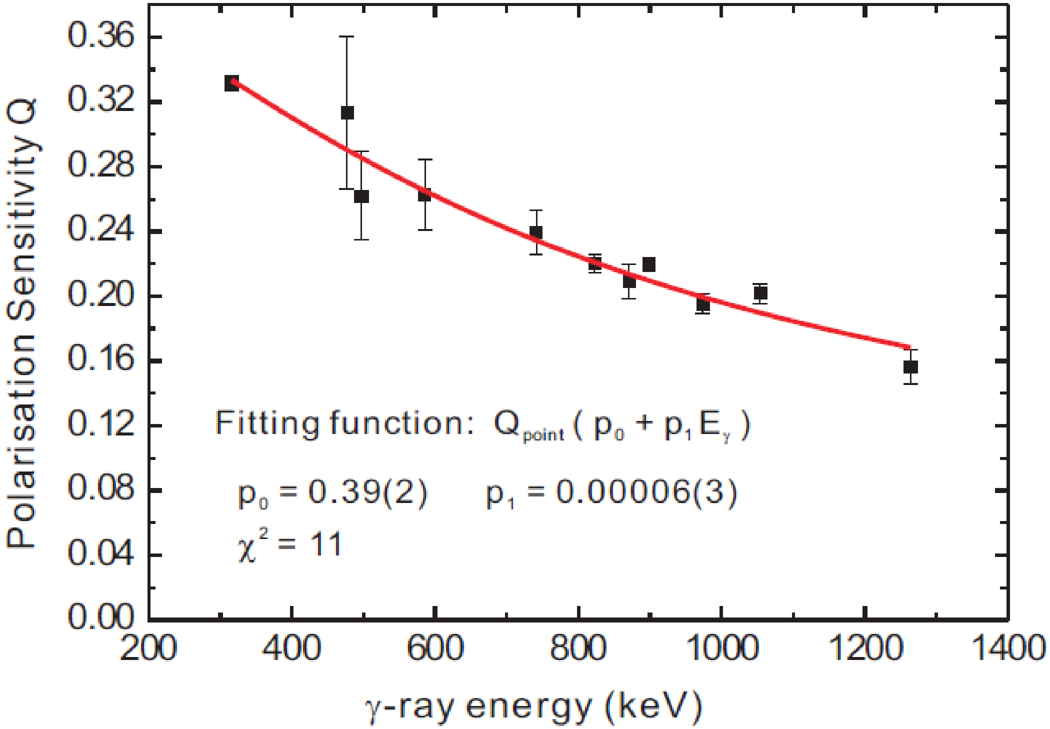
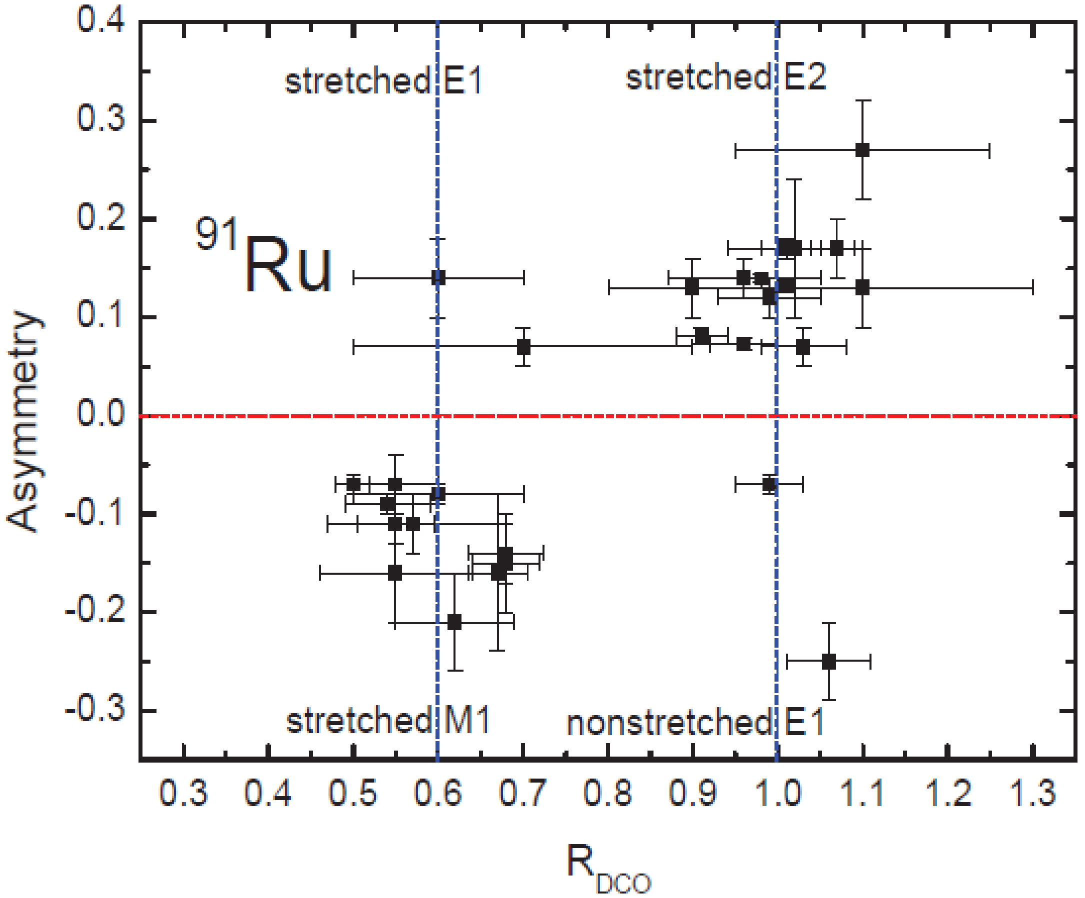


Figure of merit:

At 1368 keV, $F_{EXOGAM} = 4.4 \times F_{EUROGAM}$

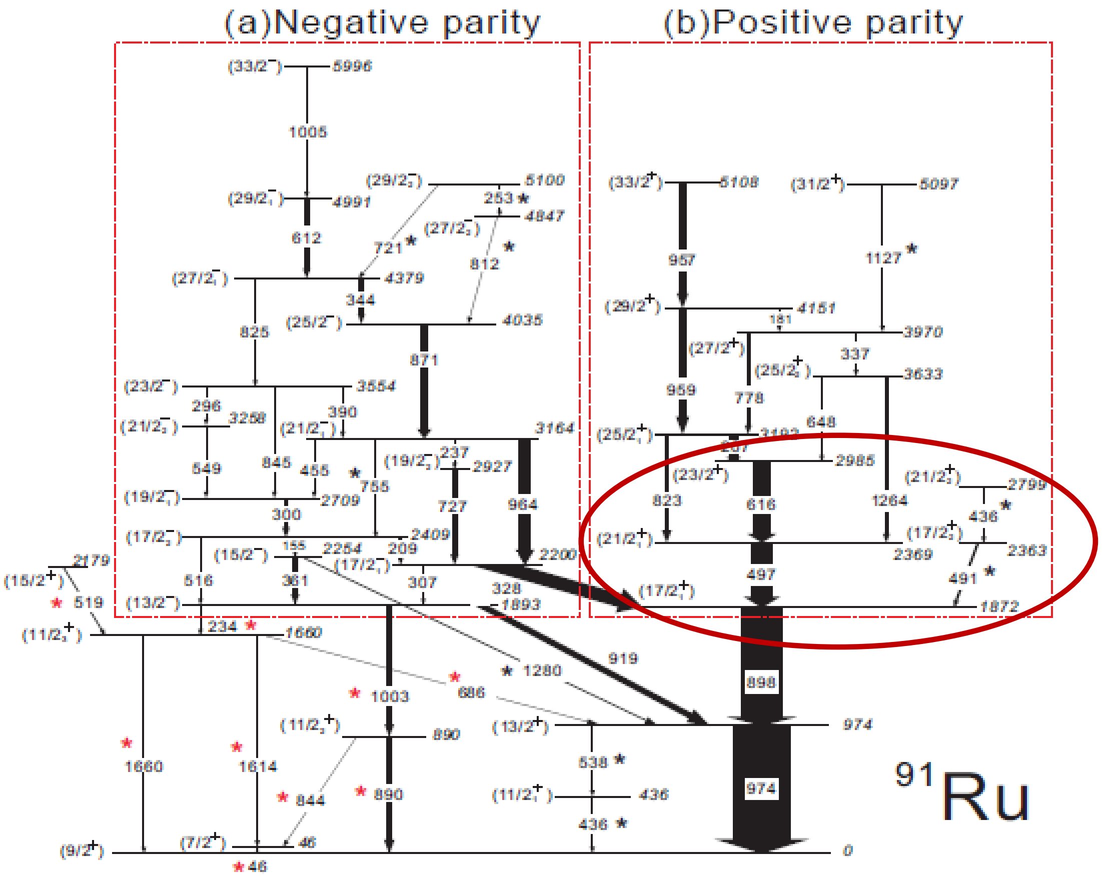
Application to ^{91}Ru

- Complete characterization of transitions



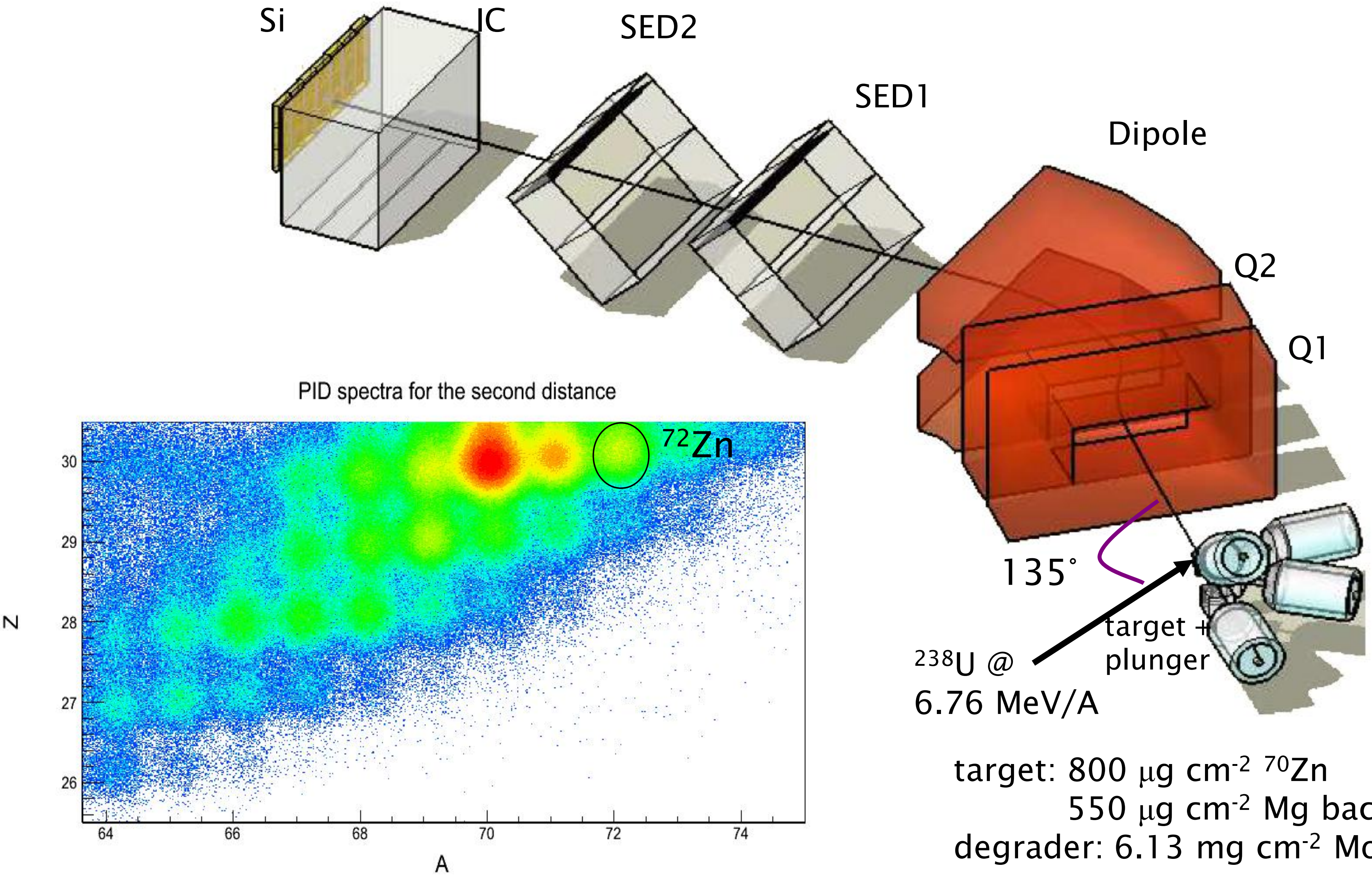
The new level scheme of ^{91}Ru

- Firm assignments of spin differences and parity (g.s. not measured)
- Several new transitions/states
- Analysis of low-energy positive parity states seems to indicate the transition from ($\pi^2\nu^{-1}$) alignment to (ν^{-3})



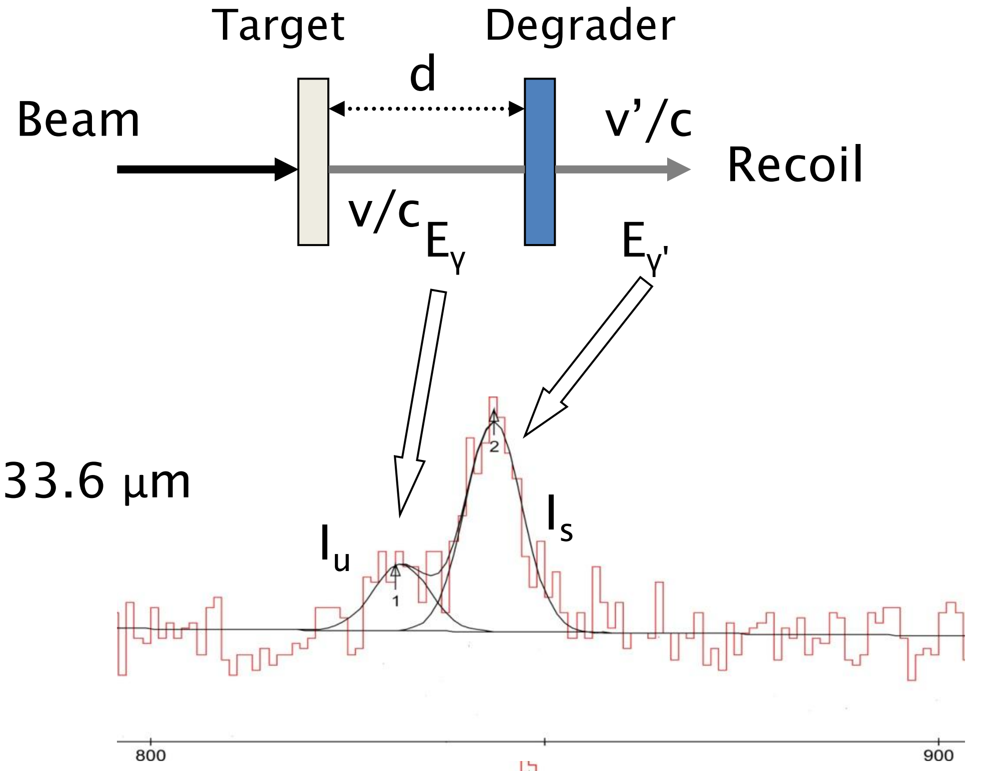
Lifetime measurements: the Zn and thePd-Zr regions

plunger at GANIL (VAMOS +EXOGAM)

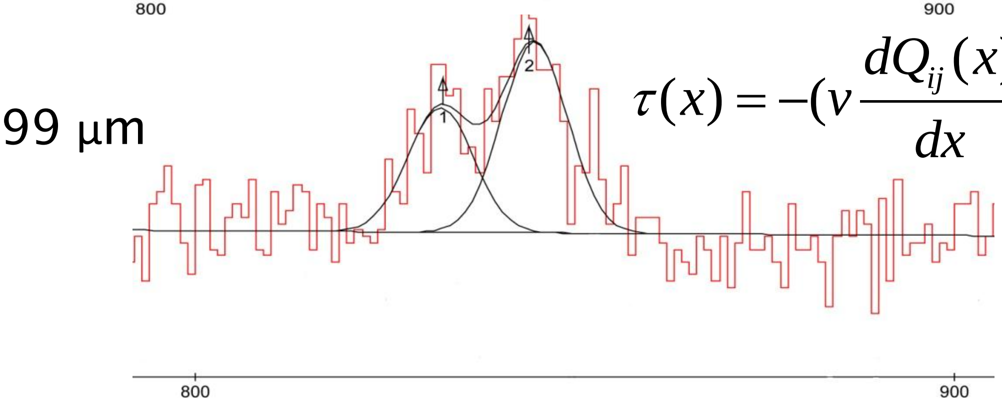


target: 800 μg cm^{-2} ^{70}Zn
550 μg cm^{-2} Mg backing
degrader: 6.13 mg cm^{-2} Mo

RDDS method

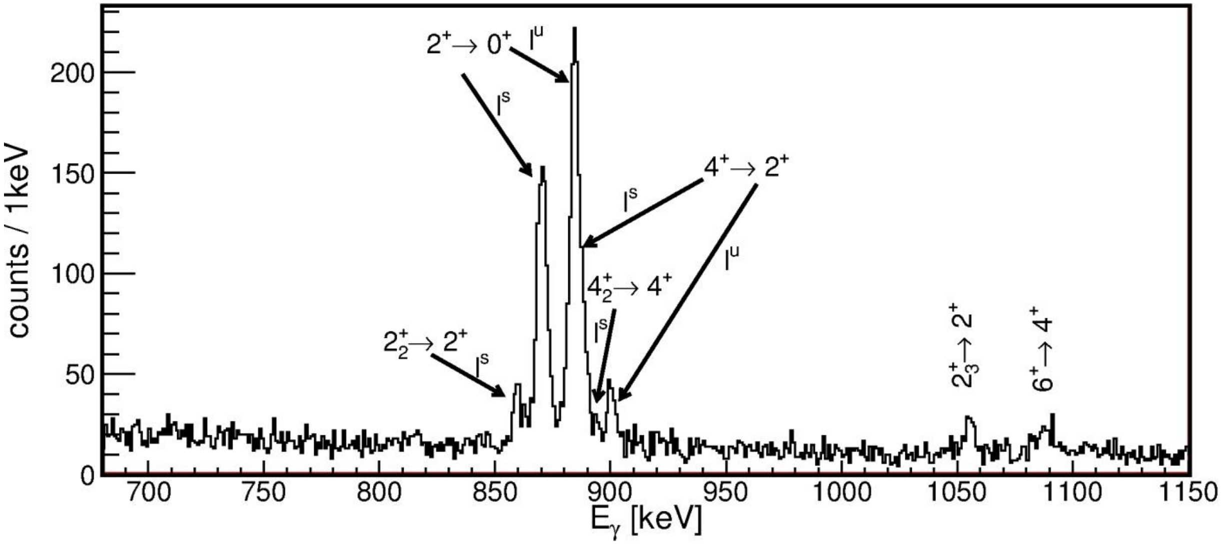


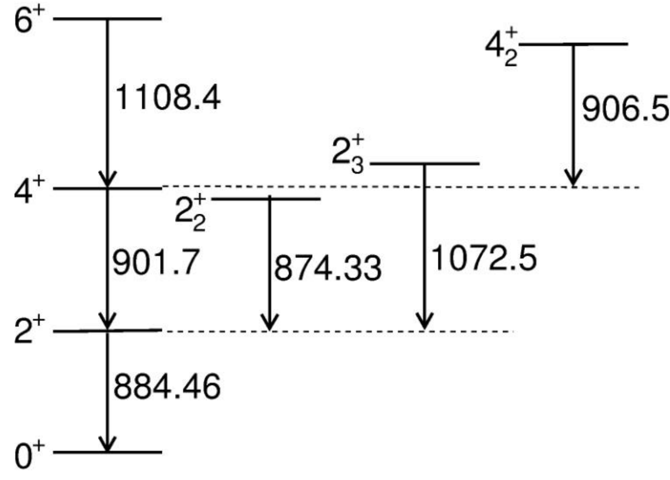
$$Q_{ij}(x) = \frac{I_u(x)}{I_u(x) + I_s(x)}$$



$$\tau(x) = -\left(v\frac{dQ_{ij}(x)}{dx}\right)^{-1}\left[Q_{ij}(x) - \sum_h b_h \frac{I^u_{hi}(x) + I^s_{hi}(x)}{I^u_{ij}(x) + I^s_{ij}(x)} Q_{hi}(x)\right]$$

^{70}Zn

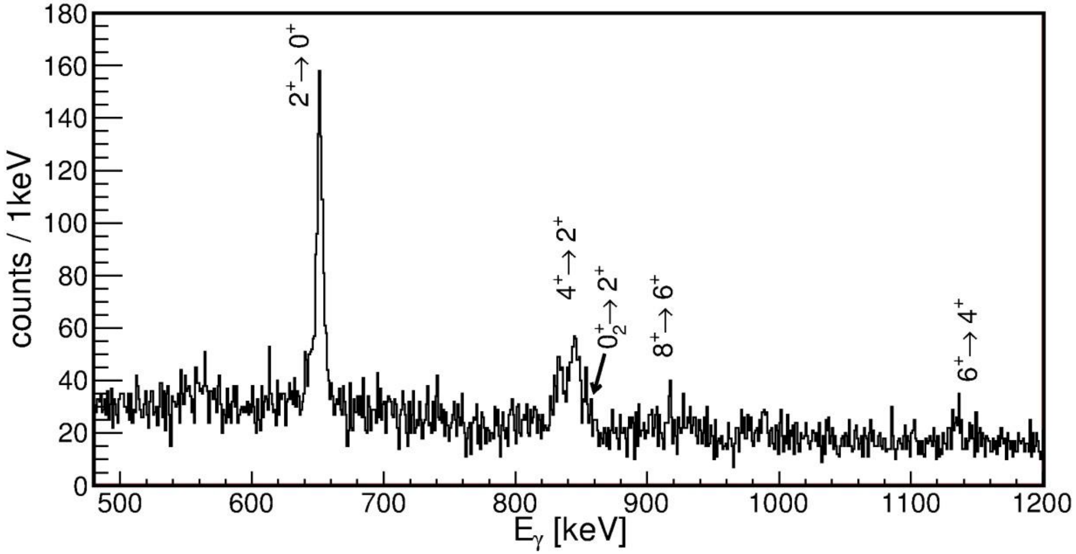


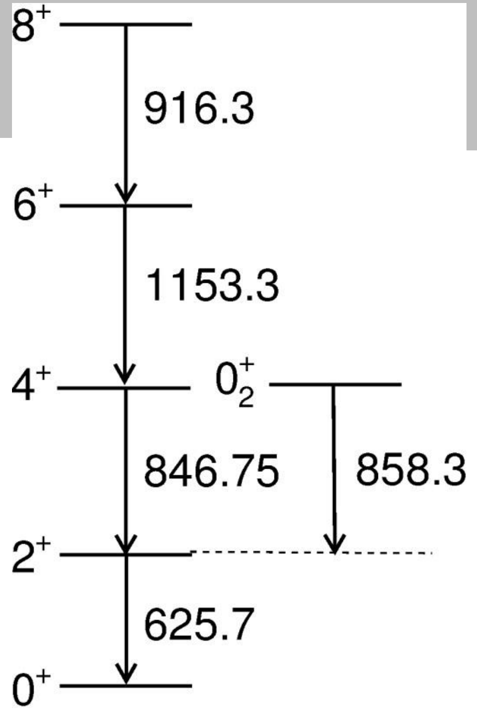


^{70}Zn	This experiment		Previous experiments	SM JUN45	SM LNPS	5DCH Gogny D1S
	τ [ps]	$B(E2; J \rightarrow J-2)$ $[e^2 fm^4]$				
2⁺	5.0 ± 0.4	303 ± 24	286^{+131}_{-68} [1] 305 ± 15 [2]	302	327	457
4⁺	4.8 ± 1.0	286 ± 61	475^{+584}_{-147} [1] 720 ± 70 [3]	394	345	861

[1] Louchart et al., submitted; [2] B Pritychenko et al., At. Data Nucl. Data Tables 98_798;
[3] P. Mücher et al., PRC79_054310

^{72}Zn





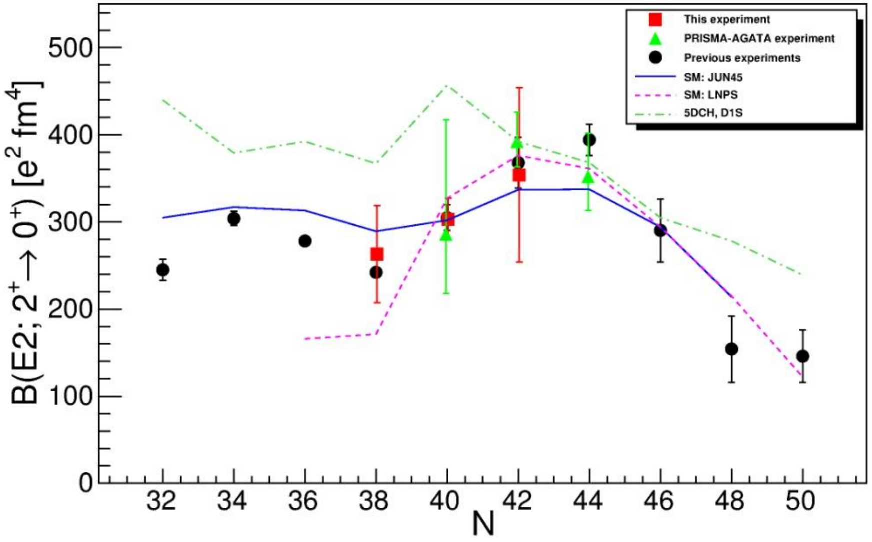
^{72}Zn	This experiment		Previous experiments	SM: JUN45	SM: LNPS	5DCH Gogny D1S
	τ [ps]	$B(E2; J \to J-2)$ [$e^2 fm^4$]				
2^+	19.4 ± 5.5	354 ± 100	392^{+34}_{-29} [1] 348 ± 42 [2] 385 ± 39 [3]	336	376	392
4^+	6.4 ± 2.4	292 ± 110	361^{+57}_{-47} [1]	349	471	768
6^+	3.0 ± 1.2	133 ± 51	134^{+57}_{-31} [1]	228	437	1111

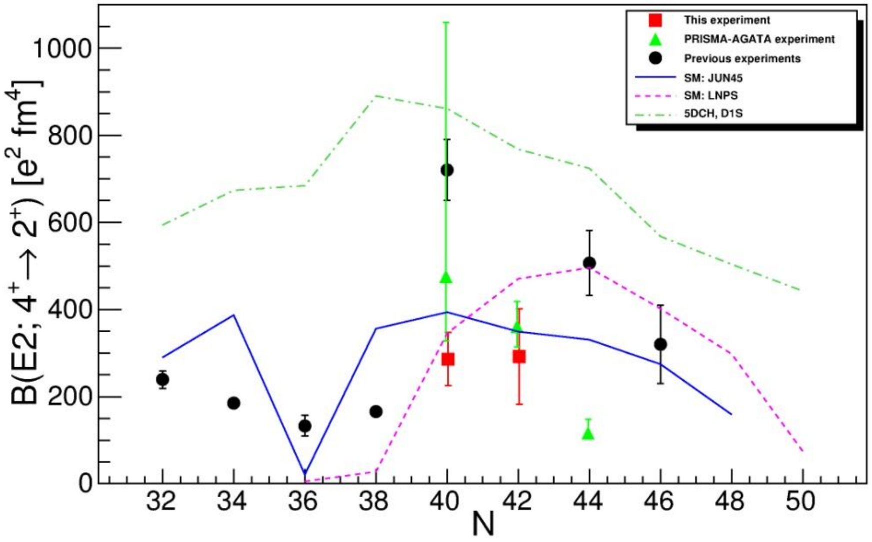
[1] Louchart et al., submitted; [2] S. Leenhardt et al., EPJ A 14_1; [3] M. Niikura et al., PRC85_054321

B(E2) systematics in even-even Zn

B(E2:2⁺→ 0⁺)

- Calcs and measurements compatible

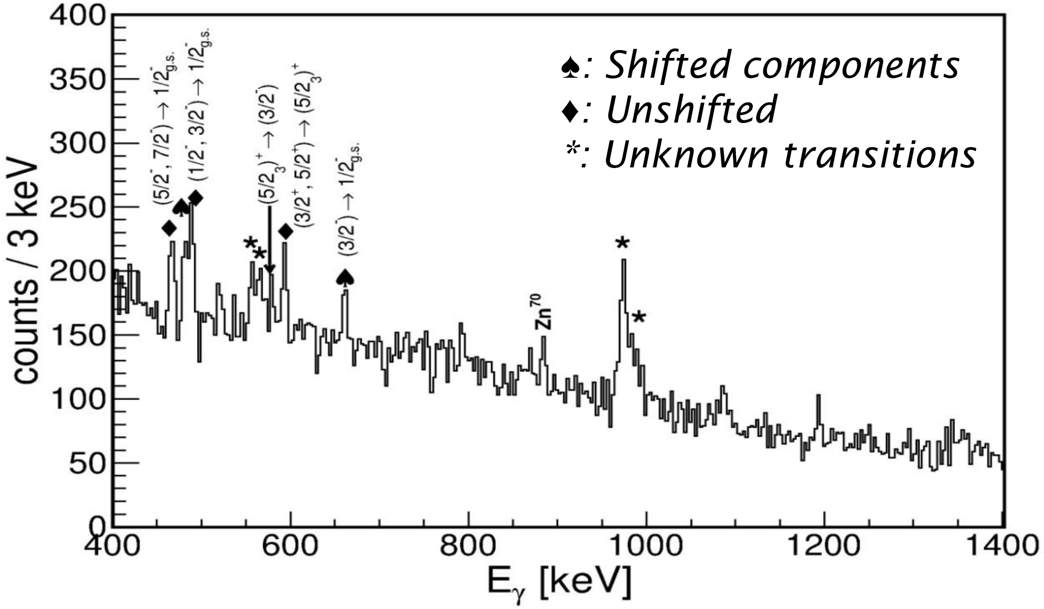


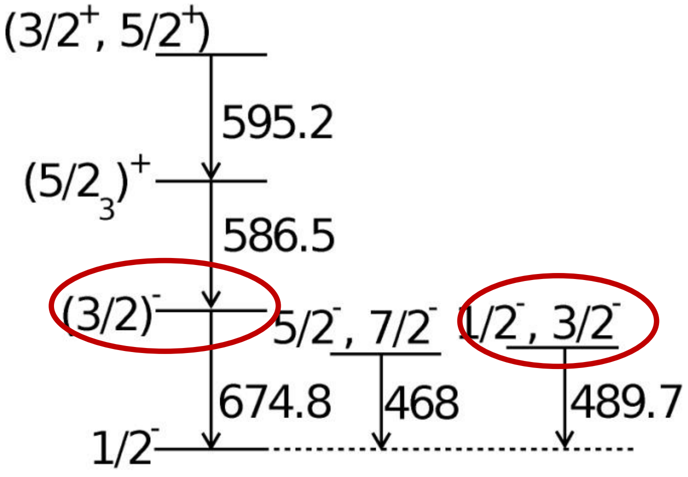


B(E2:4⁺→ 2⁺)

- Coulex larger values
- HFB overestimates B(E2)s (x3)
- SM more compatible with data
- Need to remeasure ^{70,74}Zn

^{71}Zn

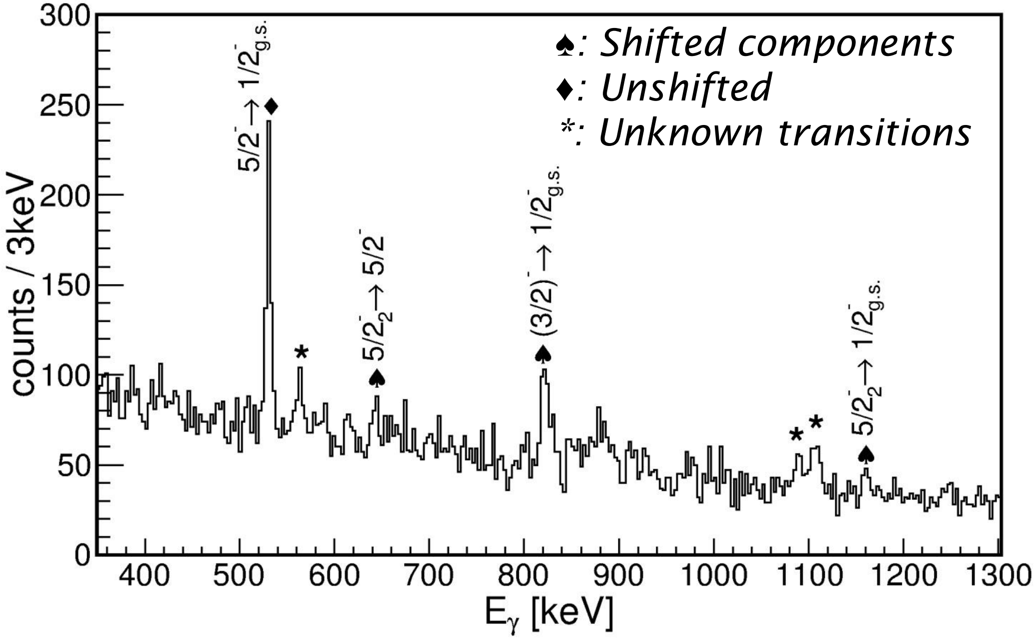


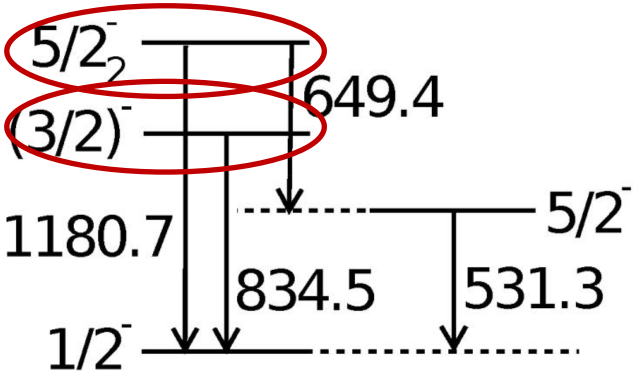


Lifetimes reported for the first time:

State	E_γ [keV]	τ [ps]
$1/2^-, 3/2^-$	489.7	7.3 ± 2.0
$(3/2)^-$	674.8	≤ 0.6
unknown	991(3)	≤ 0.6

^{69}Zn



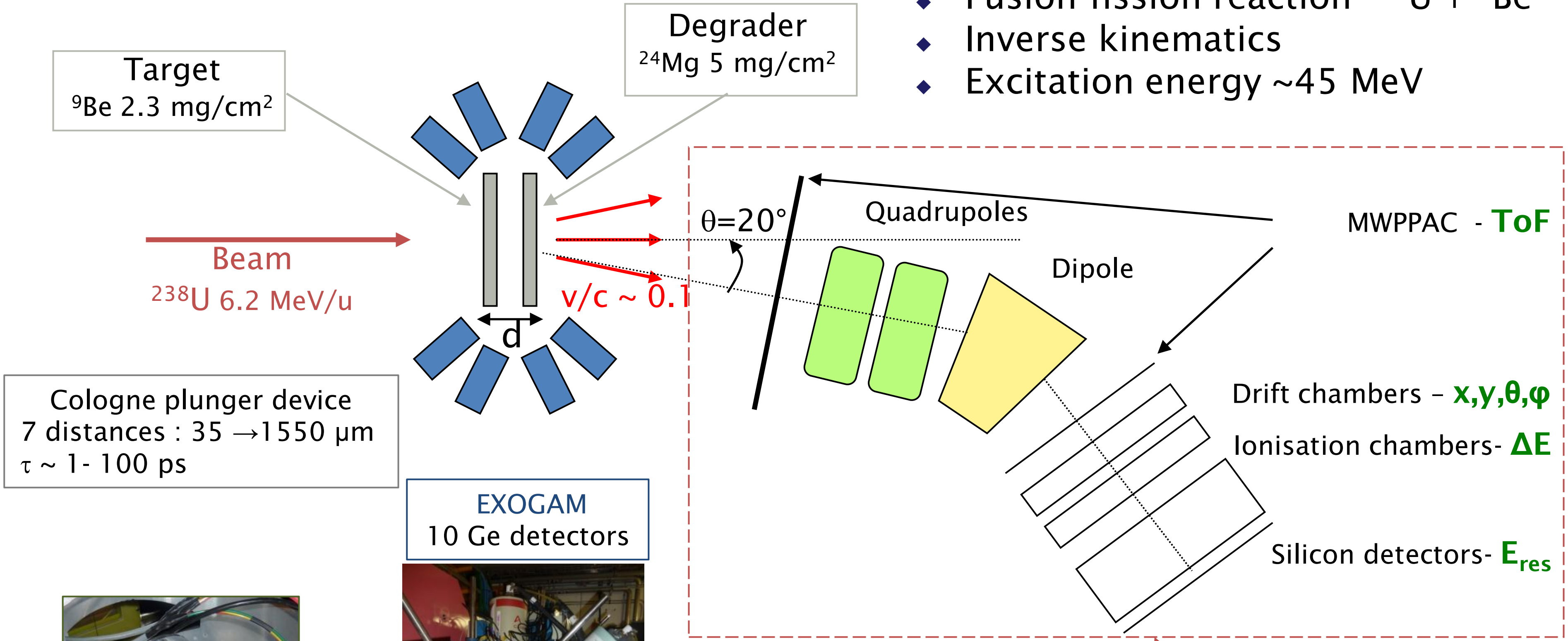


State	E_γ [keV]	τ [ps]
$(3/2)^-$	834.5	≤ 0.5
$5/2_2^-$	649.4	≤ 0.6
unknown	1109(3)	3.8 ± 1.1

Lifetimes of FF

E604 Experiment: L. Grente et al

- Fusion-fission reaction ^{238}U + ^{9}Be
- Inverse kinematics
- Excitation energy ~45 MeV



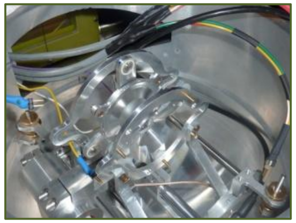
Target
^{9}Be 2.3 mg/cm^{2}

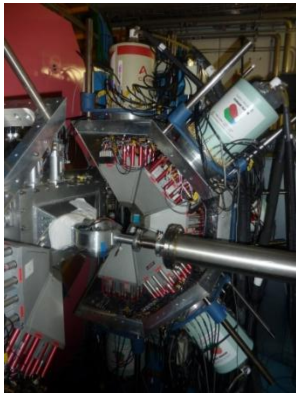
Degrader
^{24}Mg 5 mg/cm^{2}

Beam
^{238}U 6.2 MeV/u

Cologne plunger device
7 distances : 35 →1550 μm
τ ~ 1- 100 ps

EXOGAM
10 Ge detectors





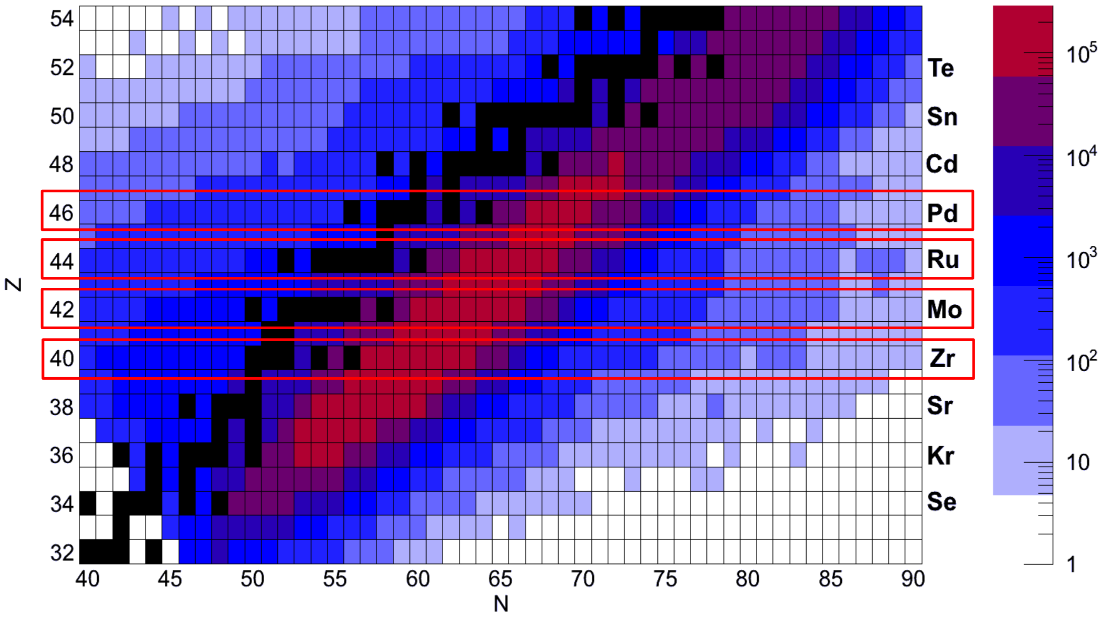
VAMOS spectrometer

Identification in Q, M et Z
of the fission fragments

Collectivity in the Pd-Zr region

- Measured yields

Measured relative yields of the detected fission fragments



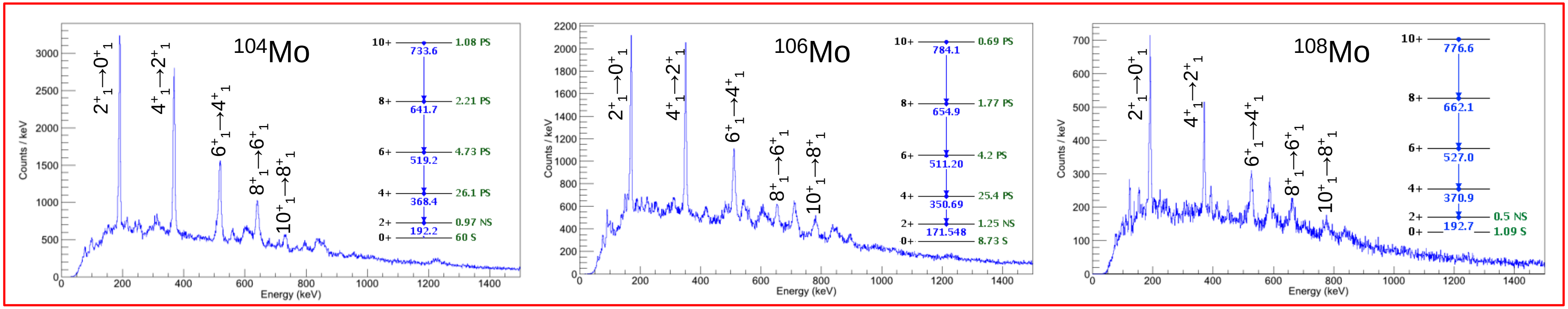
➔ Talk of MD Salsac

Courtesy L. Grente

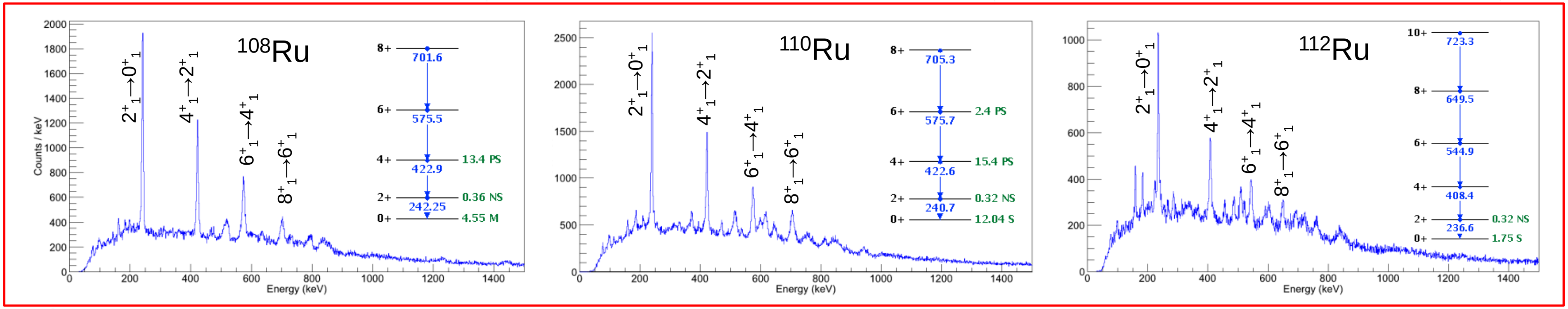
Mo-Ru-Pd spectra

Courtesy L. Grente

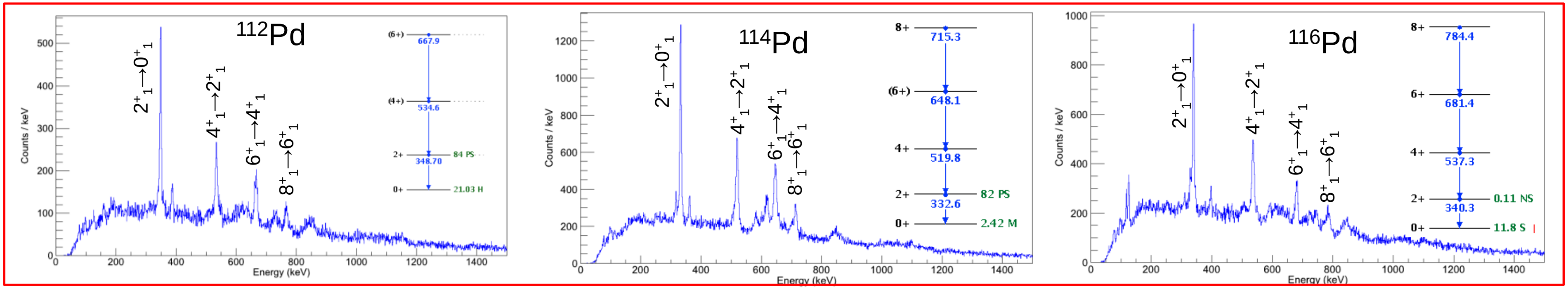
Mo



Ru



Pd



Conclusions

- Level scheme established for the 1st time in ^{92}Pd. The violation of the seniority-like level scheme shows evidence for a strong role of T=0. Confirmed by the decay of ^{96}Cd in GSI.
- The performances of the EXOGAM array as a polarimeter have been measured
- New transitions/states have been observed in ^{91}Ru and the spin and parity have been firmly established for a number of states.

- Lifetimes in Zn: compatible with recent data and for the first time in odd n-rich Zn
- Necessary to extend systematics to heavier Zn isotopes and to remeasure ^{70}Zn
- The particle-core coupling approach indicates a coexistence of s.p. and collective states in odd Zn
- Lifetimes of FF in the mass A~100 have been measured for the first time; allow to study the evolution of collectivity as a fucntion of (N,Z) and also with J

Perspectives

- ^{96}Cd experiment (Feb. 2014?)
- Analysis of EXILL data ➔ M Jentschel's talk
- AGATA at GANIL ➔ E Clément's talk
- Upgrade of SPIRAL1
- SPIRAL2

Thank you for your attention

Ciao Enrico