# "Fast Timing experiments"

L.M. Fraile for the
FATIMA (FAst TIMing Array) collaboration

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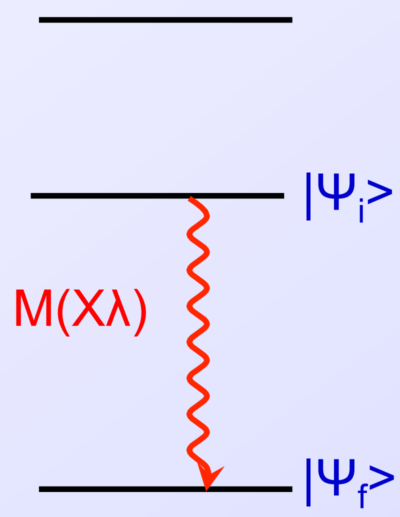
## Annual NUSTAR Week 2012

# Transition matrix elements

✓ Absolute transition matrix elements

$$B\left(X\lambda; I_i \rightarrow I_f\right) = \left(2I_i + 1\right)^{-1} \left|\left\langle \psi_f \| M(X\lambda) \| \psi_i \right\rangle\right|^2$$

$$B\left(X\lambda; I_i \rightarrow I_f\right) = \frac{L[(2L+1)!!]^2 \hbar}{8\pi(L+1)} \left(\frac{\hbar c}{E_\gamma}\right)^{2L+1} P_\gamma\left(X\lambda; I_i \rightarrow I_f\right)$$




→ Single particle estimates

- Shell evolution
- Mirror symmetries

→ B(E2) values

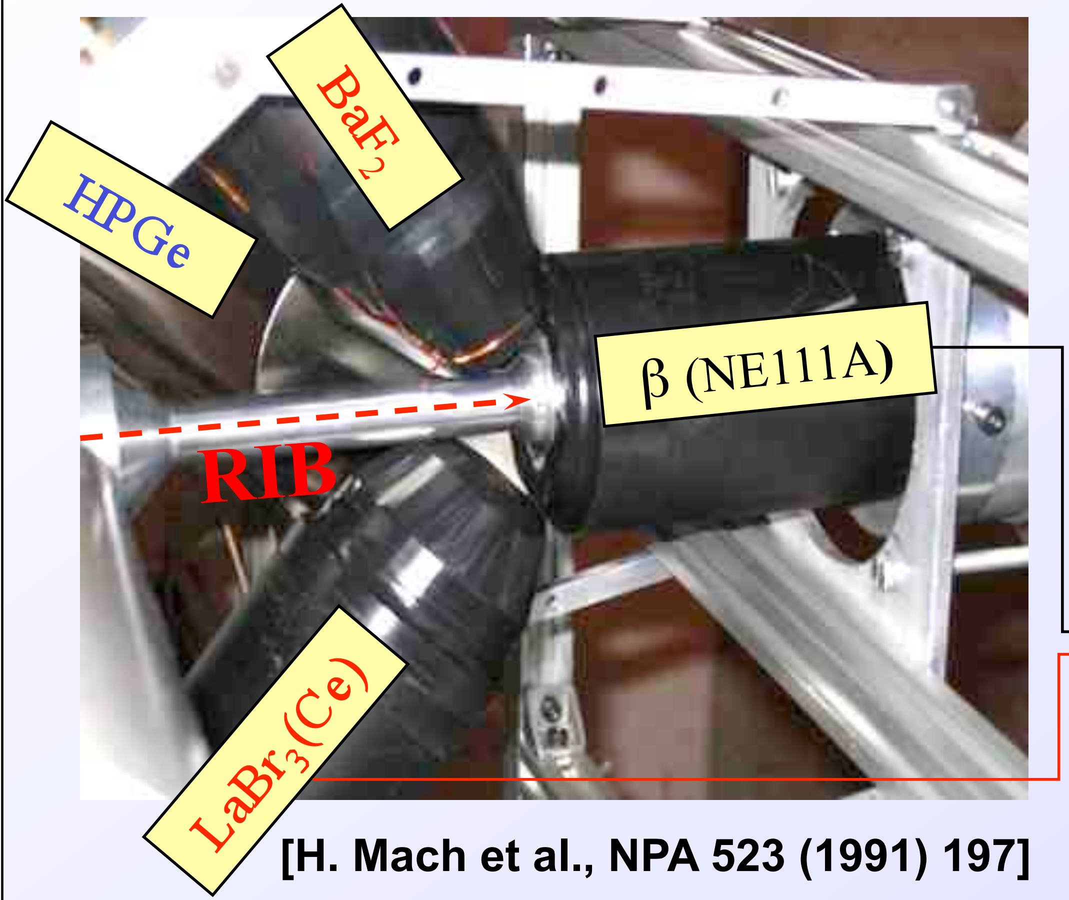
- Deformation of even-even nuclei
- Collective modes (spin dependence), shape coexistence…

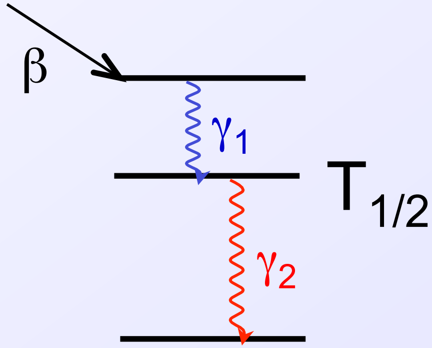
→ Collectivity

- For instance, octupole correlations…

→ Systematics

# The Advanced Time Delayed $\beta\gamma\gamma(t)$ method





**TAC**

[H. Mach et al., NPA 523 (1991) 197]

**HPGe: BRANCH SELECTION**
High energy resolution
Poor time response

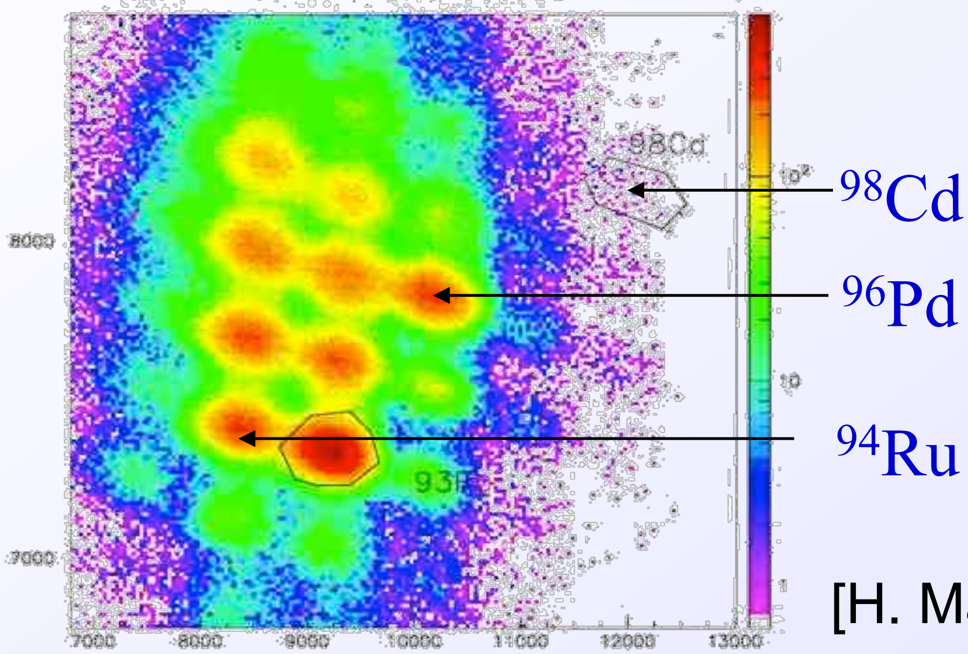
**Plastic β scintillator: TIMING**
Fast response
Efficient start detector

**$LaBr_3(Ce)/BaF_2$: TIMING**
Fast response γ-detectors
Stop detectors

→ Double coincidences: βγ: beta-Ge and beta-$LaBr_3$
→ Triple coincidences βγγ: beta-Ge-Ge and beta-Ge-$LaBr_3$

Calibrations!

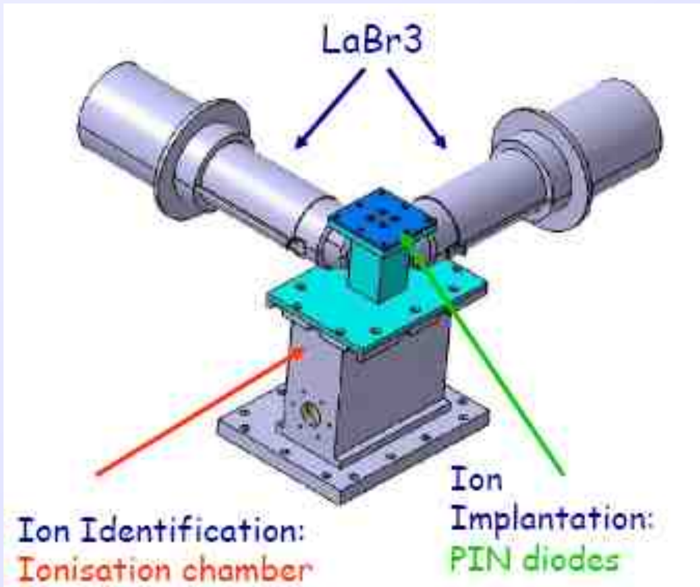
# Fast timing $\gamma\gamma(t)$




[H. Mach]

Isomer setup @ GANIL – $BaF_2$

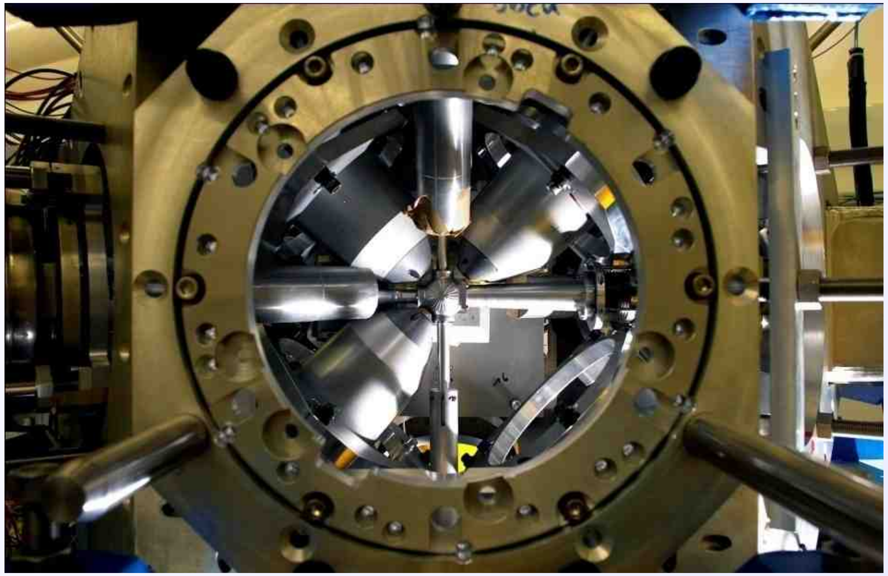

[G. Simpson]

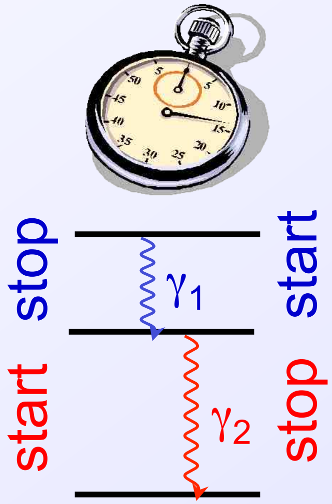


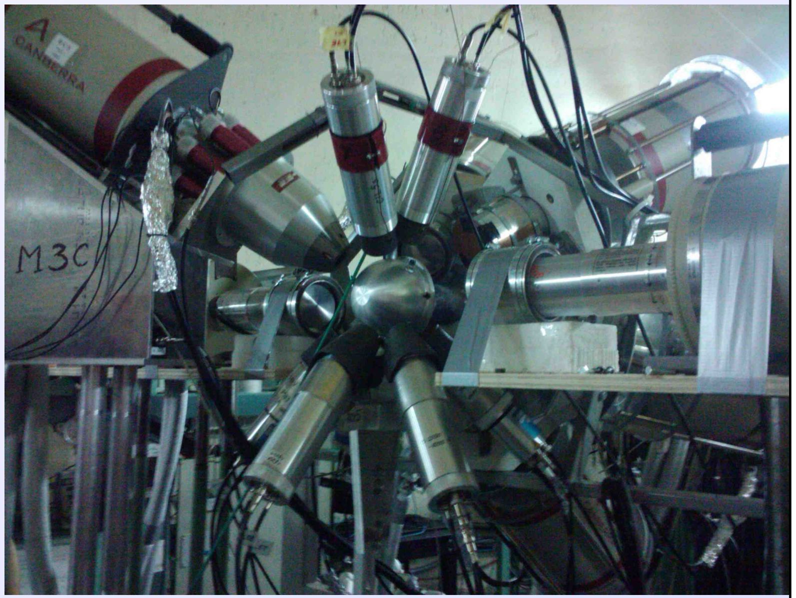

Fast-timing with $LaBr_3$ @ Lohengrin - ILL

- ✓ Beam spot reduced to 2×1.5 cm
- ✓ 4 $LaBr_3$ (Köln group)
- ✓ DGFs

# Fast timing $\gamma\gamma(t)$

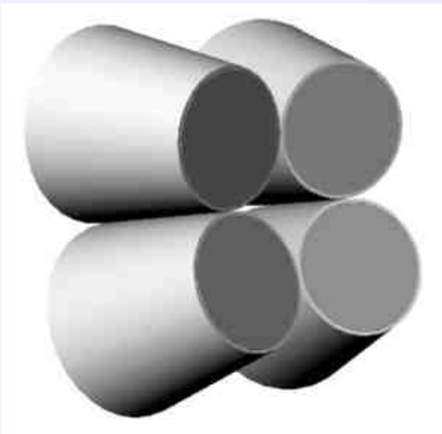


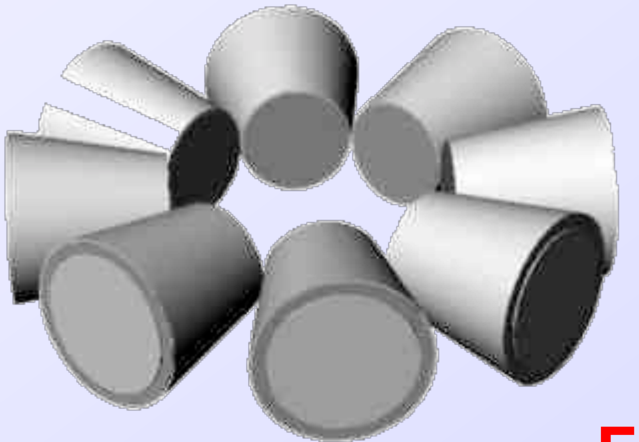


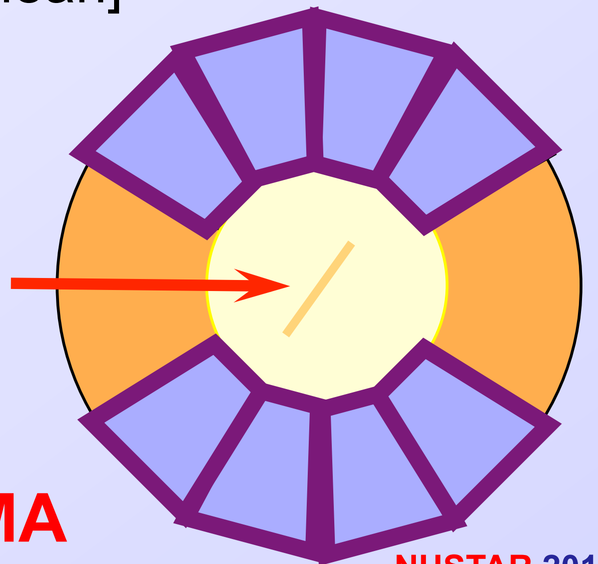




Cologne HORUS cube spectrometer
[J. Jolie]

8 HPGe & 7 $LaBr_3(Ce)$ @ Bucharest
[N. Marginean]







**FATIMA**

# Fast-timing elements

## Time resolution *vs* efficiency

- Opposite requirements
- Precision = Resolution (FWHM) / $N^{1/2}$

✓ Detectors: **$LaBr_3$:Ce**

- Experience gained with $BaF_2$ over 20 years applies to $LaBr_3$:Ce
- **Doping**
- **Size** (“as small as possible” ;-)
- **Shape** (but 44-46 mm diameter at base for coupling)
- Alternatives **$CeBr_3$**

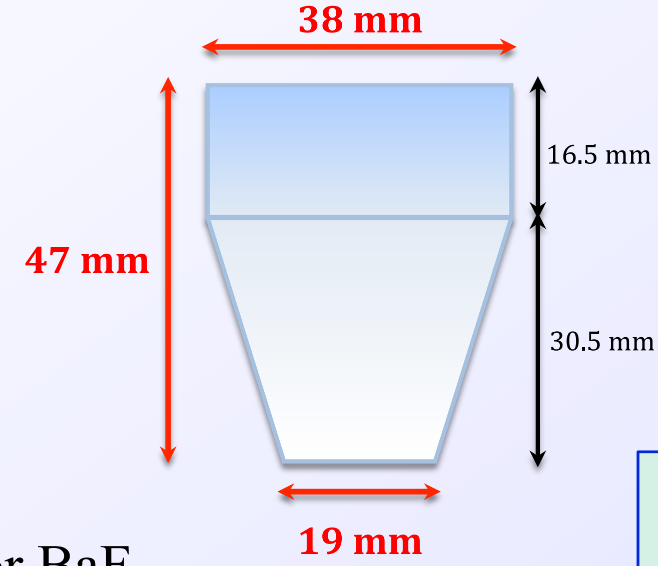
✓ Photosensors (PMs and voltage dividers)

- Best time response phototubes are 2” tubes
- Effective diameter is about 44-46 mm
- Alternatives **SiPMs**

✓ Front-end / timing electronics

- CFDs
- Digital options

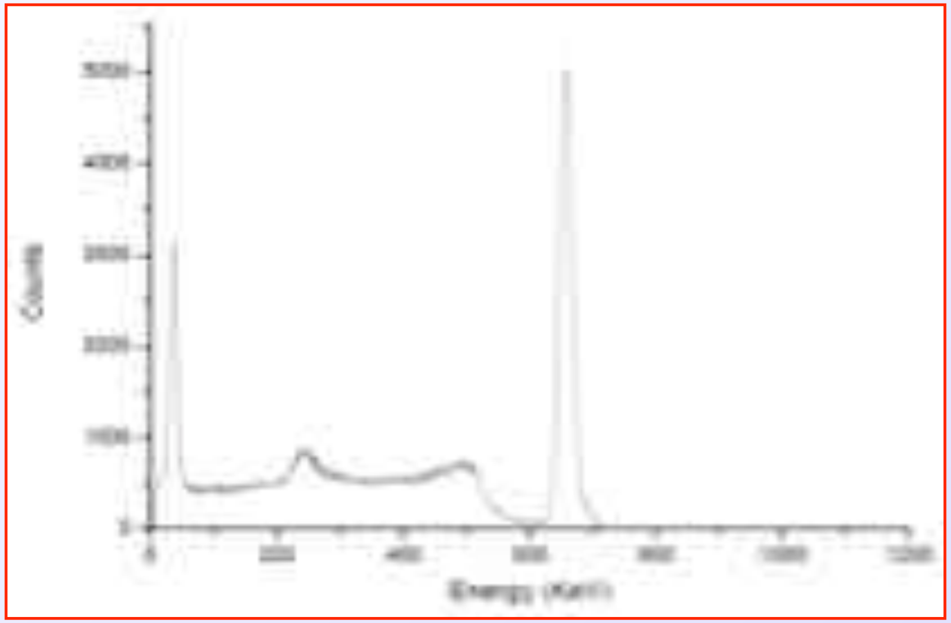
# Scintillator detectors





~30% better for $BaF_2$

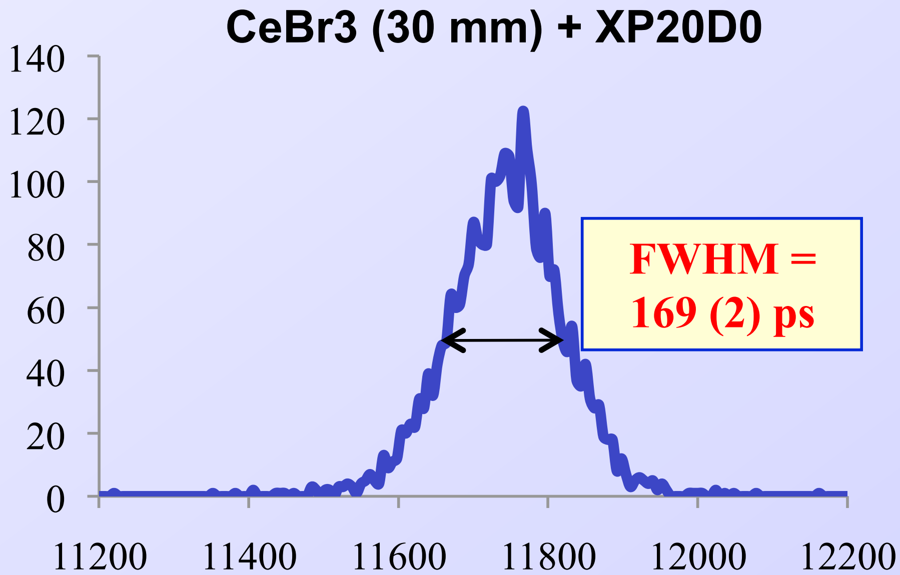
L.M. Fraile et al., IEEE NSS Conf Record



**30 mm $CeBr_3$ R9779 / XP20D0**

FWHM E resolution @ $^{137}$Cs = 3.8 %

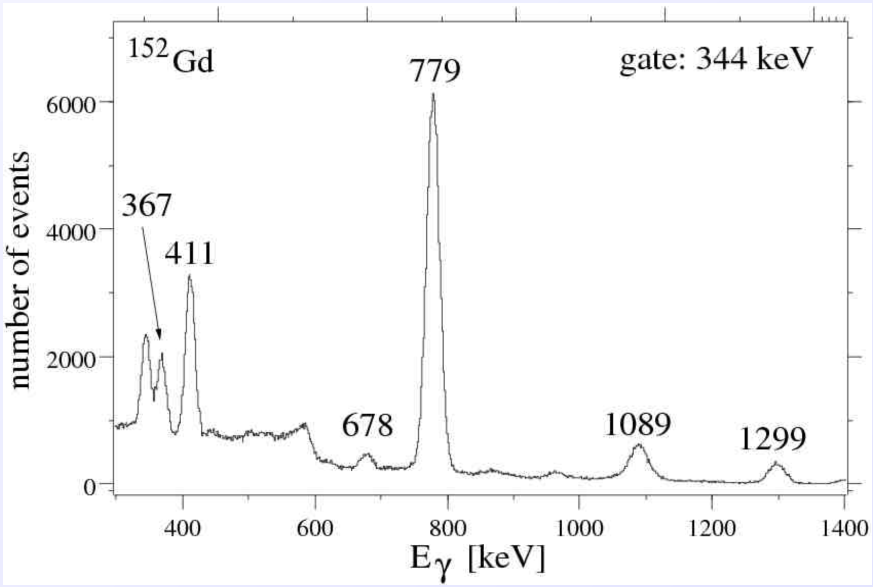
FWHM time resolution @ $^{137}$Cs = 150 ps

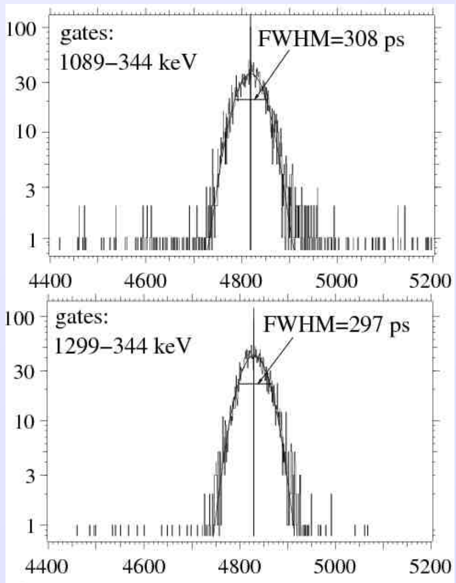


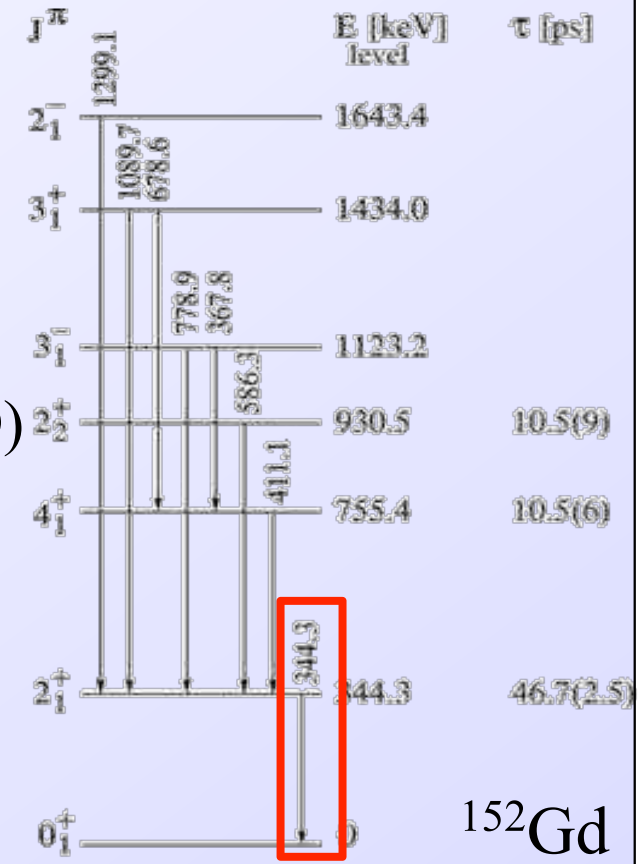

NUSTAR 2012

# γ - γ timing with $LaBr_3(Ce)$ scintillators

- ✓ In β-decay timing, for β–γ combinations
  - → FEP walk calibration
  - → Prompt (Compton) walk calibration
  - → Fine Compton to Compton calibration
  - → Walk curves for $BaF_2$ + XP2020 tunable (CFD)
- ✓ With $LaBr_3(Ce)$ γ–γ timing
  - → E resolution: selection of branches



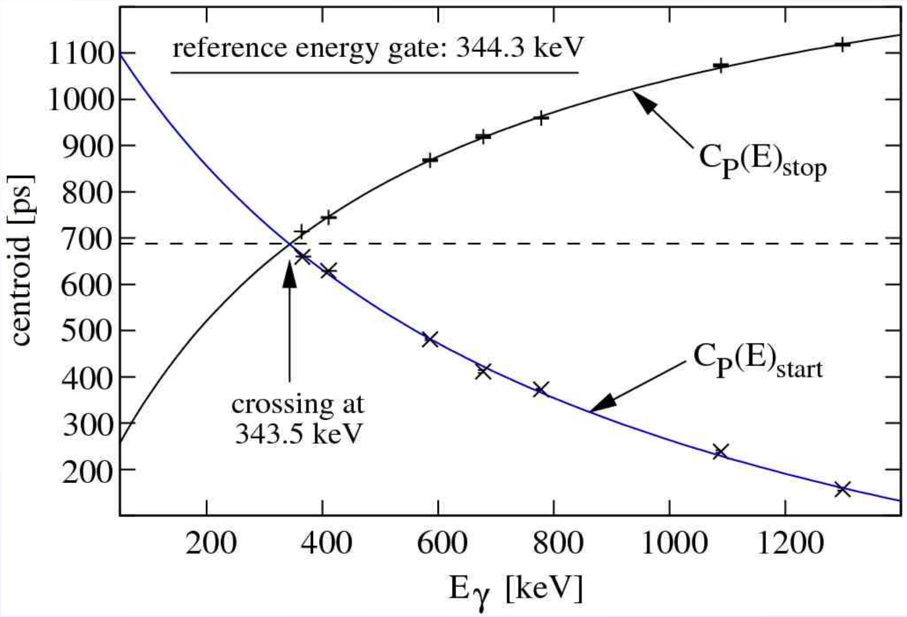



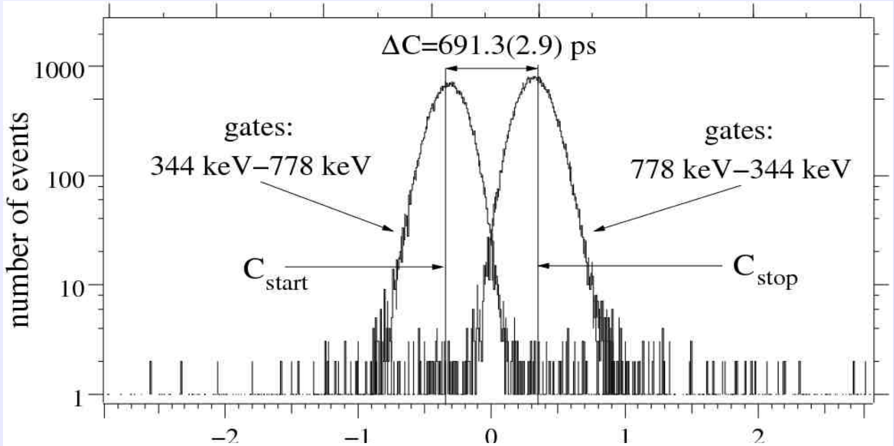

$^{152}$Eu γ-ray source

[J.-M. Régis]

# γ - γ timing with $LaBr_3(Ce)$ scintillators



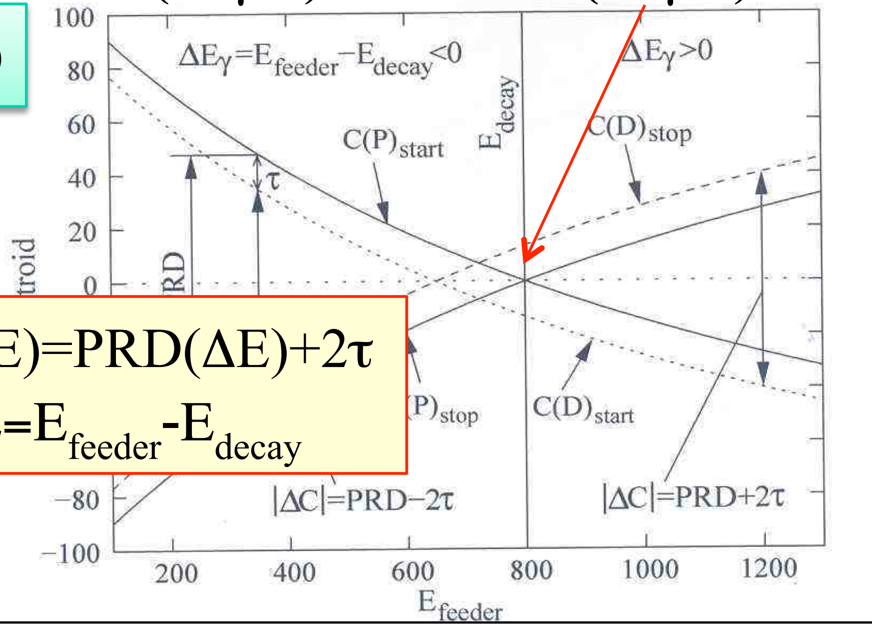

- ✓ The timing of the 2 detectors in a real γ-γ fast timing setup is **asymmetric**




- ✓ FEP walk (prompt curve)
  - → 2 prompt curves of a γ-γ fast timing setup using $\gamma_{REF}$ both as start and stop gate
- ✓ Compton walk plays a role

MSCD

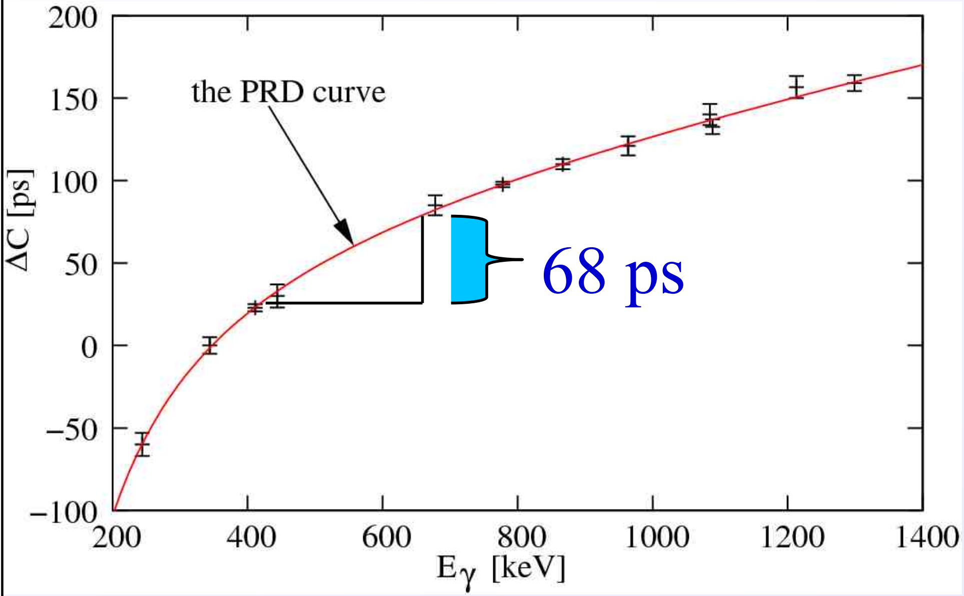
**$\Delta C(\Delta E\gamma=0) = 2\tau - PRD(\Delta E\gamma=0) = 0$**

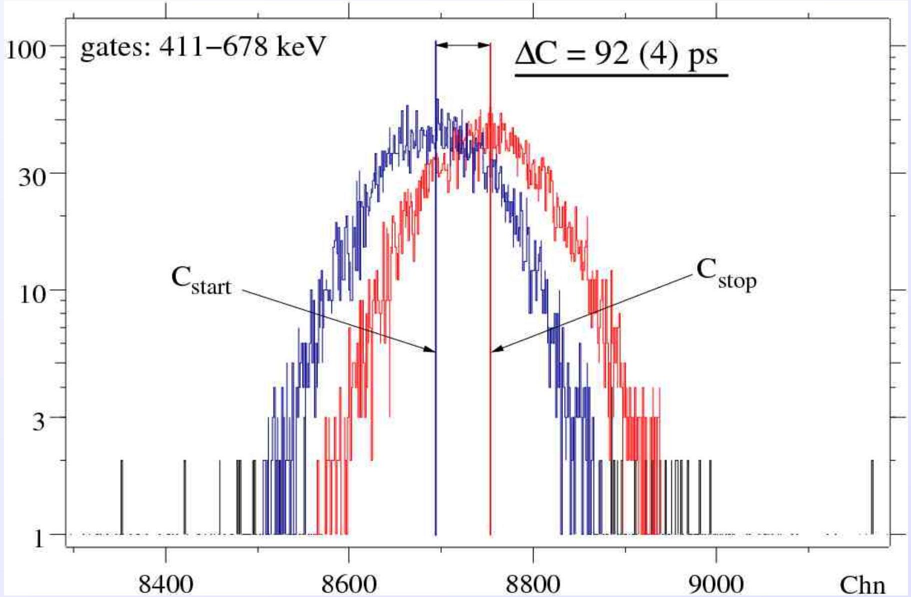


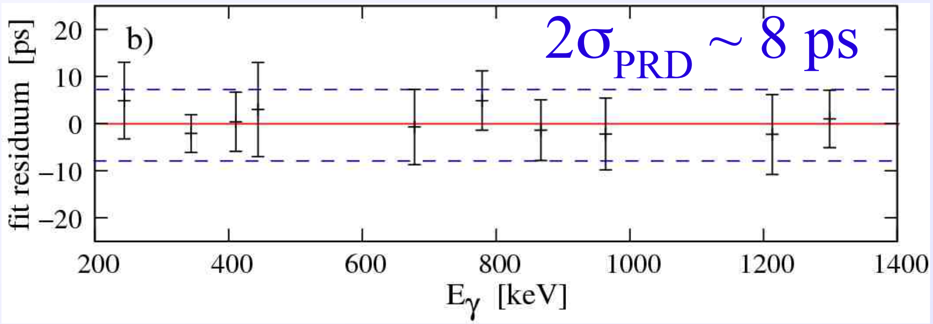

$\Delta C(\Delta E) = PRD(\Delta E) + 2\tau$
$\Delta E = E_{feeder} - E_{decay}$

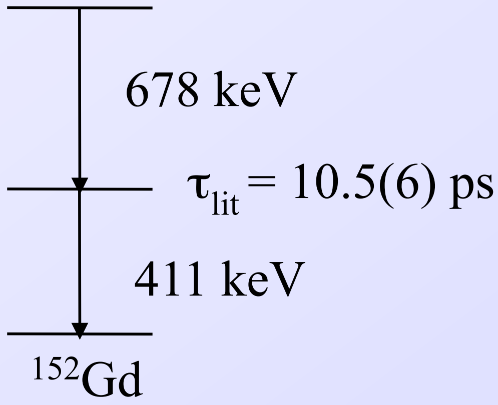
J.-M. Régis et al., NIM A 622 (2010) 83

# A lifetime measurement…




**[J.-M. Régis, J. Jolie]**

Calibration function:

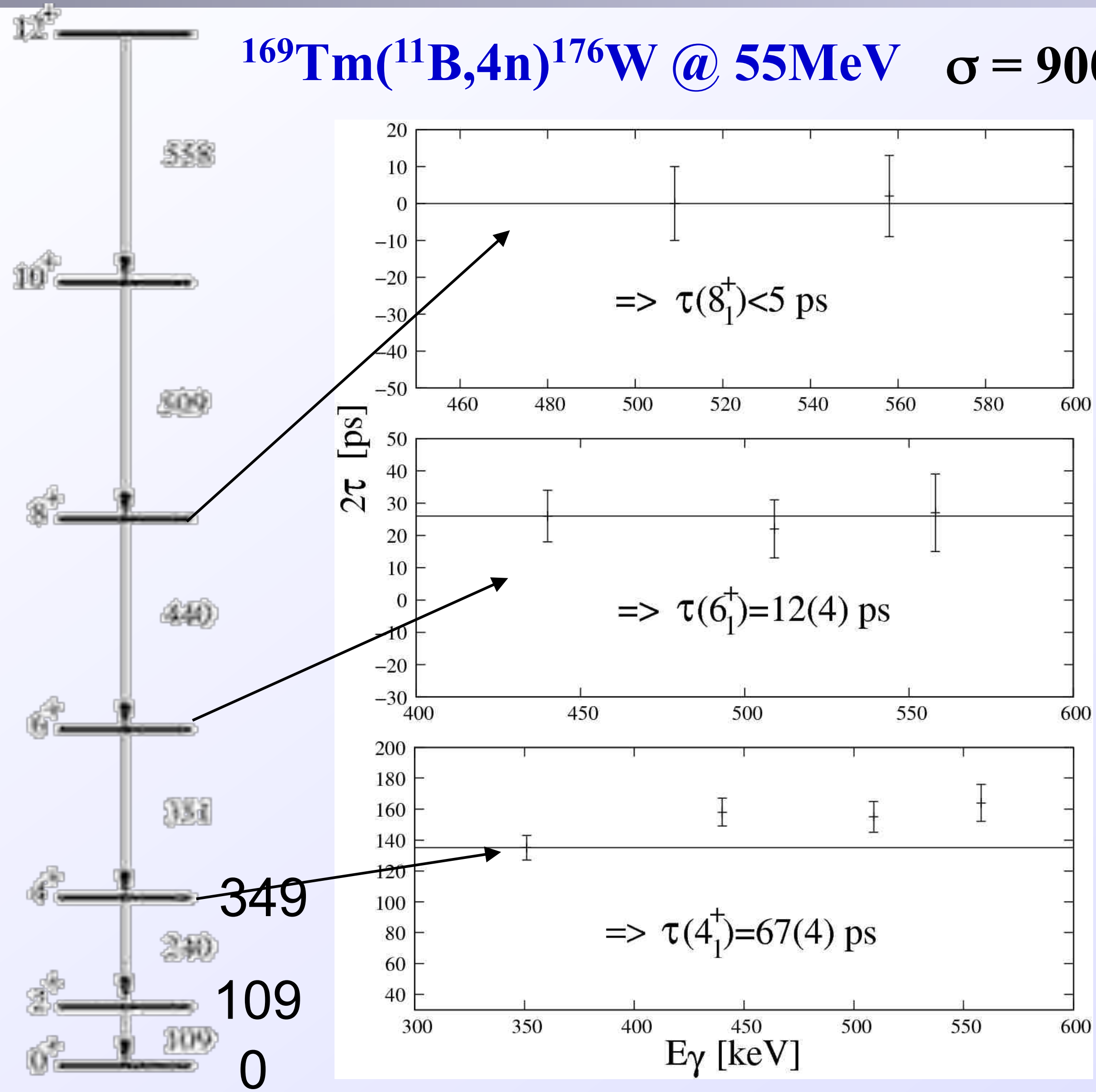
$$\Delta C(E_\gamma) = \frac{a}{\sqrt{b + E_\gamma}} + cE_\gamma + d$$

PRD(678-411) = PRD(678)-PRD(411) = 68 (8) ps

**τ = (ΔC - PRD)/2 = 12 (5) ps**

# In-beam spectroscopy at HORUS IKP

**$^{169}Tm(^{11}B,4n)^{176}W$ @ 55MeV**  **σ = 900 mb**




Yrast band in $^{176}W$,

$R_{4/2}$=E(4+)/E(2+)=3.21

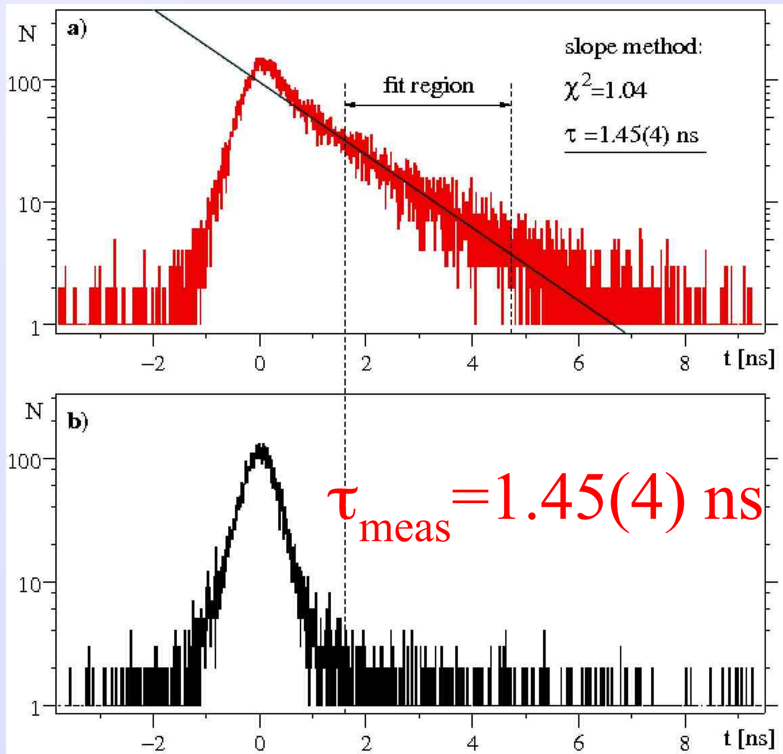
(rigid deformation: $R_{4/2}$=3.33)

Active BGO detectors:

· peak-to-background ratio @ 108 keV is improved by factor 3

· delayed low-energy background is suppressed

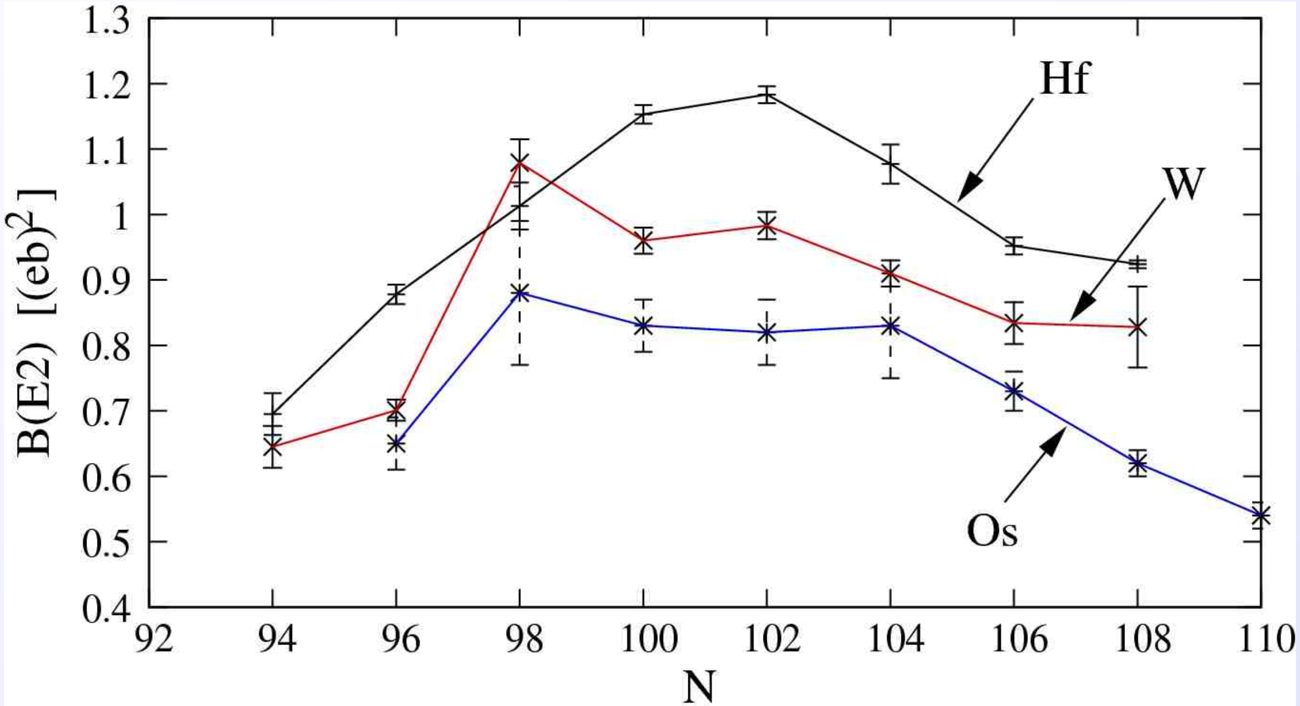
$\tau_{lit}$=1.43(2) ns ($e^-$-γ)




[J. Jolie]

# Evolution of B(E2) strength in even-even isotopic chains

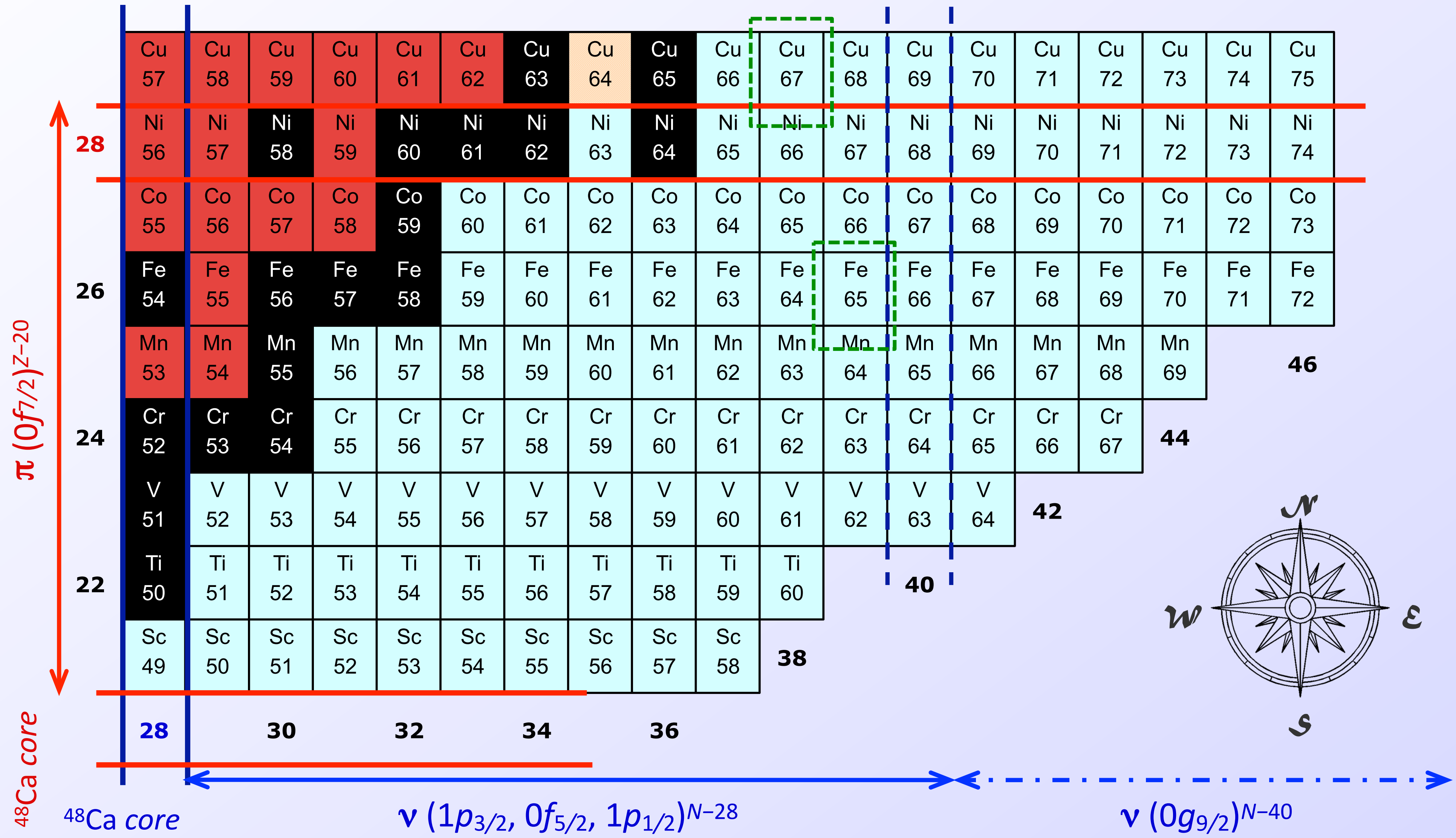
Valence proton boson number: 3 (Os), 4 (W) and 5 (Hf)



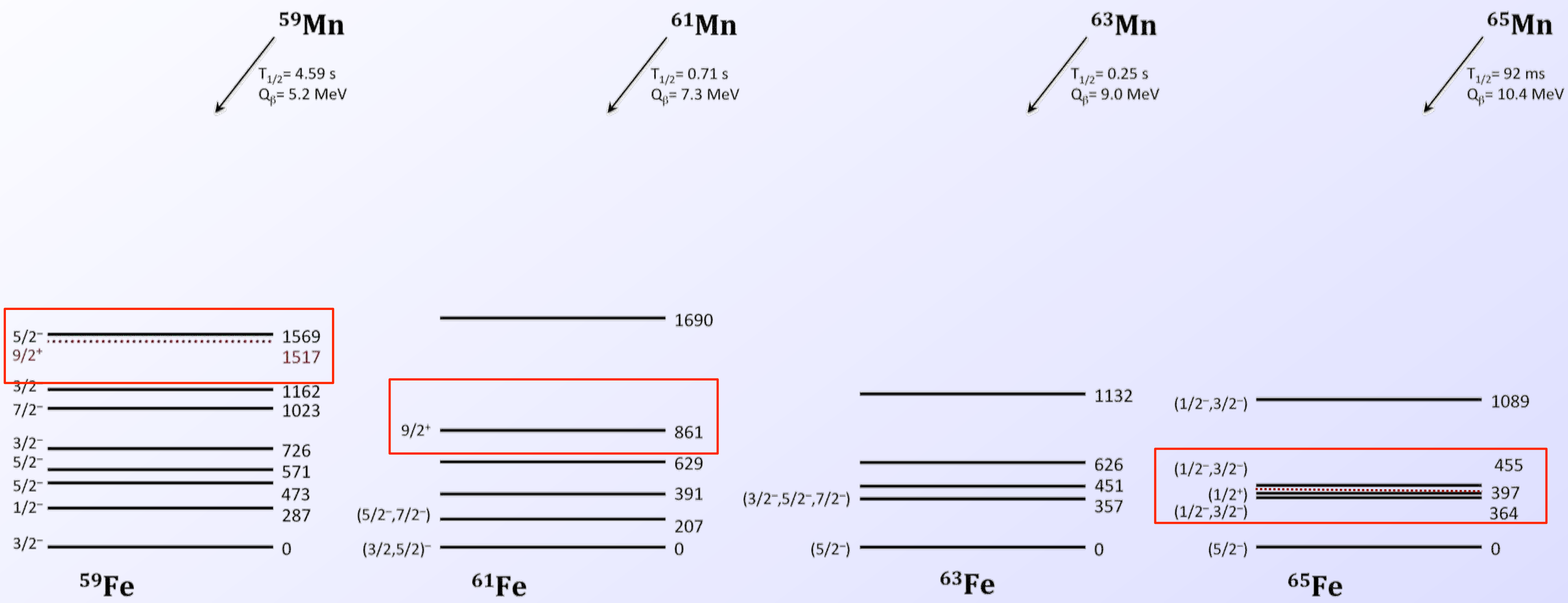

$^{176}$Os (N=100):
B. Melon, PhD thesis (2011)

- Increase of B(E2) values with valence proton boson number: IBA
- Peaking near neutron mid-shell (N=104): IBA
- Maxima at N=98 and N=102: uhm…

# Nuclear chart around $^{68}$Ni



# 2. Odd-A Fe isotopes

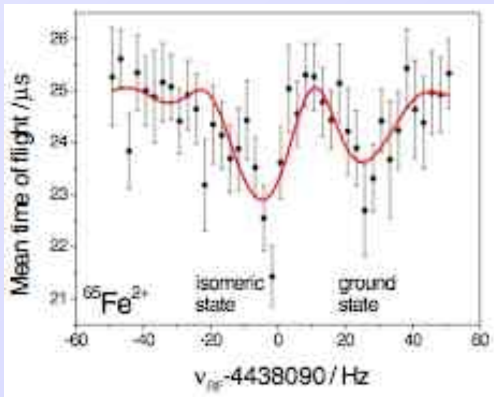



$^{57}$Fe E(9/2$^+$) = 2455 keV, A. Deacon et al., PRC 76, 054303 (2007)

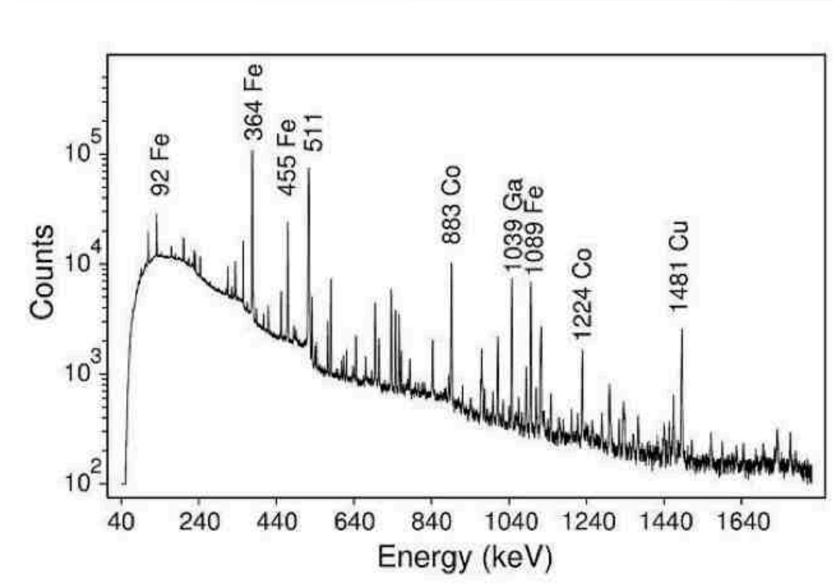
$^{65}$Fe E(9/2$^+$) = 402(5) keV, $T_{1/2} \geq 150$ ms

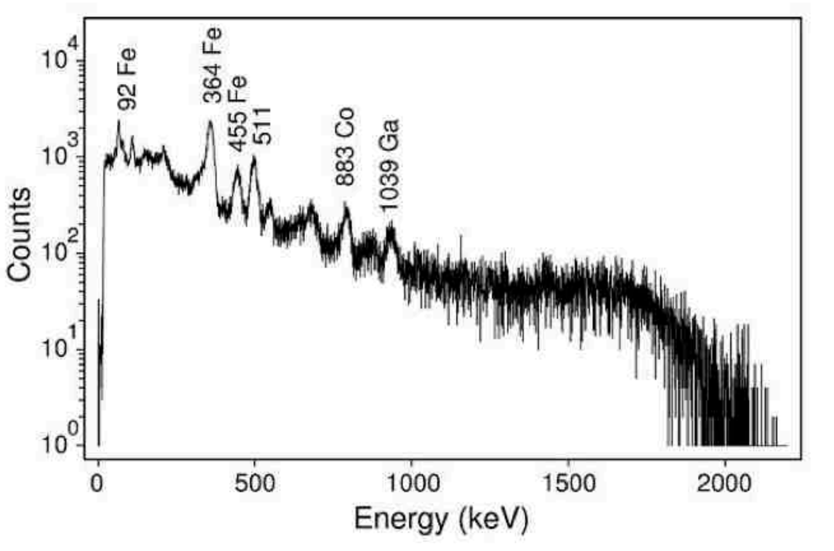
M. Block et al., PRL 100, 132501 (2008)

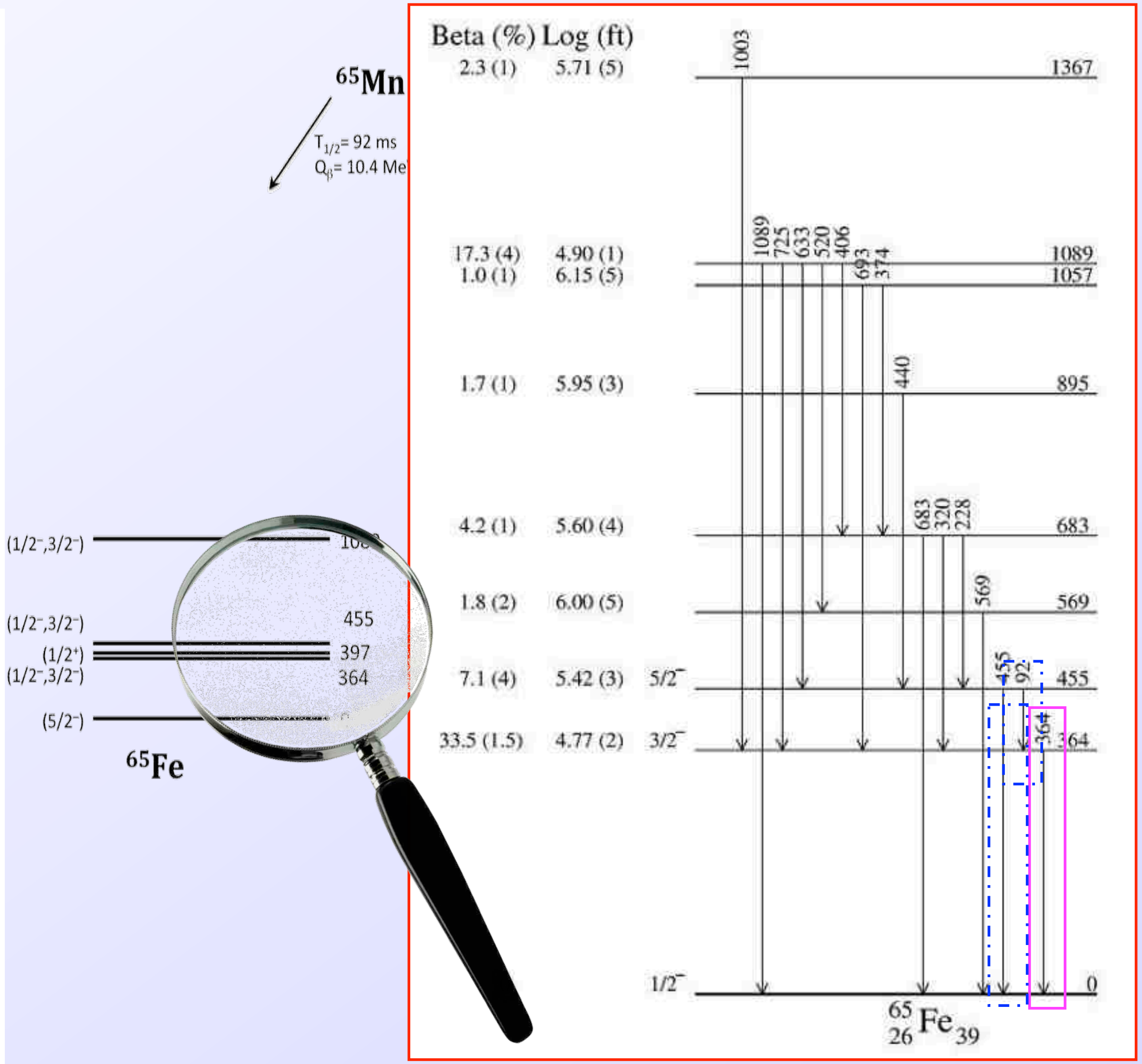
$^{67}$Fe $T_{1/2} \sim 75$ μs, J.M. Daugas et al. AIP Conf Proc 831, 427 (2006)



# Analysis $^{65}$Mn decay




Strong beta-feeding to 364, 455 and 1089 keV states, very weak g.s. feeding

# Transitions in $^{65}Fe$

✓ 364 keV level, $T_{1/2}$ = 110 ps

→ 364 keV transition (neglecting C.C.)

- E1 not expected: $1/2^-$, $3/2^-$, $5/2^-$ states or $9/2^+$ (long lifetime)
- B(E2)~52 W.u. (too high)
- B(M1)=0.0041 W.u.

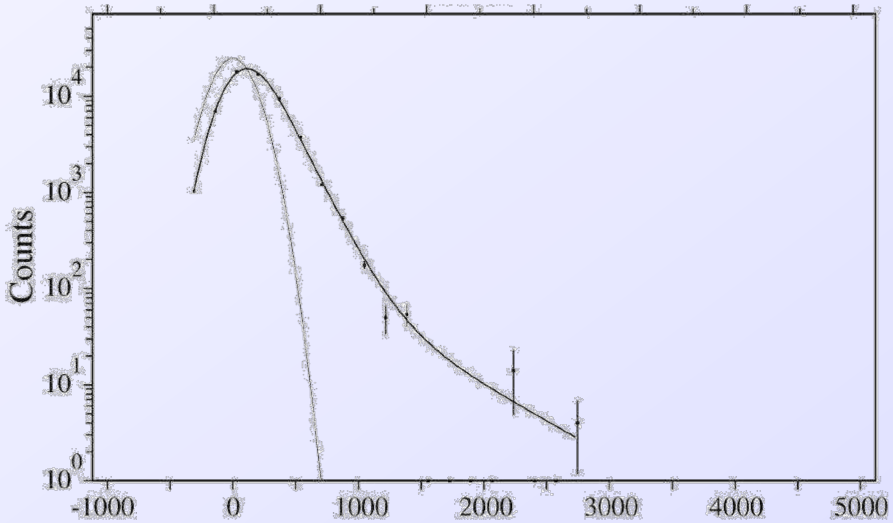
✓ 455 keV level, $T_{1/2}$ = 410 ps

→ 92 keV transition

- Similar for E1 and E2
- B(M1)=0.028 W.u.

→ 455 keV transition

- B(E1) or B(M1) too low
- B(E2)=4.4 W.u. (fits systematics)




Two dipole M1 and one E2 transition
Beta feeding from $5/2^-$

$1/2^-$ is the ground state
$3/2^-$ is the 364 keV state
$5/2^-$ is the 455 keV state

Structure at higher E
Similar situation expected in odd-A Fe isotopes
Role of the $9/2^+$ orbital

[B. Olaizola]

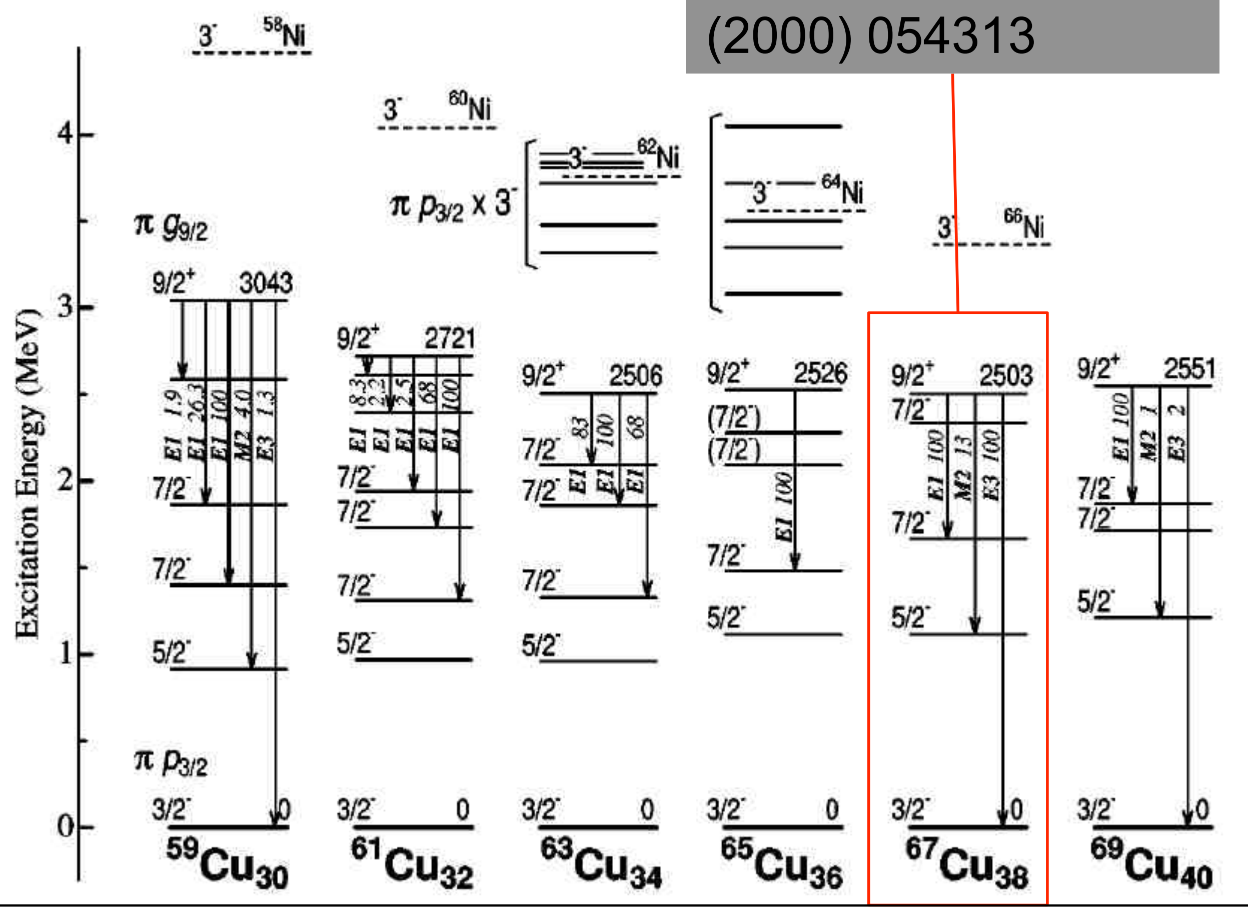
# 3. E1/E3 transitions in Cu isotopes

| | $^{59}$Cu | $^{61}$Cu | $^{63}$Cu |
|---|---|---|---|
| $T_{1/2}$ (9/2$^+$) [ps] | 0.80(35) | > 2.8 | 1.5 +3/-2 |
| B(E1; $\rightarrow 7/2^-_1$) | $9\times10^{-5}$ | < $9\times10^{-5}$ | $9\times10^{-5}$ |
| B(E1; $\rightarrow 7/2^-_2$) | $7\times10^{-5}$ | < $6\times10^{-5}$ | $4\times10^{-4}$ |

## $^{67}$Cu : $T_{1/2}(9/2^+)$ < 300 ps

- B(E3;2503 keV) > 11 W.u.
- B(E1;833 keV) > 1.1x10-6 W.u.

M.Asai et al., PRC62 (2000) 054313




If B(E1) in $^{67}$Cu is ~ $10^{-5}$ W.u., then B(E3) >> 11 W.u, out from systematics

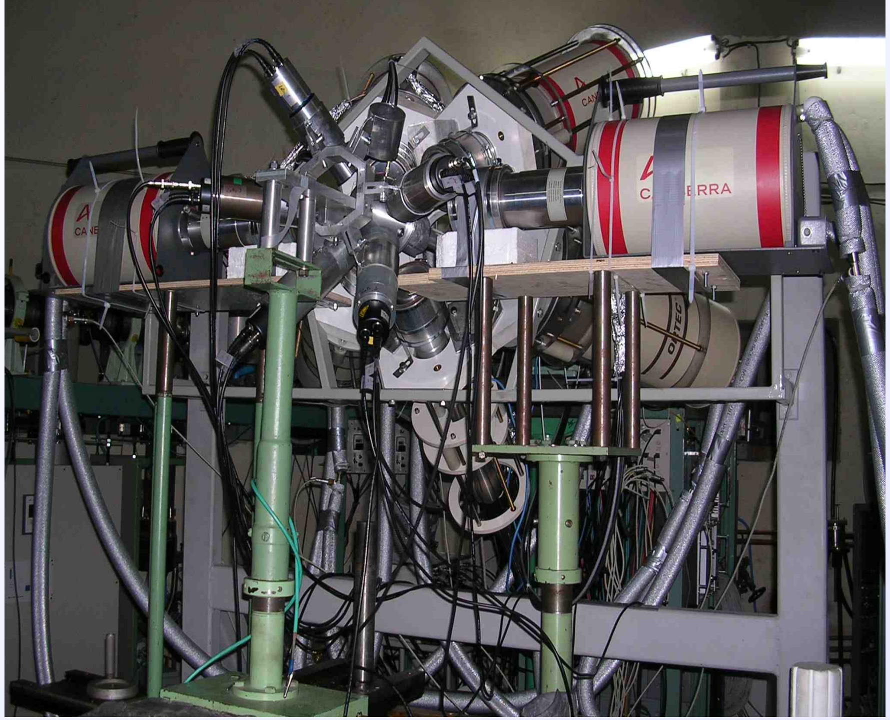
**$^{67}$Cu**: 9/2$^+$ has large $\pi g_{9/2}$ component (from transfer reactions)

E3 $\pi g_{9/2} \rightarrow \pi p_{3/2}$ enhanced by particle-octupole vibration coupling?

[N. Marginean]

# Fast-timing measurement for $^{67}$Cu

N.Marginean at al., EPJ.A46 (2010) 329




$^{64}Ni(\alpha,p)^{67}Cu$  $E_{\alpha}$ = 18 MeV

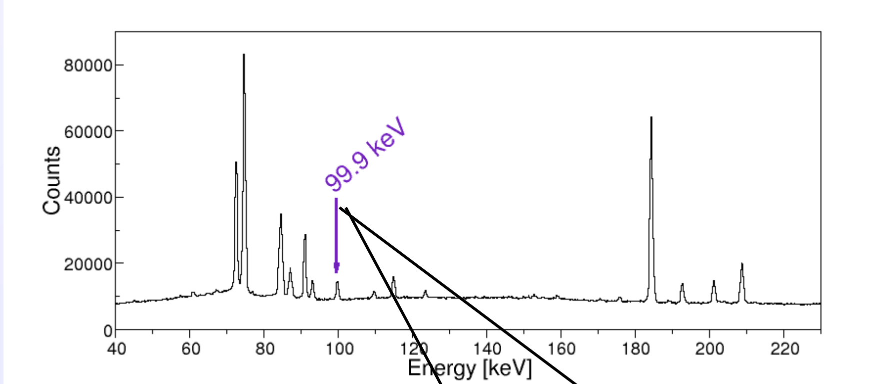
5 HP-Ge ( 55% rel. eff.)

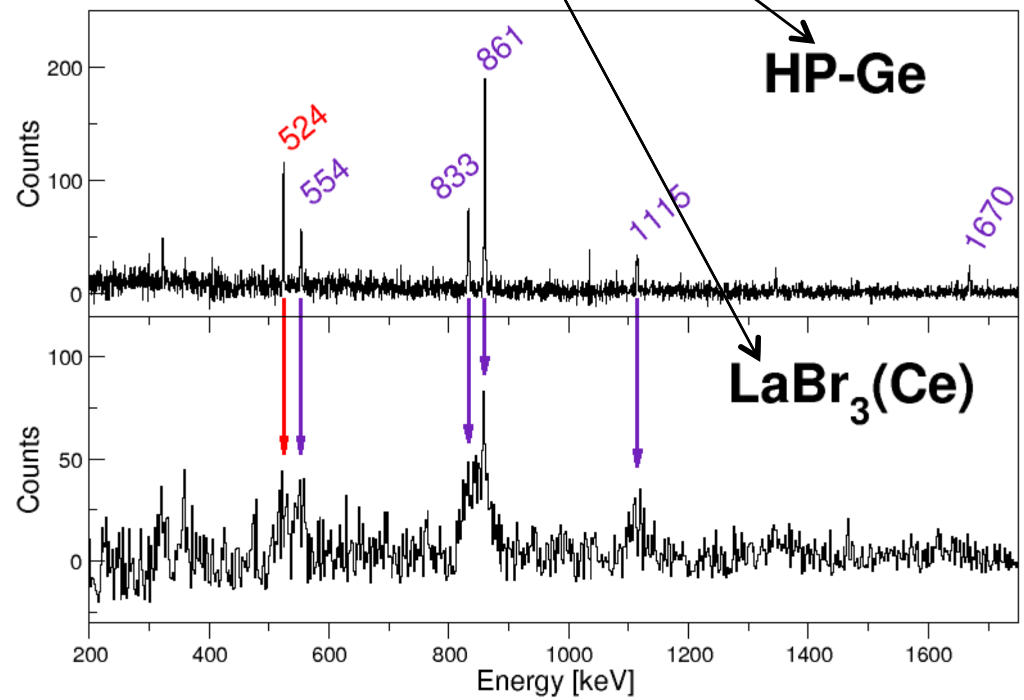
4 HP-Ge planar detectors

8 $LaBr_3(Ce)$

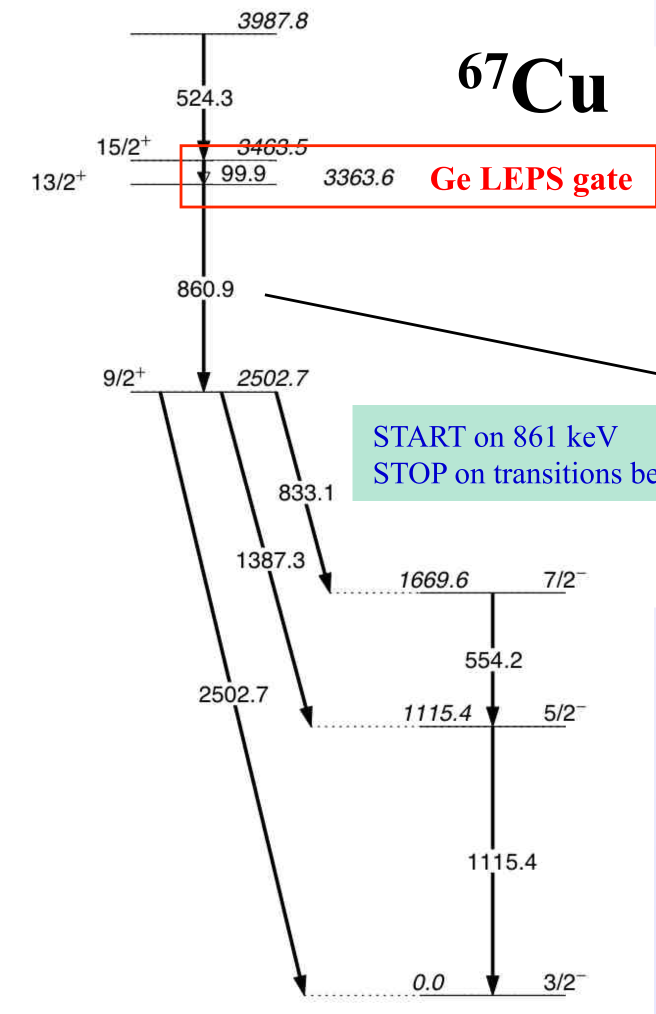
[D. Bucurescu & D. Pantelica, N. Marginean, C. Nita]

*$^{67}$Cu selected by gating on the 99.9 keV line observed with the HP-Ge LEPS*

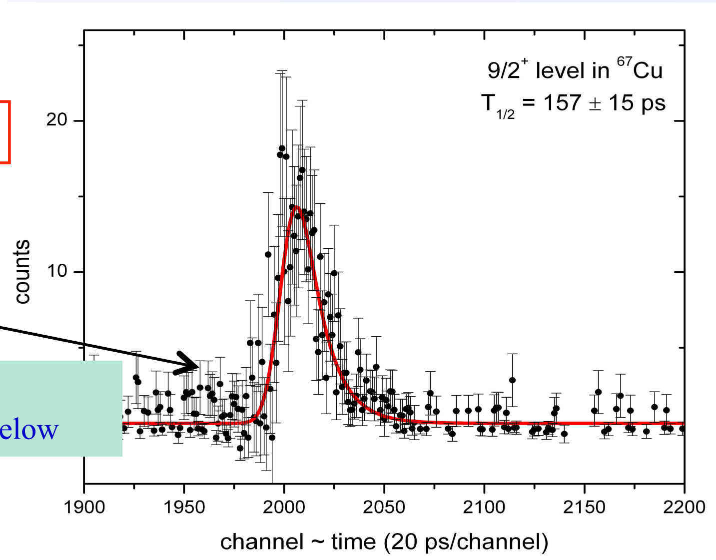


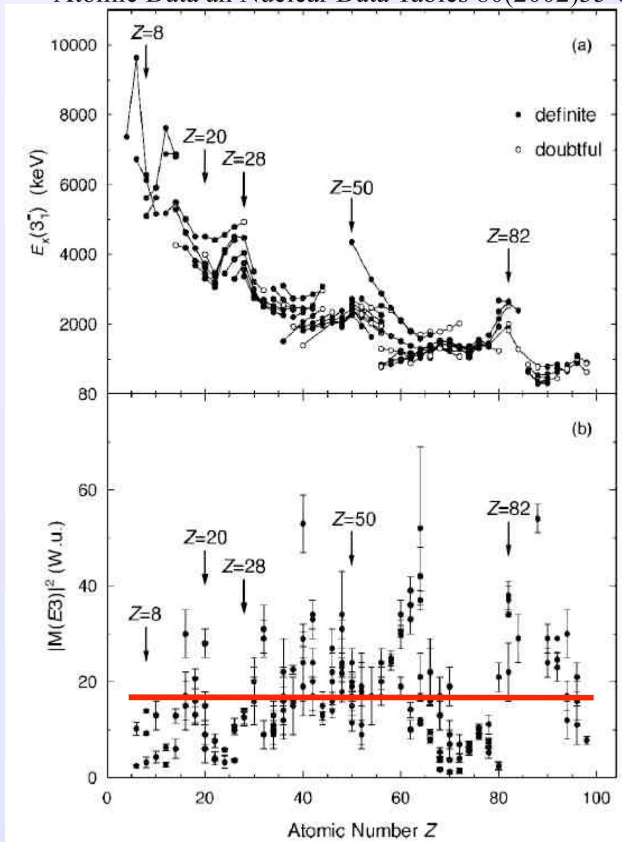
# Lifetime of positive-parity states in $^{67}$Cu




C. Nita et al.




T. Kibédi and R.H. Spear
Atomic Data an Nuclear Data Tables 80(2002)35-82



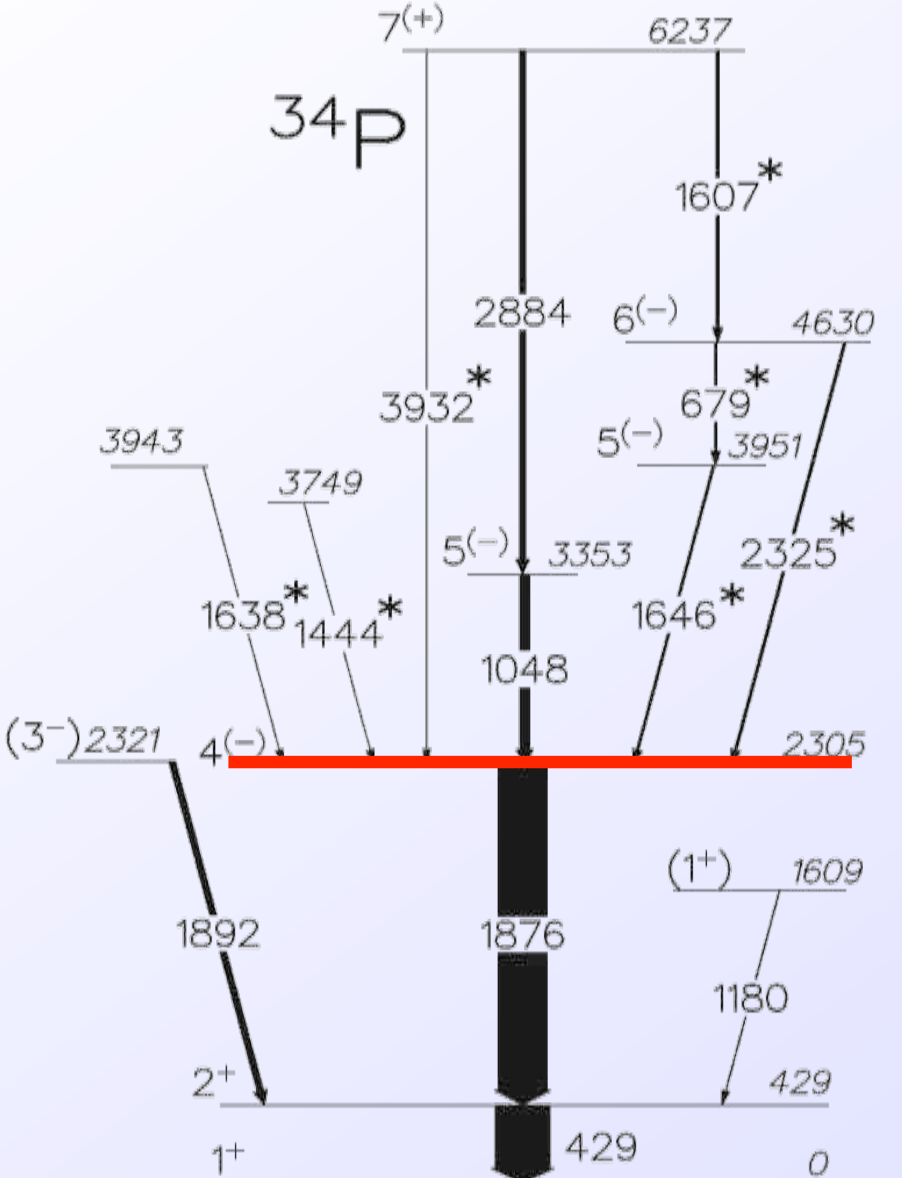

$T_{1/2}(9/2^{+}) = 157(15)$ ps

$^{67}$Cu B(E3; $9/2^{+}\rightarrow 3/2^{-}$) = 17(2) W.u.

It fits B(E3) systematics

But then… $^{67}$Cu B(E1; $\rightarrow 7/2^{-}_{1}$) = $2.6(3)\times 10^{-6}$ W.u.

# 4. M2 strengths close to island of inversion




R. CHAKRABARTI *et al* PHYSICAL REVIEW C **80**, 034326 (2009)

P. C. BENDER *et al.* PHYSICAL REVIEW C **80**, 014302 (2009)

- Recent study of $^{34}$P identified low-lying $I^{\pi}=4^{-}$ state at E=2305 keV.
- $2^{+}$ state based primarily on $[\pi 2s_{1/2} \times (\nu 1d_{3/2})^{-1}]$ configuration and $4^{-}$ state based primarily on $[\pi 2s_{1/2} \times \nu 1f_{7/2}]$ configuration: $f_{7/2} \rightarrow d_{3/2}$, M2 transition.
- Different admixtures in $2^{+}$ and $4^{-}$ states allow mixed M2/E3 transition

**The aim of experiment is to measure precision lifetime for 2305 keV state and obtain B(M2) and B(E3) values.**

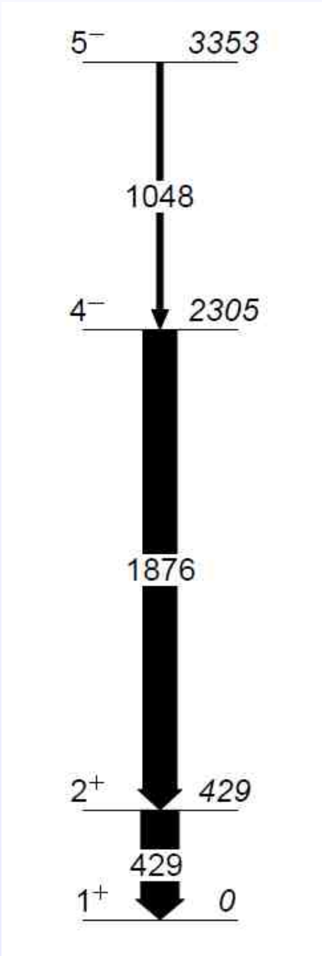
- Previous studies limit half-life to 0.3 ns < $t_{1/2}$ < 2.5ns
- New results by Bender et al. give δ=0 for mixing ratio but Chakrabarti et al. measured significant E3 mixing
- 2+ half life below 1 ps

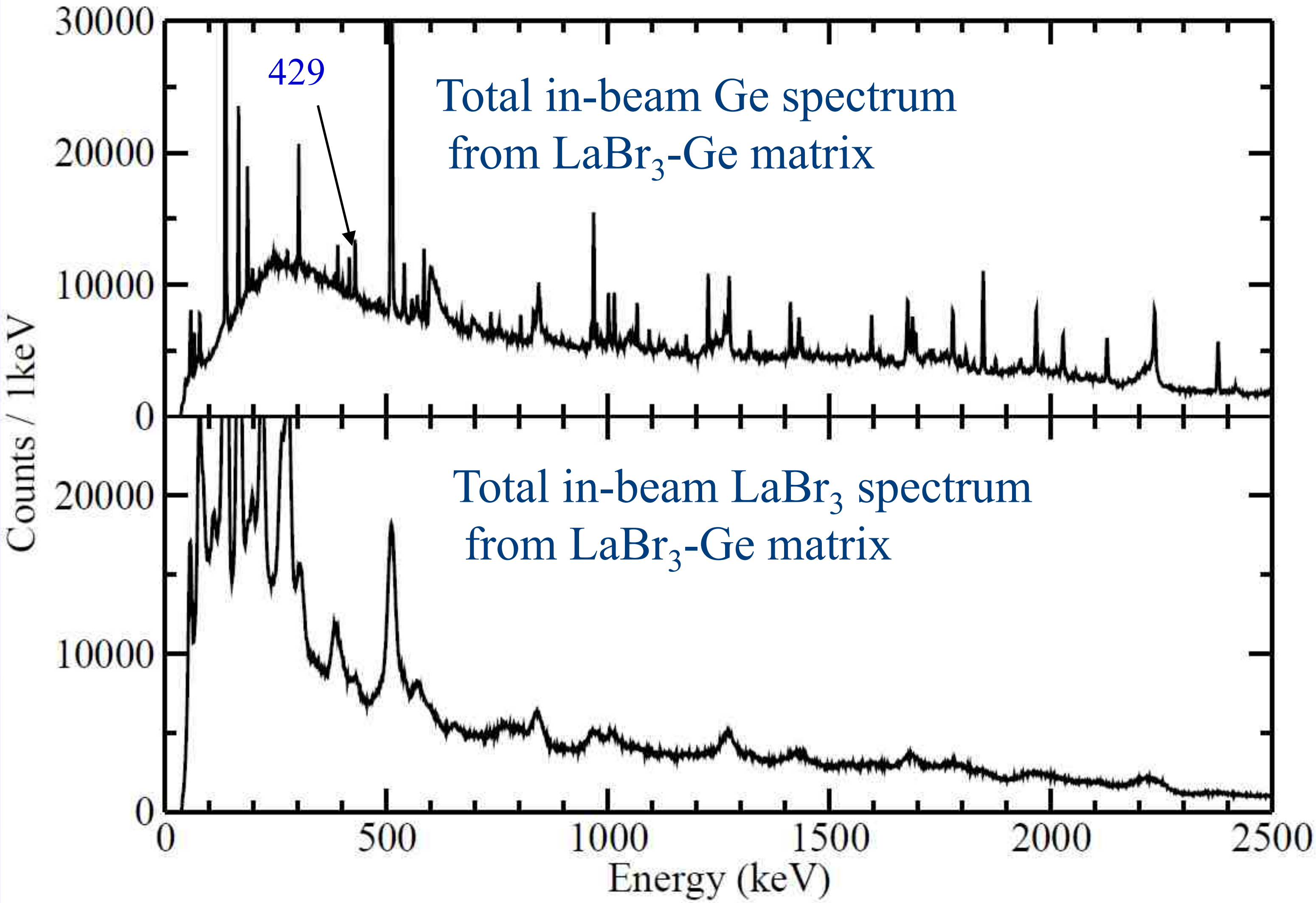
# Experiment at Bucharest

$^{18}O(^{18}O,pn)^{34}P$ fusion-evaporation at 36 MeV with ~ 5 – 10 mb

50mg/cm$^2$ $Ta_2{}^{18}O$ Enriched foil, $^{18}O$ Beam from Bucharest Tandem (~20pnA)

[P.H. Regan et al.]



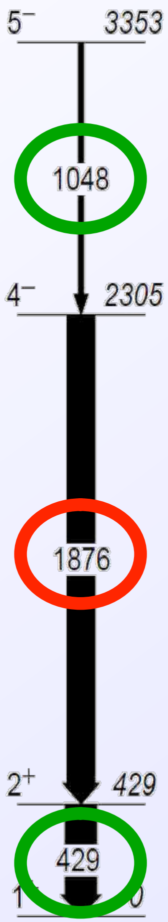
# Results

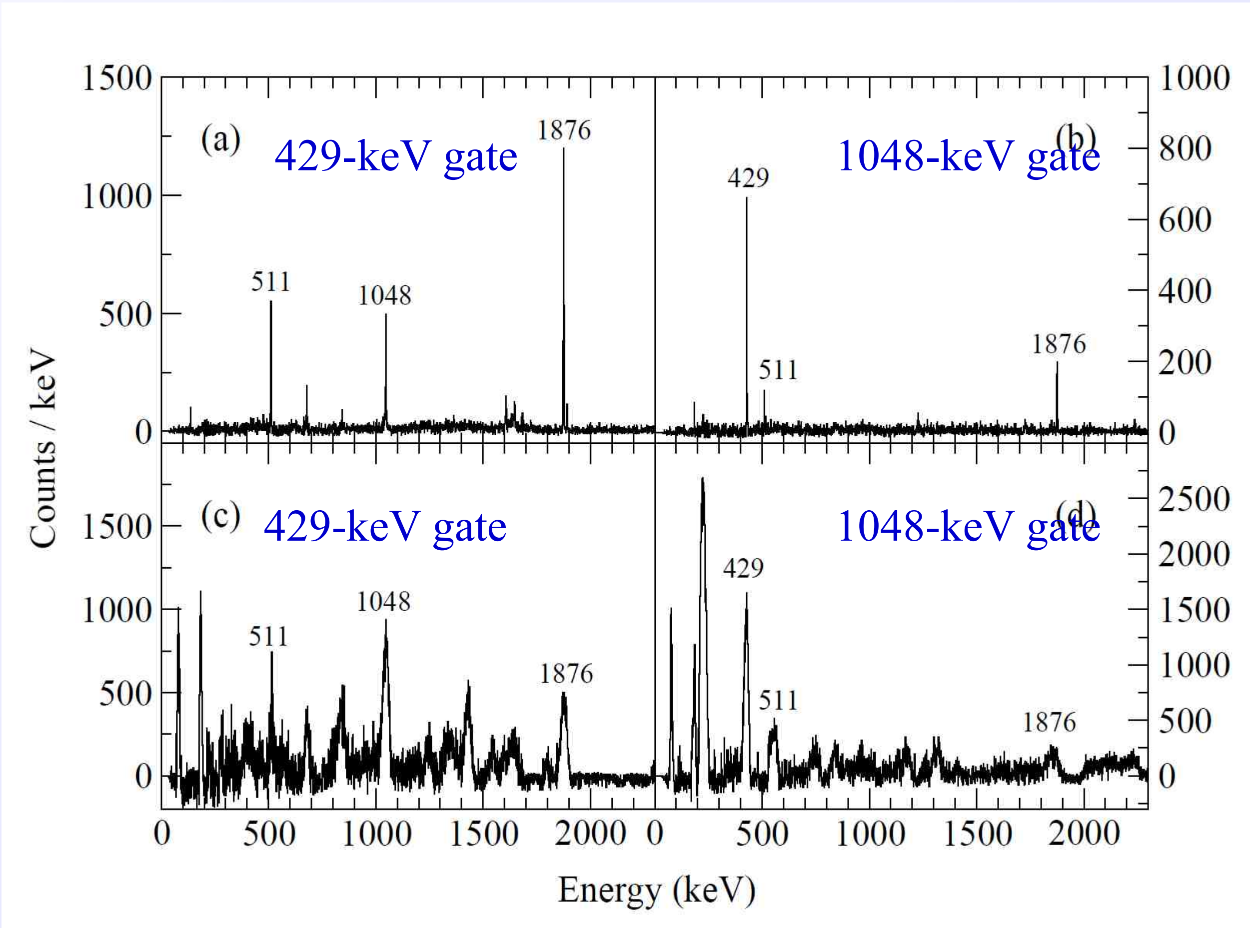
✓ HPGe gate on 1876-keV transition

→ $LaBr_3$ difference between 1048-keV and 429-keV

→ Assumes $2^+$ has negligible $T_{½}$

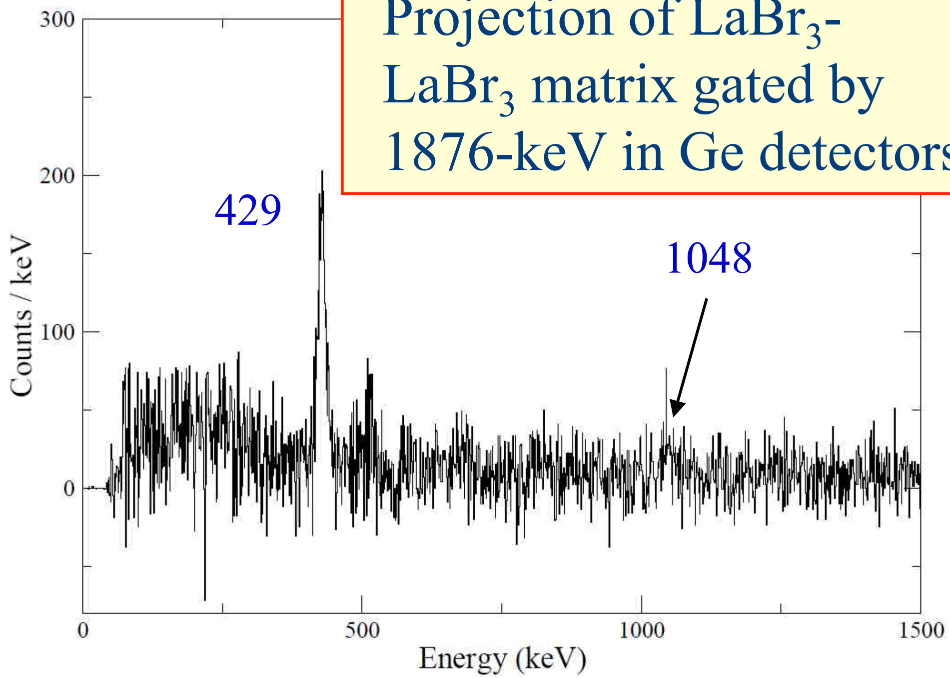
→ Otherwise limited statistics

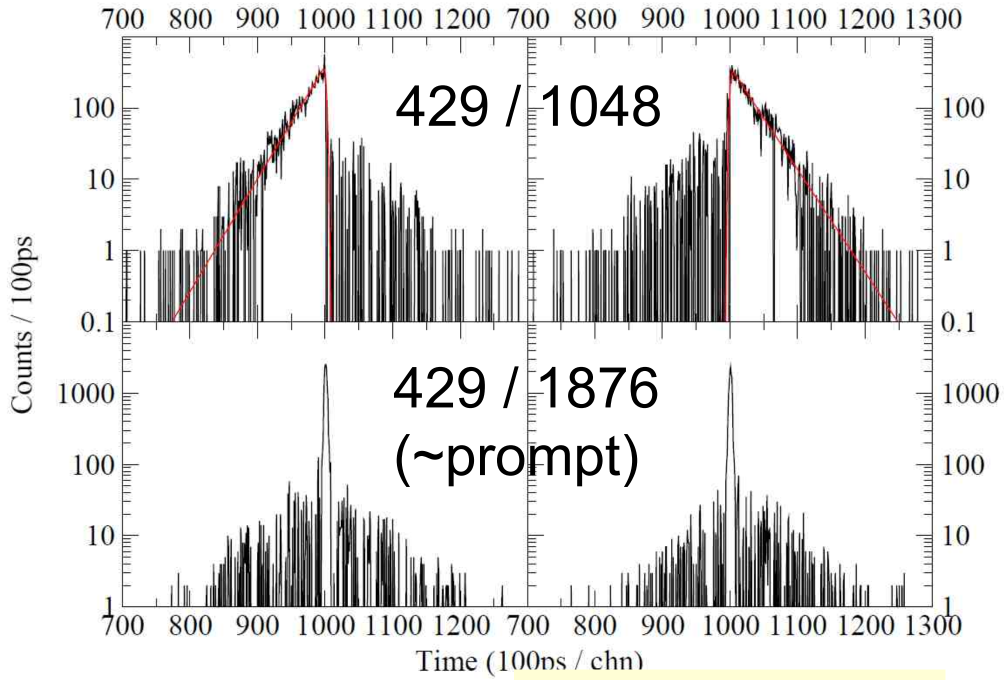


# Results

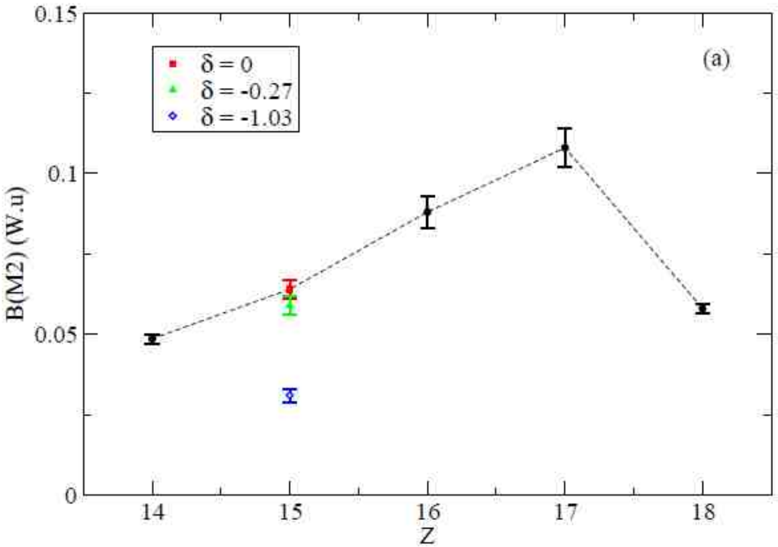
Projection of $LaBr_3$-$LaBr_3$ matrix gated by 1876-keV in Ge detectors

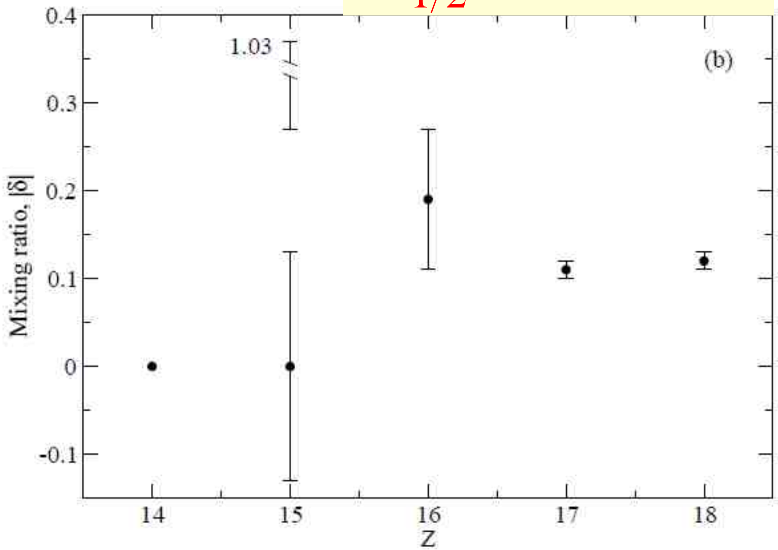


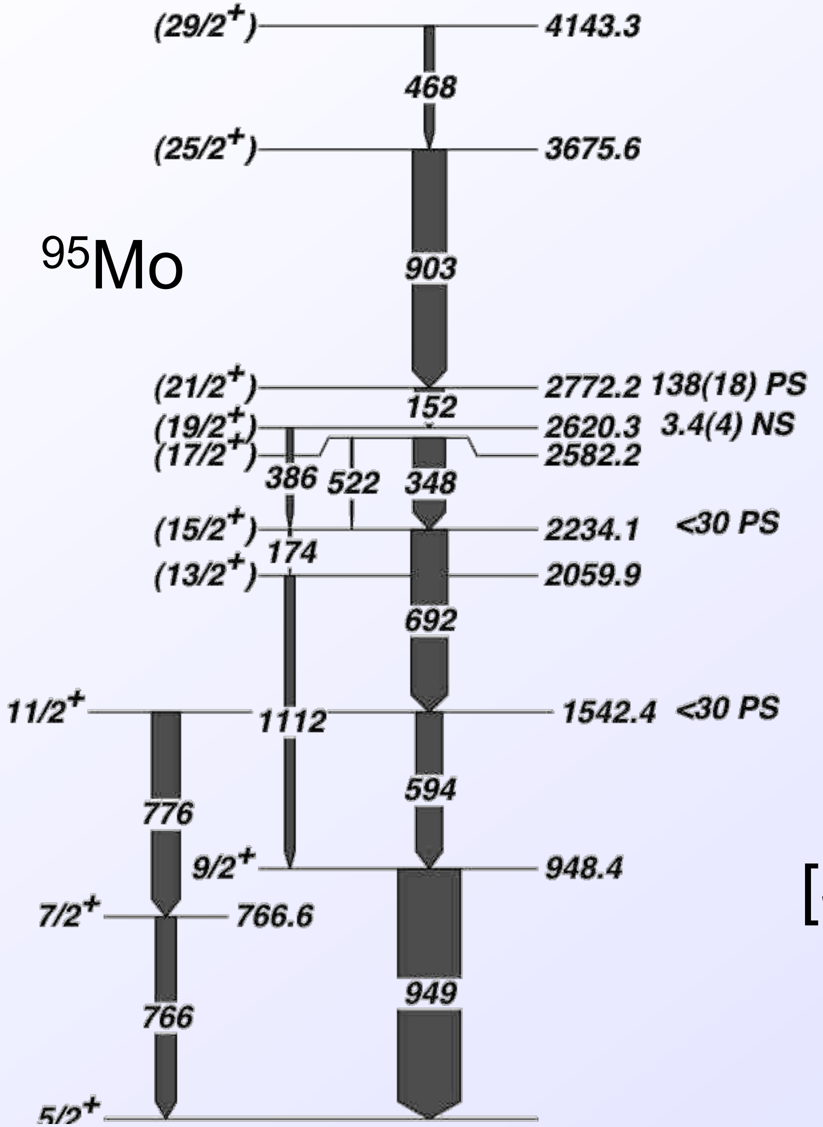

**[P.J.Mason et al., submitted to PRC]**

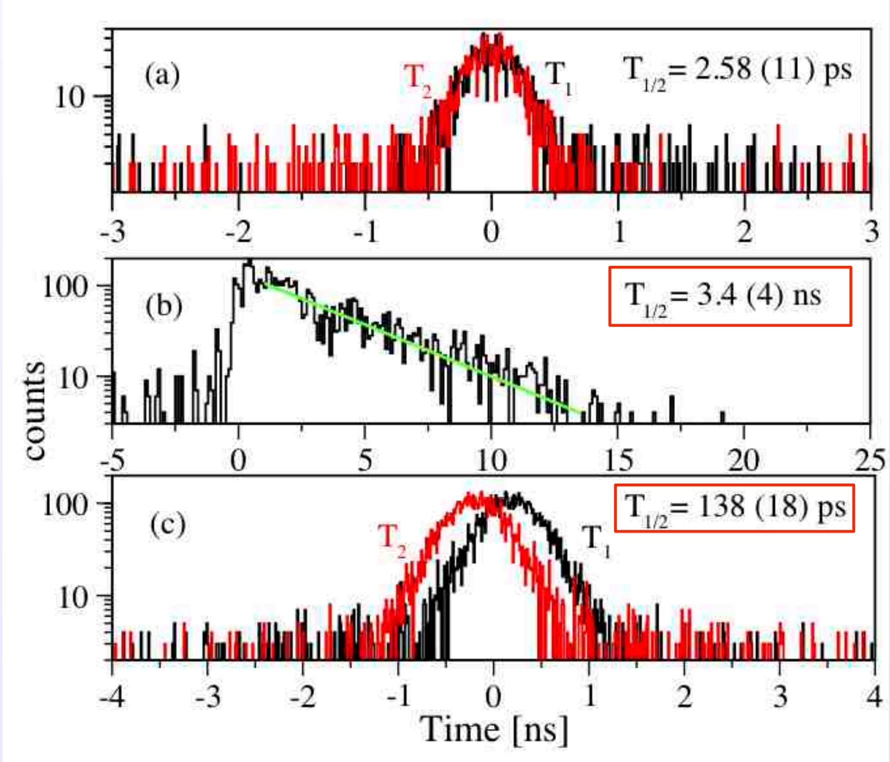
$T_{1/2} = 2.0(1)$ns



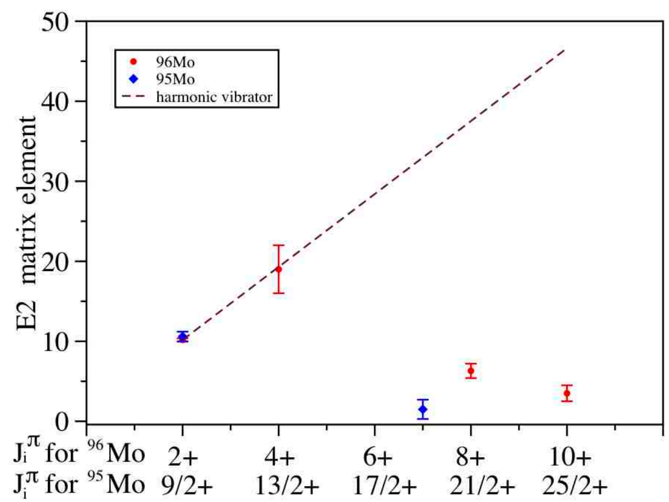



# 5. Interplay of sp and colectivity in Mo




[S. Lalkovski]




S.Kisyov et al., J.Phys.CS (submitted)
(arXiv:1112.5139v3)

# Conclusions

✓ Powerful technique

→ Application in several regions of interest

✓ Profit from scintillator/photosensor developments

→ Requires R&D and careful preparation of equipment

→ Needs accurate calibrations / understanding of systematics

✓ Experience gained

→ Beta decay

→ In beam

→ Arrays / mixed arrays

… and many results

✓ Looking forward to PRESPEC decay and FAIR

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…

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