

Fast timing studies at ISOLDE: highlights and perspectives

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Transition matrix elements

✓ Absolute transition matrix elements

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

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

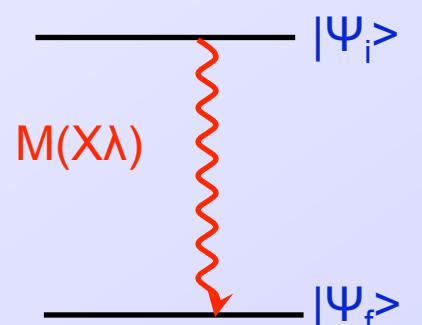
→ Single particle estimates

- Shell evolution
- Mirror symmetries

→ B(E2) values

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

→ Systematics



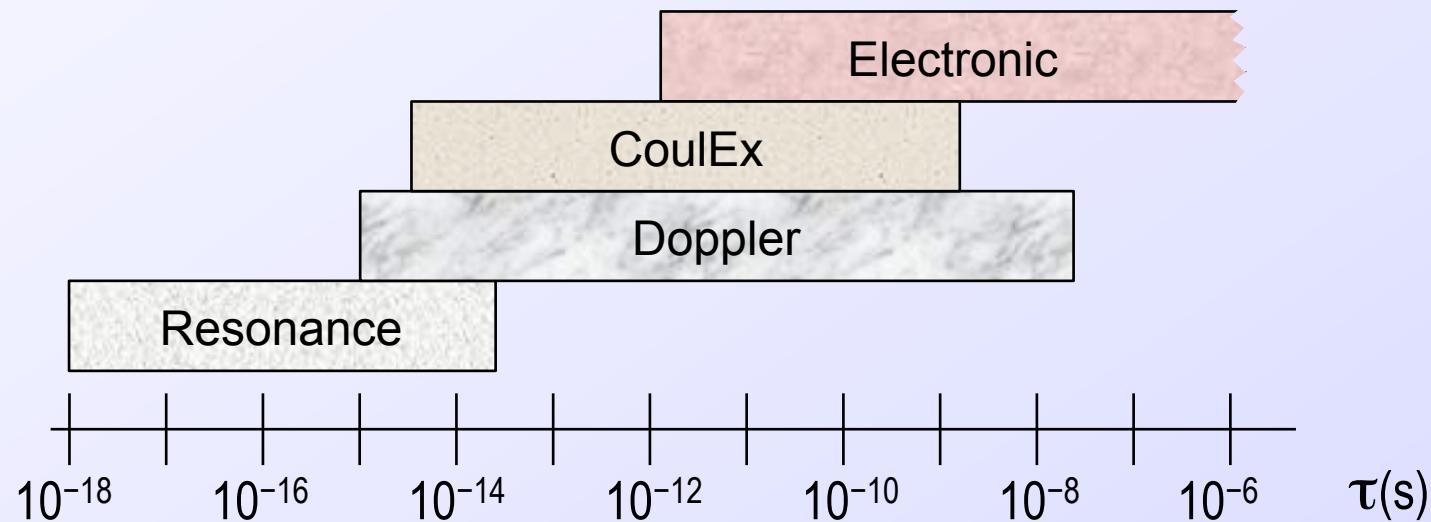
Nuclear half lives

→ Coulomb excitation

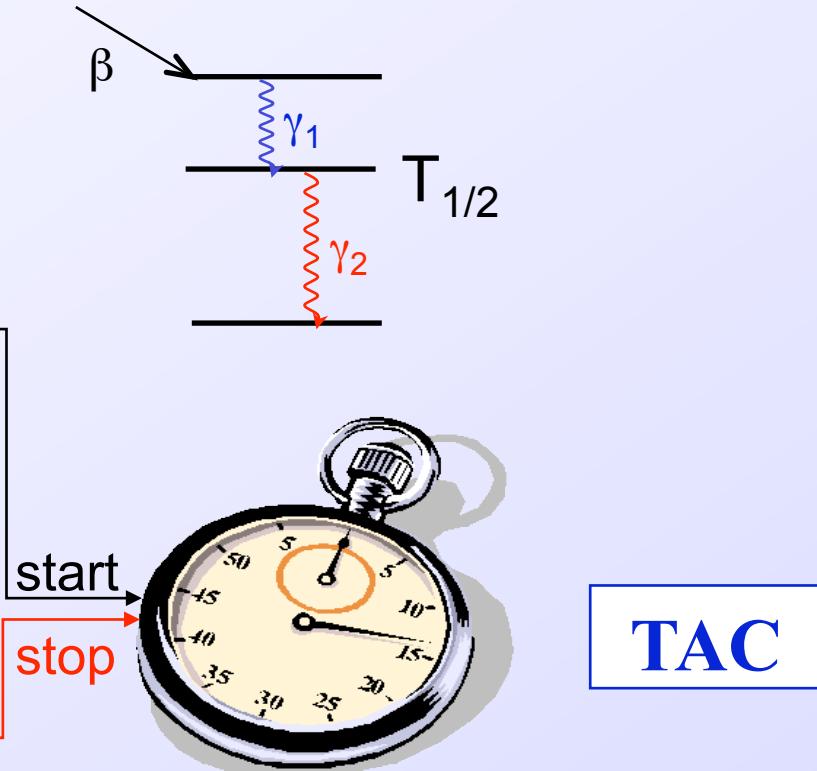
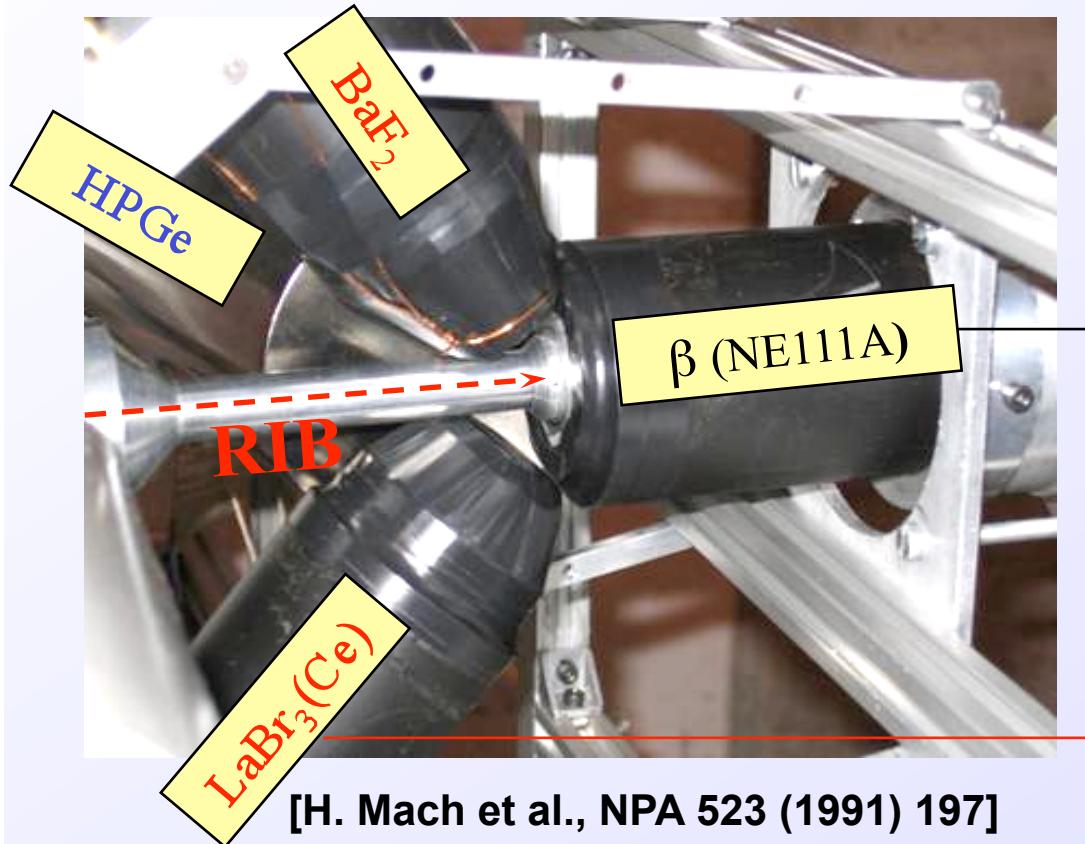
- Requires extra information / assumptions

→ Moments

Lifetimes



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



HPGe: BRANCH SELECTION

High energy resolution
Poor time response

Plastic β scintillator: TIMING

Fast response
Efficient start detector

$\text{LaBr}_3(\text{Ce})/\text{BaF}_2$: TIMING

Fast response γ -detectors
Poor energy resolution
Stop detectors

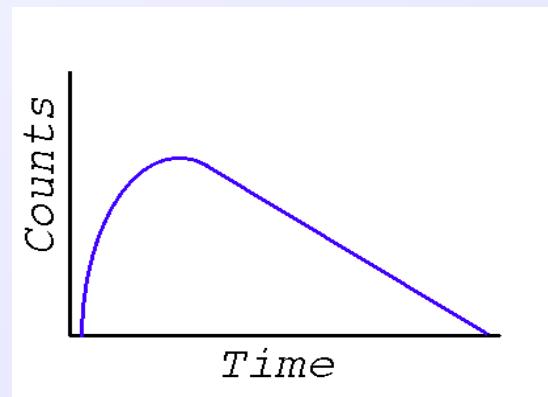
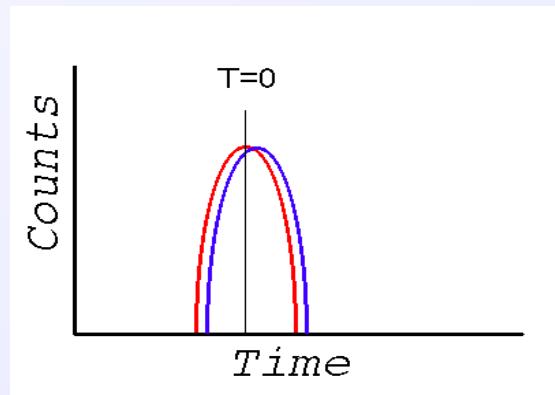
The Advanced Time Delayed $\beta\gamma\gamma(t)$ method

β -BaF₂-HPGe / β -LaBr₃-HPGe: lifetime measurements

TAC

De-convolution of slope

- Slope = $T_{1/2}$
- Range: 30 ps to 30 ns (or longer)



Centroid shift

- Shift in centroid position = τ
- Range: down to $\sim 5-10$ ps

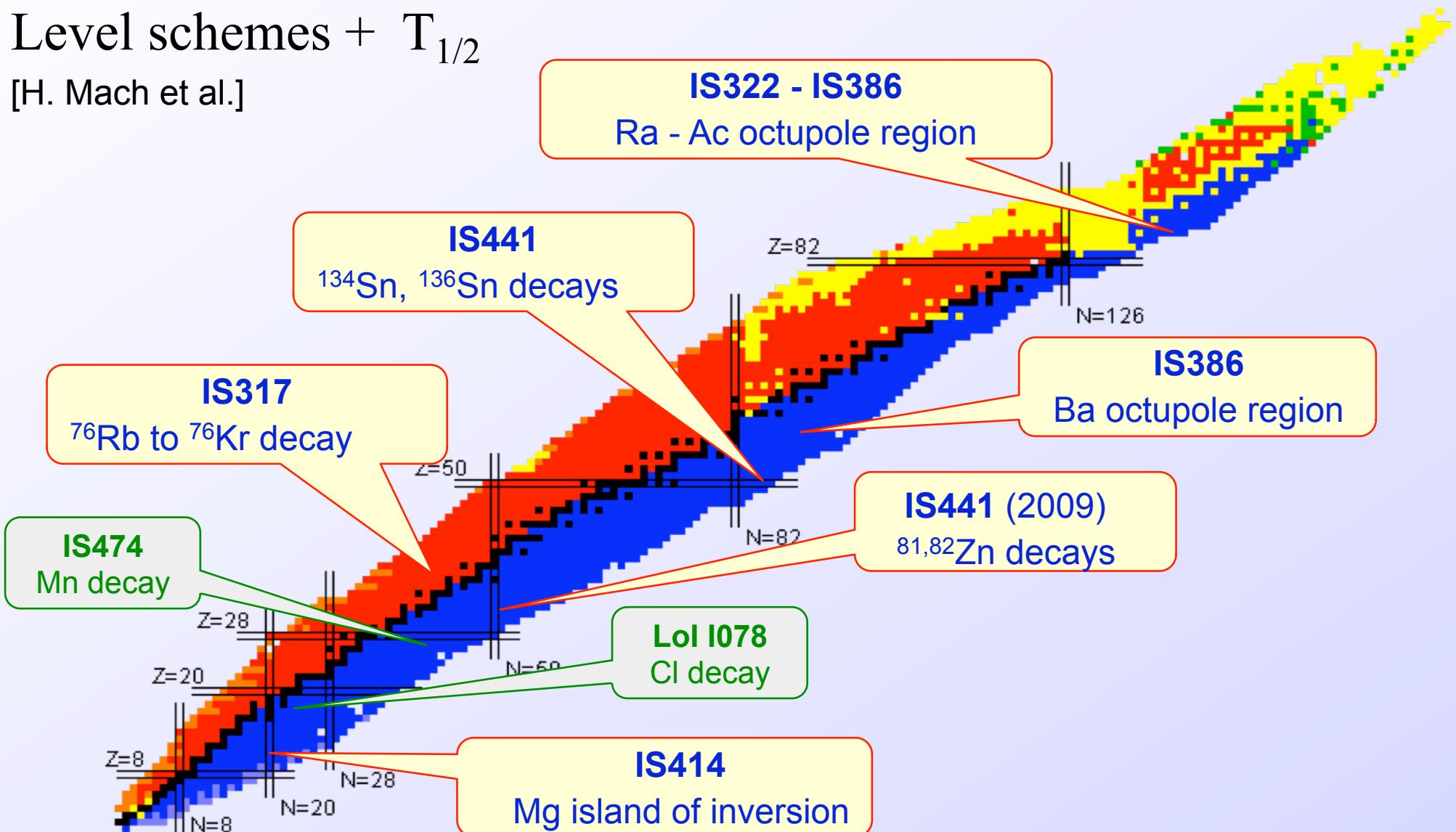
Time calibrations

β -HPGe-HPGe: coincidences, level scheme

ATD $\beta\gamma\gamma(t)$ studies at ISOLDE

Level schemes + $T_{1/2}$

[H. Mach et al.]

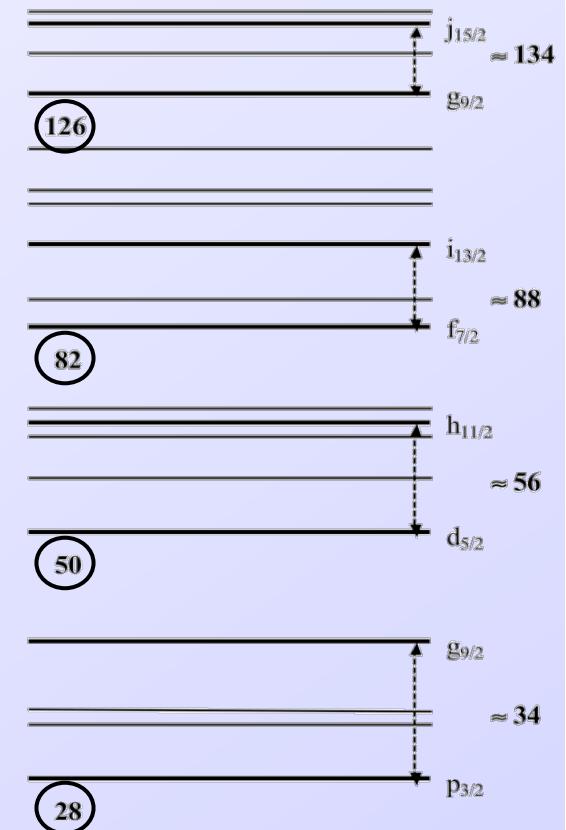


Octupole correlations A ~ 225

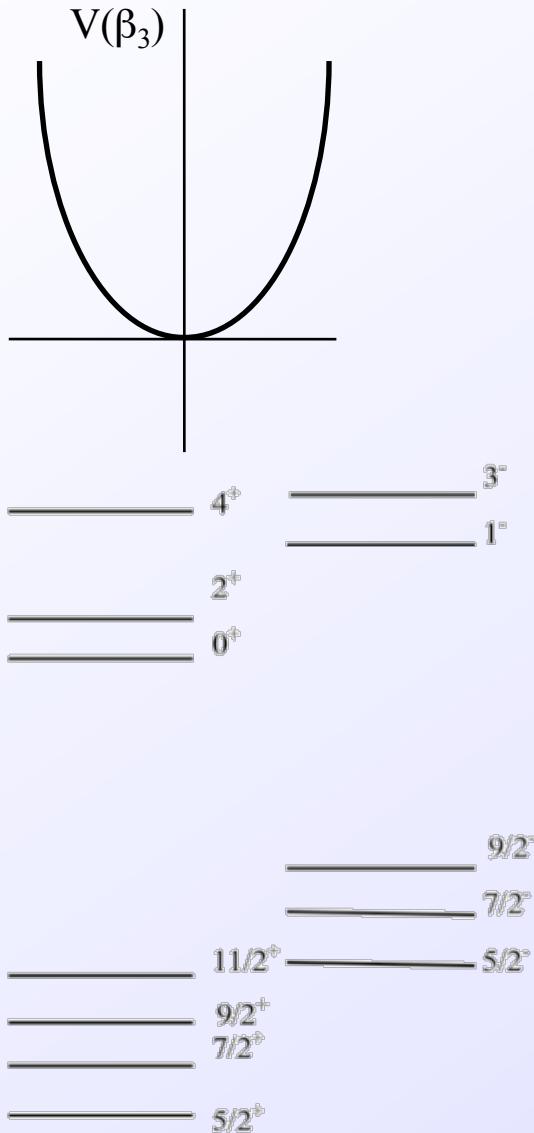
| | | | | | | | | | | | | | | | | | | | |
|----|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 92 | U 222 | U 223 | U 224 | U 225 | U 226 | U 227 | U 228 | U 229 | U 230 | U 231 | U 232 | U 233 | U 234 | U 235 | U 236 | U 237 | U 238 | U 239 | U 240 |
| | Pa 221 | Pa 222 | Pa 223 | Pa 224 | Pa 225 | Pa 226 | Pa 227 | Pa 228 | Pa 229 | Pa 230 | Pa 231 | Pa 232 | Pa 233 | Pa 234 | Pa 235 | Pa 236 | Pa 237 | Pa 238 | Pa 239 |
| 90 | Th 220 | Th 221 | Th 222 | Th 223 | Th 224 | Th 225 | Th 226 | Th 227 | Th 228 | Th 229 | Th 230 | Th 231 | Th 232 | Th 233 | Th 234 | Th 235 | Th 236 | Th 237 | Th 238 |
| | Ac 219 | Ac 220 | Ac 221 | Ac 222 | Ac 223 | Ac 224 | Ac 225 | Ac 226 | Ac 227 | Ac 228 | Ac 229 | Ac 230 | Ac 231 | Ac 232 | Ac 233 | Ac 234 | | 148 | |
| 88 | Ra 218 | Ra 219 | Ra 220 | Ra 221 | Ra 222 | Ra 223 | Ra 224 | Ra 225 | Ra 226 | Ra 227 | Ra 228 | Ra 229 | Ra 230 | Ra 231 | Ra 232 | Ra 233 | Ra 234 | | |
| | Fr 217 | Fr 218 | Fr 219 | Fr 220 | Fr 221 | Fr 222 | Fr 223 | Fr 224 | Fr 225 | Fr 226 | Fr 227 | Fr 228 | Fr 229 | Fr 230 | Fr 231 | Fr 232 | | 146 | |
| 86 | Rn 216 | Rn 217 | Rn 218 | Rn 219 | Rn 220 | Rn 221 | Rn 222 | Rn 223 | Rn 224 | Rn 225 | Rn 226 | Rn 227 | Rn 228 | Rn 229 | | | 144 | | |
| | At 215 | At 216 | At 217 | At 218 | At 219 | At 220 | At 221 | At 222 | At 223 | | 140 | 142 | | | | | | | |
| | 130 | 132 | 134 | 136 | 138 | | | | | | | | | | | | | | |

Microscopically
$$R(\theta, \varphi) = R_\alpha \left[1 + \sum_{\lambda, \mu} \alpha_{\lambda \mu} Y_{\lambda \mu}(\theta, \varphi) \right]$$

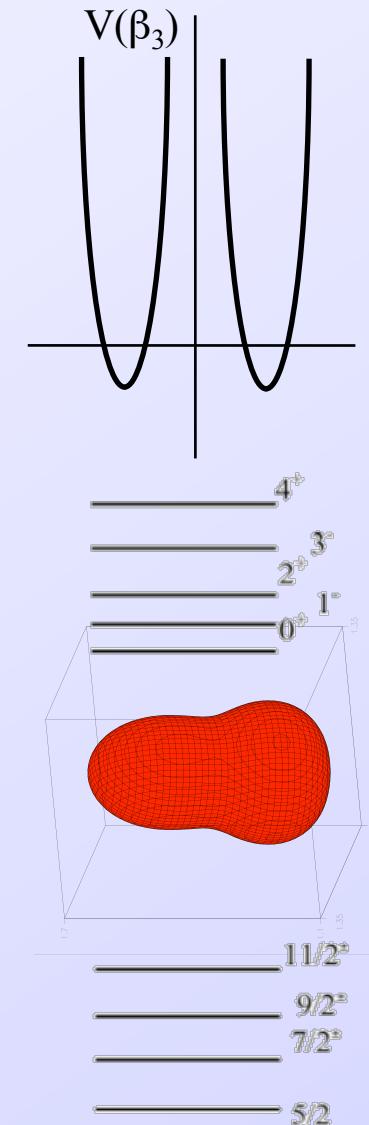
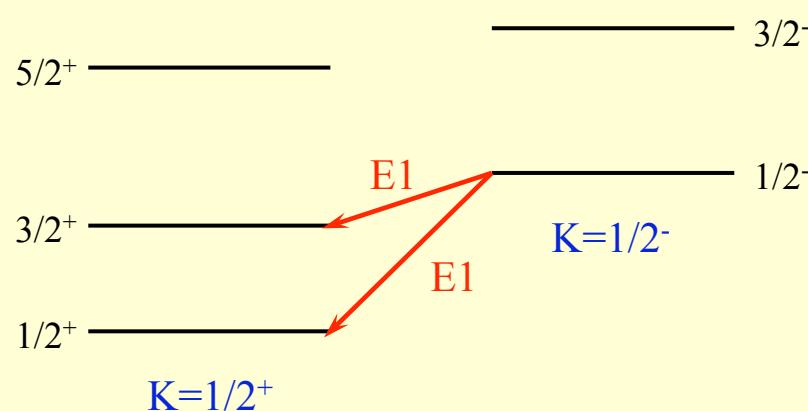
Butler & Nazarewicz, Rev. Mod. Phys. 68, 349 - 421 (1996)
J. F. Cocks et al., Phys. Rev. Lett. 78, 2920 - 2923 (1997)



Experimental signatures



- ✓ Low-lying parity doublets
 - (K, J^+) (K, J^-) bands
 - Enhanced $B(E1)$ s
- ✓ Transitional region
 - Interplay between quadrupole and octupole collectivities

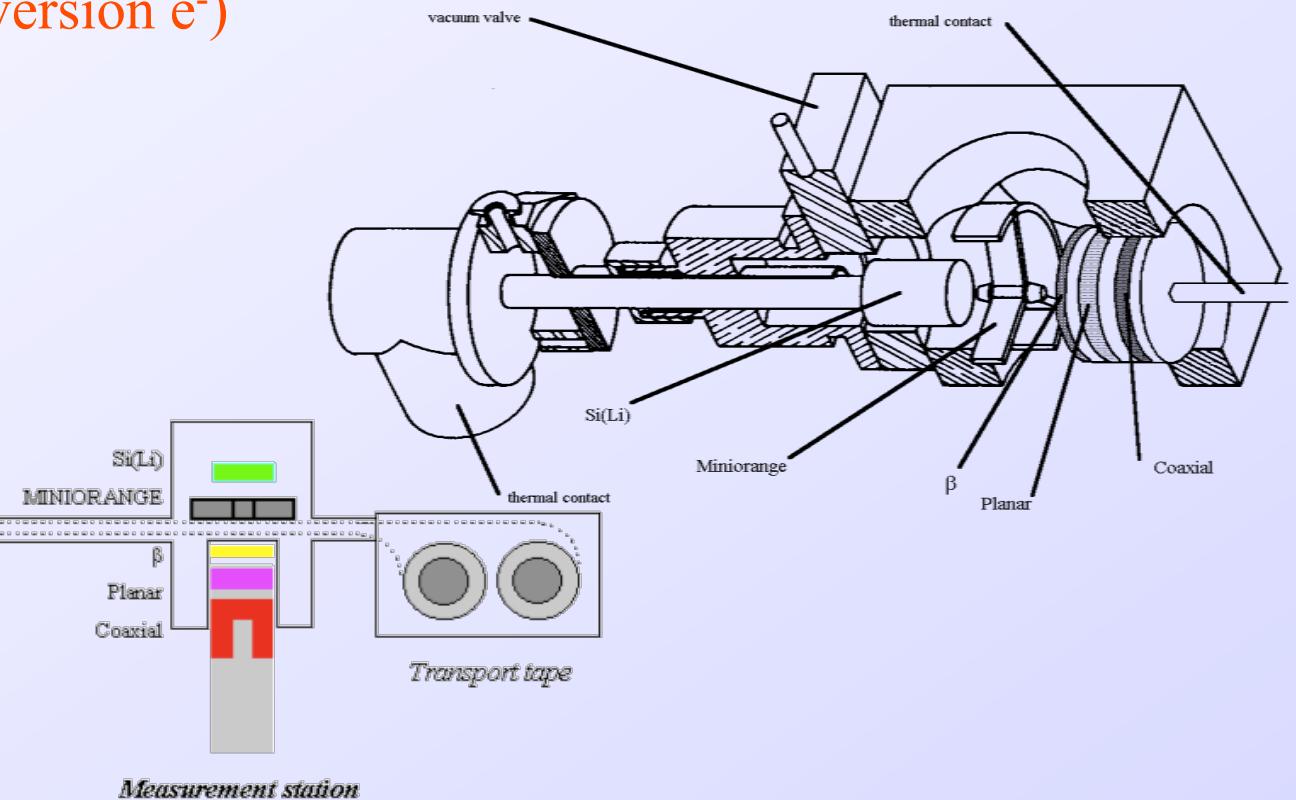
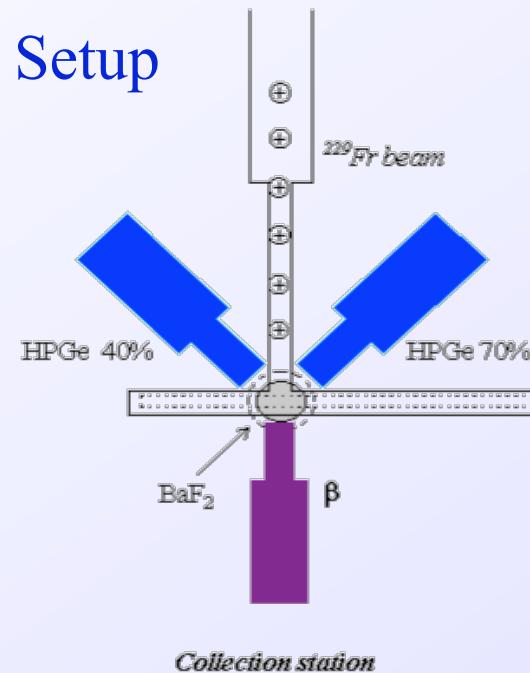


IS386 experiments

✓ Level scheme, transitions rates

- High resolution spectroscopy (coincidences)
- Multipolarities (conversion e^-)
- ATD for lifetimes

✓ Setup

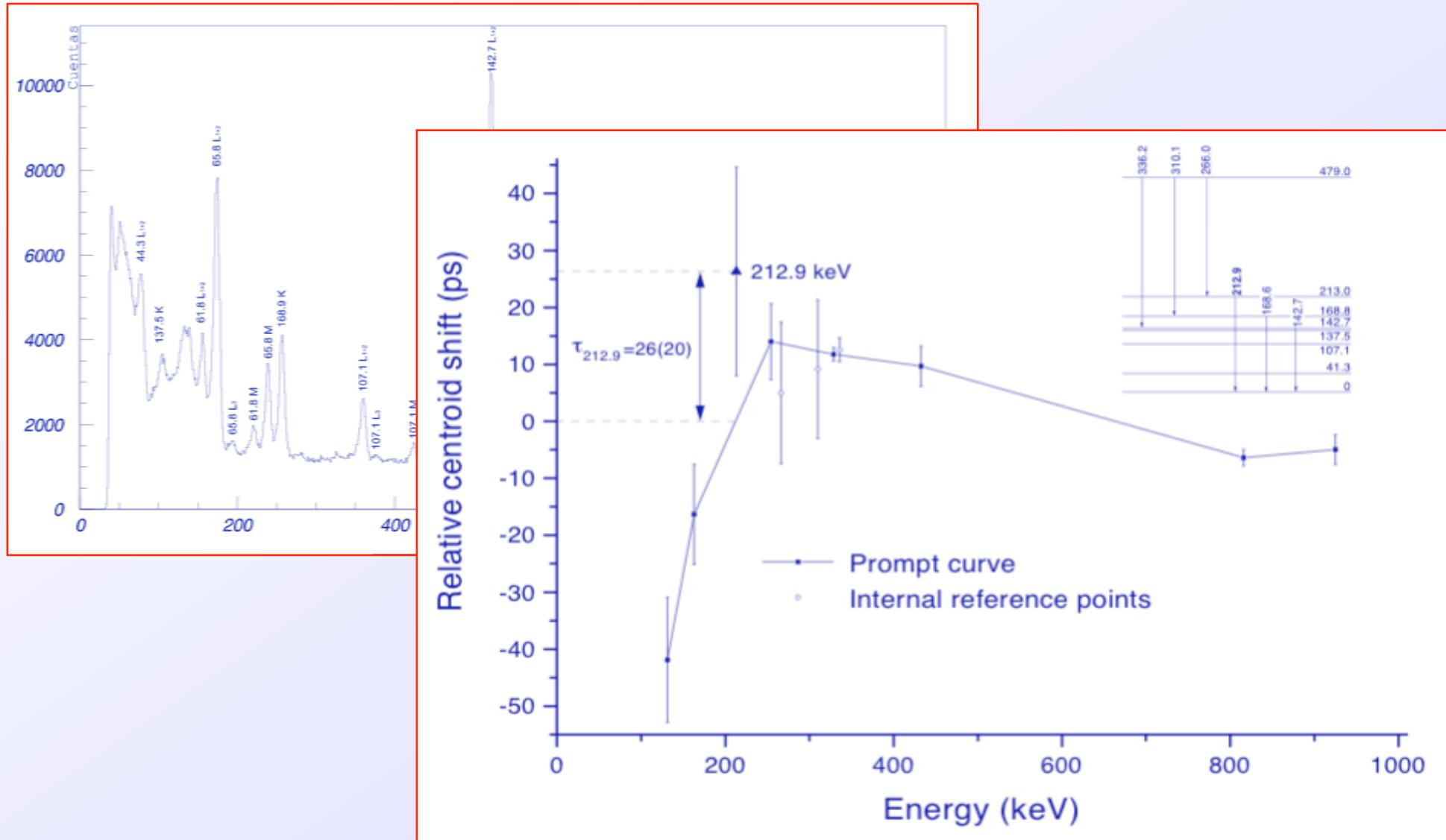


✓ Beta-decay from Ra and Fr isotopes



...

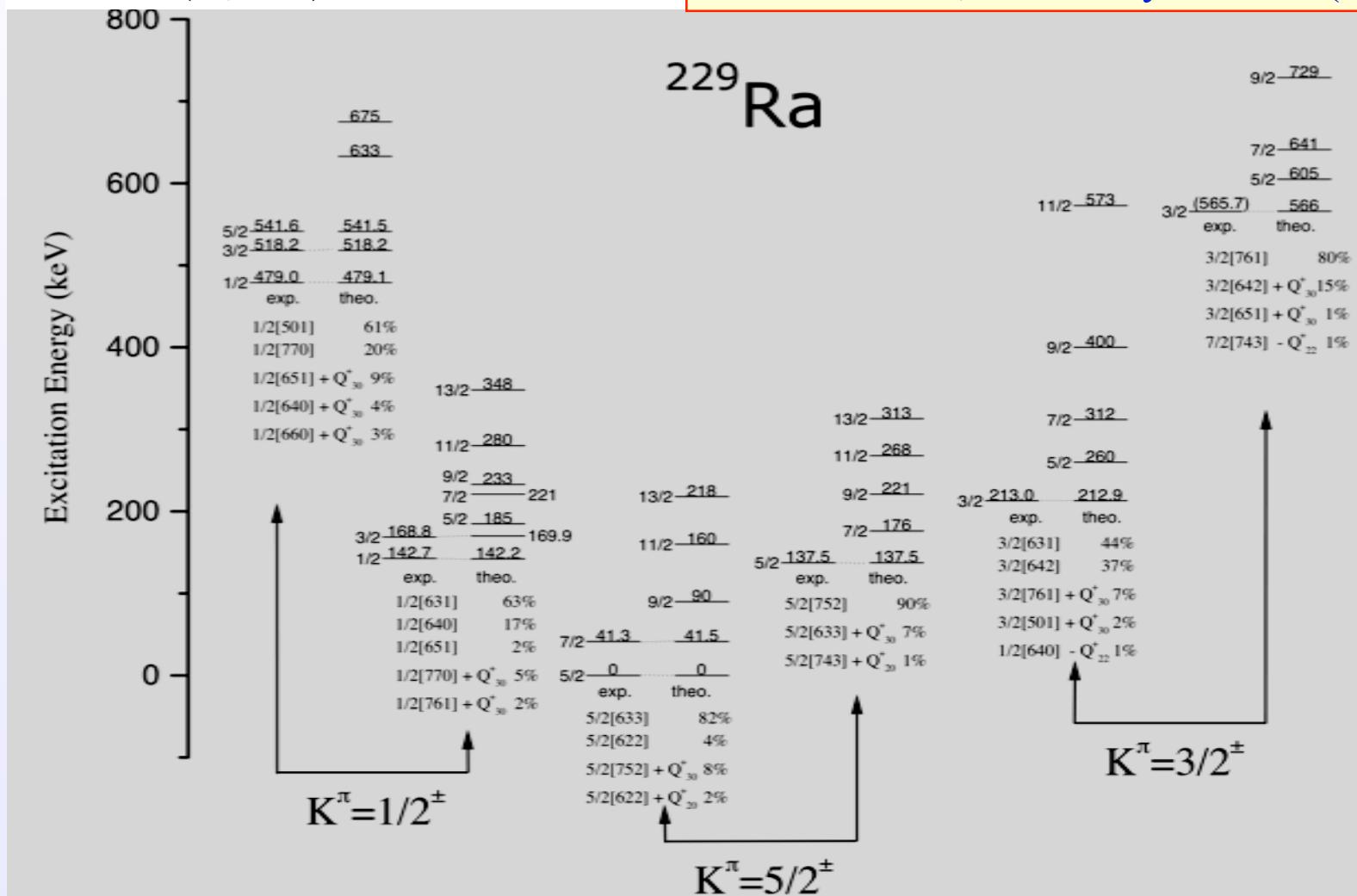
Some ^{229}Ra data



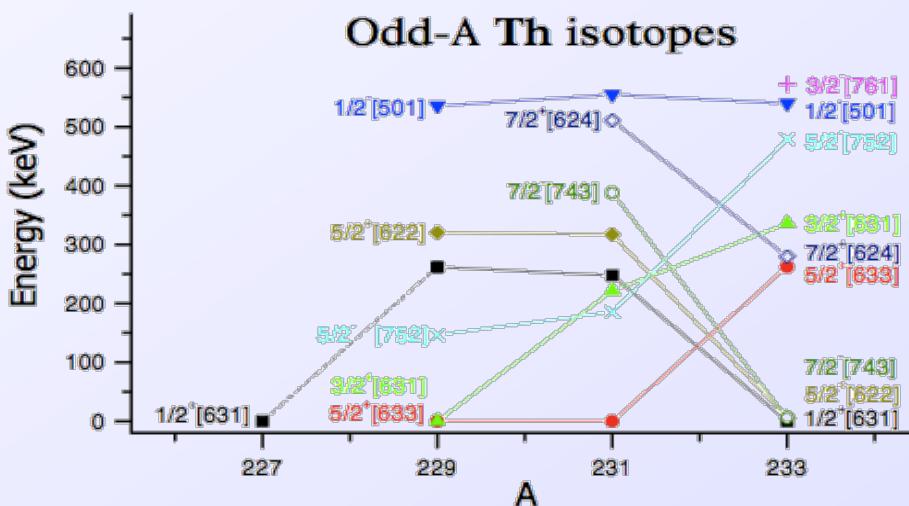
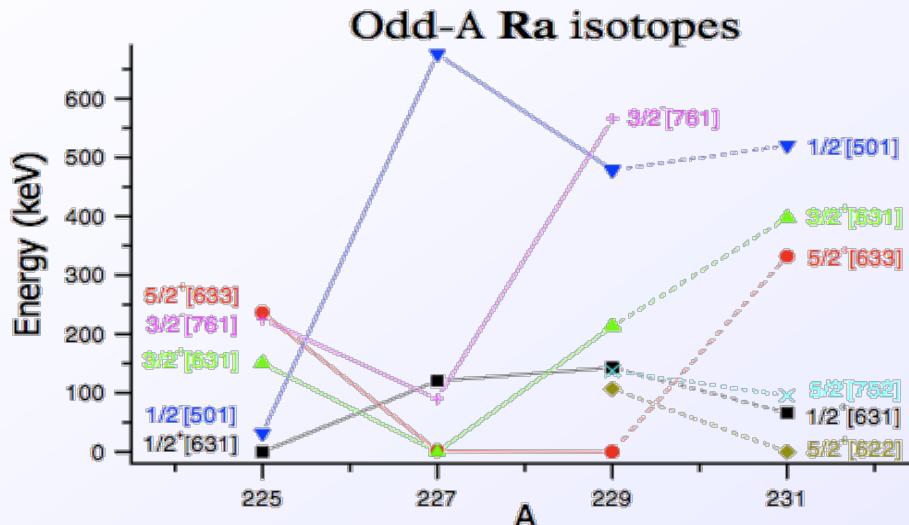
Interpretation

Rotor model plus quasiparticle-plus-phonon model (QPM) - J. Kvasil

A.J. Aas et al., Nucl. Phys. A 611 (1996) 281



Example of results



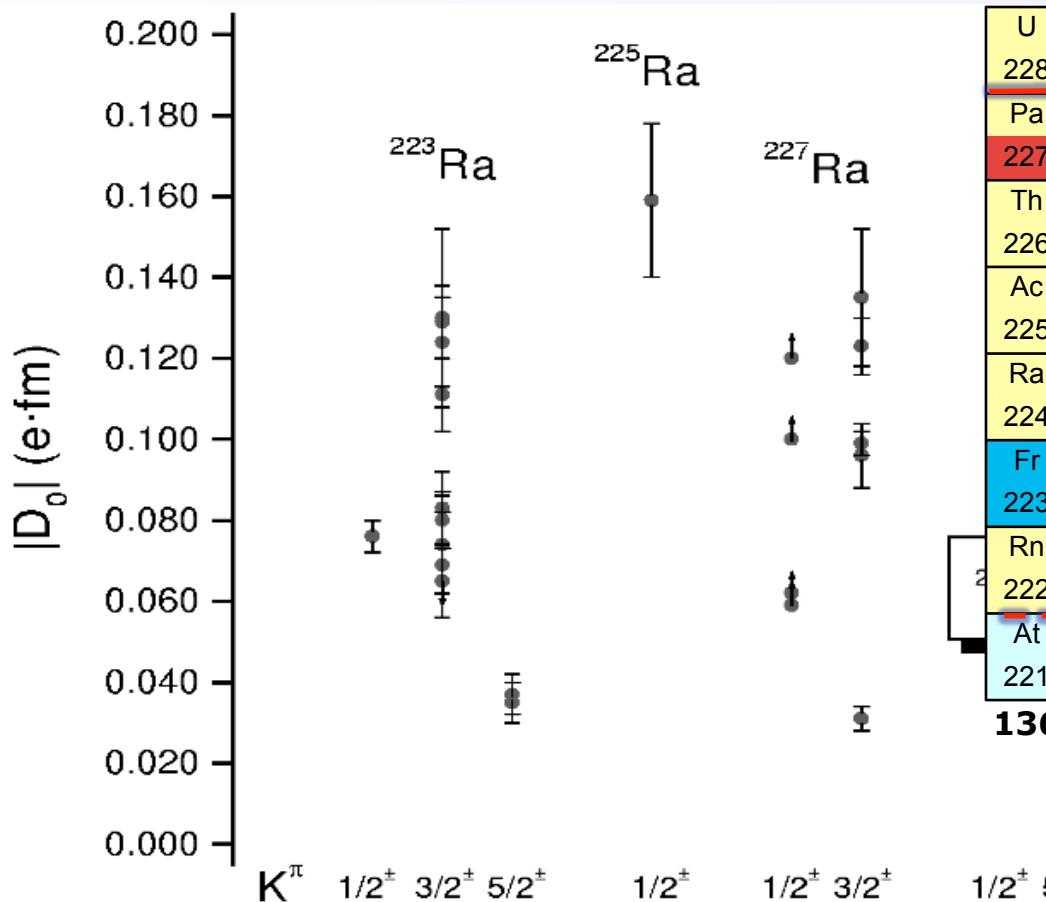
| | Level energy (keV) | J ^P | T _{1/2} |
|--------------|--------------------|------------------|------------------|
| 229Ra | 137.5 | 5/2 ⁻ | 0.66(4) ns |
| | 142.7 | 1/2 ⁺ | 17.23(12) ns |
| | 168.8 | 3/2 ⁺ | 106(18) ps |
| | 213.0 | 3/2 ⁺ | 18(14) ps |
| | 479.0 | 1/2 ⁻ | ≤ 30 ps |

| | Level energy (keV) | J ^P | T _{1/2} |
|--------------|--------------------|------------------|------------------|
| 231Ra | 66.2 | 1/2 ⁺ | ~53 μs |
| | 95.5 | 5/2 ⁻ | 4.72(6) ns |
| | 459.0 | () ⁺ | ≤ 15 ps |
| | 520.2 | 1/2 ⁻ | 92(5) ps |
| | 620.6 | | ≤ 12.5 ps |

$$B(E1; I_i \rightarrow I_f) = \frac{3}{4\pi} |\langle I_i K_{i10} | I_f K_f \rangle D_0 +$$

$$+ (-1)^{I_i + 1/2} \langle I_i - K_{i11} | I_f K_f \rangle D_1|^2$$

Octupole correlations



- ✓ Octupole correlations
 - Present but weak
 - ✓ Transition region
 - ✓ Odd A nuclei

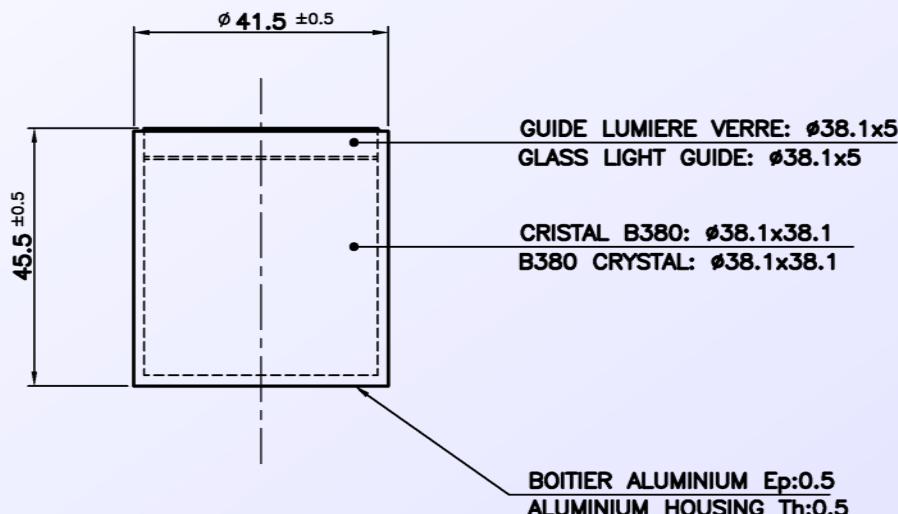
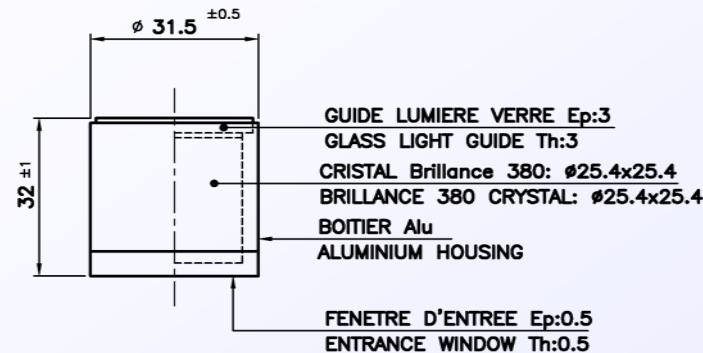
L.M. Fraile

L.M. Fraile et al., NPA 686 (2001) 71-108
K. Gulda et al., NPA 703 (2002) 45-69

R. Boutami et al., NPA 811 (2008) 244-275



LaBr₃(Ce) detectors



Larger crystals have a relatively better time resolution

25.4 x 25.4 mm since 2005

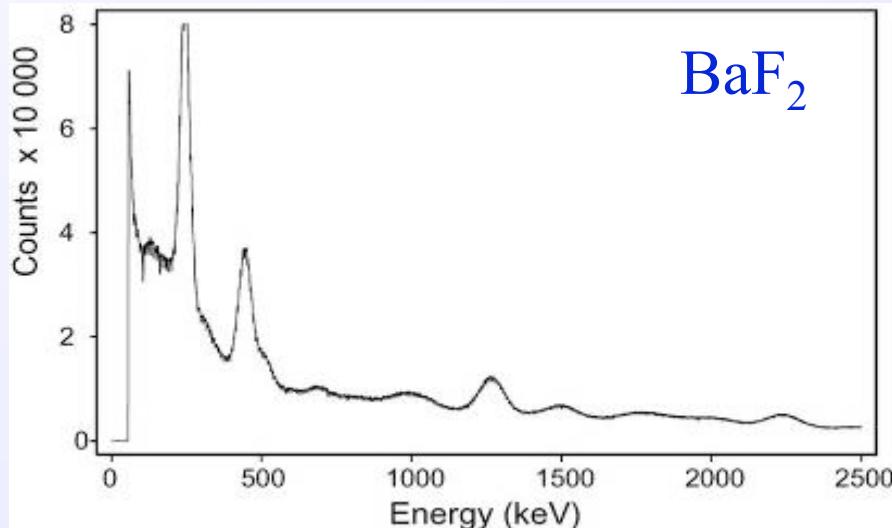
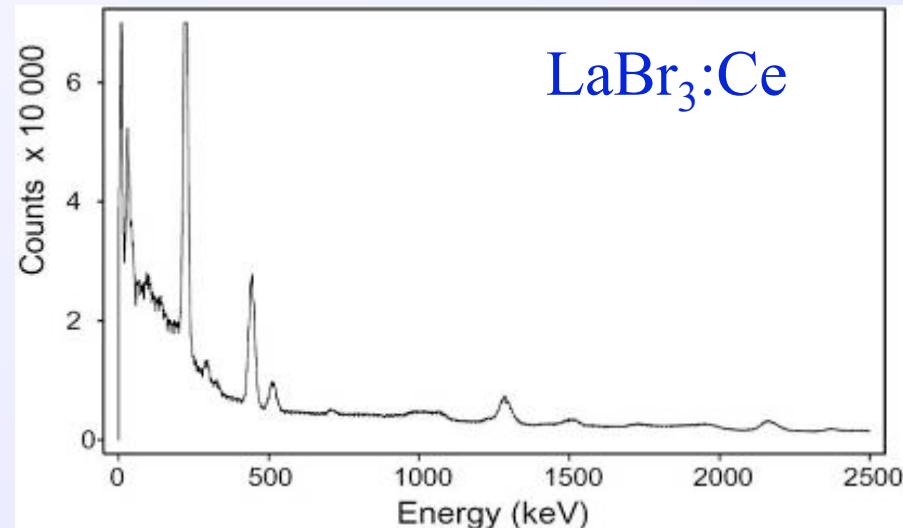
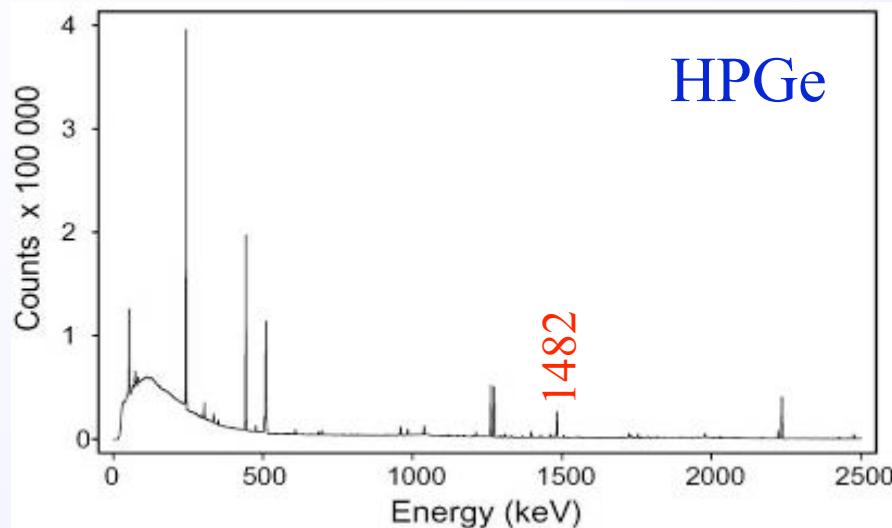
Time resolution 123(5) ps FWHM at 1.3 MeV



38.1 x 38.1 mm 5% Ce doping since 2007

Time resolution 150(10) ps FWHM at 1.3 MeV

Example from IS414: fast timing $\sim N=20$



All major lines can be resolved in LaBr₃ even in singles

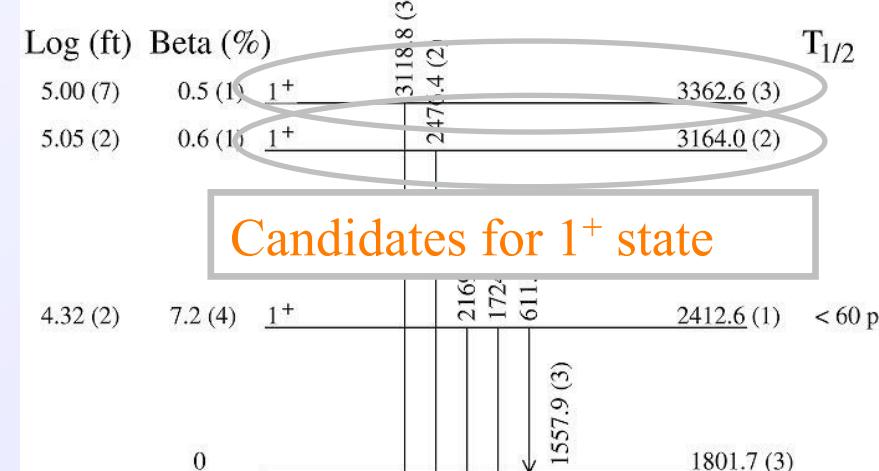
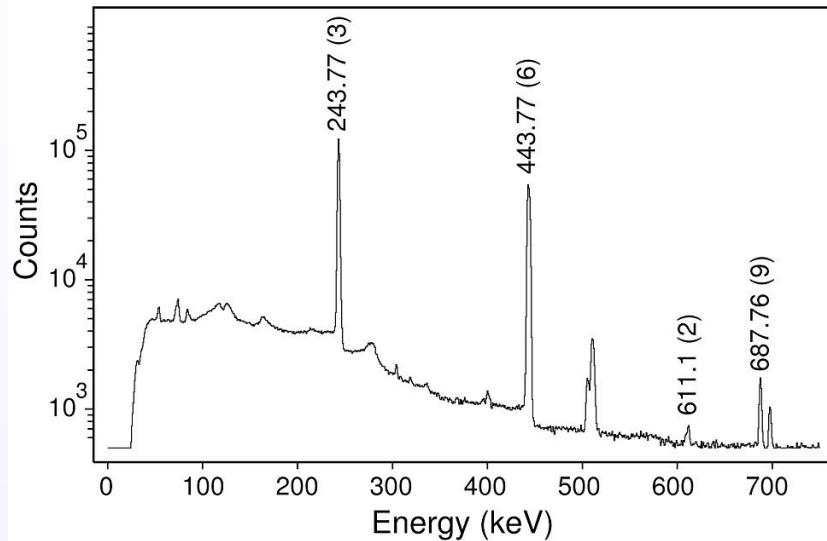
The situation improves in coincidences

The time resolution is similar for large BaF₂ (120 ps) and for LaBr₃ (130 ps) at ⁶⁰Co.

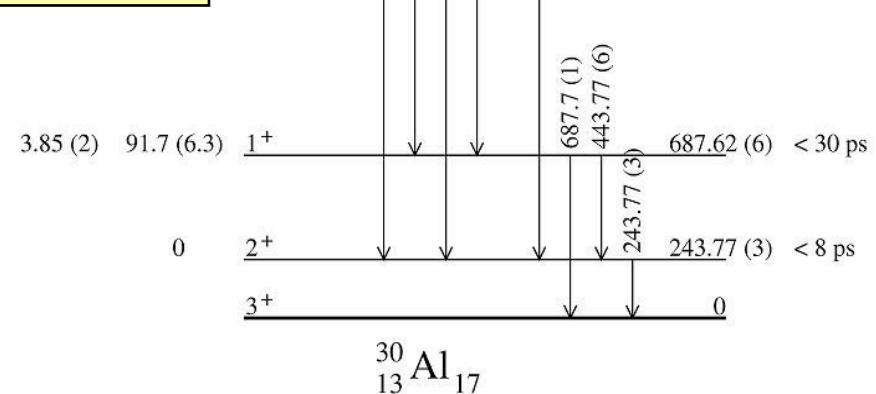
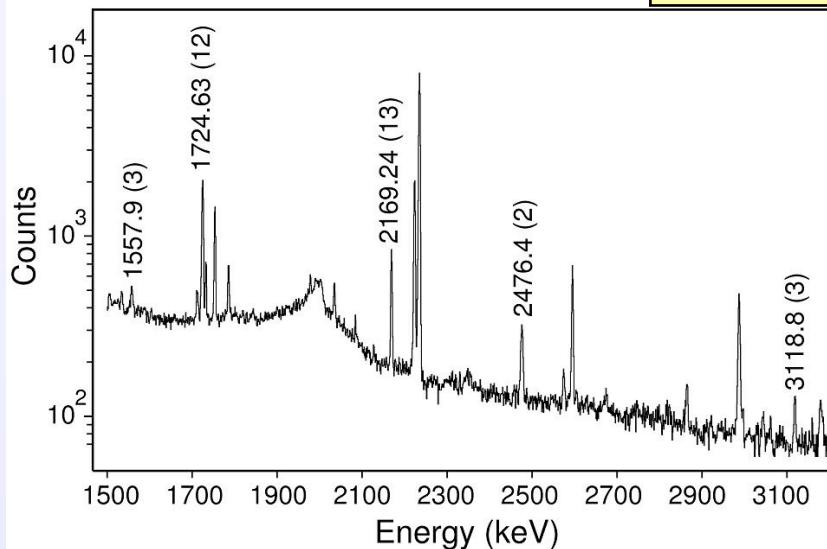
Much improved peak to Compton ratio,
critical in Fast Timing

Scattering from surrounding material of concern

Transition to the island of inversion: ^{30}Al



B. Olaizola, PRELIMINARY



XIA Digital system

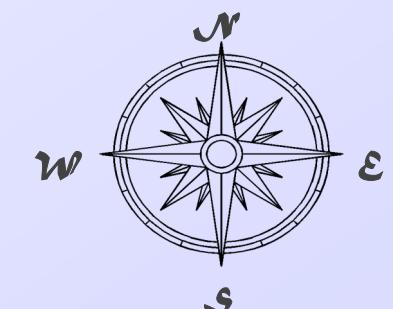
The region NE of ^{132}Sn

$\pi (0g_{7/2}, 1d_{5/2}, 1d_{3/2}, 2s_{1/2}, 0h_{11/2})^{Z=50}$

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--|--|--|
| | Cs 127 | Cs 128 | Cs 129 | Cs 130 | Cs 131 | Cs 132 | Cs 133 | Cs 134 | Cs 135 | Cs 136 | Cs 137 | Cs 138 | Cs 139 | Cs 140 | Cs 141 | Cs 142 | Cs 143 | Cs 144 | Cs 145 | Cs 146 | Cs 147 | Cs 148 | Cs 149 | Cs 150 | Cs 151 | Cs 152 | | | |
| 54 | Xe 126 | Xe 127 | Xe 128 | Xe 129 | Xe 130 | Xe 131 | Xe 132 | Xe 133 | Xe 134 | Xe 135 | Xe 136 | Xe 137 | Xe 138 | Xe 139 | Xe 140 | Xe 141 | Xe 142 | Xe 143 | Xe 144 | Xe 145 | Xe 146 | Xe 147 | 94 | 96 | | | | | |
| | I 125 | I 126 | I 127 | I 128 | I 129 | I 130 | I 131 | I 132 | I 133 | I 134 | I 135 | I 136 | I 137 | I 138 | I 139 | I 140 | I 141 | I 142 | I 143 | I 144 | I 145 | I 146 | I 147 | 92 | | | | | |
| 52 | Te 124 | Te 125 | Te 126 | Te 127 | Te 128 | Te 129 | Te 130 | Te 131 | Te 132 | Te 133 | Te 134 | Te 135 | Te 136 | Te 137 | Te 138 | Te 139 | Te 140 | Te 141 | Te 142 | | | | | | | | | | |
| | Sb 123 | Sb 124 | Sb 125 | Sb 126 | Sb 127 | Sb 128 | Sb 129 | Sb 130 | Sb 131 | Sb 132 | Sb 133 | Sb 134 | Sb 135 | Sb 136 | Sb 137 | Sb 138 | Sb 139 | | | 90 | | | | | | | | | |
| 50 | Sn 122 | Sn 123 | Sn 124 | Sn 125 | Sn 126 | Sn 127 | Sn 128 | Sn 129 | Sn 130 | Sn 131 | Sn 132 | Sn 133 | Sn 134 | Sn 135 | Sn 136 | Sn 137 | | | | | | | | | | | | | |
| | In 121 | In 122 | In 123 | In 124 | In 125 | In 126 | In 127 | In 128 | In 129 | In 130 | In 131 | In 132 | In 133 | In 134 | In 135 | | | | | 88 | | | | | | | | | |
| 48 | Cd 120 | Cd 121 | Cd 122 | Cd 123 | Cd 124 | Cd 125 | Cd 126 | Cd 127 | Cd 128 | Cd 129 | Cd 130 | Cd 131 | Cd 132 | | | | 86 | | | | | | | | | | | | |
| | Ag 119 | Ag 120 | Ag 121 | Ag 122 | Ag 123 | Ag 124 | Ag 125 | Ag 126 | Ag 127 | Ag 128 | Ag 129 | Ag 130 | | 84 | | | | | | | | | | | | | | | |
| 46 | Pd 118 | Pd 119 | Pd 120 | Pd 121 | Pd 122 | Pd 123 | Pd 124 | | | | | | 80 | | 82 | | | | | | | | | | | | | | |
| | 72 | 74 | 76 | 78 | | | | | | | | | | | | | | | | | | | | | | | | | |

$^{132}\text{Sn core}$

$\nu (1f_{7/2}, 0h_{9/2}, 1f_{5/2}, 2p_{3/2}, 2p_{1/2}, 0i_{13/2})^{N=82}$



Simple nuclei above ^{132}Sn

- ✓ Nuclear structure close to the N=82 Z=50 double shell closure
 - Understanding of the effect of large N/Z
 - Transition rates required to constraint calculations (^{135}Sb)
 - Experimental information needed to define better the M1 operator parameters north-east of ^{132}Sn
 - Evolution of collectivity
- ✓ Topical region for r-process
 - Nuclear input for modeling
 - Waiting points
- ✓ IS441 fast-timing experiment at ISOLDE
 - Sn separated using molecular beams of SnS^+
 - Application of $\text{LaBr}_3(\text{Ce})$ to timing

Fast timing RESULTS on ^{134}Sb , ^{135}Sb and ^{136}Te

^{135}Sb ($^{132}\text{Sn} + \text{p} + 2\text{n}$) status

✓ Fission of ^{248}Cm

→ Yrast levels, $\pi g_{7/2}, (\nu f_{7/2})^2$ configuration

[Bhattacharyya et al. Eur. Phys. J. A3 (1998) 109]

✓ Beta decay at OSIRIS and ISOLDE

→ Low energy of $5/2^+$ at 282 keV!

[A. Korgul et al., Phys. Rev. C64 (2001) 021302(R)]

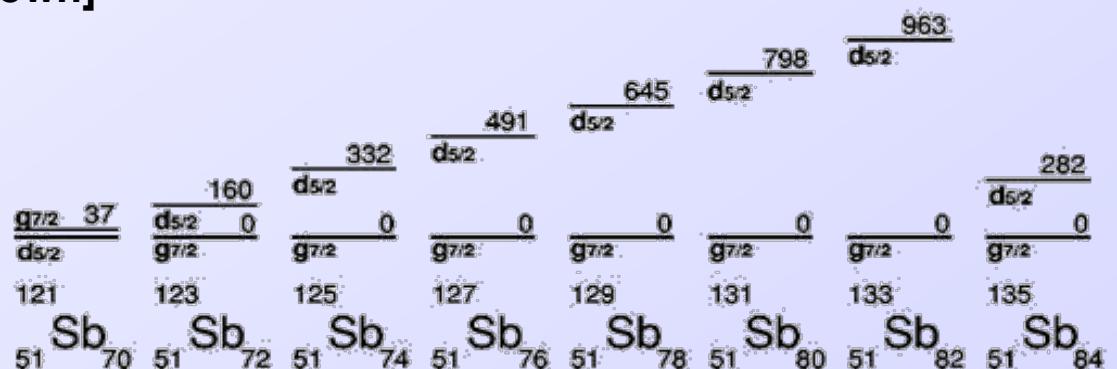
[J. Shergur et al., Phys. Rev. C65 (2002) 034313]

✓ Systematics $d_{5/2}, g_{7/2}$ [B.A. Brown]

→ Diffuse nuclear surface?

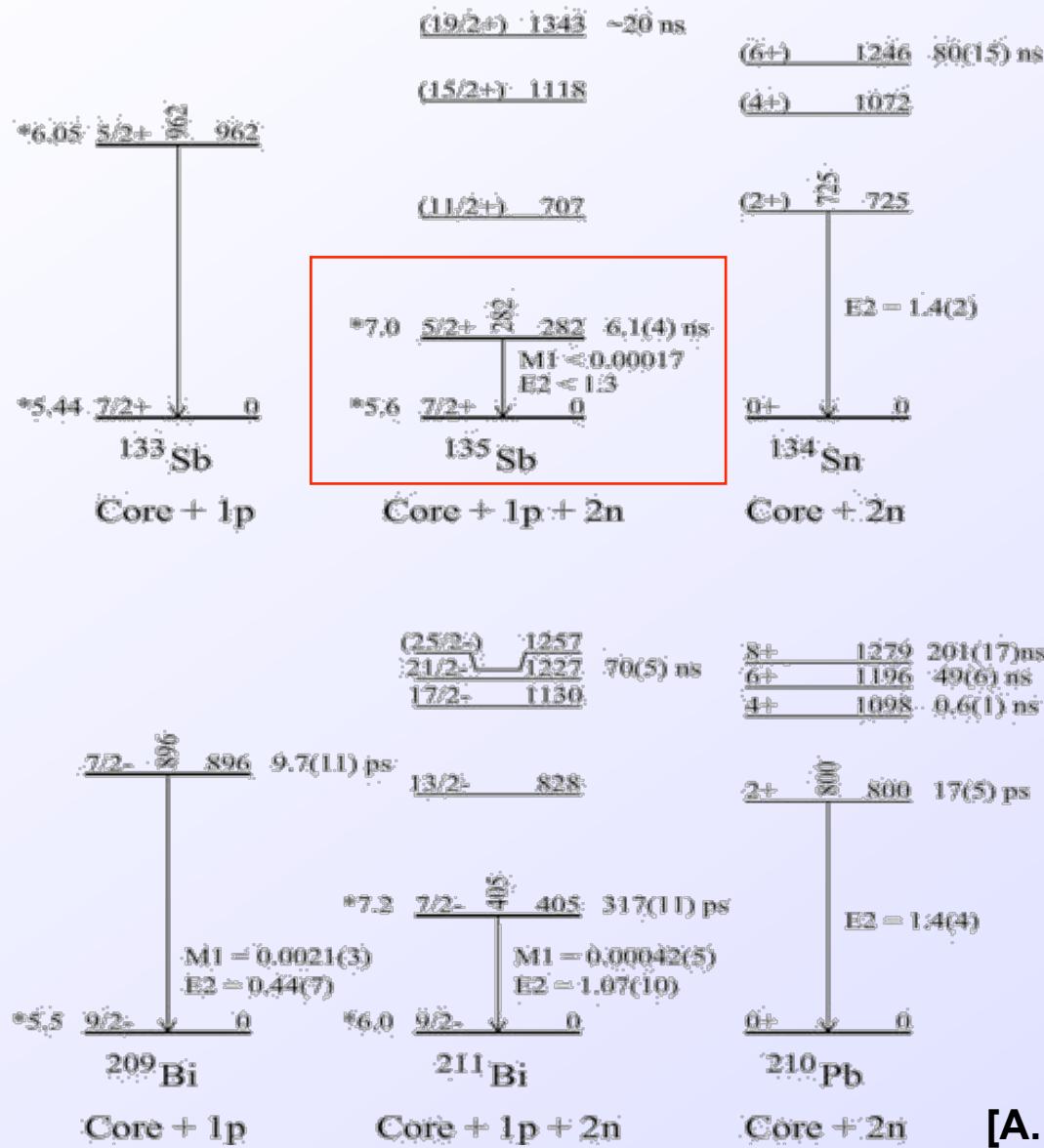
→ Selective shift of $d_{5/2}$ orbit

→ $d_{5/2} - 300$ keV



[J. Shergur et al., Phys. Rev. C72 (2005) 024305]

135Sb status



- ✓ $T_{1/2} = 6.1 (0.4) \text{ ns}$
 $\rightarrow M1 < 0.00017 \text{ W.u.}$
 $\rightarrow E2 < 1.3 \text{ W.u.}$

- ✓ Long level lifetime
 \rightarrow No collectivity
 \rightarrow Mainly s.p. states

$$7/2^+ = 75\% \pi g_{7/2}(vf_{7/2})^2$$

$$5/2^+ = 45\% \pi d_{5/2}(vf_{7/2})^2 + \\ 23\% \pi g_{7/2}(vf_{7/2})^2 + \dots$$

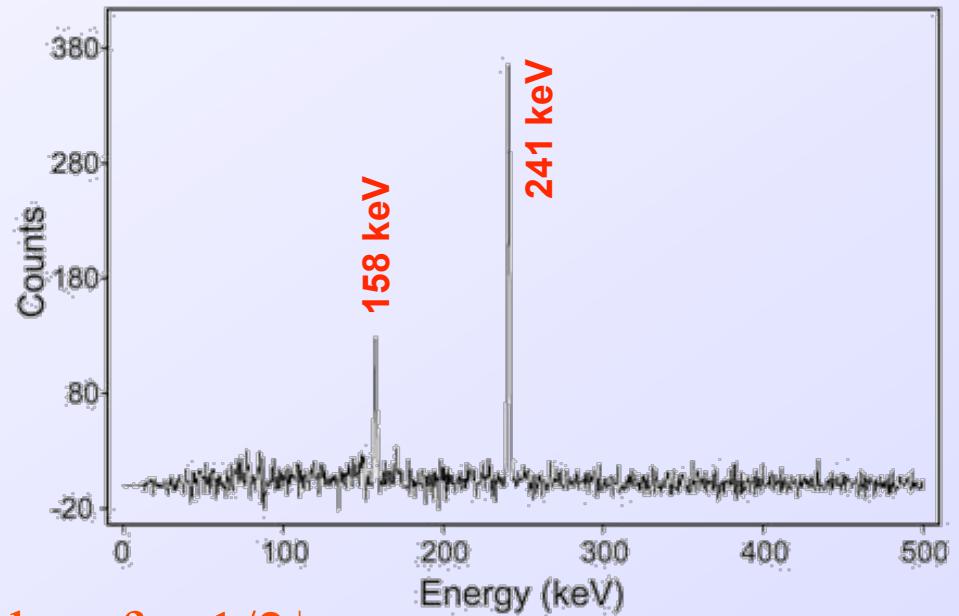
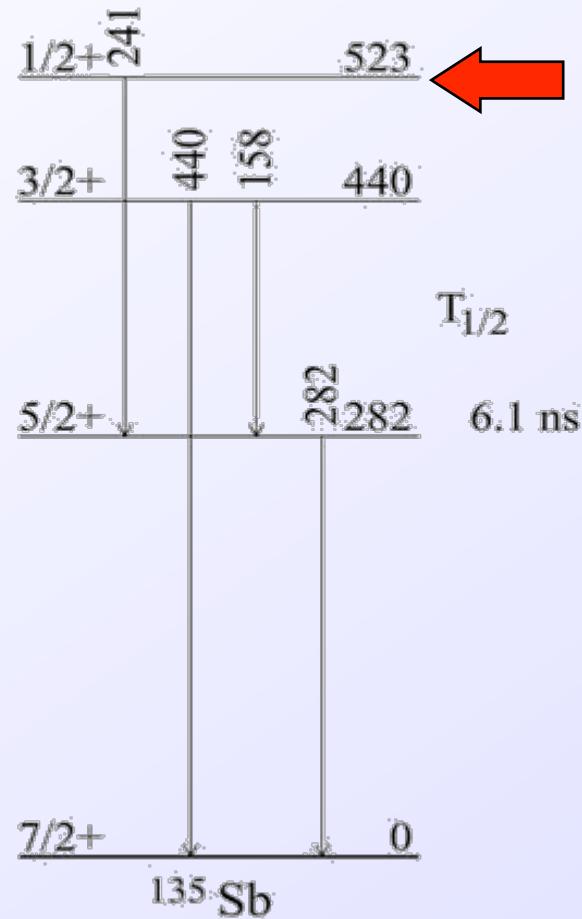
- ✓ The low E of the 282 keV is still a puzzle
- ✓ Missing $1/2^+$ state: coupling of $\pi d_{5/2}$ to the 2^+ of the core.

[A. Korgul et al., EPJ A 32, 25–29 (2007)]

ISOLDE WS 2009

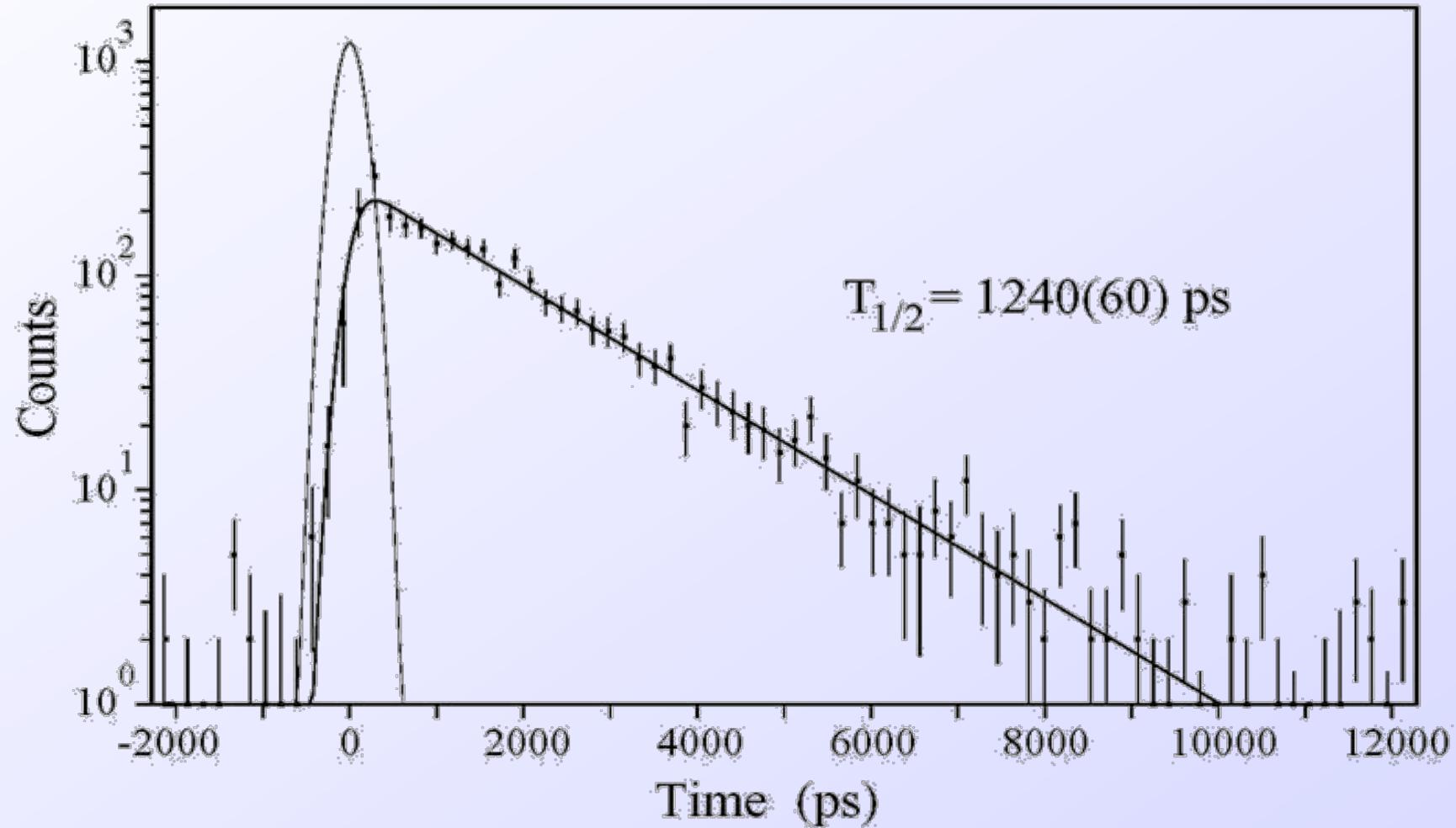
^{135}Sb results: coincidences

- ✓ From the β -n decay of ^{136}Sn
 - $\gamma\gamma$ gating on 282 keV

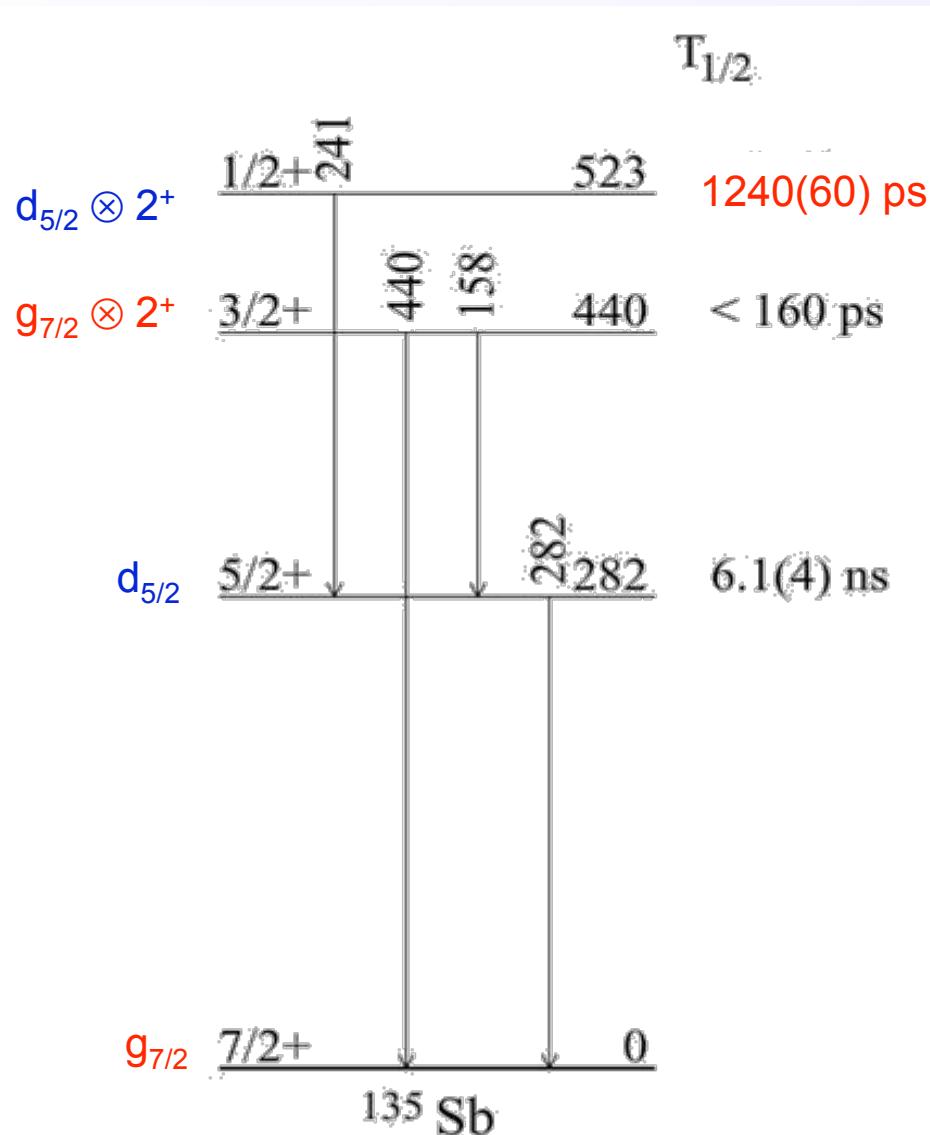


- Candidate for $1/2^+$
 - E2 feeding to $5/2^+$
 - Model $\rightarrow 1/2^+ = 5/2^+ \otimes 2^+$ core
 - Collective E2
- Similarly for $3/2^+$
 - $3/2^+ = 7/2^+ \otimes 2^+$ core
 - Collective E2 to $7/2^+$, retarded M1 to $5/2^+$

^{135}Sb results: lifetime of the $1/2^+$ state



^{135}Sb results: transition probabilities



241: $\mathbf{B(E2; 1/2 \rightarrow 5/2) = 12.7 (6) \text{ W.u.}}$

440: $\mathbf{B(E2; 3/2 \rightarrow 7/2) > 4.3 \text{ W.u.}}$

158: $\mathbf{B(M1; 3/2 \rightarrow 5/2) > 0.004 \text{ W.u.}}$

282: $\mathbf{B(E2; 5/2 \rightarrow 7/2) < 1.3 \text{ W.u.}}$

282: $\mathbf{B(M1; 5/2 \rightarrow 7/2) < 0.00017 \text{ W.u.}}$

Core excitation:

^{134}Sn $\mathbf{B(E2; 2 \rightarrow 0) = 1.42 (24) \text{ W.u.}}$

(^{136}Te) $\mathbf{B(E2; 2 \rightarrow 0) = 5.0 (7) \text{ W.u.}}$

^{135}Sb results: comparison to shell model

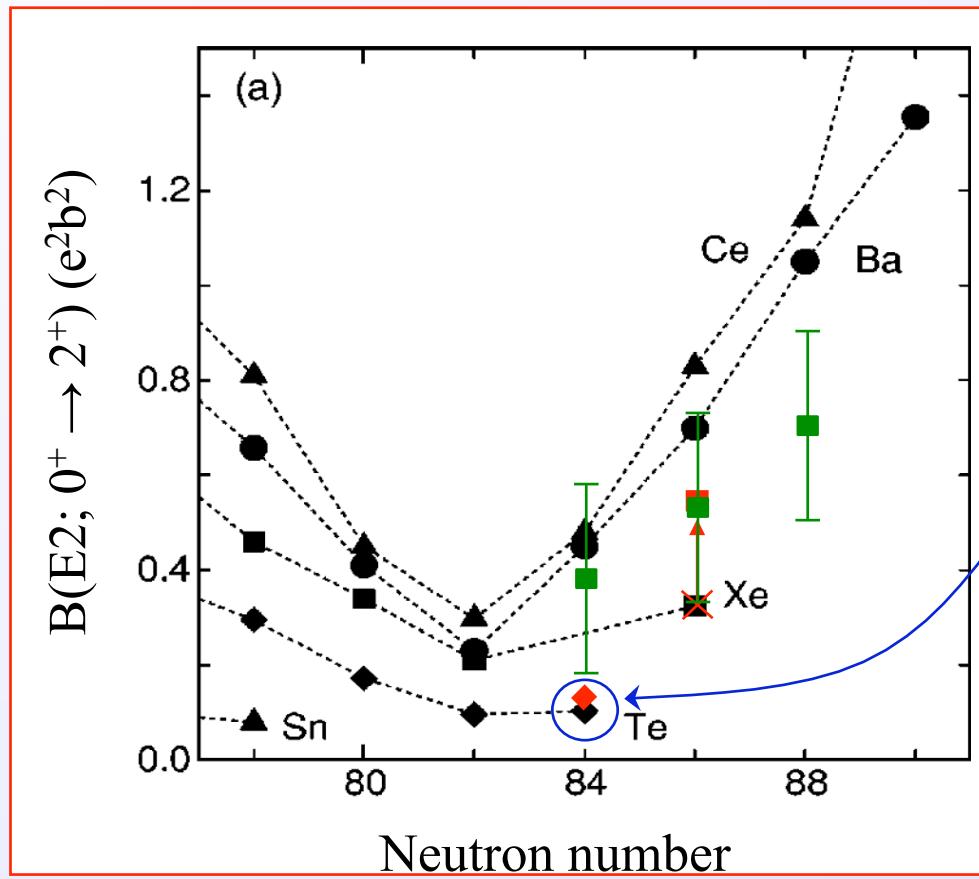
| Levels | Exp (keV) | Brown* | Covello & Gargano (keV) |
|---------------------------|--|--------|----------------------------|
| $7/2^+$ | 0 | 0 | 0 |
| $5/2^+$ | 282 | 316 | 391 |
| $3/2^+$ | 440 | 408 | 509 |
| $1/2^+$ | 523 | 527 | 678 |
| Transition | Exp | Brown* | Covello Gargano |
| $1/2^+ \rightarrow 5/2^+$ | $B(E2) = 527(26) \text{ e}^2\text{fm}^4$ | 678 | 566 |
| $5/2^+ \rightarrow 7/2^+$ | $B(M1) < 0.0003 \mu_N^2$ | 0.0021 | 0.0040 |
| | $B(E2) < 54 \text{ e}^2\text{fm}^4$ | 29 | 32 |

Very collective $B(E2; 1/2^+ \rightarrow 5/2^+)$

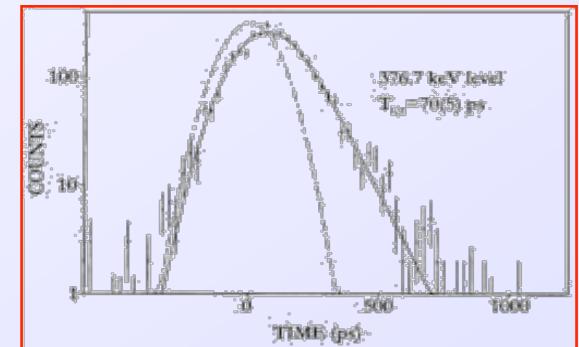
Not in agreement with very low $B(E2; 2 \rightarrow 0)$ rate in ^{136}Te

^{136}Te ($^{132}\text{Sn} + 2\text{p} + 2\text{n}$) status

B(E2; $0^+ \rightarrow 2^+$) rates in the region:



$$B(E2; 2^+ \rightarrow 0^+) = 245(50) \text{ e}^2 \text{fm}^4 \quad \text{ATD gives } \tau = 41.6(8.4) \text{ ps}$$



^{140}Xe : $T_{1/2} = 70(5)$ ps 60% shorter

[A. Lindroth et al., PRL 82 (1999) 4783]

$^{138,140,142}\text{Xe}$ CoulEx @ REX-ISOLDE

[T. Kröll et al., Eur. Phys. J. 150 (2007)]

[D. Radford et al., PRL 89 (2002) 222501]

TABLE II. $B(E2; 0^+_1 \rightarrow 2^+_1)$ values ($e^2 b^2$) measured in the present work, compared with shell-model calculations (SM) and adopted values from Ref. [8].

| Nuclide | This Work | SM | Adopted [8] |
|-------------------|-----------|-------|-------------|
| ^{132}Te | 0.172(17) | | |
| ^{134}Te | 0.096(12) | 0.088 | |
| ^{136}Te | 0.103(15) | 0.25 | |
| ^{128}Te | 0.346(26) | | 0.383(6) |
| ^{136}Ba | 0.46(4) | | 0.410(8) |

^{136}Te results: lifetime of the 2^+ state

✓ Summary of results

$$B(E2; 2^+ \rightarrow 0^+) = 208(29) \text{ e}^2\text{fm}^4$$

[D.Radford et al. PRL 88 (2002) 222501]

$$B(E2; 2^+ \rightarrow 0^+) = 245(50) \text{ e}^2\text{fm}^4$$

This work, $\tau=41.6(8.4) \text{ ps}$

Preliminary!

Calculations:

$$B(E2; 2^+ \rightarrow 0^+) = 500 \text{ e}^2\text{fm}^4$$

A. Covello [D.Radford PRL 88 (2002) 222501]

$$B(E2; 2^+ \rightarrow 0^+) = 180 \text{ e}^2\text{fm}^4$$

J. Terasaki [PRC 66, 054313 (2002)]

$$B(E2; 2^+ \rightarrow 0^+) = 320 \text{ e}^2\text{fm}^4$$

A. Covello [D.Radford et al., Proc. World Sci. 2003]

$$B(E2; 2^+ \rightarrow 0^+) = 300 \text{ e}^2\text{fm}^4$$

N. Shimizu [PRC 70 054313 (2004)]

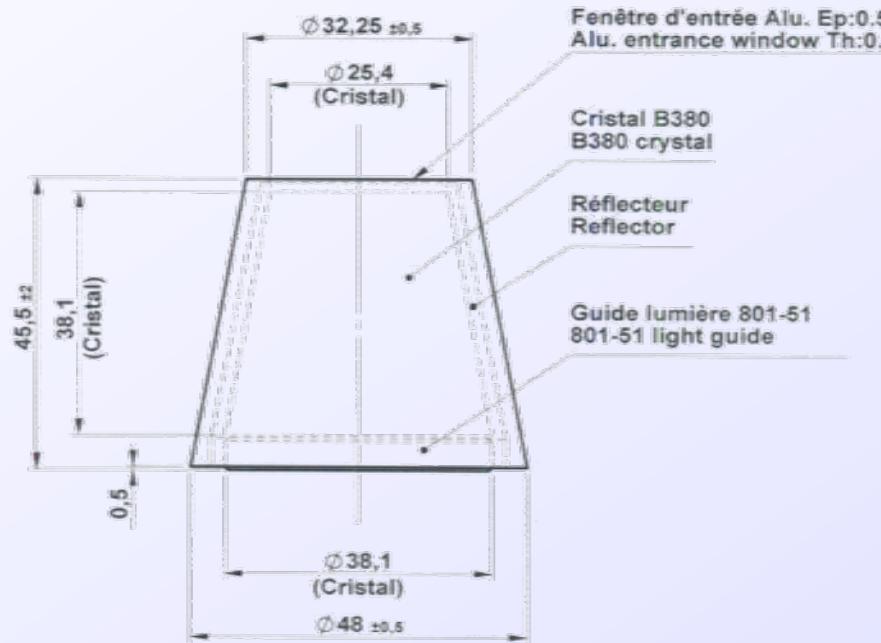
$$B(E2; 2^+ \rightarrow 0^+) = 452 \text{ e}^2\text{fm}^4$$

A. Brown

$$B(E2; 2^+ \rightarrow 0^+) = 360 \text{ e}^2\text{fm}^4$$

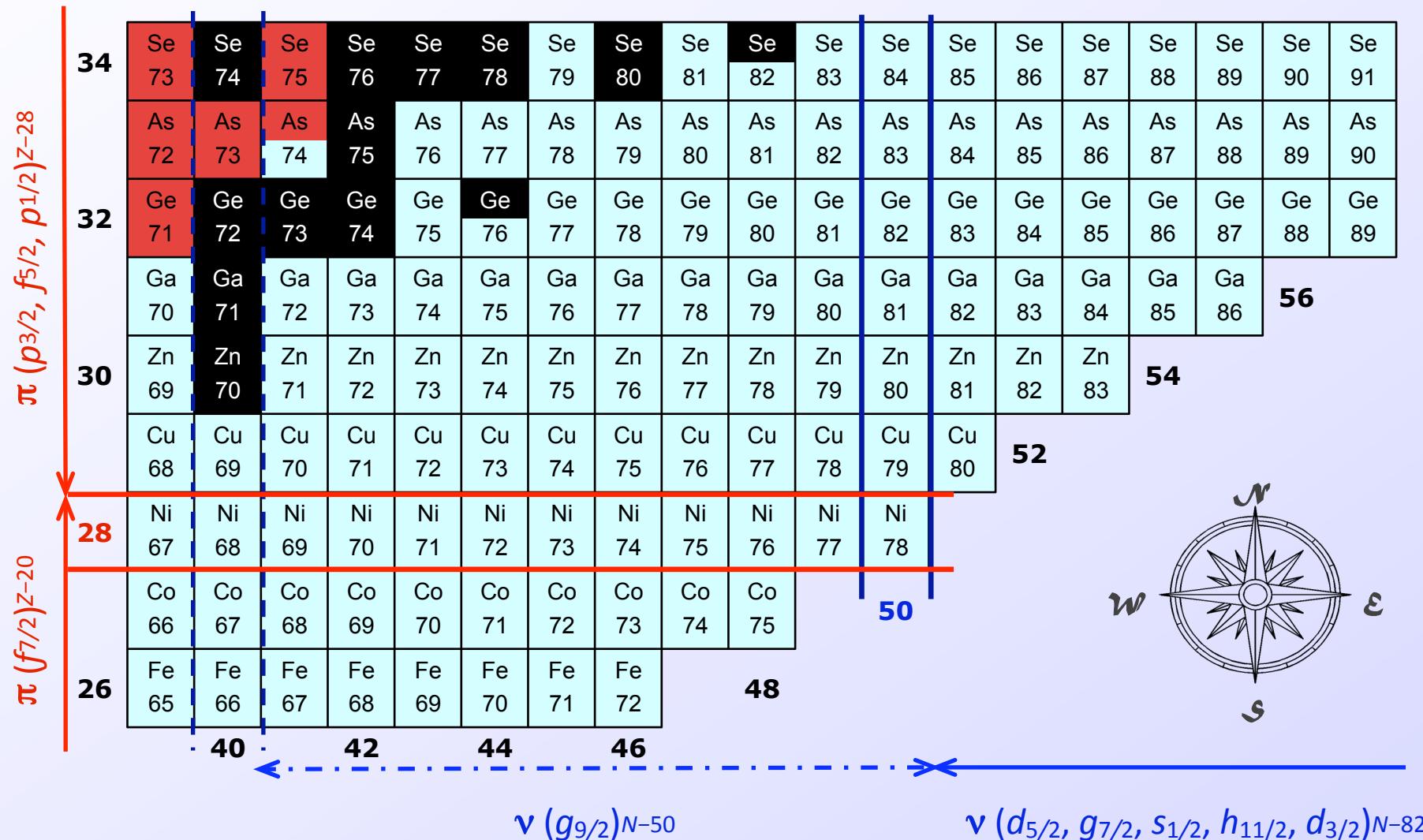
A. Covello and A. Gargano

Truncated LaBr₃(Ce) detectors

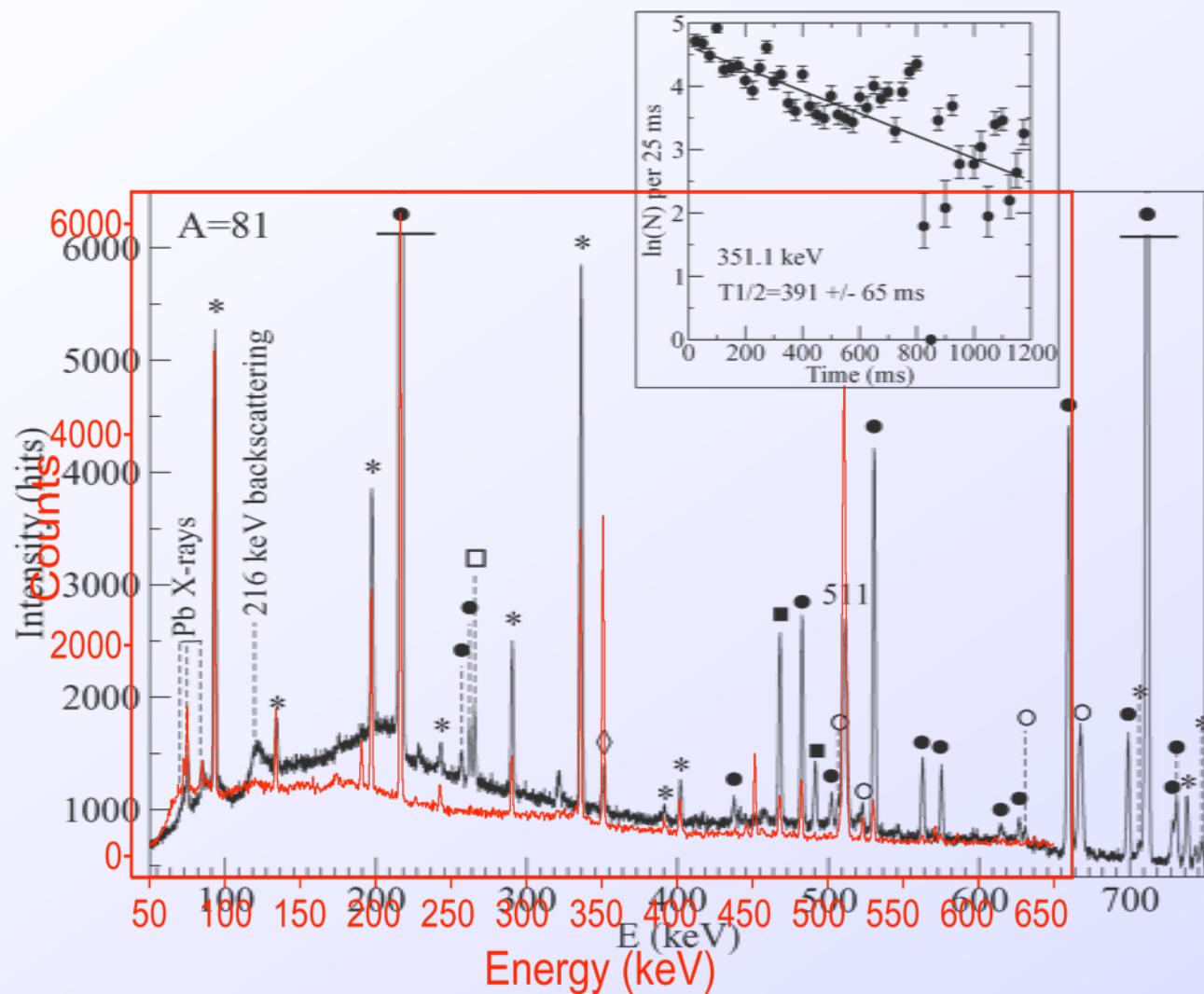


- ✓ The truncated cone geometry should have better time resolution than the cylindrical geometry (about 30% improvement for BaF₂ crystals)
- ✓ High cost! (about 60% higher than for a cylinder)
- ✓ TEST Oct 2009: FWHM = 140 ps compared to 160 ps
- ✓ Small crystal still better

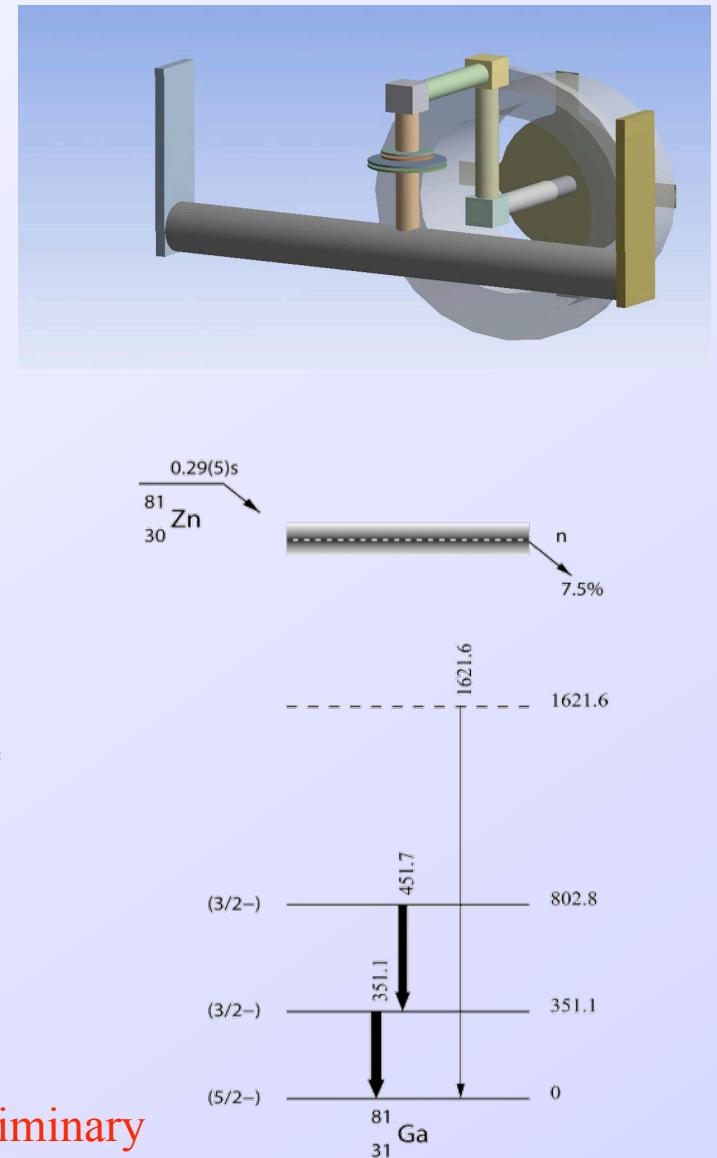
ATD $\beta\gamma\gamma(t)$ measurements above ^{78}Ni



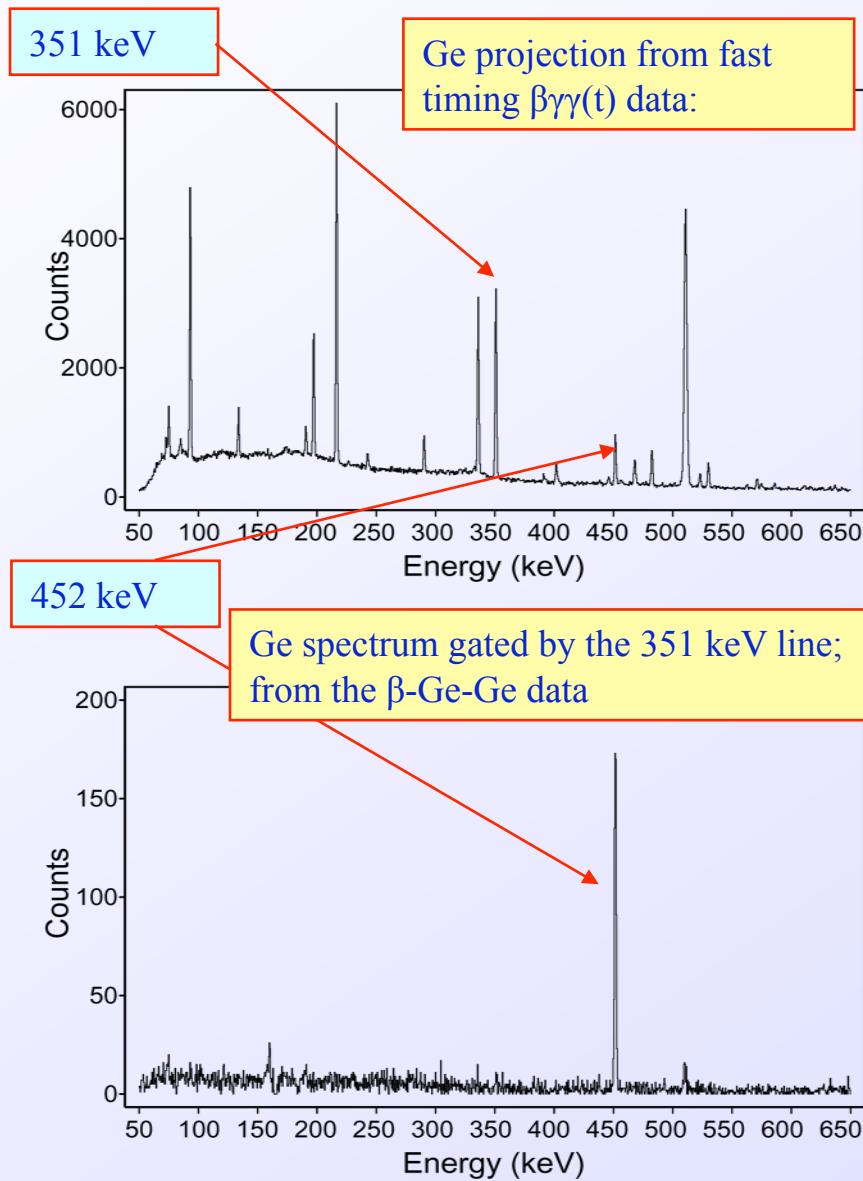
IS441 (Oct 2009): ^{81}Zn decay



PARRNe: D.Verney, PRC 76, 054312 (2007) $\beta\gamma$
 ISOLDE H. Mach et al. IS441 Oct 2009, $\beta\gamma$, $\frac{1}{2}$ data, Preliminary



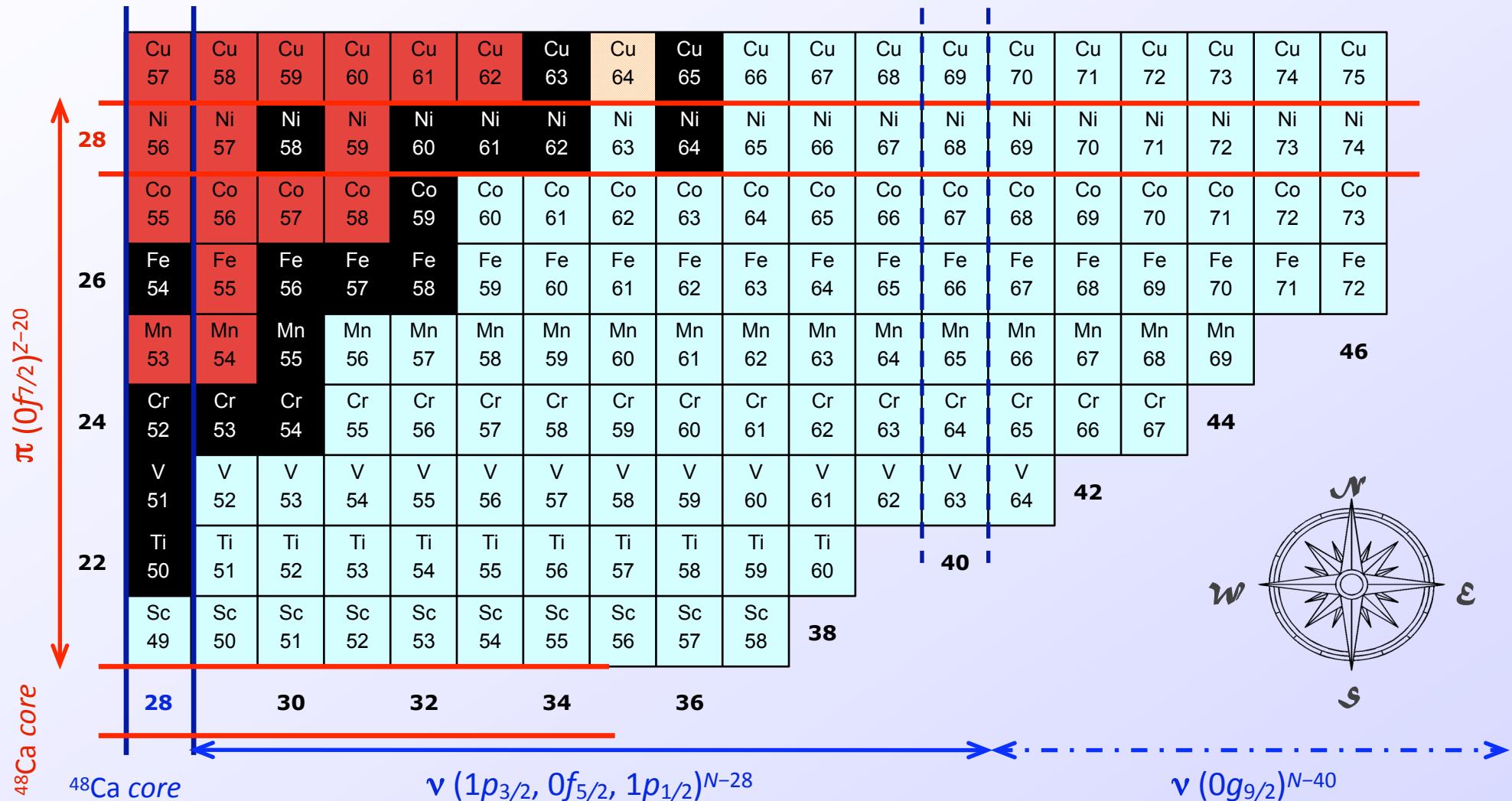
IS441 (Oct 2009): ^{81}Zn decay



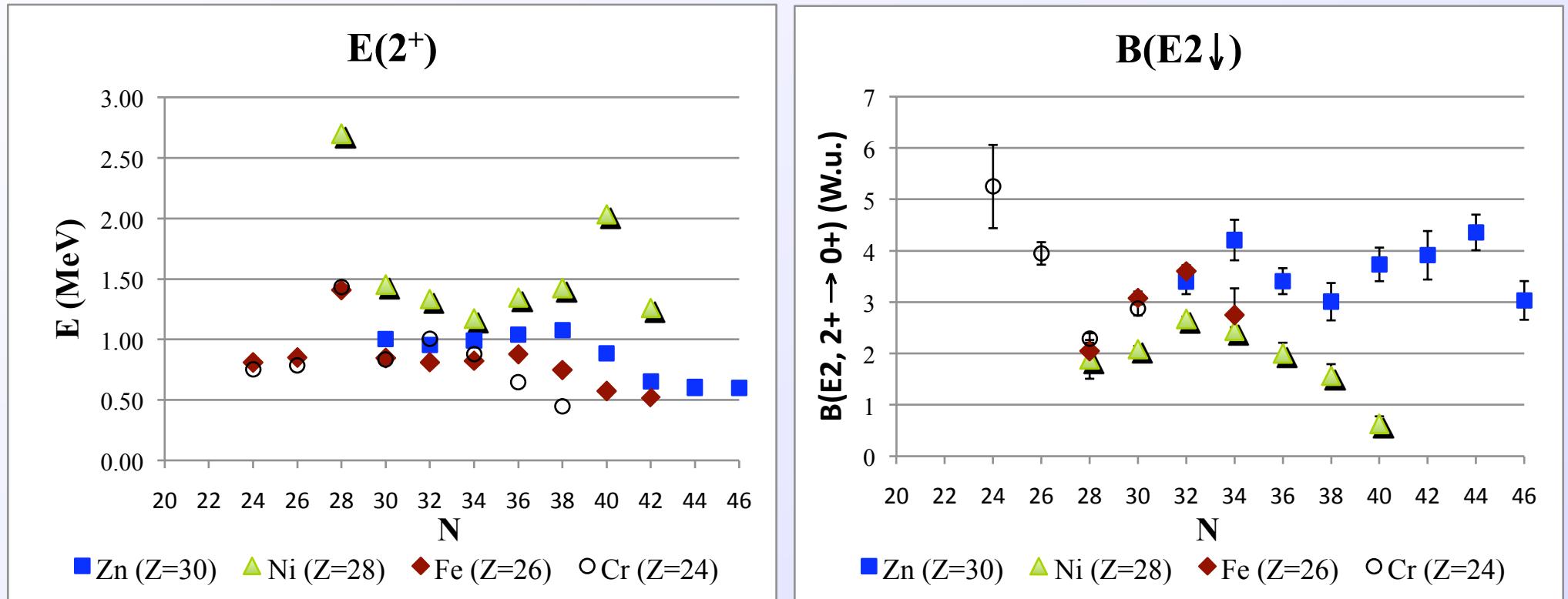
- ✓ Magic N=50 nucleus
 - Very clean conditions
 - New γ s identified
 - Level scheme confirmed
 - Other coincident γ s (in Ga)
 - Lifetimes for low-lying states
- ✓ (Scant) Data on ^{82}Zn
 - Test run
 - Evidence for beta-decay
 - no strong gammas
 - ... needs analysis



Prospects: Nuclear chart below ^{68}Ni



Prospects: nuclei below ^{68}Ni



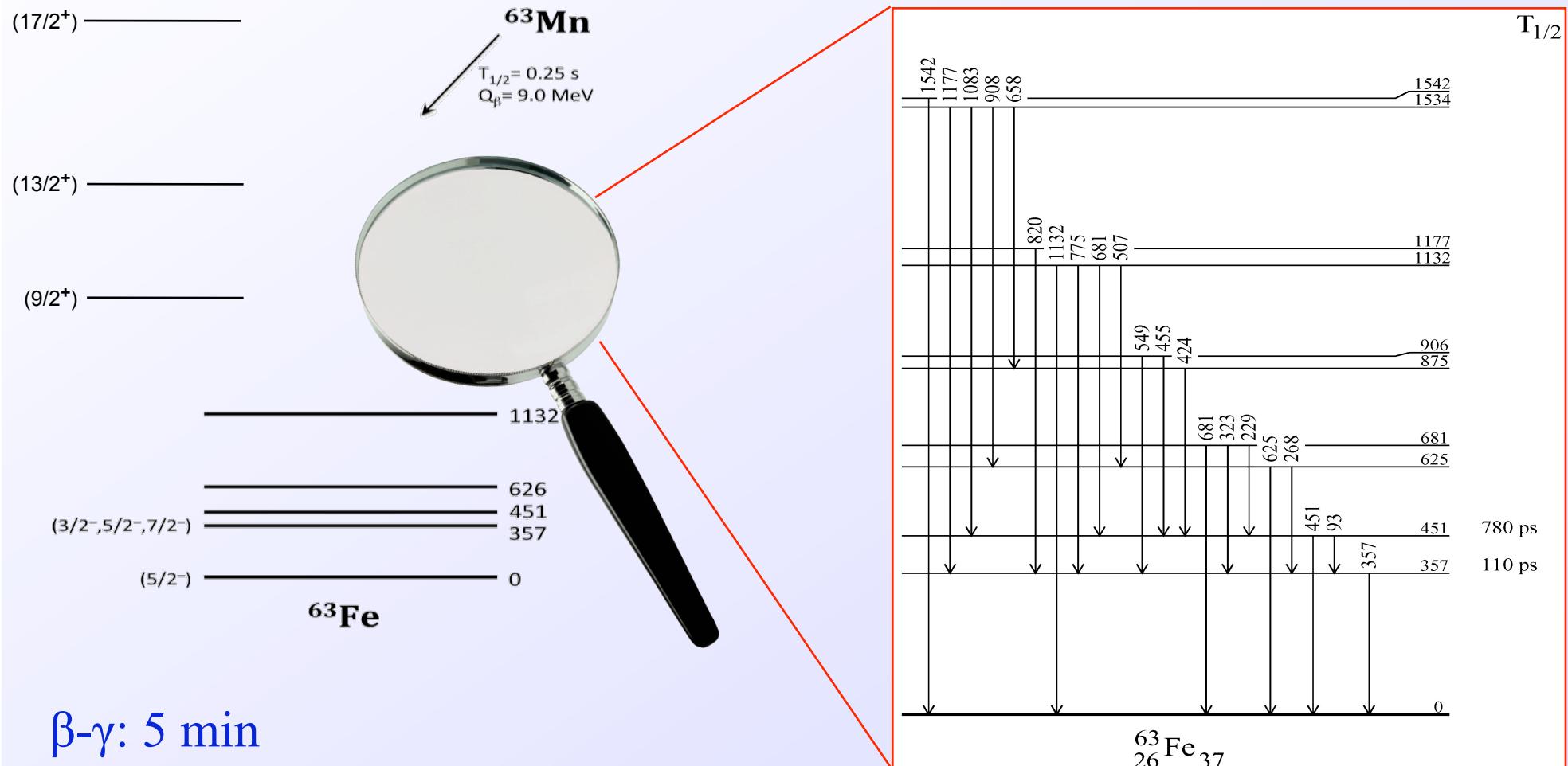
$^{64,66}\text{Fe}$, 2^+ states (most intense transitions), M. Hannawald et al., PRL 82, 1391 (1999)

S. Lunardi et al., PRC 76, 034303 (2007)

[Talk J.J. Valiente-Dobón]

^{68}Fe $E(2^+) = 522$ keV, J.M. Daugas et al., FINUSTAR, AIP Conf Proc 831, 427 (2006)

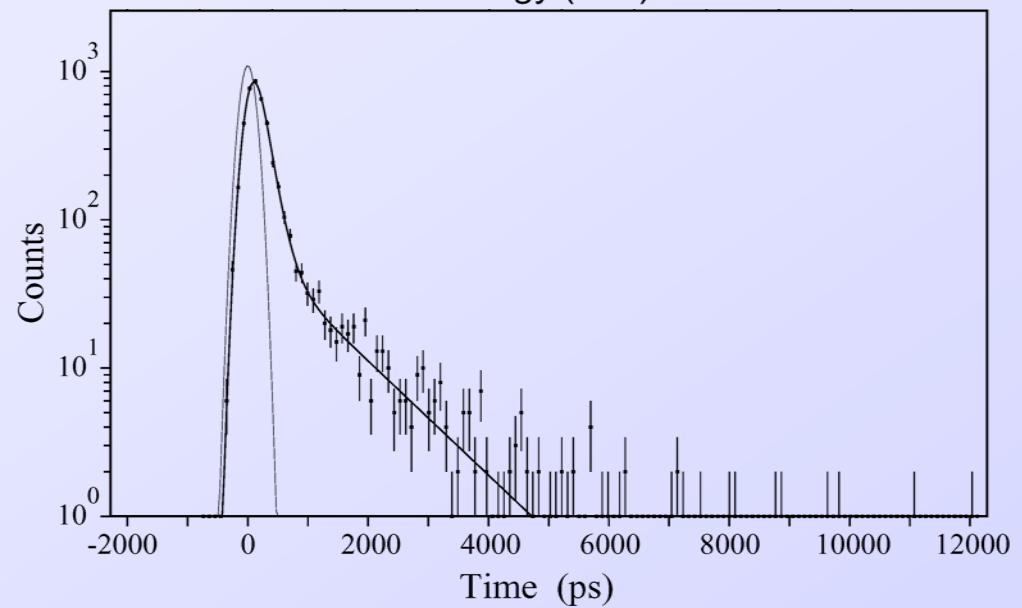
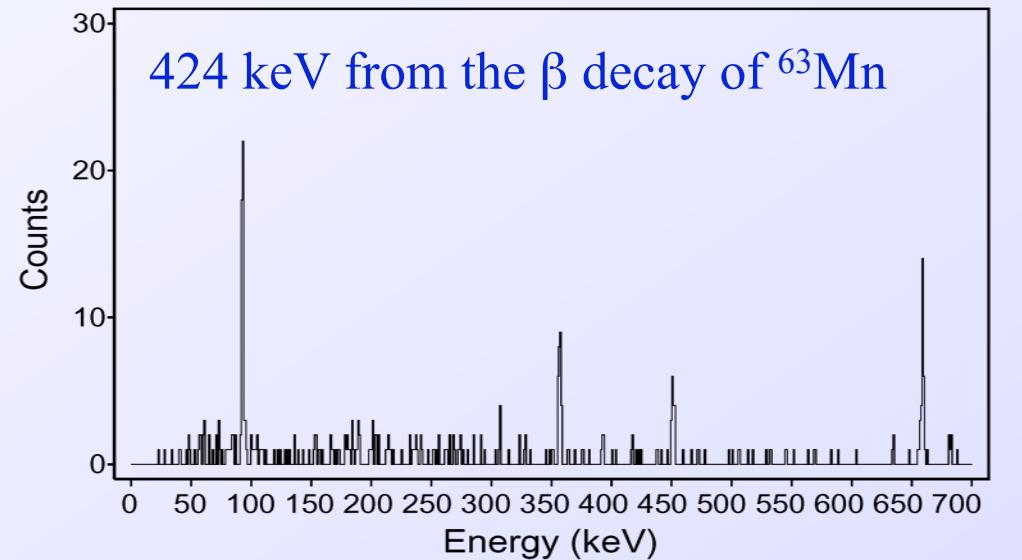
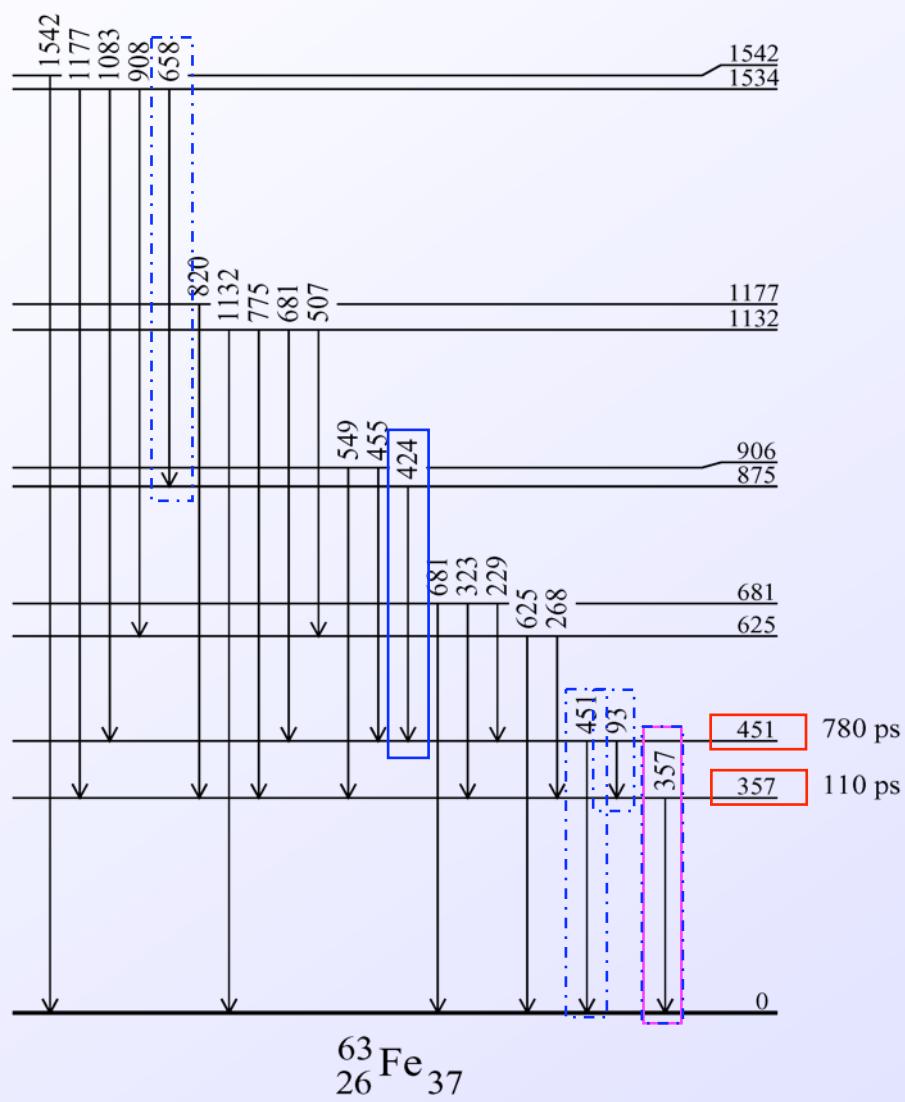
Pre-analysis ^{63}Mn decay



β - γ : 5 min
 β - γ - γ : 17 min
(in saturation)

Strong beta-feeding to 357, 451 and 1132 keV states, very weak g.s. feeding

Pre-analysis ^{63}Mn decay



Transitions in ^{63}Fe

✓ 357 keV level, $T_{1/2} = 110 \text{ ps}$

→ 357 keV transition (neglecting conversion coefficient)

- E1 not expected: $1/2^-$, $3/2^-$, $5/2^-$ states or $9/2^+$ (long lifetime)
- $B(E2) \sim 60 \text{ W.u.}$ (too high)
- $B(\underline{M1}) = 0.0079 \mu_N^2$

✓ 451 keV level, $T_{1/2} = 780 \text{ ps}$

→ 93 keV transition

- Similar for E1 and E2
- $B(\underline{M1}) = 0.028 \mu_N^2$

→ 451 keV transition

- $B(E1) = 3.2 \times 10^{-6} e^2 \text{ fm}^2$ (low)
- $B(M1) = 2.9 \times 10^{-4} \mu_N^2$ (low)
- $B(\underline{E2}) = 1.4 \text{ W.u.}$ (nicely fits systematics)

Low-lying levels in ^{63}Fe

- ✓ Two dipole M1 and one E2 transition
 - Either $1/2^-$, $3/2^-$, $5/2^-$
 - or $5/2^-$, $3/2^-$, $1/2^-$
- ✓ Beta feeding from $5/2^-$
 - 357 and 451 keV
 - not to ground state
- ✓ Similar to ^{57}Fe

$1/2^-$ is the ground state
 $3/2^-$ is the 357 keV state
 $5/2^-$ is the 451 keV state

Need more statistics to elucidate structure at higher E
Similar situation expected in odd-A Fe isotopes
Role of the $9/2^+$ orbital

Summary

- ✓ Transition rates are very sensitive tools to map nuclear properties and unravel surprising features of nuclei
 - i.e. low-lying structure of nuclei close to ^{132}Sn
- ✓ Fast timing provides unique independent information
 - complementary to other advanced spectroscopic techniques
- ✓ Applied in beta-decay at ISOLDE since 1994
- ✓ Developments ongoing on crystals, photosensors and electronics
 - better precision / enhanced sensitivity towards more exotic nuclei

The fast timing collaboration

Uppsala, LPSC Grenoble, U Complutense Madrid, Cologne,
Warsaw, IEM Madrid, IFIC Valencia, CSNSM Orsay,
Swierk, Notre Dame, GANIL, Gent, GSI, Naples, Århus, Sofia,
Jyväskylä, NIPNE Bucharest, Oslo, ILL Grenoble, UA Madrid,
Rež, Munich, CERN

Thank you!

