Structure beyond the N=50 shell closure in neutron-rich nuclei in the vicinity of ^{78}Ni: The case of N=51 nuclei

G. Duchêne[1], **F. Didierjean[1]**, D. Verney[2], G. de Angelis[3], C. Fransen[4], R. Lozeva[1], J. Litzinger[4], A. Dewald[4], M. Niikura[2], D. Bazzacco[5], E. Farnea[5], S. Aydin[5], A. Bracco[6], S. Bottoni[6], L. Corradi[3], F. Crespi[6], E. Ellinger[4], E. Fioretto[3], S. Franchoo[2], A. Goasduff[1], A. Gottardo[5], L. Grocutt[7], M. Hackstein[4], F. Ibrahim[2], K. Kolos[2], S. Leoni[6], S. Lenzi[5], S. Lunardi[5], Menegazzo[5], D. Mengoni[5], C. Michelagnoli[5], T. Mijatovic[8], V. Modamio[3], O. Möller[9], G. Montagnoli[5], D. Montanari[5], A. Morales[6], D.R. Napoli[3], F. Nowacki[1], F. Recchia[3], E. Sahin[3], F. Scarlassara[5], L. Sengele[1], K. Sieja[1], J. F. Smith[7], A. Stefanini[3], C. Ur[5], J.J. Valiente Dobon[3], V. Vandone[6]

1 IPHC/CNRS-University of Strasbourg (F)
2 IPNO/CNRS-University Paris Sud-11 (F)
3 INFN LNL (I)
4 IKP University of Cologne (D)
5 INFN and University of Padova (I)
6 INFN and University of Milano (I)
7 University of Paisley (UK)
8 Ruder Boskovic Institute (Cr)
9 IKP, TU Darmstadt (D)

Beyond N = 50

N = 50 nuclei

- Holy grail : ^{78}Ni
- Great exp and theo effort

What is beyond N = 50 ?

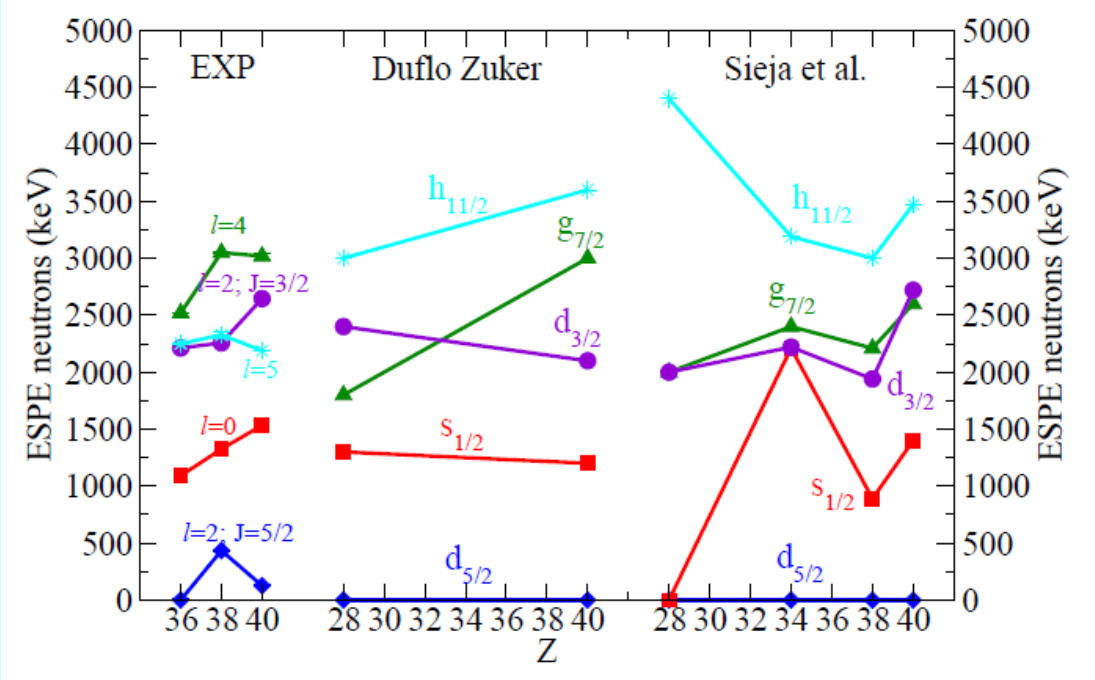
- $3s_{1/2}$, $2d_{3/2}$, $2d_{5/2}$, $1g_{7/2}$, $1h_{11/2}$ orbitals
- Precise orbital ordering not fixed as well as their evolution vs Z

Low lying states in N=51 nuclei

Known for Z > 40

Of two nature:

- single-particle states
- or core-particle coupling

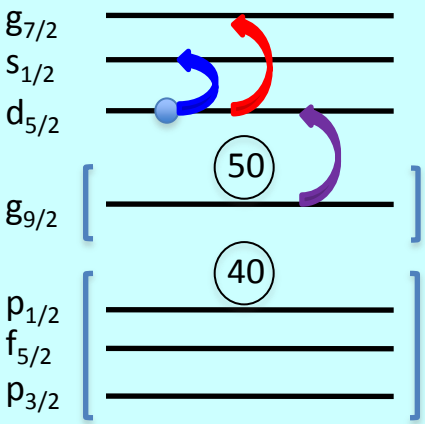


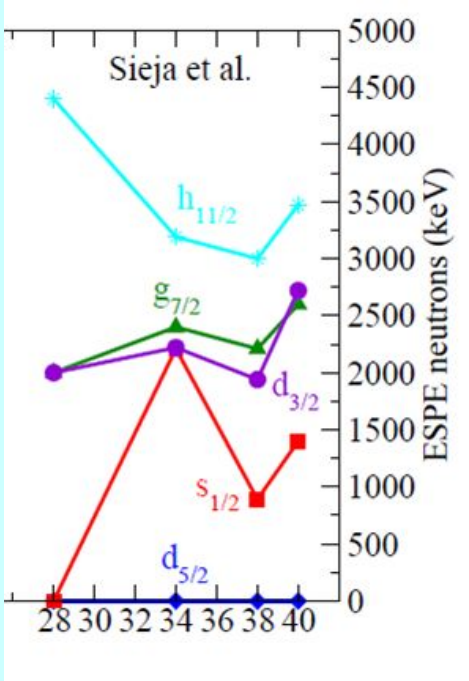
J. Duflo and A.P. Zuker, Phys. Rev. C59, R2347 (1999)
K. Sieja et al., Phys. Rev. C79, 064310 (2009)

N = 51 nuclei

Single-particle states

- Ig.s. = $5/2^+$ firmly established for $36 \leq Z \leq 50$
  ^{87}Kr ^{101}Sn
- Down sloping $1/2^+$ states for $Z \leq 40$; carries the major part of the $\nu 3s1/2$ strength
- **$7/2^+$** state corresponds to an excitation into the $1g_{7/2}$ orbital
- **$9/2^+$** state corresponds to an excitation across the N=50 gap, a 2p-1h $d_{5/2}^2\, g_{9/2}^{-1}$ neutron configuration
- Fed via (d,p) reactions for $34 < Z < 38$
- Neutron stripping strongly enhanced for single-particle states and large spectroscopic factors deduced





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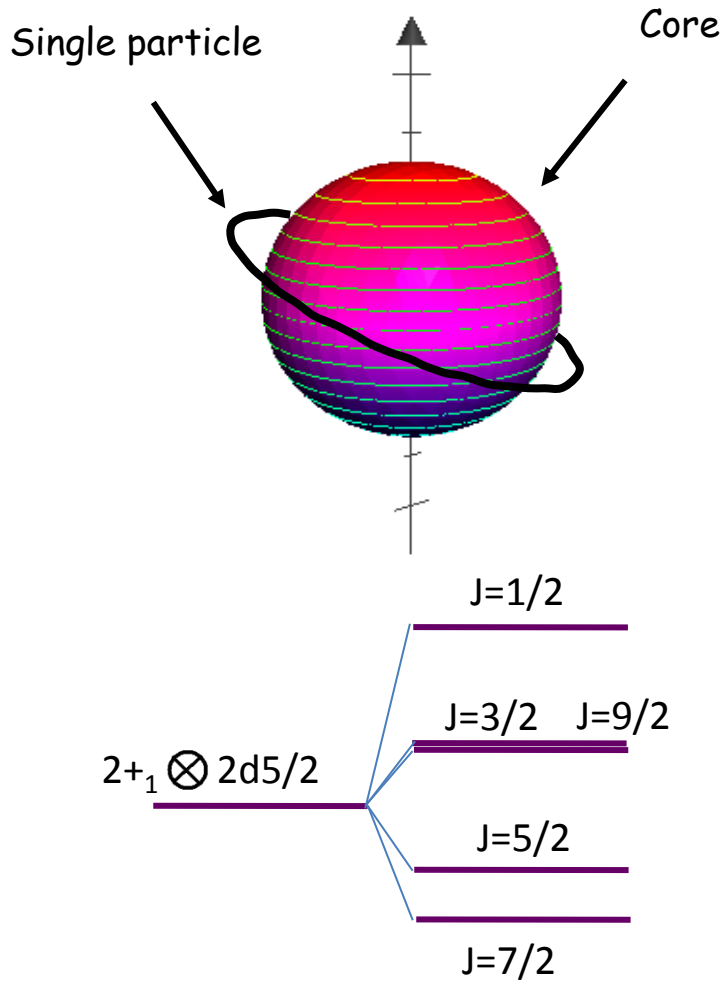
N = 51 nuclei

Core-particle coupling

- Weak-coupling scheme $2^+_{Core} \otimes \nu d5/2$
  N. Auerbach, Phys. Lett. B27, 127 (1968)
- The weak-coupling scheme applies as long as the N=50 gap is strong
- Generates a multiplet of 5 states ($1/2^+$ to $9/2^+$) with $7/2^+$ at lowest energy in case of a quadrupolar core excitation
- Barycentre is similar to $E_x(2^+)_{Core}$
- Spectroscopic factor (SF) of core-coupled states are nearly zero (non stripping state)



D. Verney courtesy

G. Duchêne

Physics motivation

Porquet & Sorlin

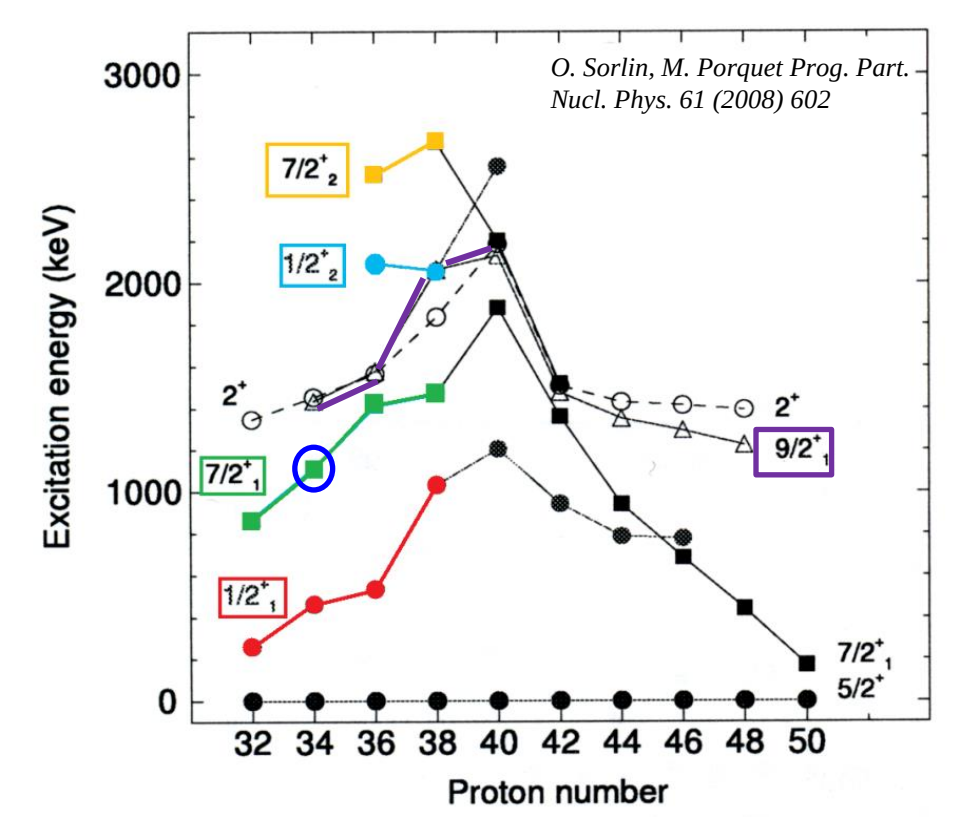
- Energies of $9/2_1^+$ follows closely the 2^+ core energies -> should be a rather pure core-coupled configuration

- *"Energies of the low lying $1/2_1^+$ and $7/2_1^+$ states depart significantly from that of the 2^+ core at Z < 38 and Z > 44"*

  -> single-particle states

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

- The $1/2_2^+$ and $7/2_2^+$ states are most likely core coupled



Thomas

- (d,p) reaction to populate ^{85}Se
- G.s. is $5/2^+$, $1/2_1^+$ (SF = 0.3 +/- 0.09), $7/2_1^+$ (SF = 0.77 +/- 0.27) or $3/2_1^+$ (SF = 0.06 +/- 0.09)

J.S. Thomas et al., Phys. Rev. C76, 044302 (2007)

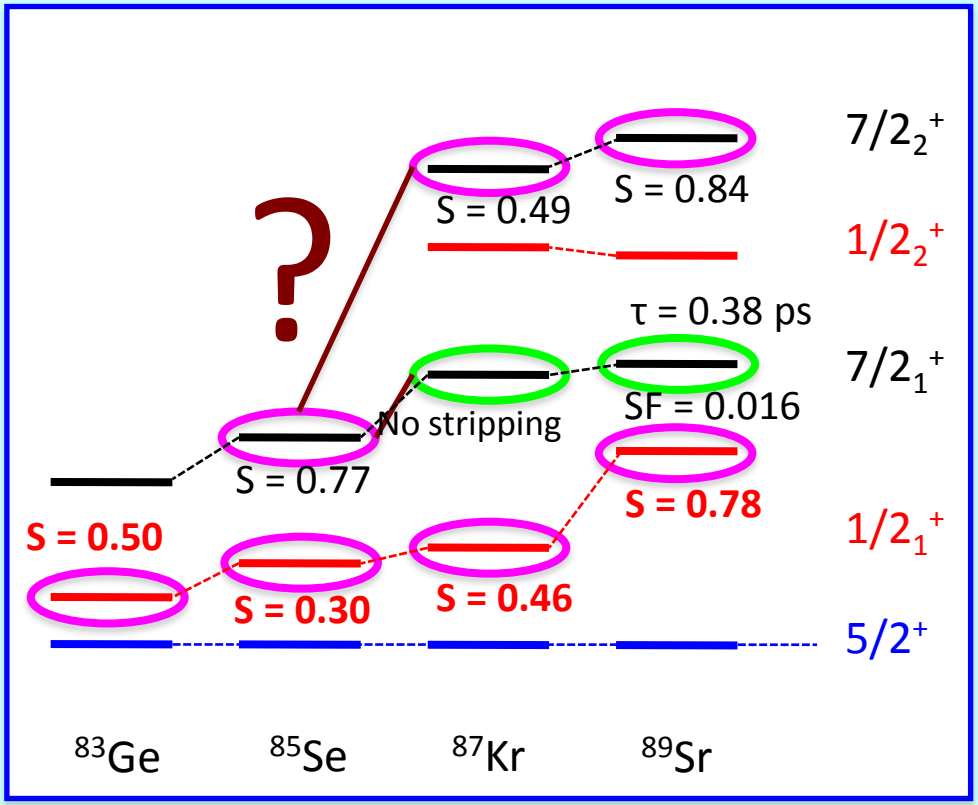
Physics motivation

Contradictory assignments

- States have been populated in N = 51 nuclei by (d,p) transfer
  - States with sizable SF correspond likely to single-particle config. with rather long decay times
  - States with small SF are likely core-coupled

From NNDC

- **$9/2_1^+$** lifetime in **^{89}Sr**: τ =0.30 (9) ps
  likely core-coupled
- **$7/2_1^+$** SF and lifetime in **^{89}Sr**:
  SF=0.016 and τ = 0.38 (14) ps
  and there is no stripping in **^{87}Kr**
  likely core-coupled
- **$7/2_2^+$** SF in **^{89}Sr** and **^{87}Kr**:
  SF=0.84 and SF=0.49, resp.
  likely single particle
- **$7/2_1^+$** SF in **^{85}Se**:
  SF=0.77
  likely single particle



Sudden E* drop by ~1.4 MeV of the $\nu g_{7/2}$ single-particle config. by removal of 2p from ^{87}Kr to ^{85}Se

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Lifetime calculations

Single-particle config

$\nu\,(g_{7/2})$ or $\nu(g_{9/2})^{-1}(d_{5/2})^{2}{}_{0}$ → $\nu(d_{5/2})$

Core-coupled config

Core 2^+ x $\nu(d_{5/2})$ → Core 0^+ x $\nu(d_{5/2})$

Calculated lifetimes of the 7/2+ states done by D. Verney (IPN Orsay)

nucleus	$\tau(7/2^+)$ $2^+ \otimes d_{5/2}$	$\tau(7/2^+)$ $0^+ \otimes g_{7/2}$
^{89}Sr	0.16 ps	14.9 ps
^{87}Kr	0.19 ps	23.2 ps
^{85}Se	0.42 ps	79.5 ps
^{83}Ge	1.01 ps	309 ps

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Lifetime measurement @ LNL with AGATA + PRISMA

Goal

- Determine the nature of first $7/2^+$ and $9/2^+$ excited states

Method

- Populate and study several N=51 nuclei (^{87}Kr, ^{85}Se, ^{83}Ge)
- Determine the order of magnitude of the lifetimes
  - Around or below 1 ps (fast) → core-coupled config
  - Above 10 ps (slow) → single-particle config

Technique

- Recoil Distance Doppler Shift method (RDDS)

- Small cross sections → two positions
  - 35 (1) μm ~14 shifts
  - 253 (2) μm ~14 shifts

Experimental setup

- AGATA Demonstrator + PRISMA + Koeln plunger

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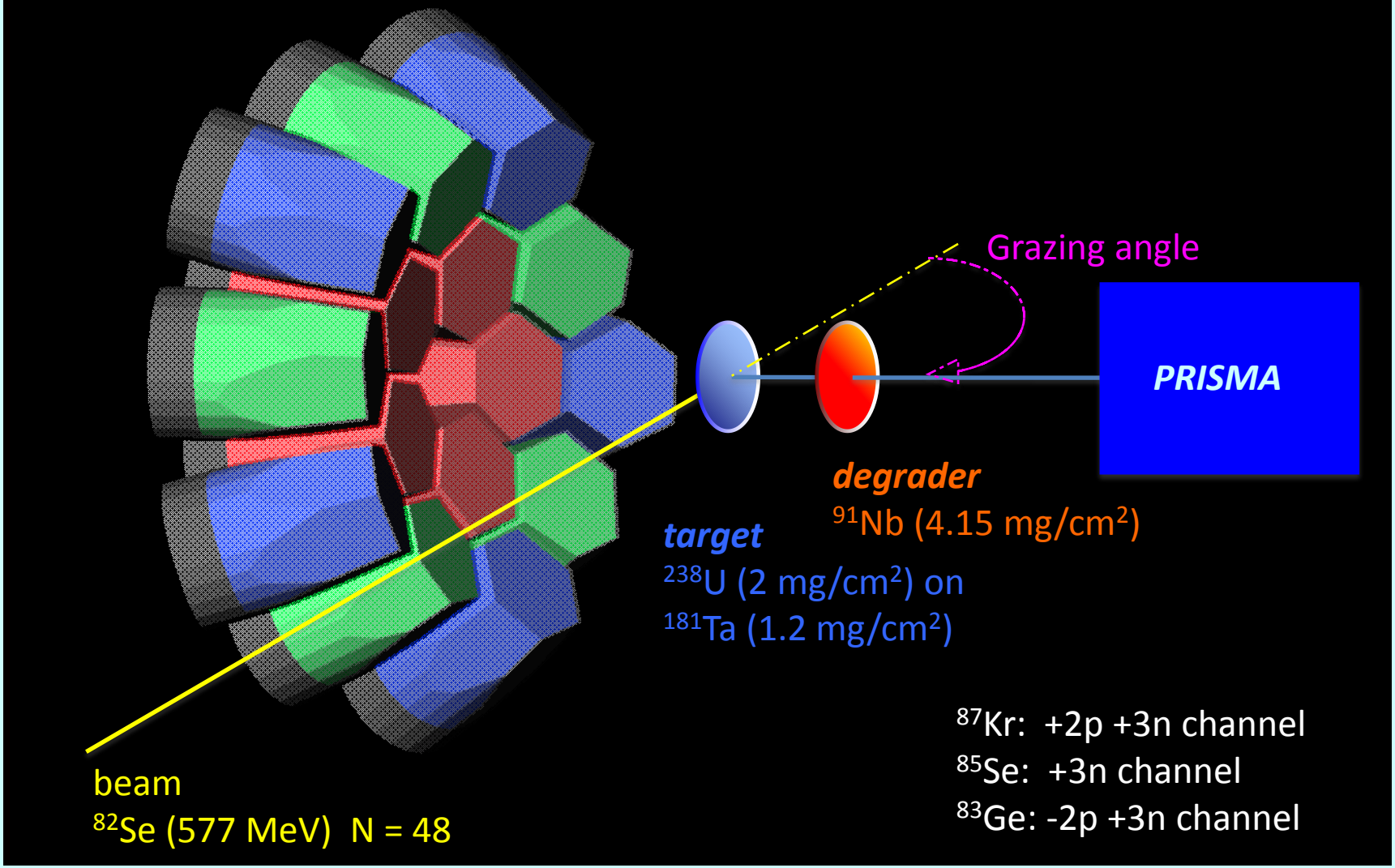
Lifetime measurement @ LNL with AGATA + PRISMA

Recoil Distance Doppler Shift Method



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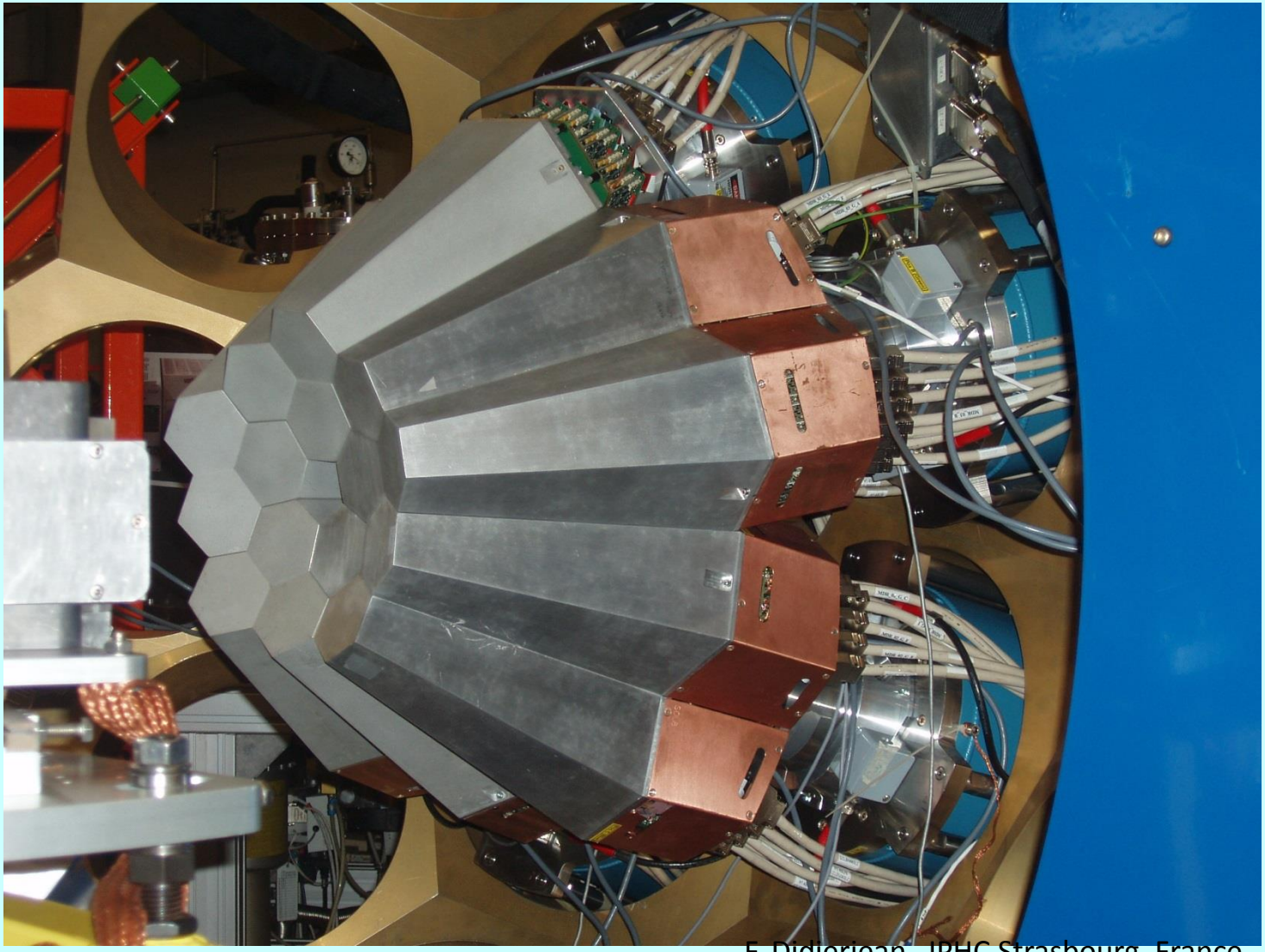
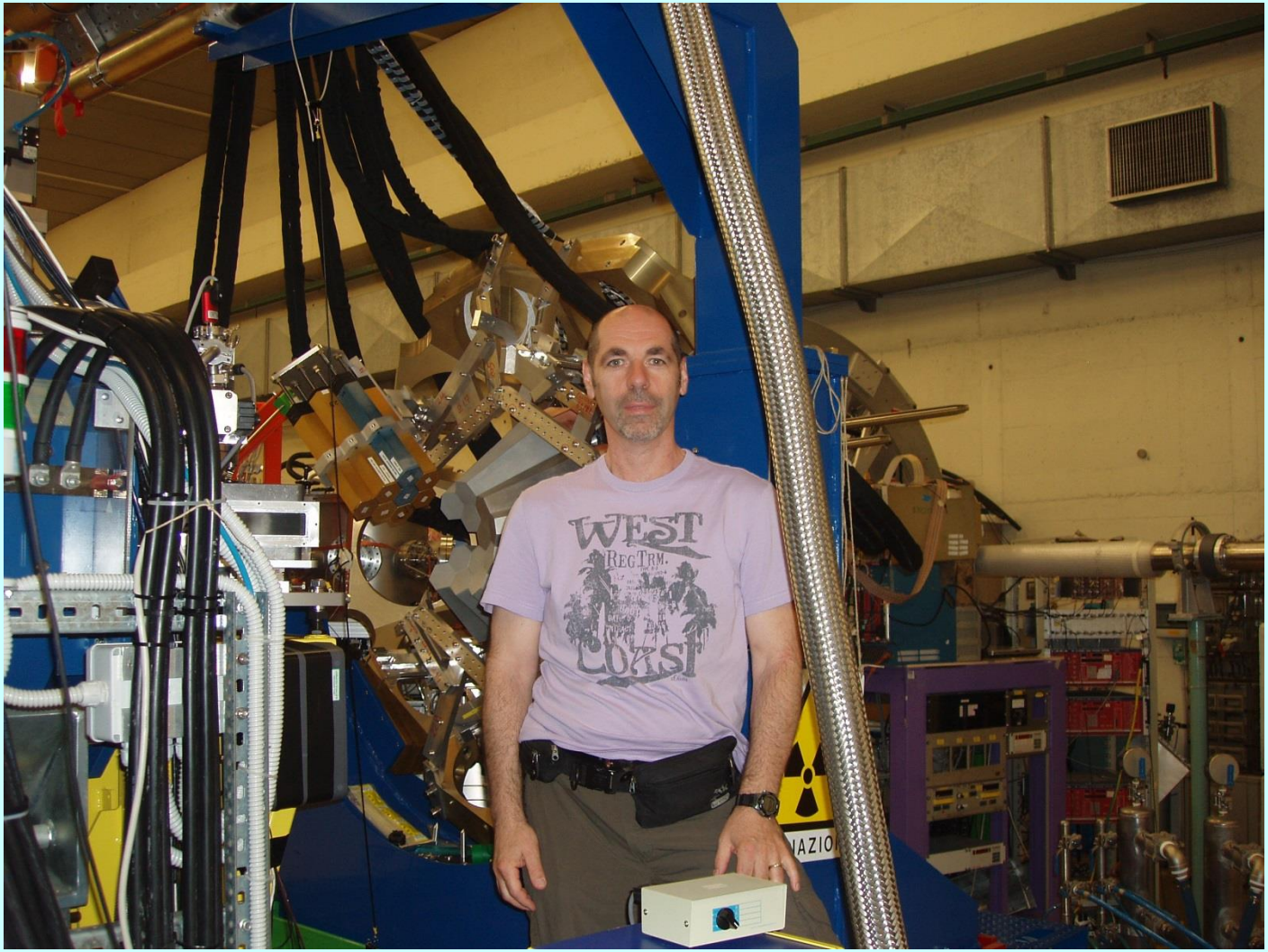
AGATA @ LNL



F. Didierjean IPHC Strasbourg, France

G. Duchêne

AGATA @ LNL



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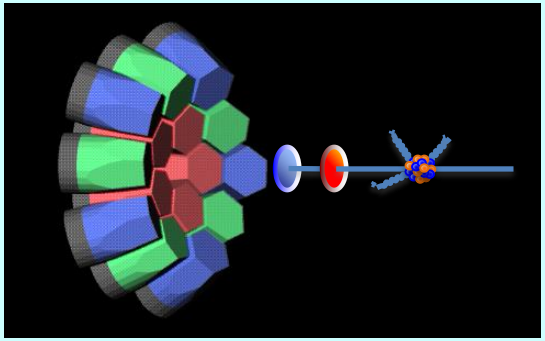
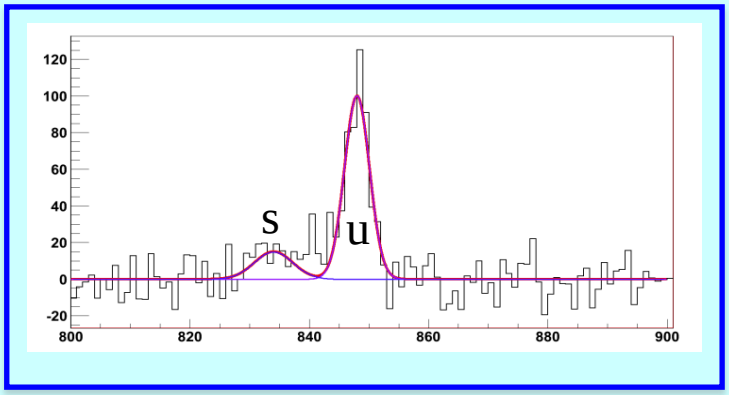
F. Didierjean IPHC Strasbourg, France

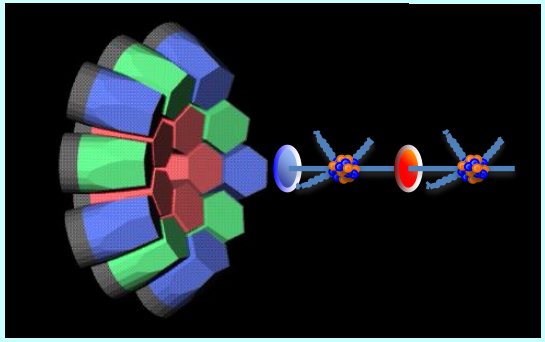
Principle of the RDDS method

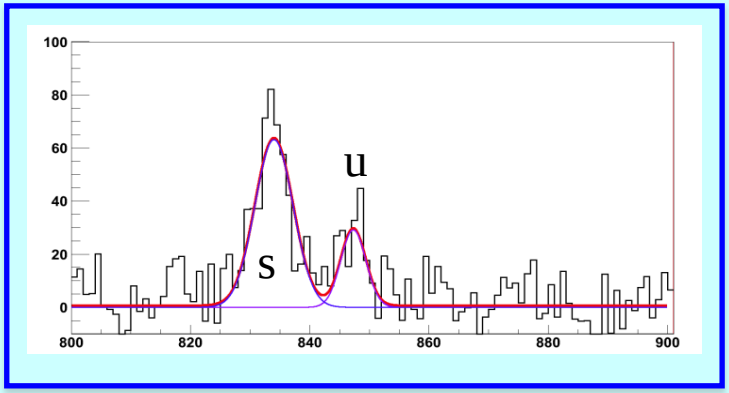
plunger distance : 35 µm





plunger distance : 253 µm





d : target to degrader distance
τ : effective lifetime of the state
v : speed of the γ emitter

$$R_i = \frac{I_u}{I_u + I_s}$$

$$\tau_i^{eff} = -\frac{d}{v \, . \, Ln(R_i)}$$

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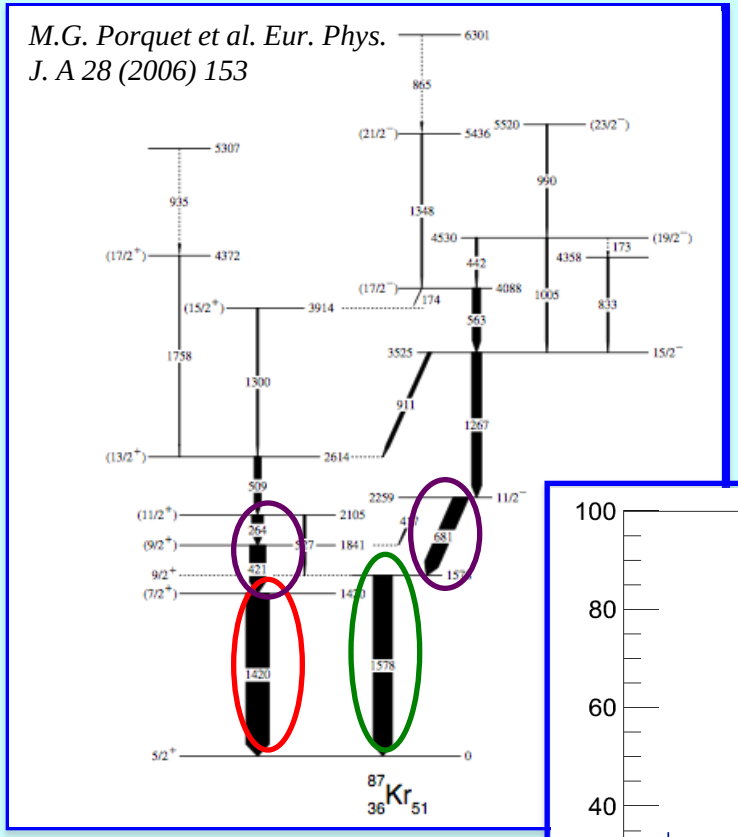
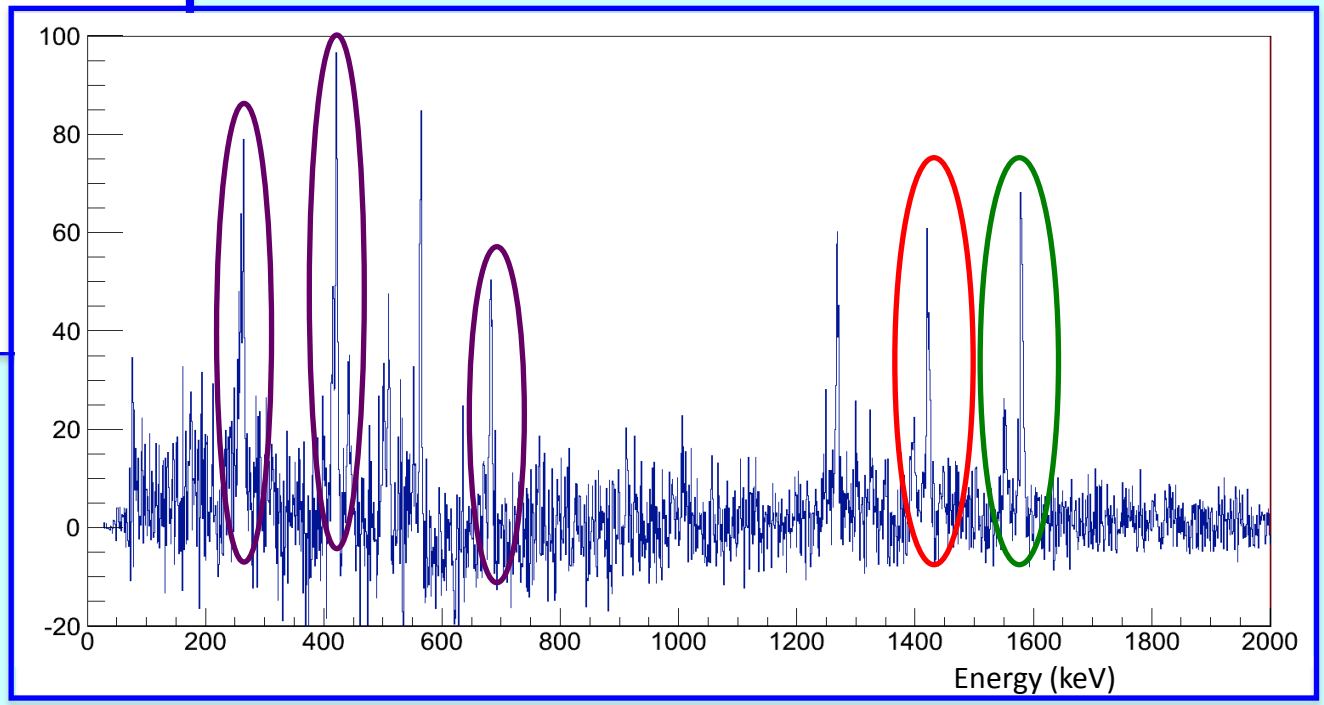
^{87}Kr spectrum - all distances



$9/2_1^+ \rightarrow 5/2^+$

$7/2_1^+ \rightarrow 5/2^+$

feeding



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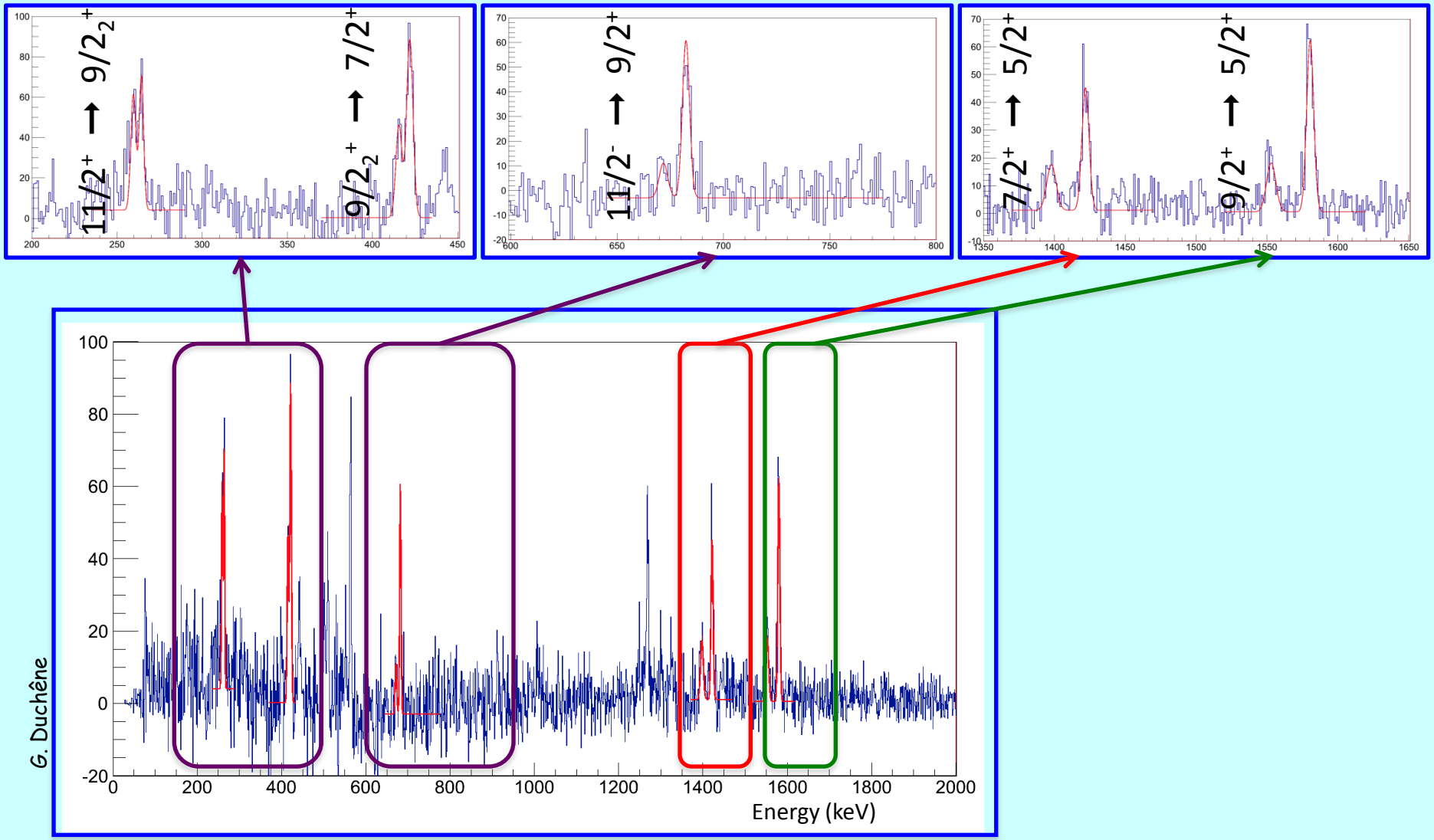
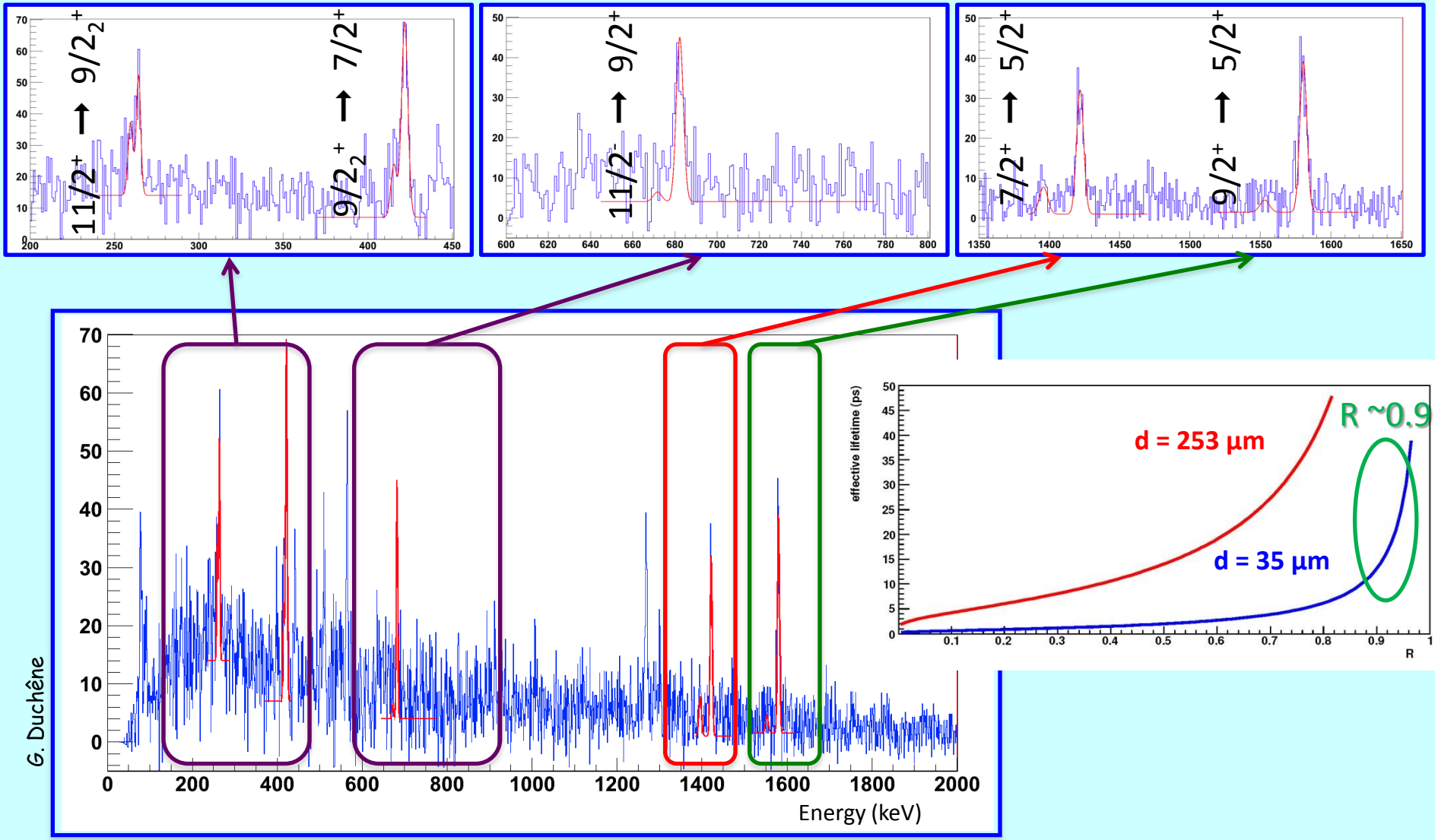
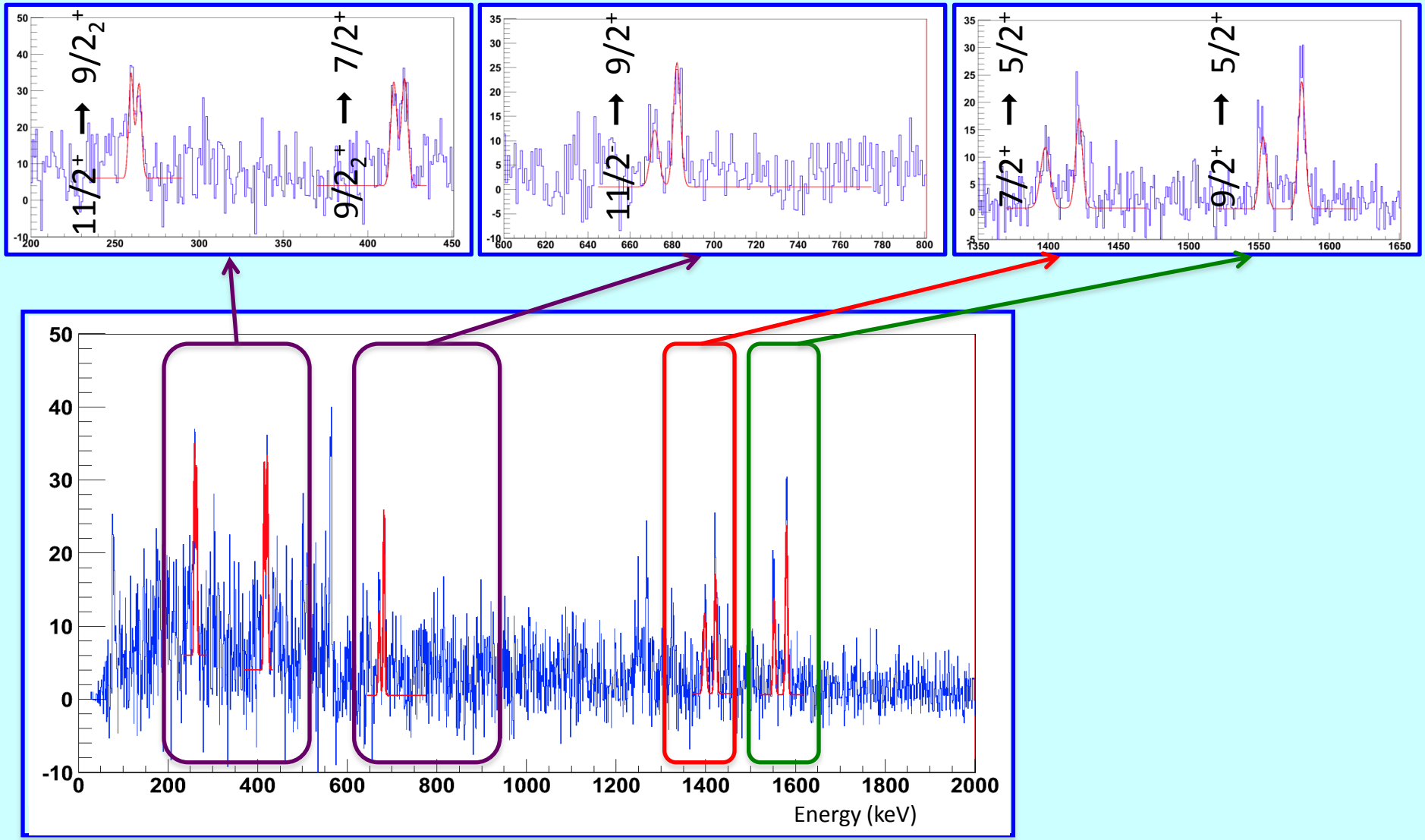
^{87}Kr spectrum - all distances



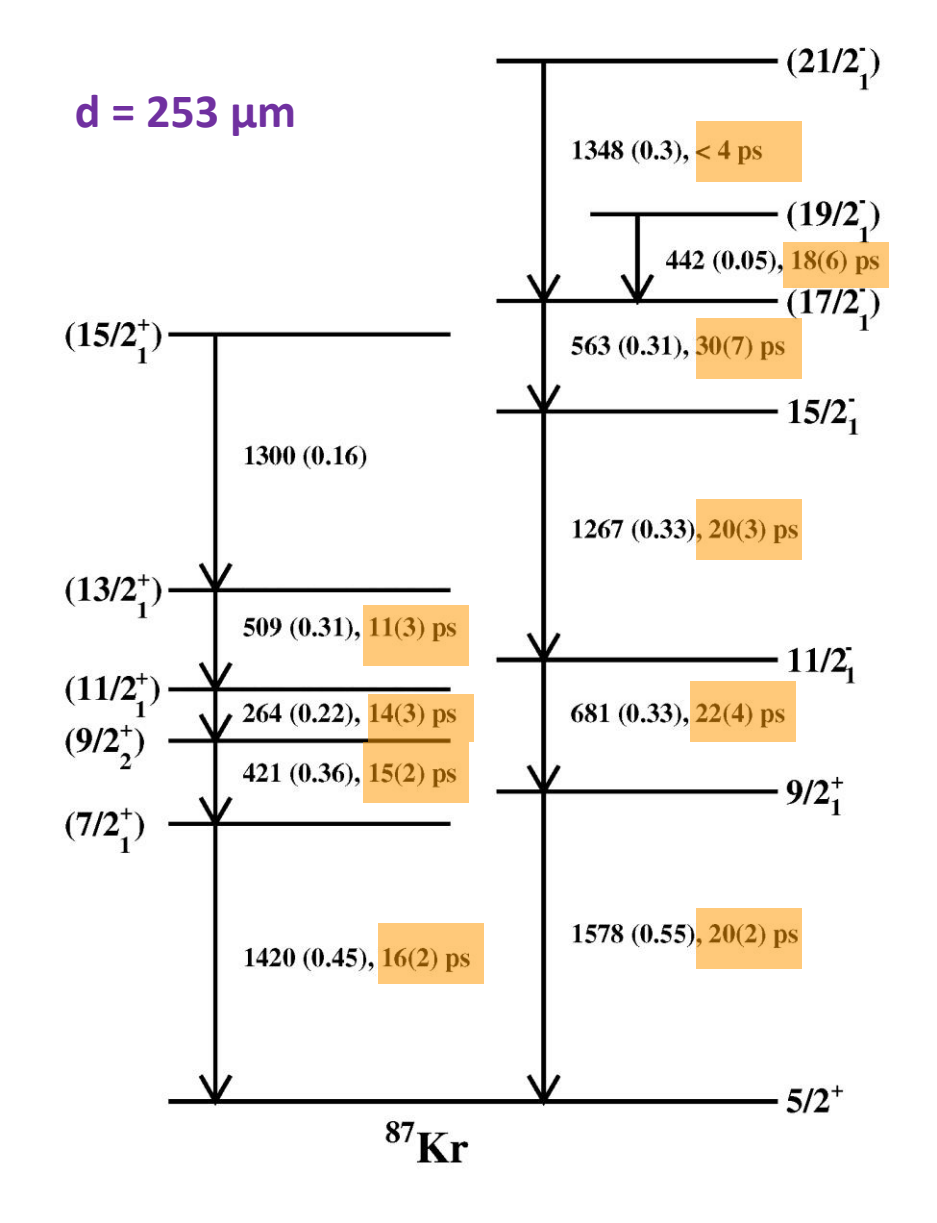
^{87}Kr spectrum: d = 35 μm



^{87}Kr spectrum: d = 253 μm



^{87}Kr: effective lifetimes



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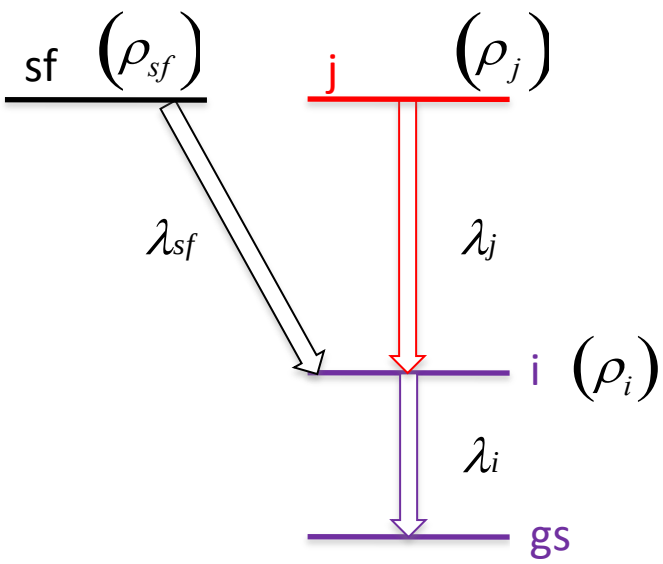
Bateman equations



$$\begin{cases} \dfrac{d\ N_{sf}(t)}{dt} = -\lambda_{sf} N_{sf}(t) \\ N_{sf}(t) = \rho_{sf}.\exp\left(-\lambda_{sf} t\right) \end{cases}$$

$$\begin{cases} \dfrac{d\ N_j(t)}{dt} = -\lambda_j N_j(t) \\ N_j(t) = \rho_j.\exp\left(-\lambda_j t\right) \end{cases}$$

$$\lambda = 1/\tau^{eff}$$

$$\boxed{\frac{d\ N_i(t)}{dt} = \lambda_{sf} N_{sf}(t) + \lambda_j N_j(t) - \lambda_i N_i(t)}$$

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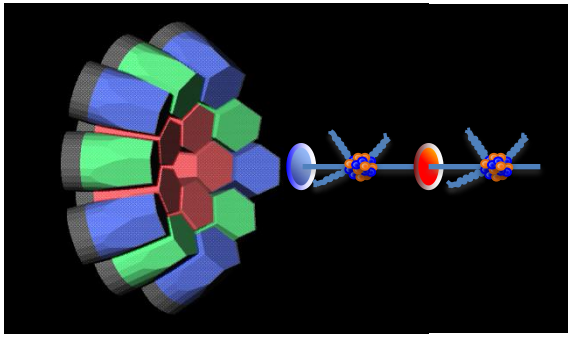
Bateman equations

$$\lambda_i \int_0^t N_i(t)\,dt = \frac{\lambda_i \rho_{sf} \lambda_{sf}}{\lambda_i - \lambda_{sf}} \left[\frac{1}{\lambda_{sf}} \left(1 - e^{-\lambda_{sf} t} \right) - \frac{1}{\lambda_i} \left(1 - e^{-\lambda_i t} \right) \right]$$
$$+ \frac{\lambda_i \rho_j \lambda_j}{\lambda_i - \lambda_j} \left[\frac{1}{\lambda_j} \left(1 - e^{-\lambda_j t} \right) - \frac{1}{\lambda_i} \left(1 - e^{-\lambda_i t} \right) \right]$$



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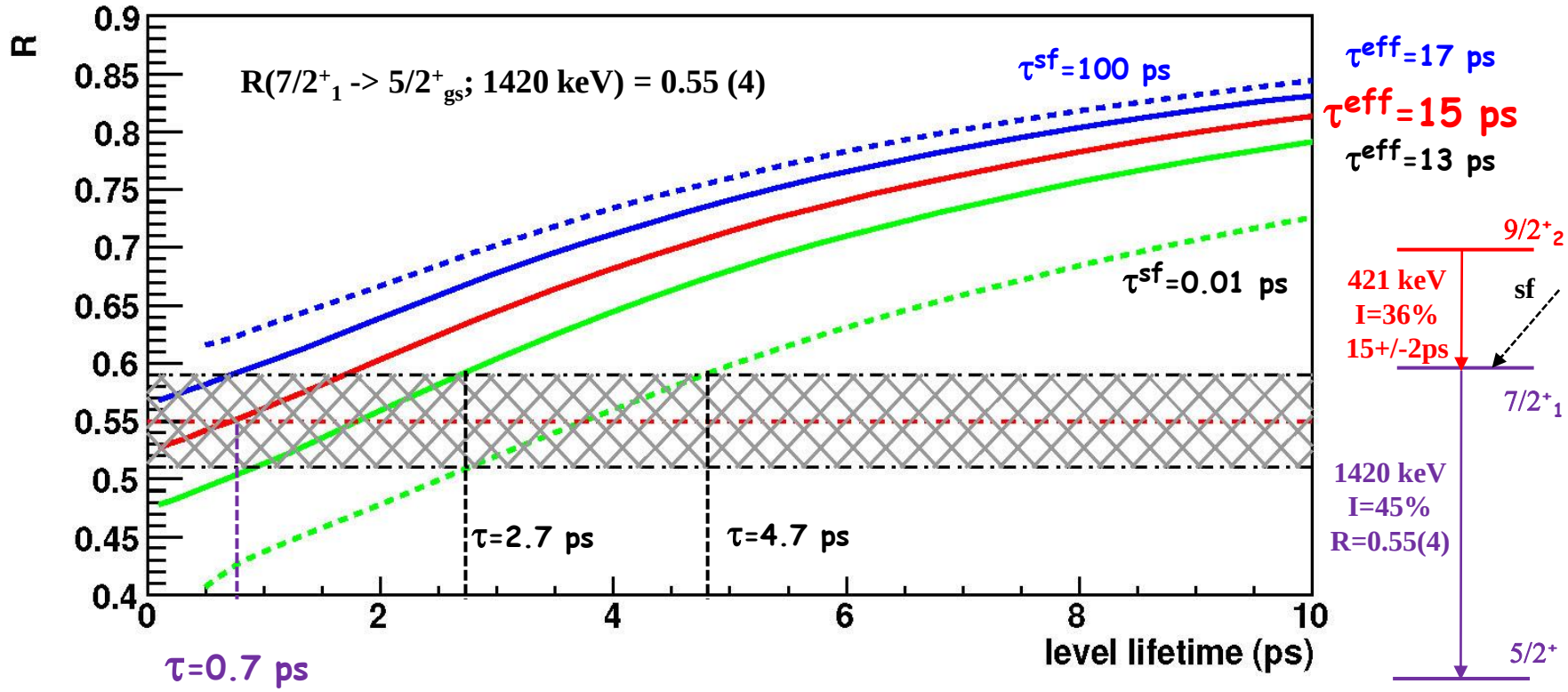
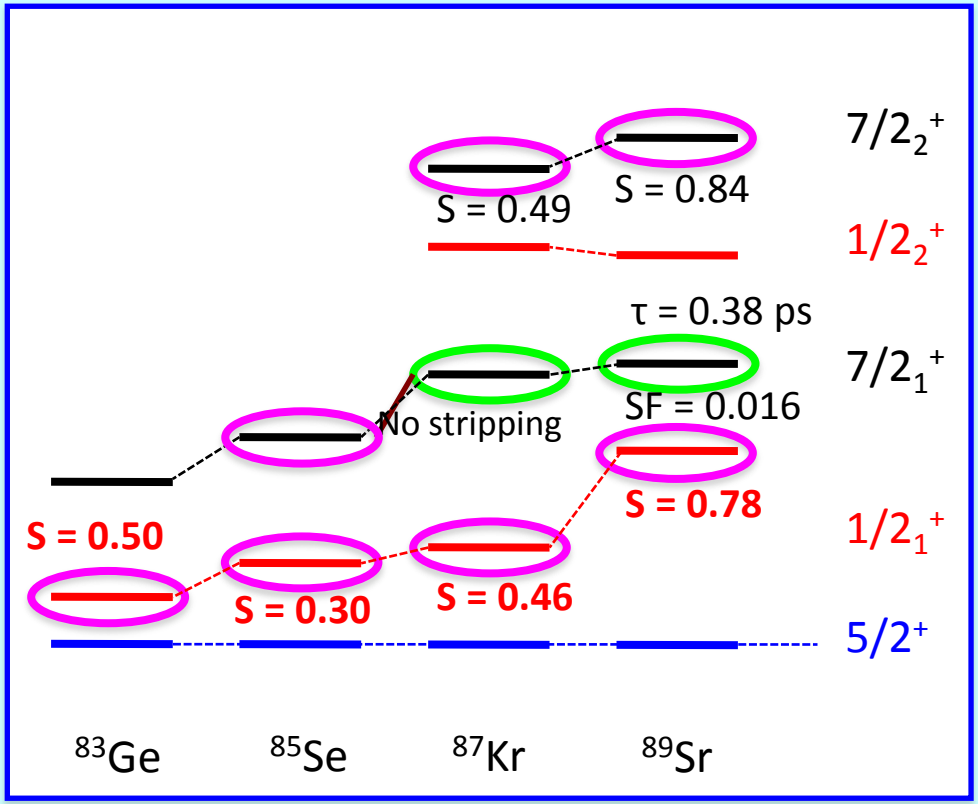
^{87}Kr: $(7/2^+_1)$ state lifetime



τ=0.7 ps (+2.0/-0.7) ps without sf

τ=0.7 ps (+4.0/-0.7) ps with sf


7/2₂⁺
S = 0.49
S = 0.84
1/2₂⁺
τ = 0.38 ps
7/2₁⁺
No stripping
SF = 0.016
S = 0.78
S = 0.50
1/2₁⁺
S = 0.30
S = 0.46
5/2⁺
83Ge
85Se
87Kr
89Sr

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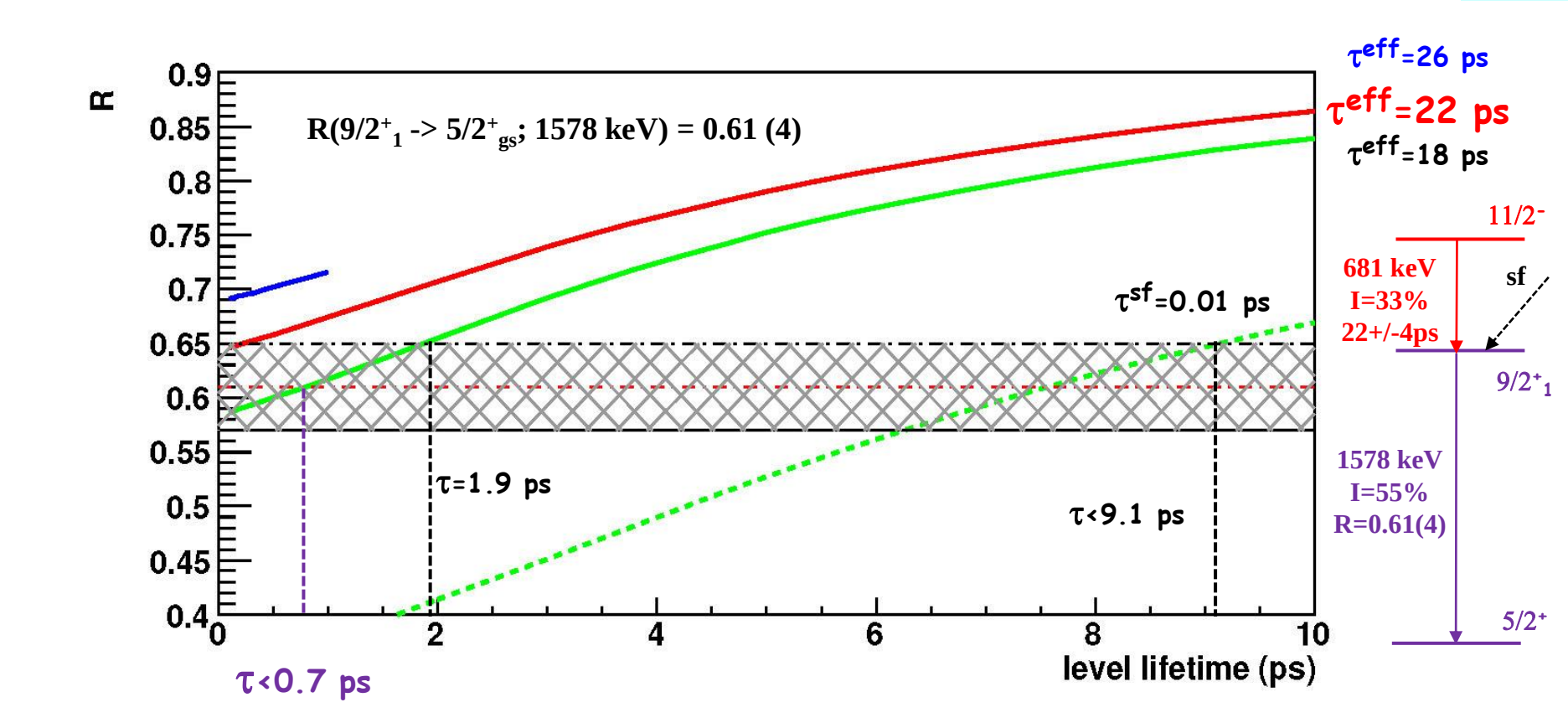
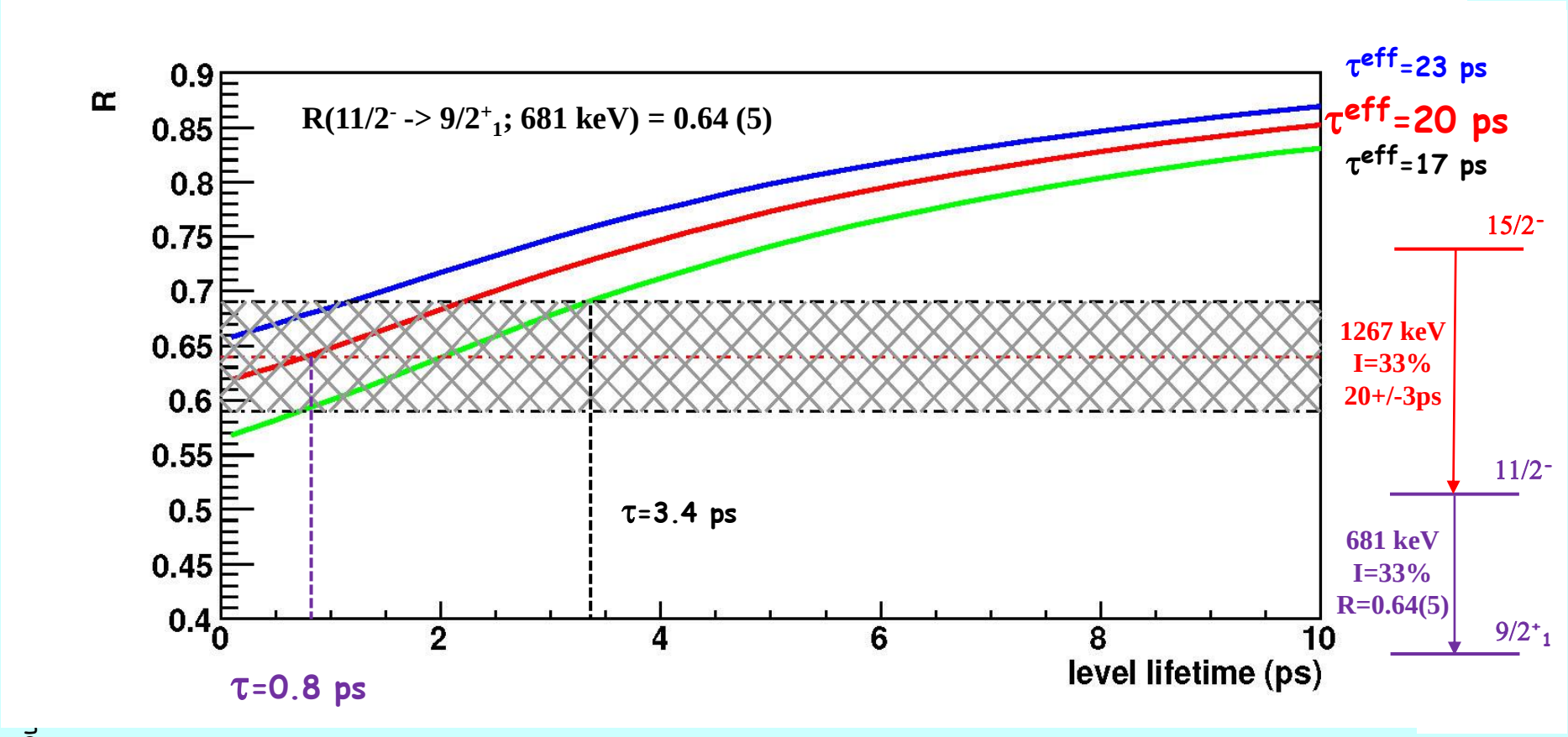
^{87}Kr: $(9/2^+_1)$ state lifetime



τ<0.7 ps (+1.2/-0.7) ps without sf

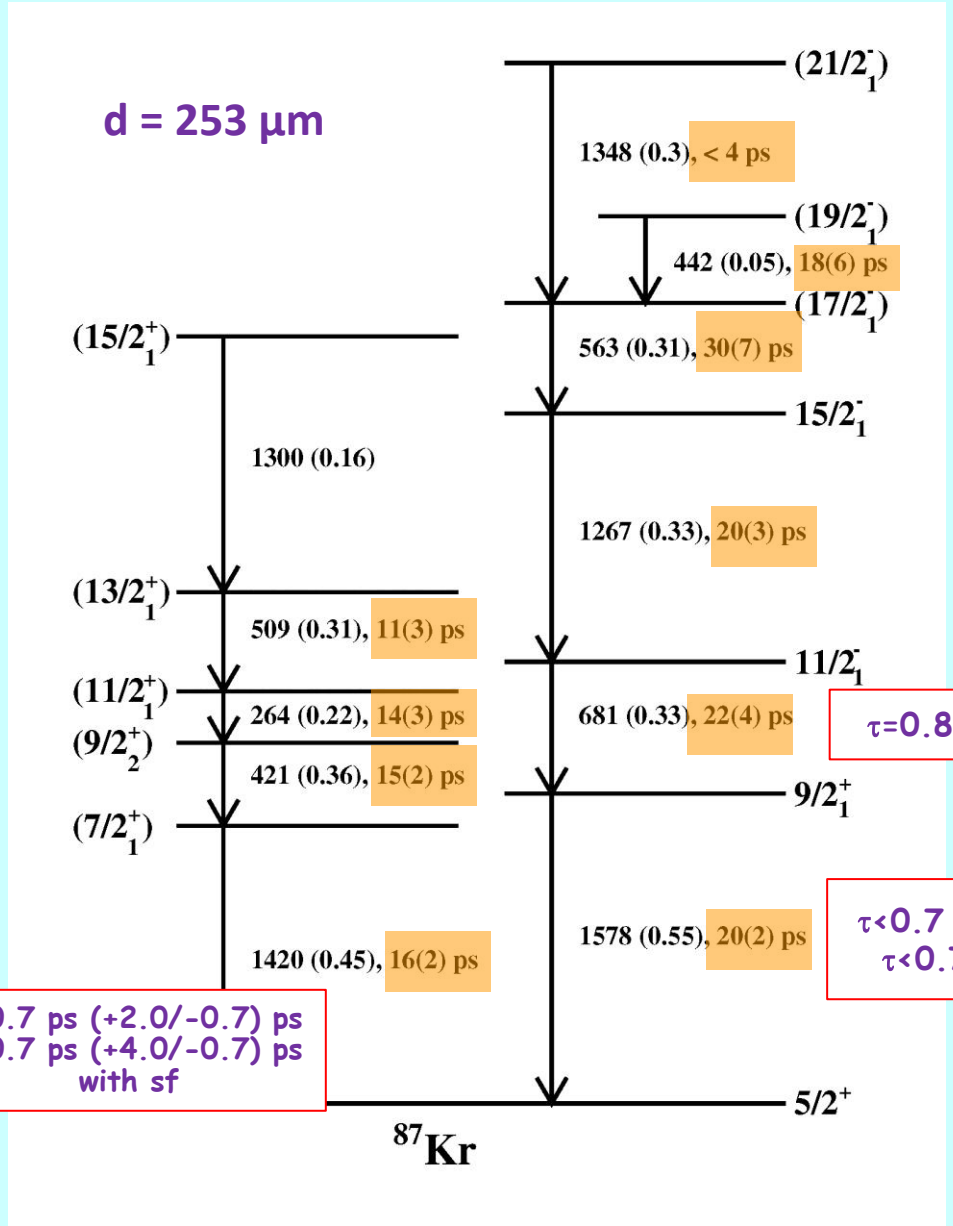
τ<0.7 ps (+8.4/-0.7) ps with sf

^{87}Kr: $(11/2^-_1)$ state lifetime



τ=0.8 ps (+2.6/-0.8) ps

^{87}Kr: lifetimes



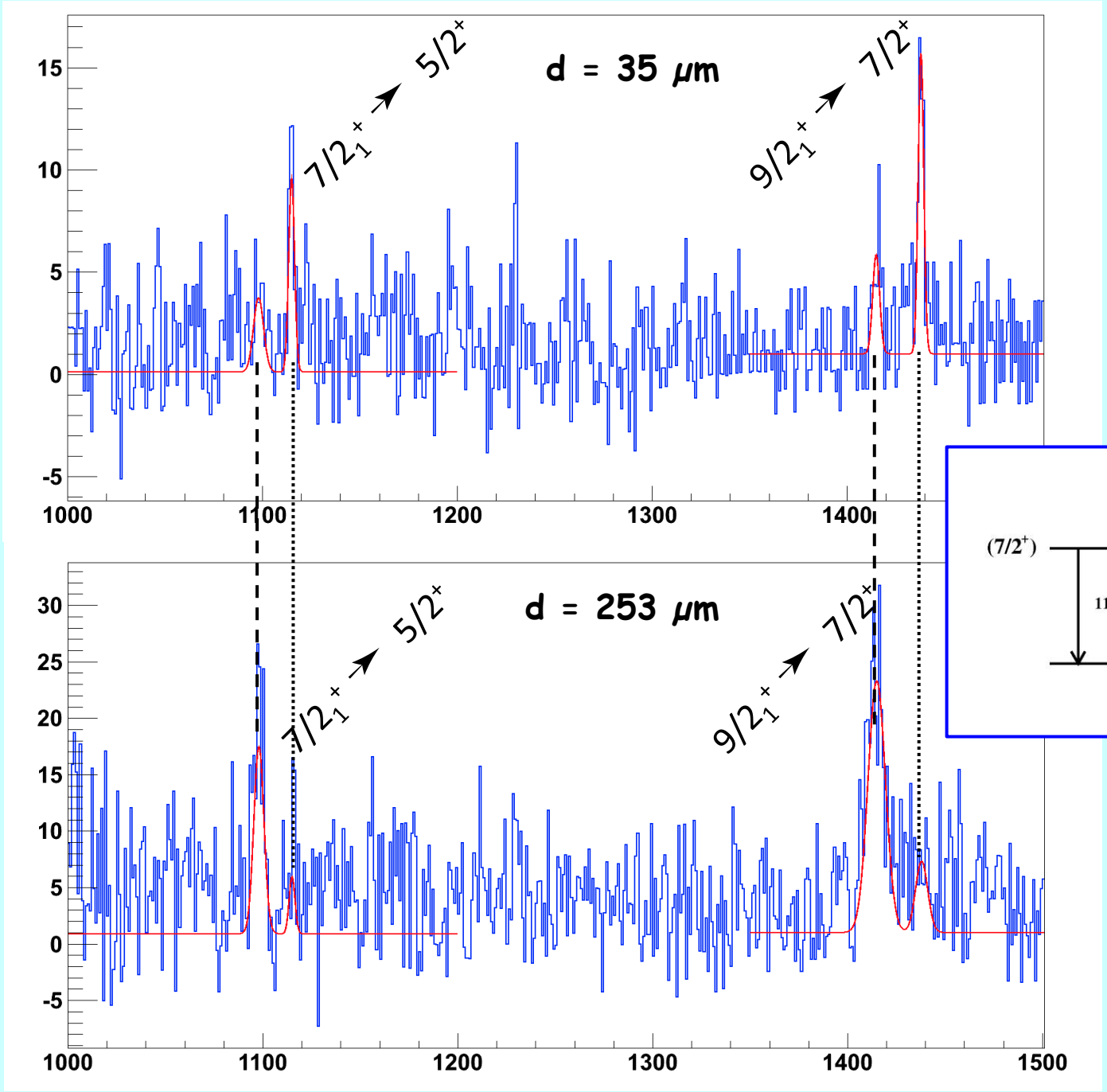
τ=0.8 ps (+2.6/-0.8) ps

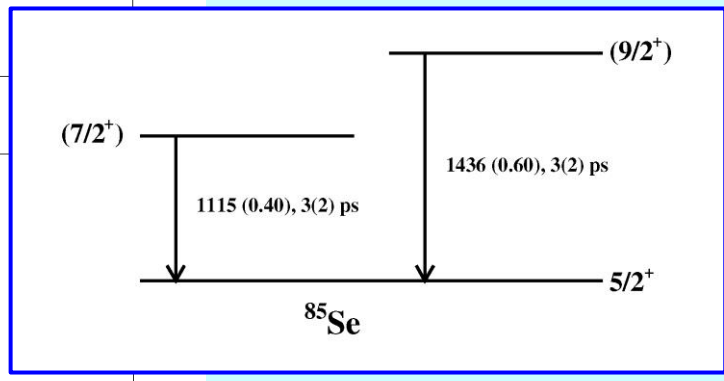
τ<0.7 ps (+1.2/-0.7) ps without sf
τ<0.7 ps (+8.4/-0.7) ps with sf

τ=0.7 ps (+2.0/-0.7) ps
τ=0.7 ps (+4.0/-0.7) ps
with sf

Lifetimes of low-lying states in ^{87}Kr are short lived and of core-coupled config

^{85}Se spectra





Effective lifetimes in ^{85}Se: $7/2_1^+$ and $9/2_1^+$

Plunger distances (µm)	$7/2_1^+ \rightarrow 5/2^+$		$9/2_1^+ \rightarrow 5/2^+$	
	R(1115 keV)	τ_{eff} (ps)	R(1436 keV)	τ_{eff} (ps)
35	0.65(3)	3(2)	0.65(3)	3(2)
253	<0.11	<4	<0.11	<4

Calculated lifetimes for ^{85}Se states are:

- **0.42 ps** for core-coupled config
- **79.5 ps** for single-particle config

Independently of the feeding lifetimes, lifetimes of both states in ^{85}Se are short lived and the core-coupled config is dominating

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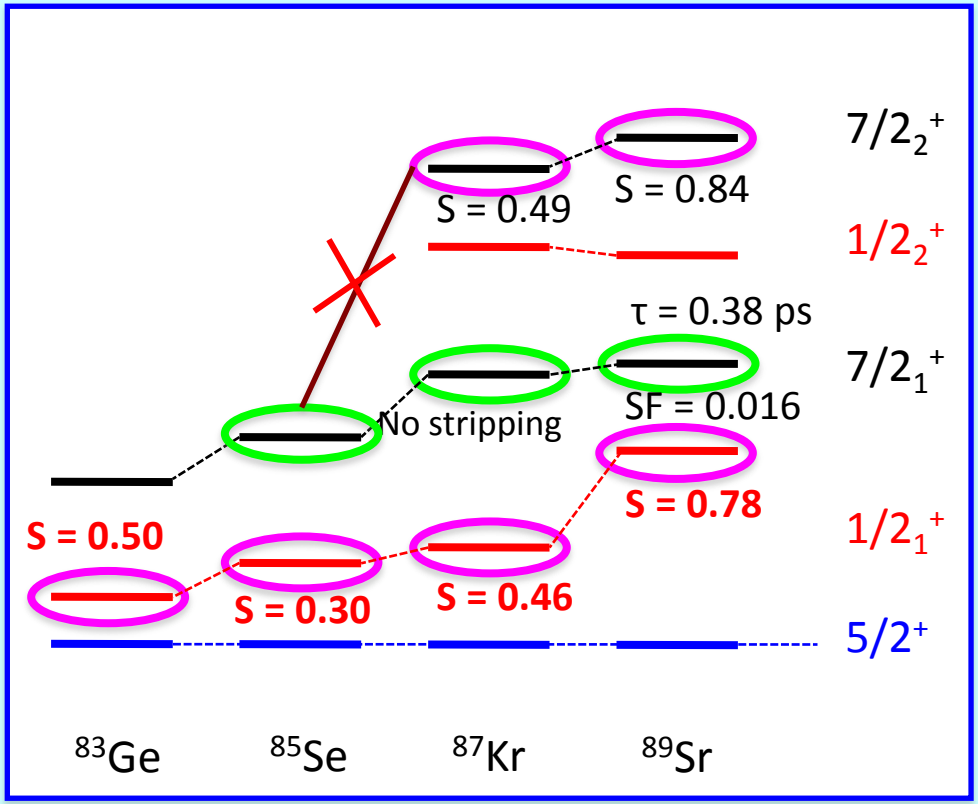
7/2$_2^+$
S = 0.49
S = 0.84
1/2$_2^+$
τ = 0.38 ps
7/2$_1^+$
No stripping
SF = 0.016
S = 0.78
S = 0.50
1/2$_1^+$
S = 0.30
S = 0.46
5/2$^+$
^{83}Ge
^{85}Se
^{87}Kr
^{89}Sr

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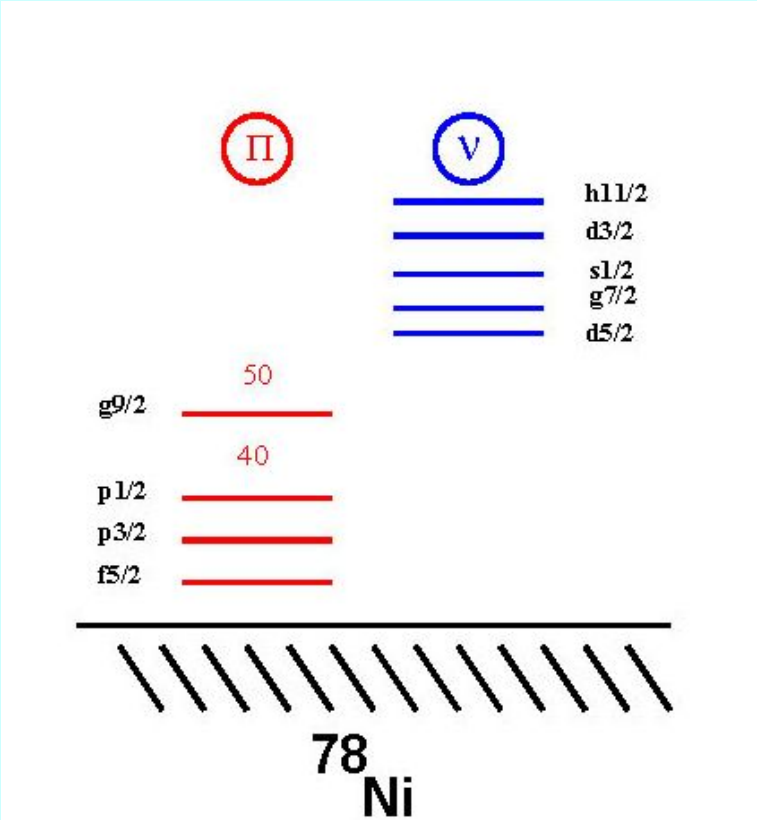
SM calculations



K. Sieja courtesy

- ππ interaction fit to new data on N=50
- νν GCN5082 interaction
- πν monopole corrected G-matrix
- Proven successful and predictive in a large number of applications

		$7/2^+$ -> gs	$9/2^+$ -> gs
^{87}Kr	Exp.	$\tau=0.7\ ^{+4.0}_{-0.7}$ ps	$\tau< 0.7\ ^{+8.4}_{-0.7}$ ps
	SM	M1: 0.44 ps E2: 0.51 ps	E2: 1.09 ps
^{85}Se	Exp.	$\tau^{eff} \sim 3(2)$	$\tau^{eff} \sim 3(2)$
	SM	M1: 0.31 ps E2: 0.50 ps	E2: 1.40 ps

Excellent theory-experiment agreement -> core-coupled structures

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Summary and perspectives

Summary

- Lifetimes of low-lying $7/2_1^+$ and $9/2_1^+$ states have been measured in ^{87}Kr and ^{85}Se N=51 nuclei to determine their single-particle or core-coupled character
- Nuclei have been produced at LNL using the ^{82}Se + ^{238}U multi-nucleon transfer reaction; Setup: AGATA Demonstrator (5TC) + PRISMA + Koeln Plunger
- The RDDS technique has been used with a Nb degrader
- The main goal of the experiment is to determine the order of magnitude of these lifetimes, only two plunger positions were used 35 and 253 μm
- Batman equations were used to extract lifetime values in ^{87}Kr and effective lifetime values in ^{85}Se
- Measured lifetime values indicate that both states in both nuclei are short lived and their structures are compatible with core-coupled configurations
- Shell-model calculations using a ^{78}Ni core and π(fpg)-ν(sdgh) valence space in j-coupling mode predict low-lying states mainly based on core-coupled configurations
- Theoretical and experimental lifetimes are in very good agreement

Perspectives

- Two AGATA@GANIL experiments, a long one (14d) for spectroscopy studies in the same mass region and a plunger one (9d) for study of N=51 nuclei lifetimes down to ^{83}Ge (3 positions), have been run in April and May

G. Duchêne