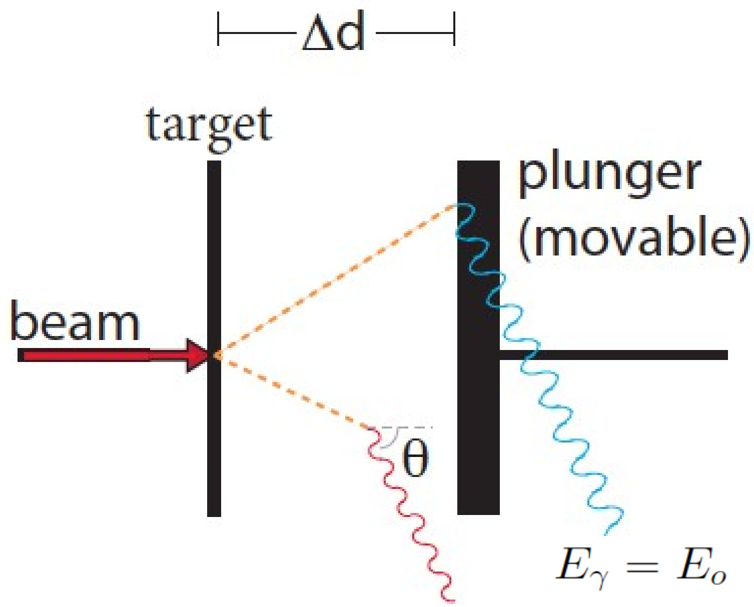
Overview Lecture 2:

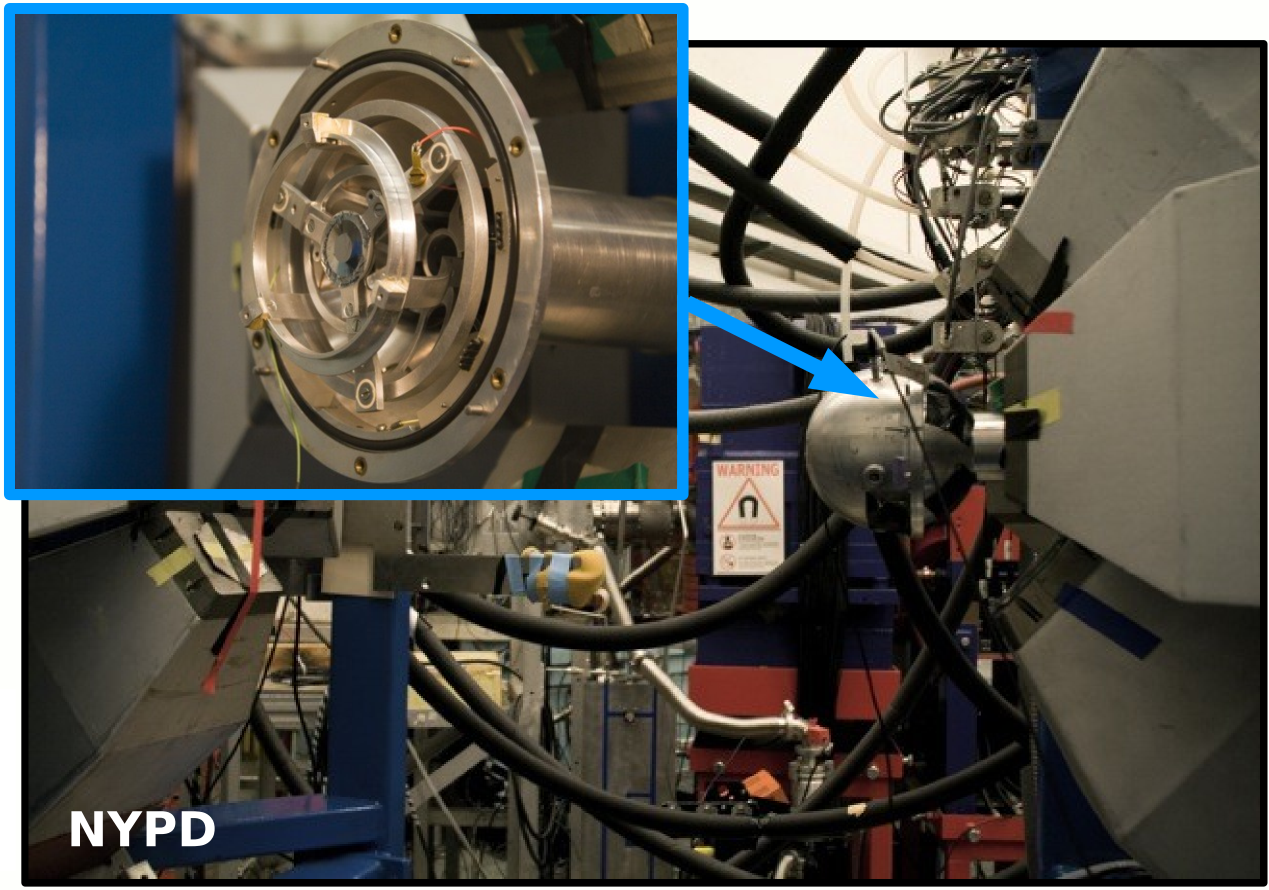
- Inverese Kinematics Lifetimes and g Factors – g - Plunger
  - „Troubles” in Inverse Kinematics, and how to use them
  - Proof of principle: Pd Chain
  - Next Projects ...
- The femto-second regime – Nuclear Resonance Fluorescence
  - Introduction to Photon-Scattering
  - Example: Investigation of ^{76}Se with Continuous and „Laser” Beams

(g-)Plunger Experiments

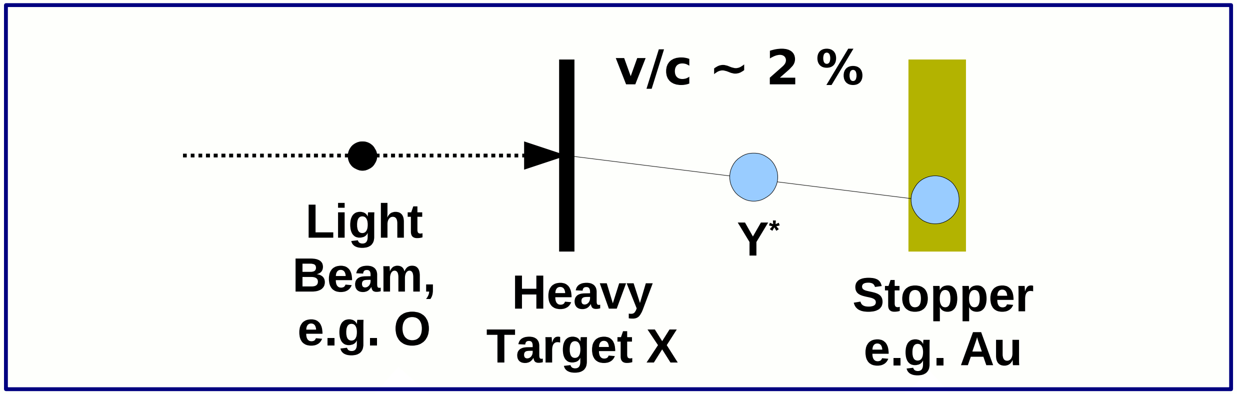
Recoil Distance Doppler Shift (RDDS) method
-> pico-second regime

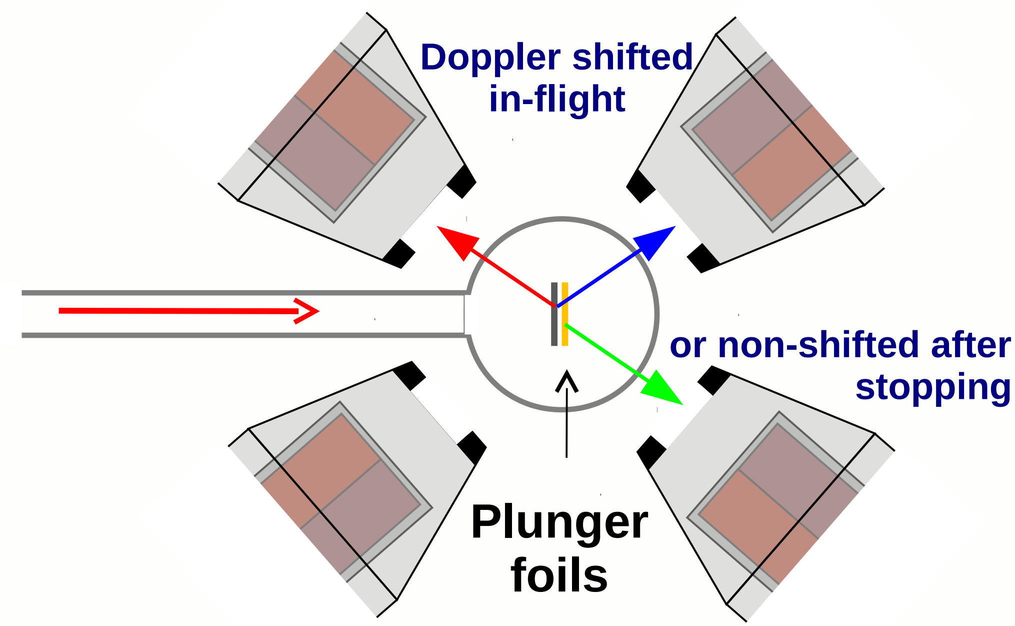


$$E'_\gamma = E_o\left(1 + \frac{v}{c}\cos(\theta)\right)$$



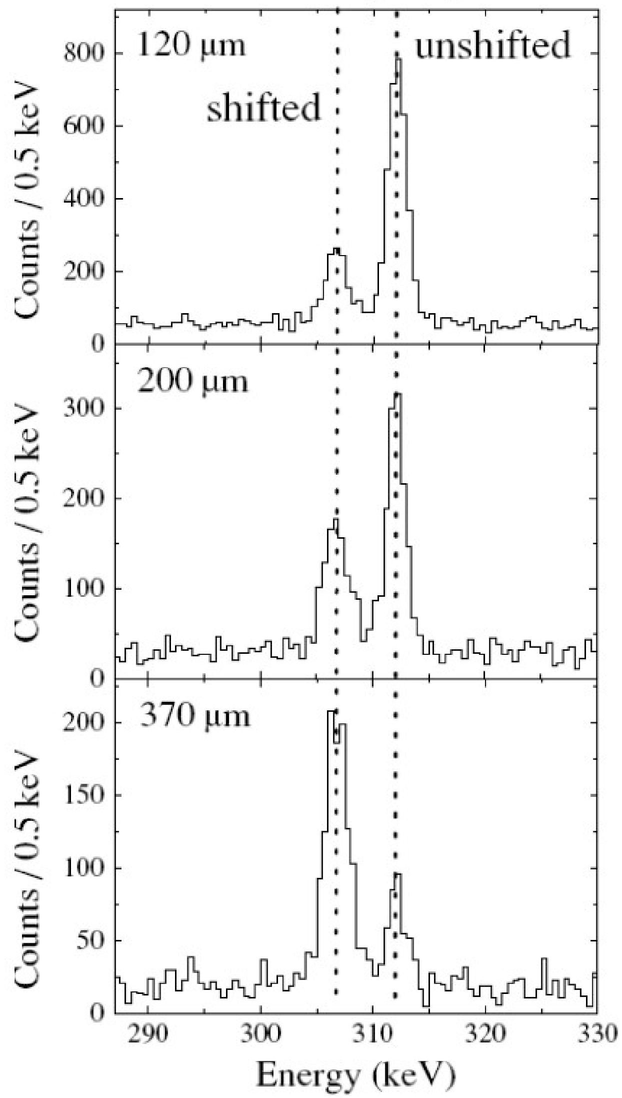
Yale Plunger





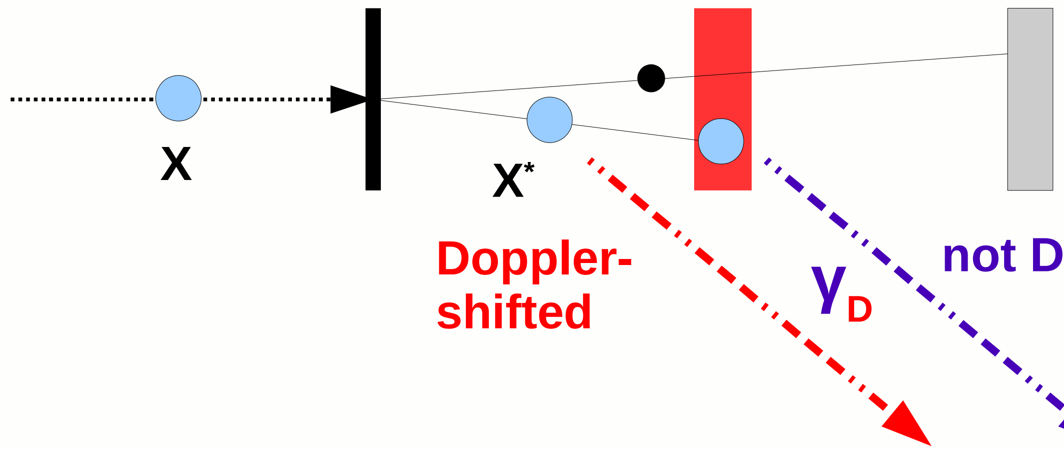
$$E_{sh} = E_o(1 + \frac{v}{c}\cos\theta)$$

^{166}Hf: $4_1^+ \rightarrow 2_1^+$



Recoil Distance Method

v/c~5-10%

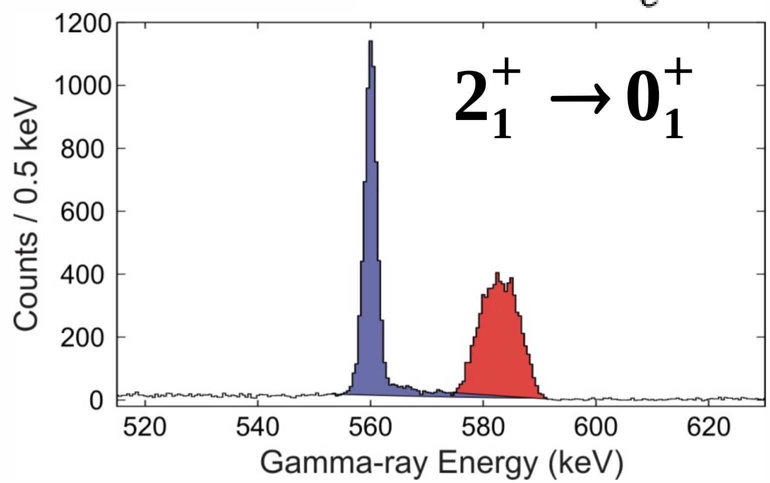


Important now, next order

+ β²/2

$$E_{sh} = E_o(1 + \frac{v}{c}\cos\theta)$$

High recoil velocity
-> large separation of peaks
(and some problems we didn't have before....)
All I show is Coulomb Excitation
-> direct excitation, no feeding !



Intensity correction of γ rays

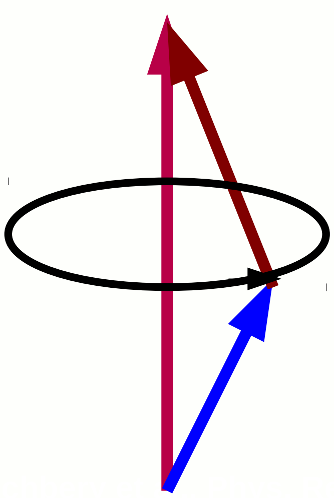
Attenuation coefficients (solid angle) of the detectors - Q

Solid angle of the particle detector – attenuation of the angular distribution

Lorentz boost $d\Omega/d\Omega' = (E\gamma/E\gamma_0)^2 = [1 + (E\gamma - E\gamma_0)/E\gamma_0]^2$

Nuclear Deorientation

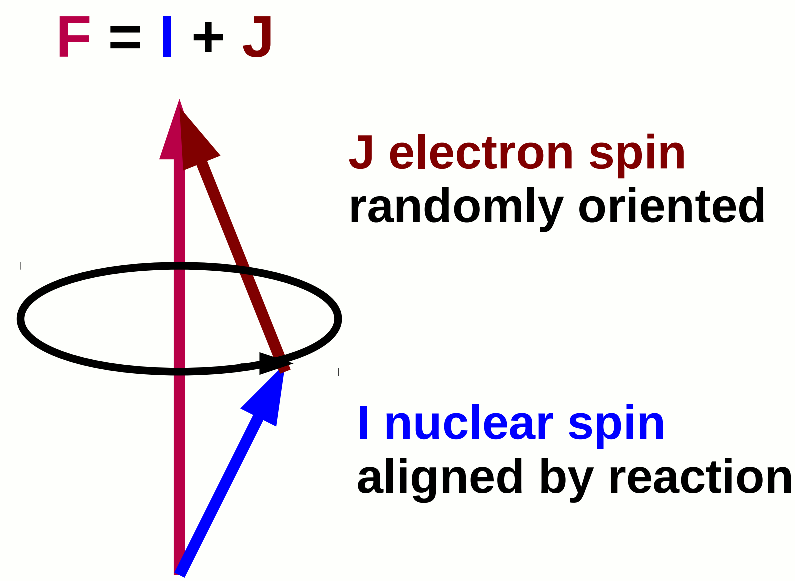
Hyperfine Interaction:
Precession of the nuclear spin I and the electron spin J about the total spin F



Nuclear Deorientation (RIV)

Make use of "Recoil Into Vacuum" (RIV)

=> Angular distribution is attenuated!
By precession of the nuclear spin due to the hyperfine interaction
→ deorientation coefficients.



$$W(\theta)=1+\Sigma_{i=2,4}\, G_i(t)\, Q_i\, B_i\, F_i\, P_i(\cos\theta)$$

G_i depend on magnetic moment (interacting with electrons)

$$G_k(t)=\alpha_k+(1-\alpha_k)\cdot\exp[-(g\cdot d)/(v\cdot C_k)]$$

⇒ 3 parameters: α_k, g, C_k

A. Stuchbery et al., PRC 76, 034307 (2007)

Distance dependent angular distribution:

$$\frac{A_{2/4}^{exp}}{A_{2/4}^{coulex}(d=0)}=G_{2/4}$$

Angular Distributions

$$W_0(\Theta) = \sum_k A_k P_k(\cos\Theta)$$

$$A_k = \sqrt{2I+1}\rho_0^k R_k Q_k = B_k R_k Q_k$$

Initial alignment characterized by: $B_k = \sqrt{2I+1}\rho_0^k$

$$\rho_q^k = \sum_{mm'} (-1)^{I+m'} \langle I - m' I m | kq \rangle \rho_{m'm}$$ **„statistical tensor"**

and $\rho_{m,m'} = a_m a_{m'}^*$

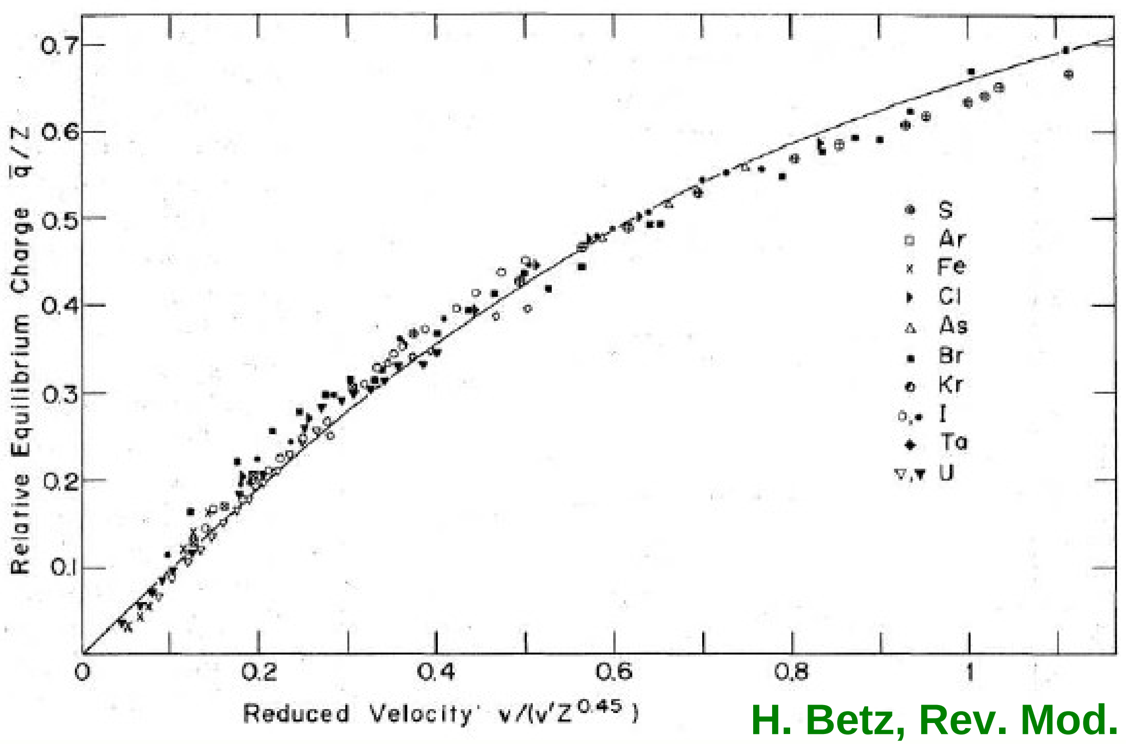
a_m **is the *m* component of the nuclear WF, and *m* is the component of the spin along the z-axis**

$R_k Q_k$ **stat. coefficients and attenuation due to solid angle... can be calculated analytically**

Since we use Coulomb excitation, which is a well-known E-M process, all the above can be calculated from Coulex Theory.

Parameters going into HF

Charge state of the ion exiting the target.



H. Betz, Rev. Mod. Phys. 44, 465 (1972)

Depends on velocity. Average charge state is reached while passing through the target foil.
(Avg. charge state reached within a fraction of the target at these velocities.)

-> Avg. charge state determines atomic physics (electron-configurations)

Parameters going into HF

$$E_{\mathrm{HF}} = -\vec{\mu}_I \vec{B}_{\mathrm{HF}} \qquad \vec{B}_{\mathrm{HF}} \propto \vec{J} \qquad \vec{\mu}_I = g_i \vec{I} \mu_N$$

$$E_{\mathrm{HF}} = A \frac{\vec{I} \cdot \vec{J}}{\hbar^2}$$

$$\vec{F} = \vec{I} + \vec{J} \qquad \langle \vec{I} \cdot \vec{J} \rangle = \frac{1}{2} \hbar^2 \left[F(F+1) - I(I+1) - J(J+1) \right]$$

Typical values: HF – splittings 10^{-6} – 10^{-7} eV ; B_{HF} ~ 2-3 kT

We don't quite know the atomic physics (values of *I*).

Deorientation

Since the nuclear ensemble is deorienting with time, we need a factor (function) to take this into account:

$$W(\Theta, t) = \sum_k G_k(t) A_k P_k(\cos\Theta)$$

If there is no stopper (that is „normal” Recoil Into Vacuum – RIV):

$$W_p(\Theta) = \langle W(\Theta, t)\rangle = \frac{1}{\tau}\int_0^\infty e^{-t/\tau} W(\Theta, t)\mathrm{d}t \quad = \sum_k A_k G_k(\infty) P_k(\cos(\Theta))$$

$$G_k(\infty) = \langle G_k(t)\rangle = \frac{1}{\tau}\int_0^\infty e^{-t/\tau} G_k(t)\mathrm{d}t$$

with excited state lifetime τ

If we would *know* the electron configurations (but we *don't*)

$$G_k(t) = \sum_{F,F'} C_{IJ}^{F,F'}(k)\cos(\omega_{F,F'}t)$$

$$C_{IJ}^{F,F'}(k) = \frac{(2F+1)(2F'+1)}{2J+1}\begin{pmatrix} F & F' & k \\ I & I & J \end{pmatrix}^2$$

$$\omega_{F,F'} = g\frac{\mu_N}{\hbar}B_{\mathrm{HF}}\frac{F(F+1)-F'(F'+1)}{2J}$$

(for each electron configuration)

Too Complicated !

We need a more empirical approach:

$$G_k(t) = \sum_i q(J_i) \sum_{F,F'} C_{IJ}^{F,F'}(k) \cos(\omega_{FF'} t)$$

q(J) is a distribution of electron configurations.

Let us assume that electronic configurations (states) are much *longer-lived* than the excited nuclear state -> Static Limit !

If the electronic states have a broad distribution, then the Larmor frequencies of the precessions are also broadly distributed.

-> Broad distribution of Larmor frequencies with some Lorentzian distribution width Γ_k , which depends on the nuclear magnetic moment.

Broad distribution leads to exponential behavior of G_k, and the initial orientation will never *completely* be destroyed -> „hard-core" parameter α_k

$$G_k(t) = \alpha_k + (1 - \alpha_k) \cdot \exp(-\Gamma_k t)$$

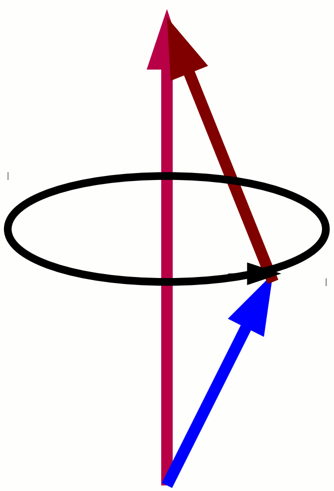
$$\alpha_k = \sum_F \frac{(2F+1)^2}{2J+1} \begin{pmatrix} F & F' & K \\ I & I & J \end{pmatrix}^2$$

we use as a parameter, since F, J unknown

Nuclear Deorientation (RIV)

Make use of "Recoil Into Vacuum" (RIV)

F = I + J



J electron spin
randomly oriented

=> Angular distribution is attenuated!
By precession of the nuclear spin due to the hyperfine interaction
→ deorientation coefficients.

I nuclear spin
aligned by reaction

$$W(\theta)=1+\Sigma_{i=2,4}\, G_i(t)\, Q_i\, B_i\, F_i\, P_i(\cos\theta)$$

G_i depend on magnetic moment (interacting with electrons)

$$G_k(t)=\alpha_k+(1-\alpha_k)\cdot\exp[-(g\cdot d)/(v\cdot C_k)]$$

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A. Stuchbery et al., PRC 76, 034307 (2007)

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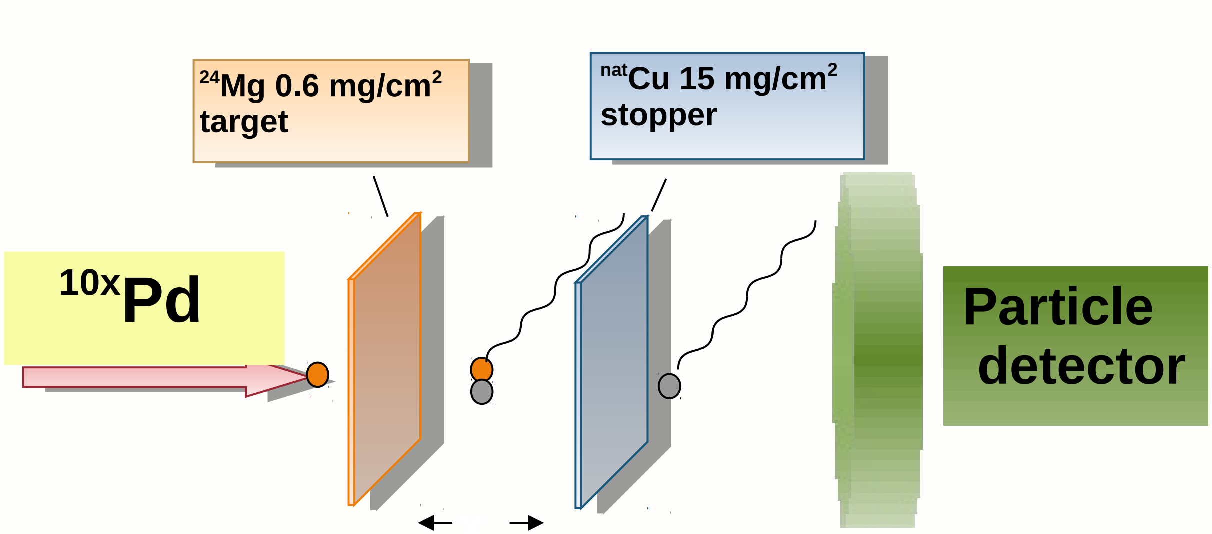
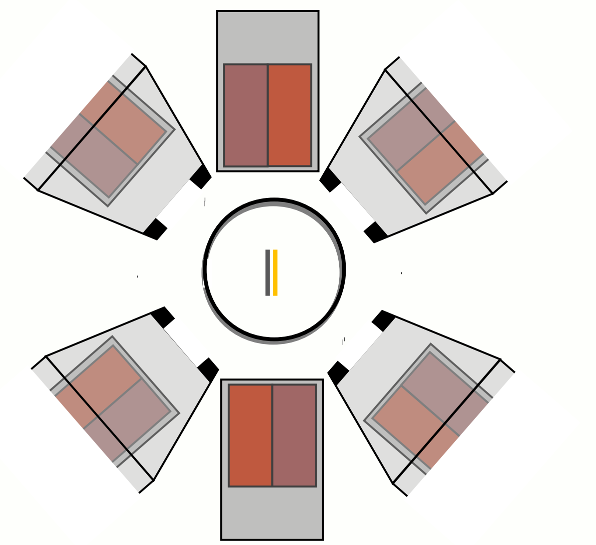
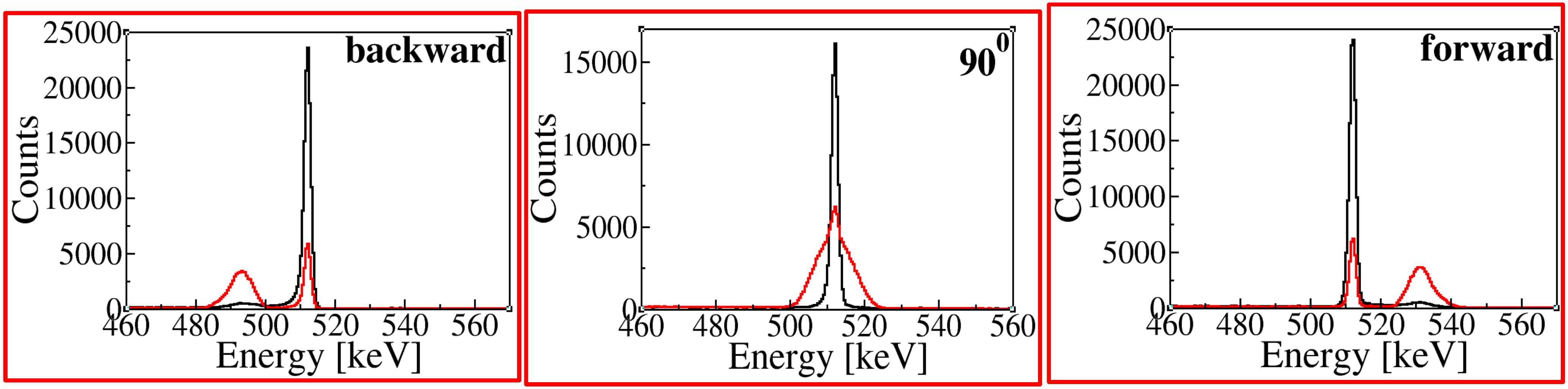
G - Plunger



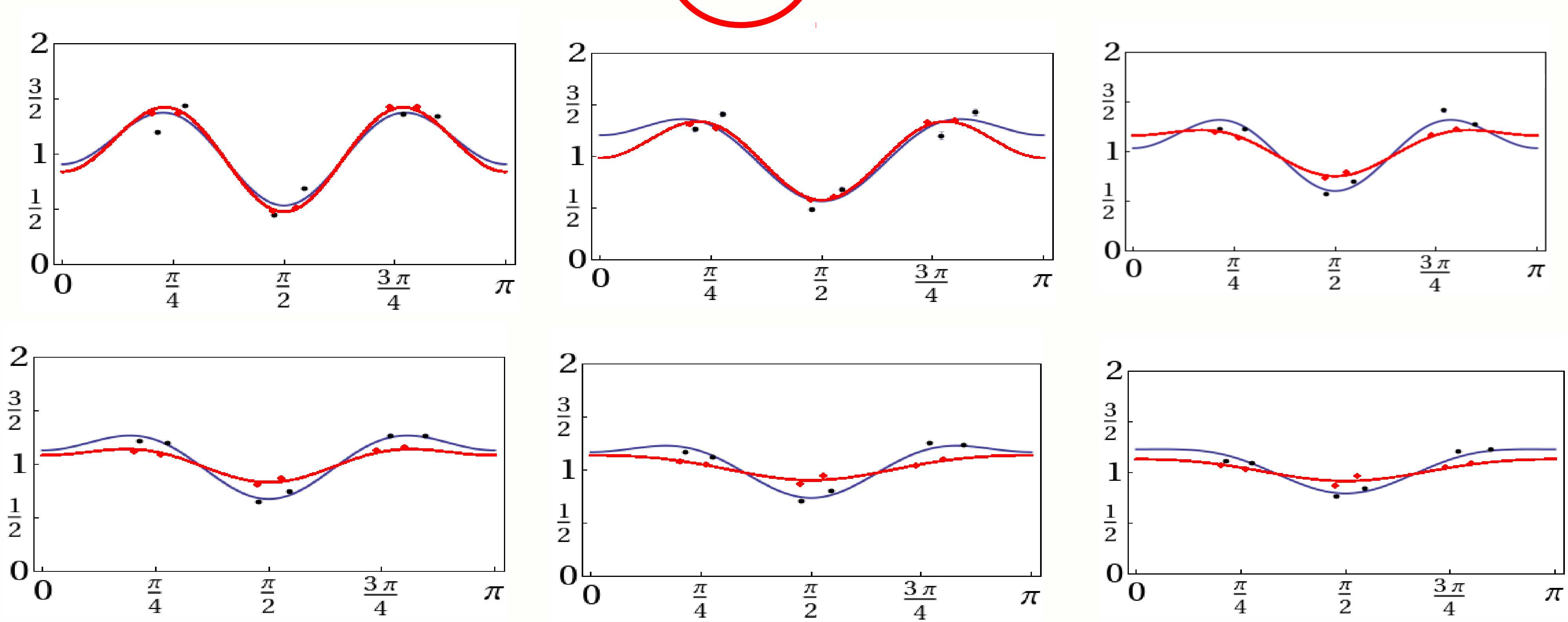




High recoil velocity (v/c ~ 6 %)
-> large Doppler shift allows precise lifetime measurement

T-Dependent Angular Distribution (or: TDRIV)

$$W(\theta)=1 + \sum_{i=2,4} G_i(t)\, Q_i\, B_i\, F_i\, P_i(\cos\theta)$$



- Doppler-shift
- Stopped

Example of experimental and theoretical calculation of angular distribution for the stopped and the Doppler shift component

G - Plunger TDRIV analysis

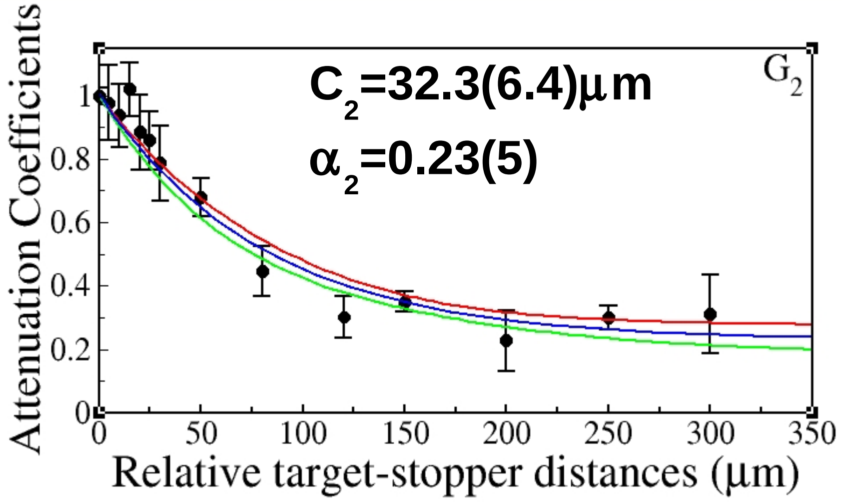
$$G_k(t)=\alpha_k+(1-\alpha_k)\cdot\exp[-(g\cdot(d-d_0)/(v\cdot C_k)]$$

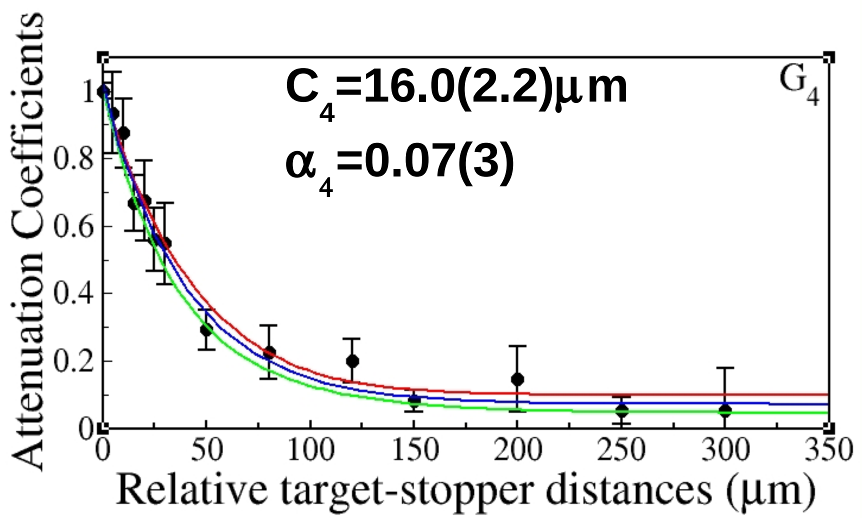
A. Stuchbery et al., PRC 76, 034307 (2007)

"calibrate" C_k of in one isotope with known g factor (^{106}Pd)

- **measure the time dependent attenuation**
- **"calibrate" an isotopic chain**

$$g(2_1^+;{}^{106}\mathrm{Pd})^{\mathrm{NNDC}} = +0.398(21)$$





We have 2 Peaks – use them !

$$W(\Theta, t) = \sum_k G_k(t) A_k P_k(\cos\Theta)$$

stopped peak:

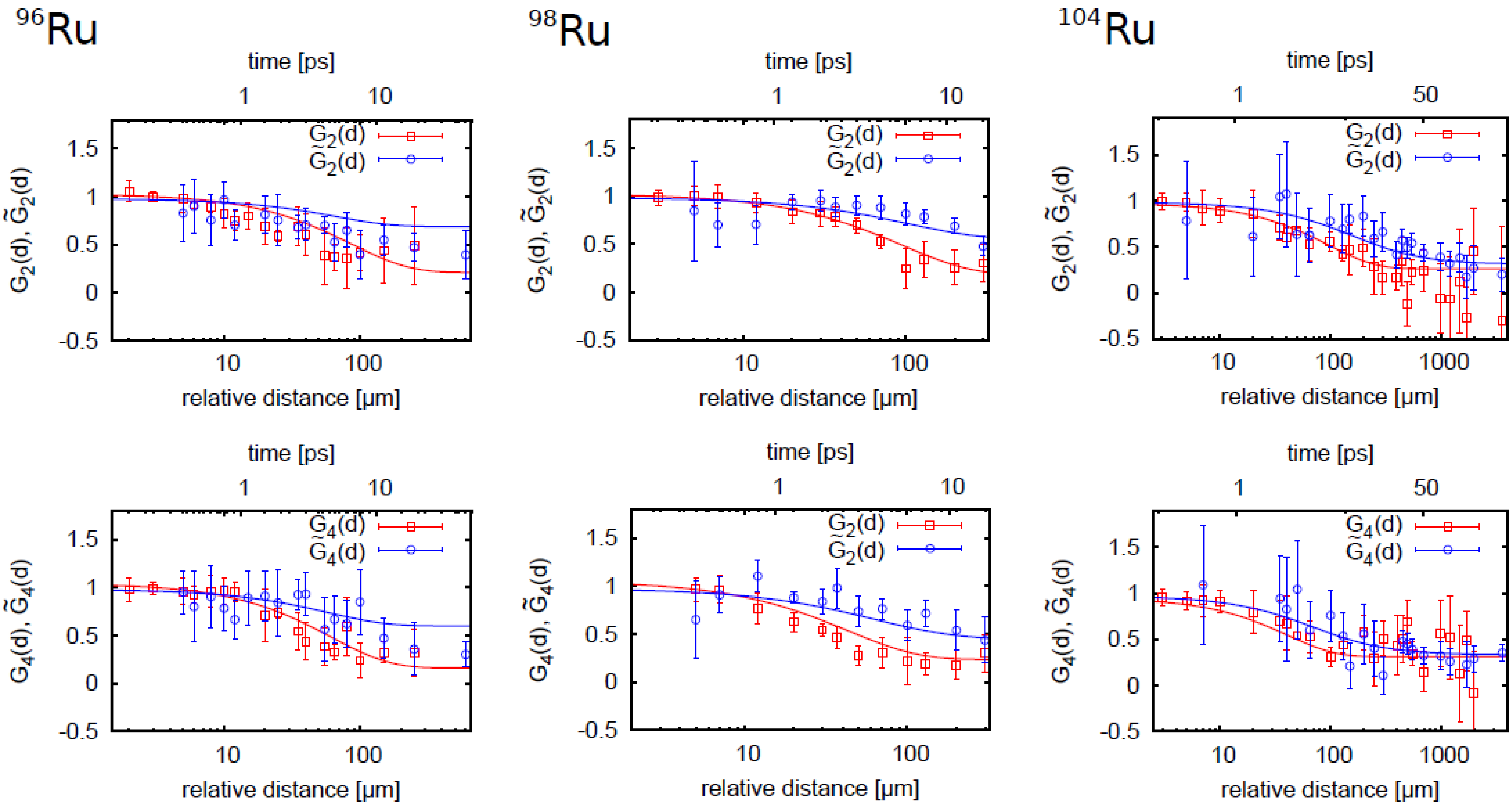
$$G_k(t) = \alpha_k + (1 - \alpha_k) \cdot \exp(-\Gamma_k t)$$

flight peak (decayed somewhere on the way):

$$G_k^{(\tau)}(d) = \frac{\int_0^d \left(\alpha_k + (1-\alpha_k)\exp\left(-\Gamma_k \frac{x-d_0}{v}\right)\right) \cdot \exp\left(-\lambda \frac{x-d_0}{v}\right) \mathrm{d}x}{\int_0^d \exp\left(-\lambda \frac{x-d_0}{v}\right) \mathrm{d}x}$$

$$= \alpha_k + \frac{(1-\alpha_k) \cdot \exp\left((-\Gamma_k - \lambda)\frac{d-d_0}{v}\right) \cdot \frac{\lambda}{\Gamma_k + \lambda}}{1 - \exp\left(-\lambda \frac{d-d_0}{v}\right)}$$

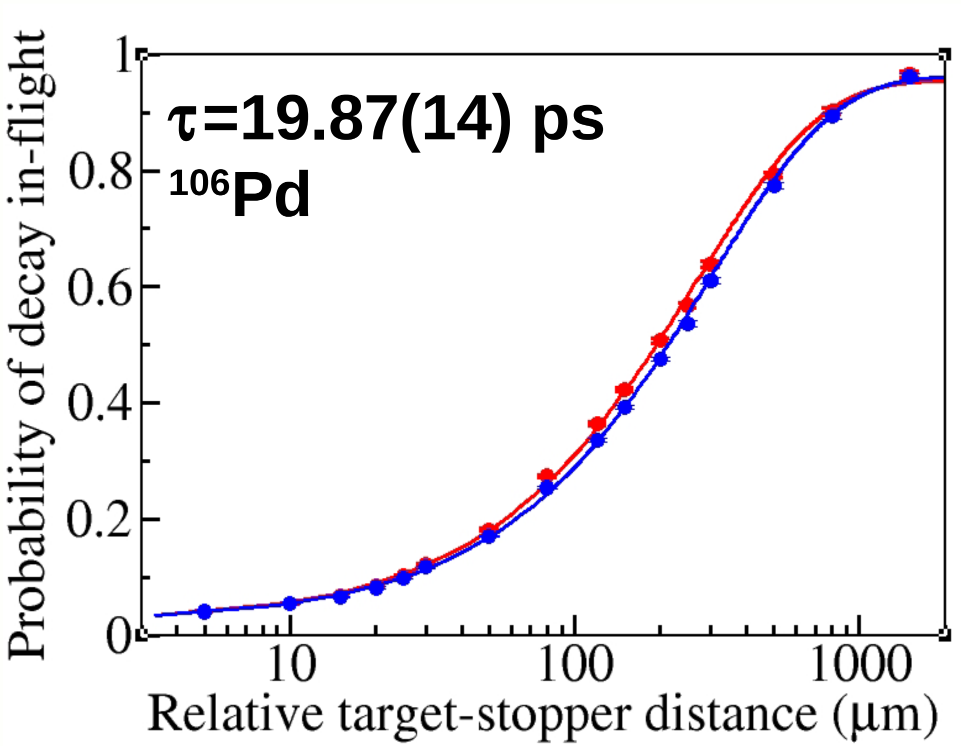
Simultaneous fit for each Isotope



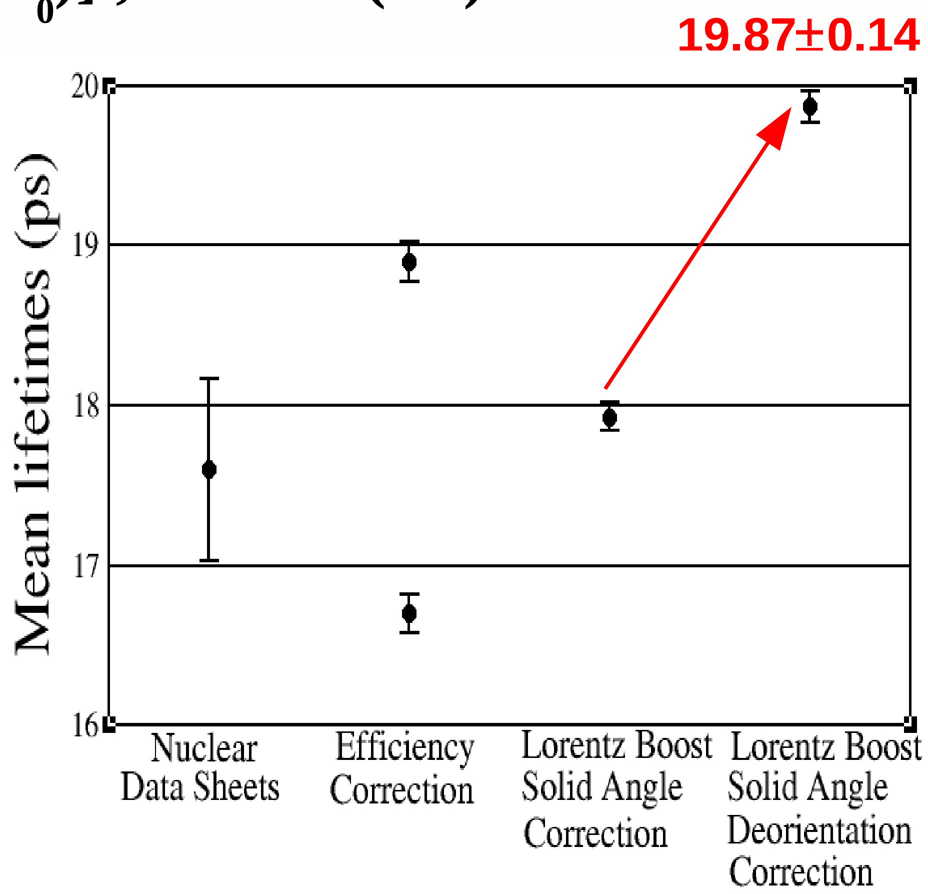
G - Plunger Lifetime Analysis

Negligible feeding => simple decay curve: $P(d) = I_\gamma^{(doppler-shift)} / I_\gamma^{(total)}$

$$P(d) = 1 - \exp[-\lambda\cdot(d-d_0)] \; ; \quad \lambda = 1/(v\cdot\tau)$$



- without deorientation correction
- with deorientation correction



Relative g-Factor Measurements

(The method does not give the sign of the g factor !)

		Reference	
Adopted value[1] $g(2_1^+)$	**+0.46(4)**	**+0.398(21)**	**+0.36(3)**
	^{104}Pd	**^{106}Pd**	**^{108}Pd**
This work	**|0.52(10)|**	**0.40(2)**	**|0.32(5)|**
IBM-2[2]	0.42	0.392	0.366
Shell-Model		0.5	

[1] Evaluated Nuclear Structure Data File
[2] Kim, Gelberg, Mizusaki, Otsuka, von Brentano, Nucl. Phys. A 604, 163 (1996)
[3] G. Gurdal et al., Phys. Rev. C 82, 064301 (2010); SM-Int: JJ45PN (Hjorth-Jensen), Ni-core, fpg, dg

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Adopted value $\tau(2_1^+)$	**14.9(9)** ^{104}**Pd**	**17.6(6)** ^{106}**Pd**	**34.6(18)** ^{108}**Pd**
This work	**15.64(18)**	**19.87(14)**	**39.05(67)**

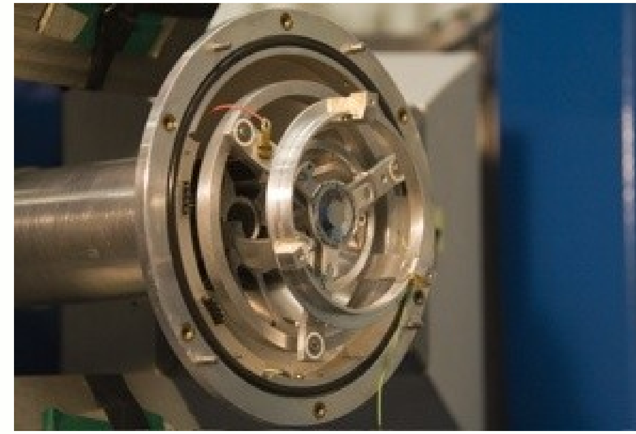
Even worse: **This change in τ will affect the g factor as well!**

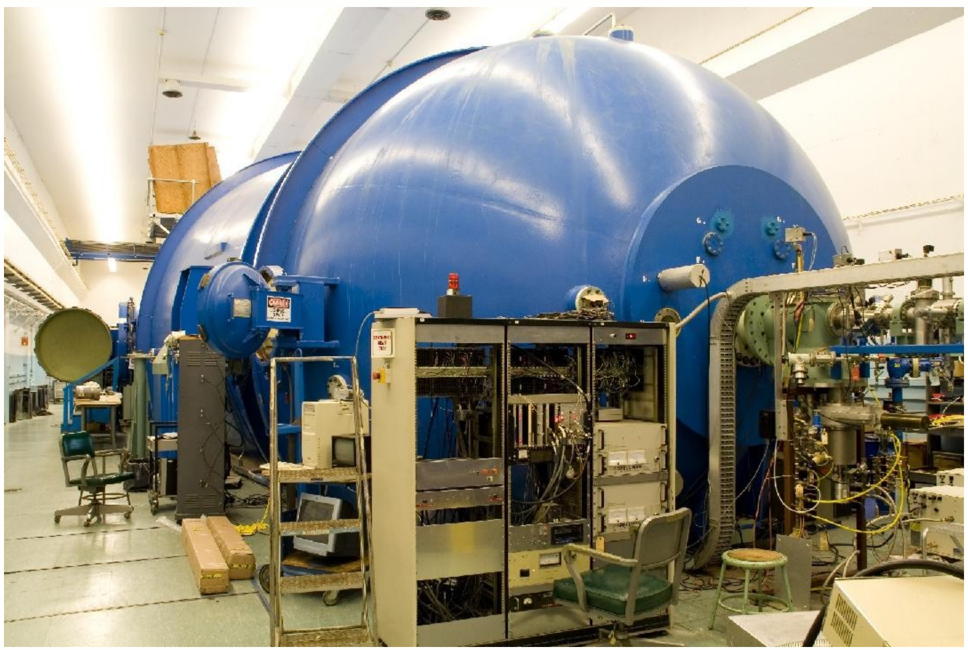
G – Plunger Experiments so far

Use of stable beams at the WNSL Tandem accelerator.

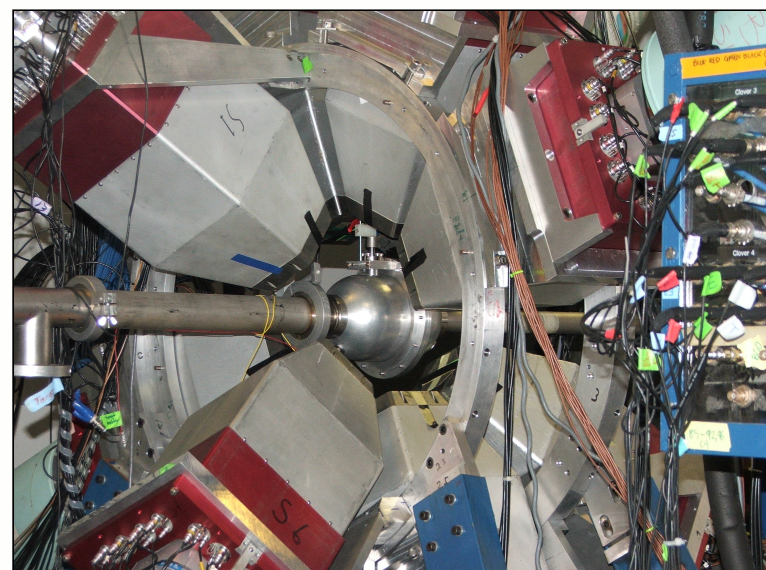
Restricted to stable beams, understaffed

-> ceased operation in 2011.



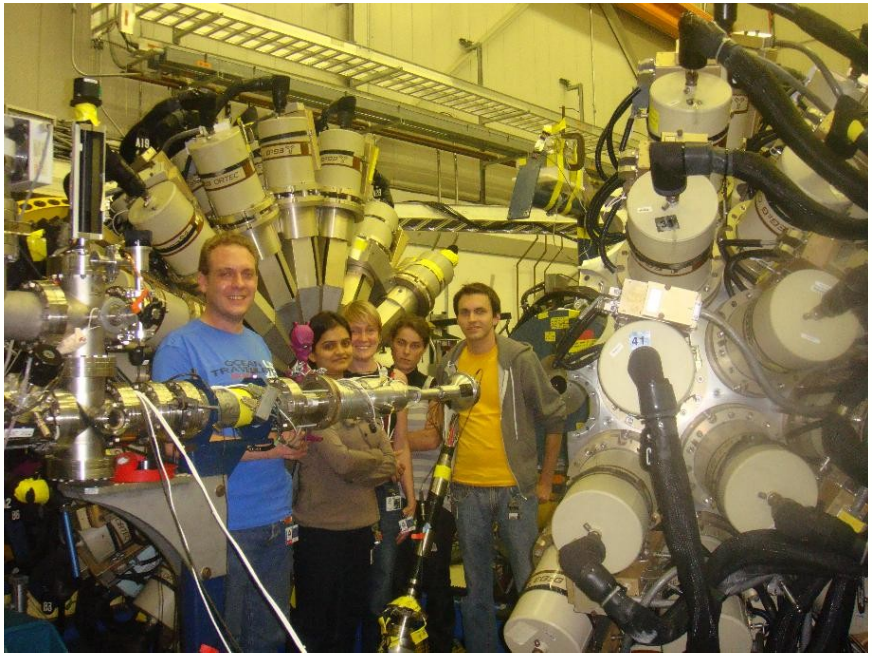


Used the YRAST-Ball array – work to be continued at other facilities with stable AND unstable beams !



$^{104-108}$Pd: G. Ilie, in preparation & CGS 14
^{96,98,104}Ru: D. Radeck, PRC 85, 014301 (2012)
^{92,94}Zr: Matt Hinton, MPhys U. Surrey (UK)

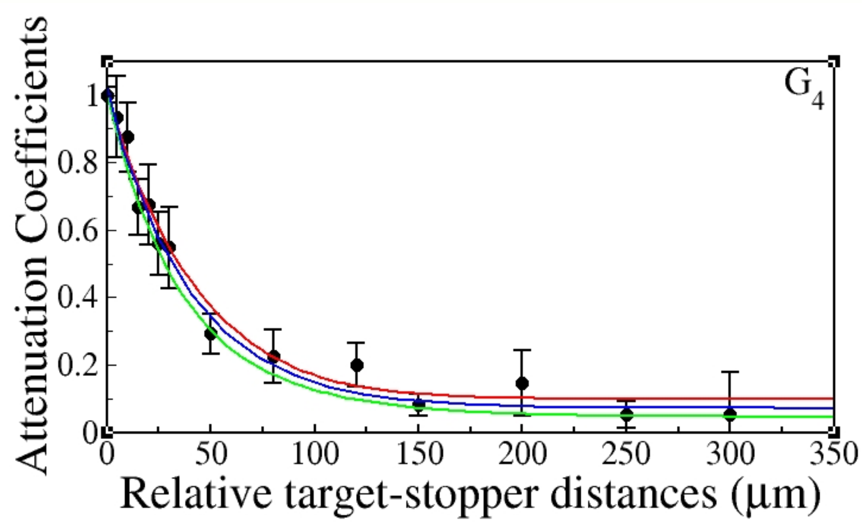
G – Plunger at Argonne / NSCL



First g-plunger experiment device at ATLAS / Gammsphere: ^{138,142}Ce
October 2011 **– analysis with F. Naqvi**
Plan: use radioactive CARIBU beams in future experiments. Later: ReA3 Beams at NSCL.

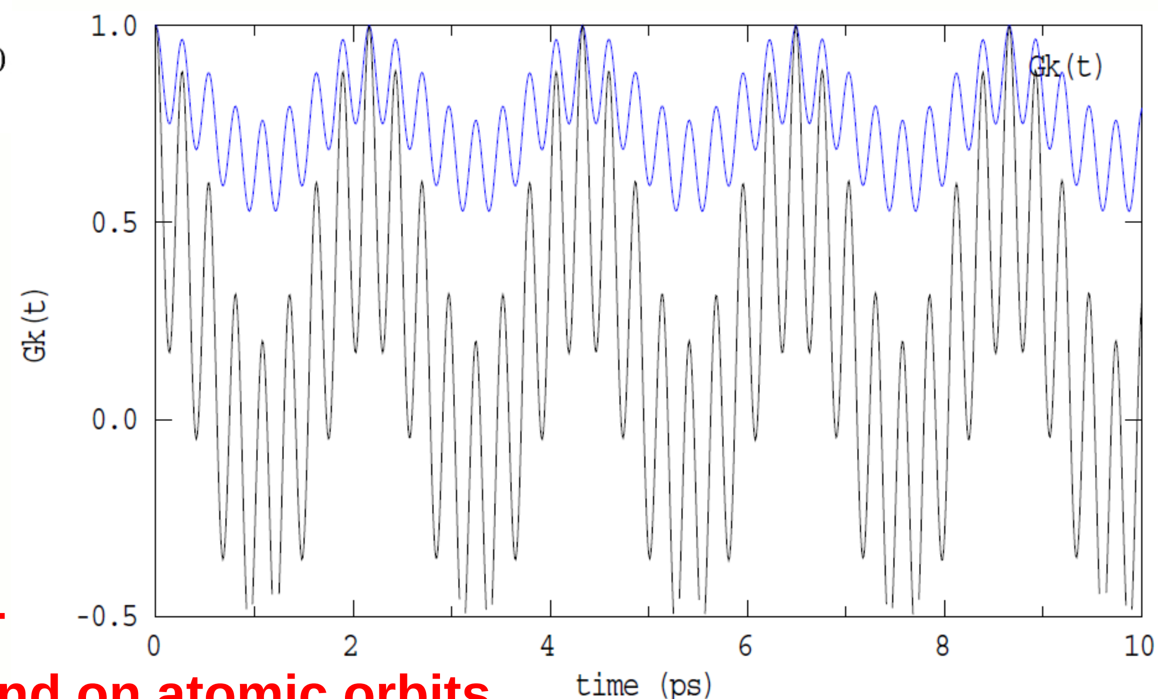
New plunger to be built for experiments with Re-accelerated radioactive beams.

New approach to test the g-plunger technique with relativistic beams. Has to ovecome one complication!



v/c ~ 6%, Charge State ~ 8-12 +

-> nice exponential behavior...



v/c ~ 40%, Charge State ~ Z - 1 +

-> fast oscillations, details depend on atomic orbits

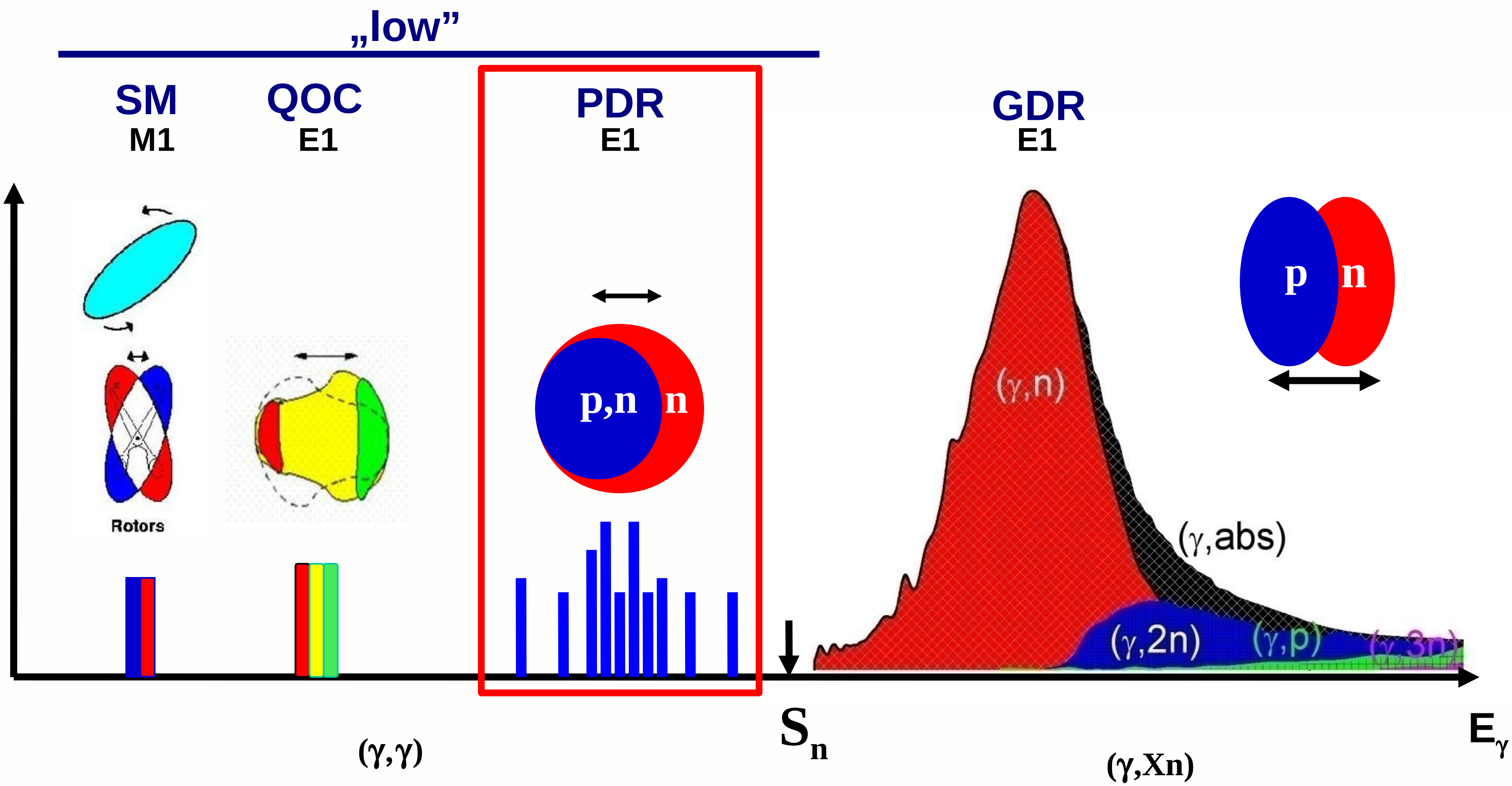
Needs understanding and testing with stable beams first.

Region 1

fs - regime

(One way to get there is similar to plunger, but by looking at the stopping process leading to a Doppler-Lineshape – we saw this. Alternative: cross-section measurements!)

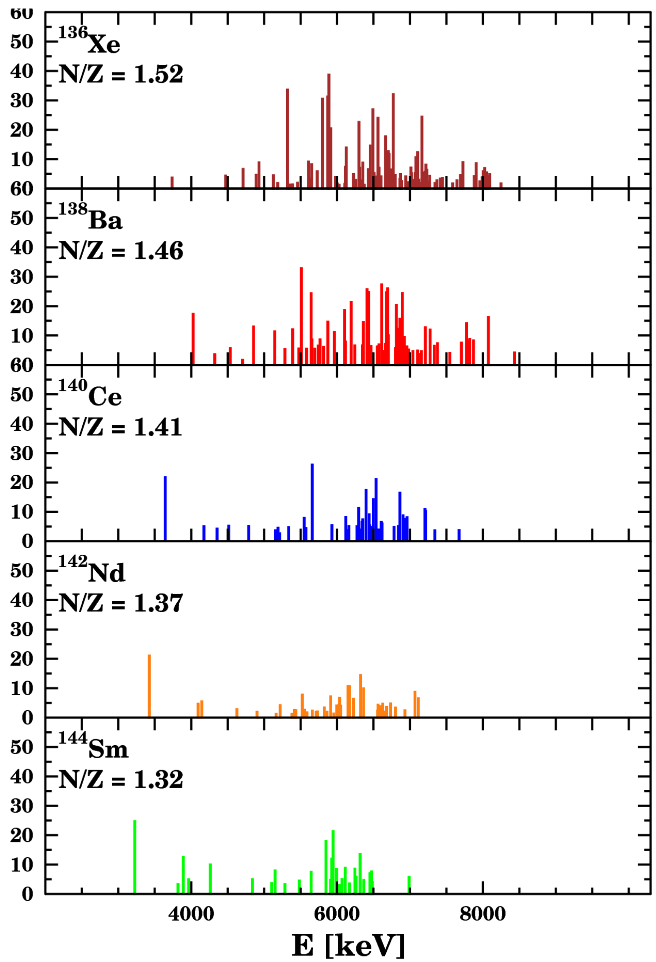
Low-Lying Dipole Strength



GDR	• Giant Dipole Resonance: E_x ~ 10 - 20 MeV, B(E1) ~ 5 - 10 W.u.
SM	• Orbital "Scissors" mode: E_x ~ 3 MeV, B(M1) ~ 3 μ_N^2
QOC	• Two Phonon Excitation: E_x ~ 4 MeV, B(E1) ~ 10^{-3} W.u.
PDR	• Pygmy Dipole Resonance ?

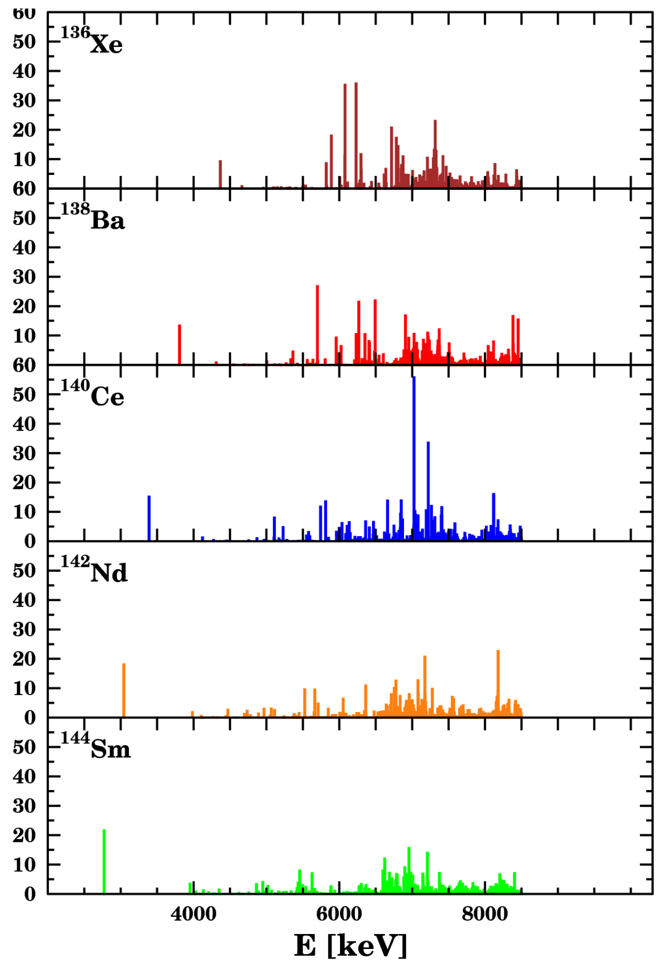
N/Z Dependence

Experiment



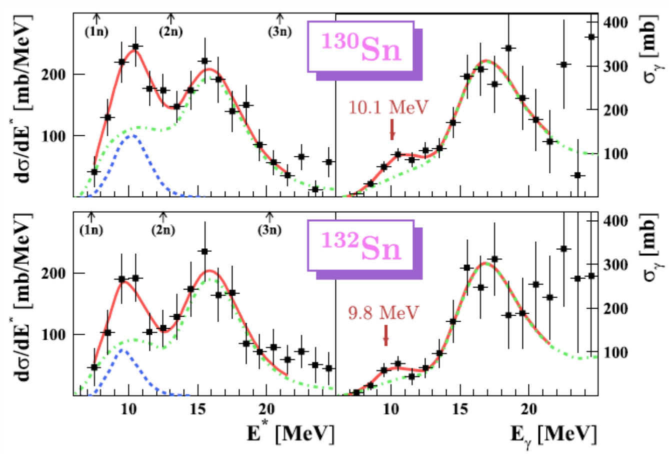
S. Volz et al., Nucl. Phys. **A779** (2006) 1

Quasiparticle-Phonon-Model (QPM)

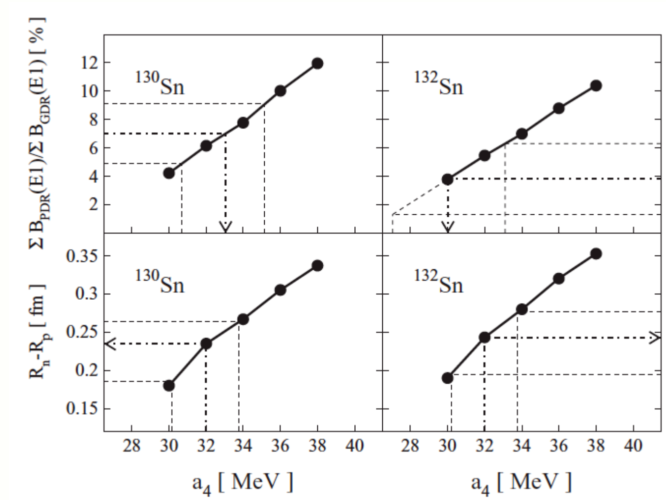


V. Yu. Ponomarev

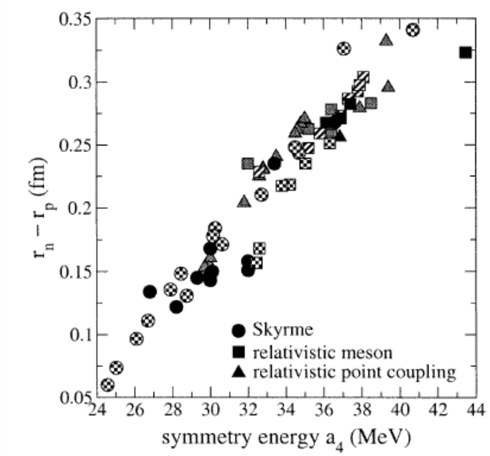
PDR <-> Neutron Skin



P. Adrich et al., PRL 95 (2005) 132501



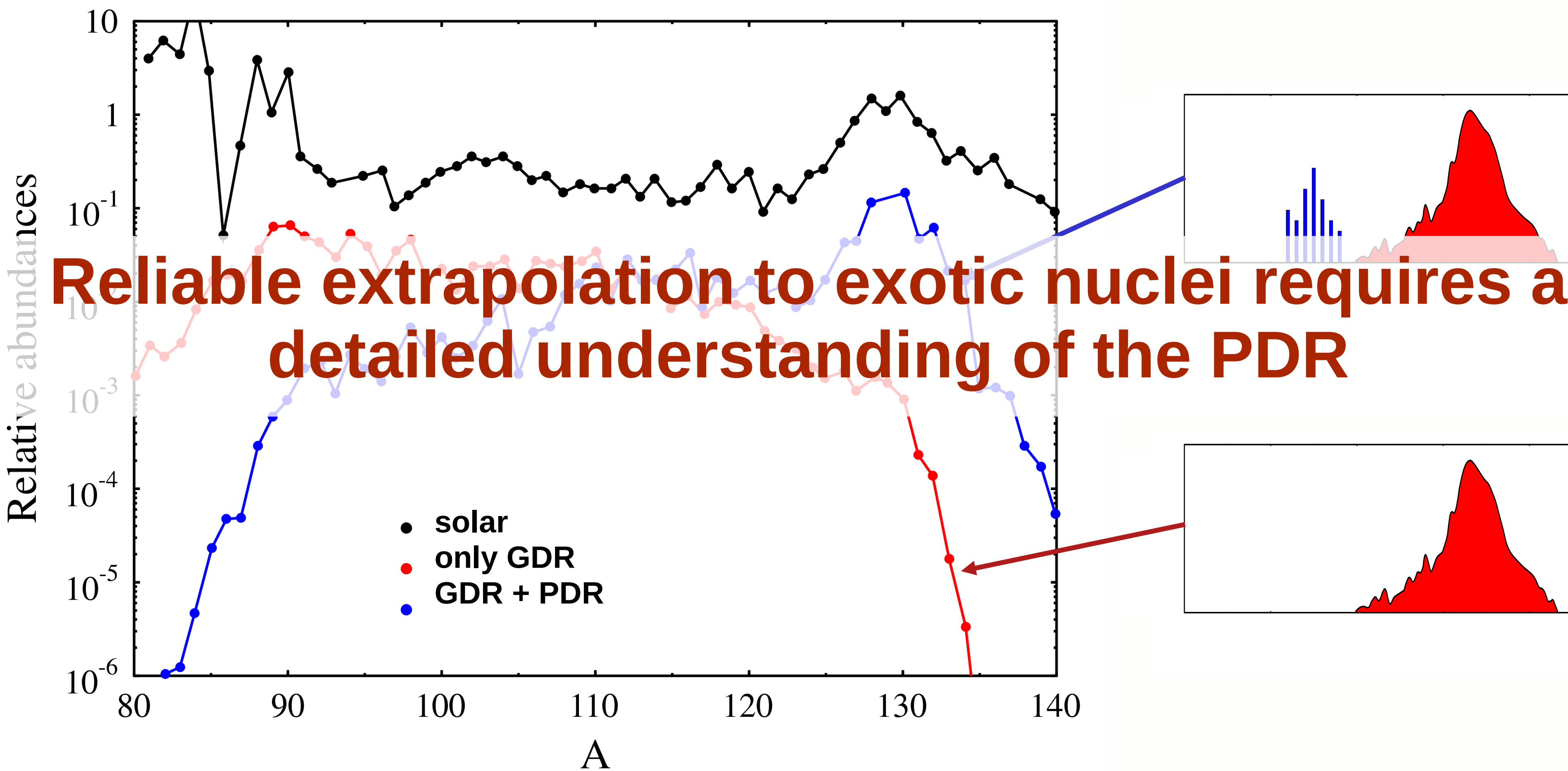
A. Klimkiewicz, Nils Paar et al, PRC 76 (2007) 051603(R)



R.J.Furnstahl NPA 706(2002)85-110

Clear dependence on neutron skin !

Possible influence of the PDR on the r-process:



Reliable extrapolation to exotic nuclei requires a detailed understanding of the PDR

S. Goriely, Phys. Lett. B 436 (1998) 10

PDR in ^{76}Ge / ^{76}Se

- **Structural Motivation: Evolution of the PDR toward deformed nuclei !**
- **„Side Motivation”:**

<u>An odd situation:</u>

Learn about a weakly interacting particle by look at a strongly interacting system.

- **Why nuclear structure?**
  - **First claim on the observation of 0ν2β decay ^{76}Ge → ^{76}Se has been made (Heidelberg-Moscow)**
  - **New experiments just started or are about to start (GERDA / MAJORANA)**
  - **Observation of the decay rate is not sufficient to extract masses**
  - **Need: Nuclear Matrix Elements !!**
  - **Can only be extracted from nuclear theory**
  - **=> scrutinize involved theories**

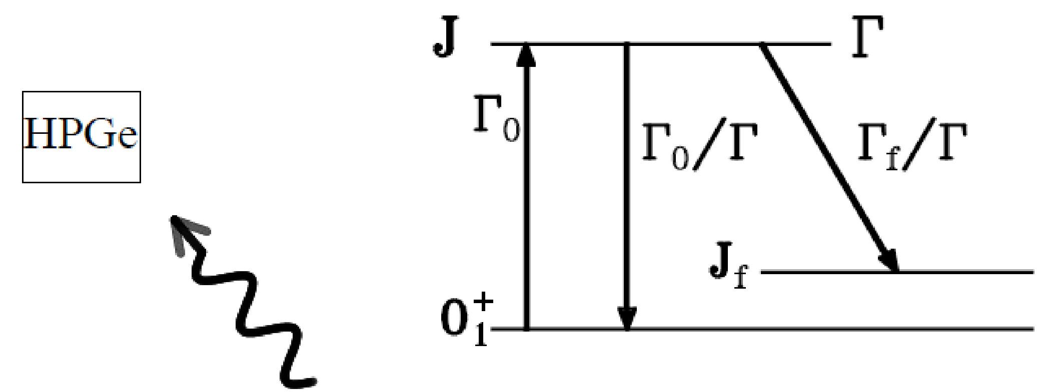
- **Some selected experiments going that way:**
  - **Schiffer et al.: ground state wave functions from transfer reactions**
  - **WNSL: gamma-spectroscopy on intermediate nuclei**
  - **<u>HIGS/TUNL/Darmstadt(GER): dipole response of 0ν2β candidates</u>**
  - **UK Lexington: γ-spectrocopy after neutron scattering**
  - **ANU (Australia): electron spectroscopy**
  - **TRIUMF: in-trap spectroscopy => EC decay branchings**

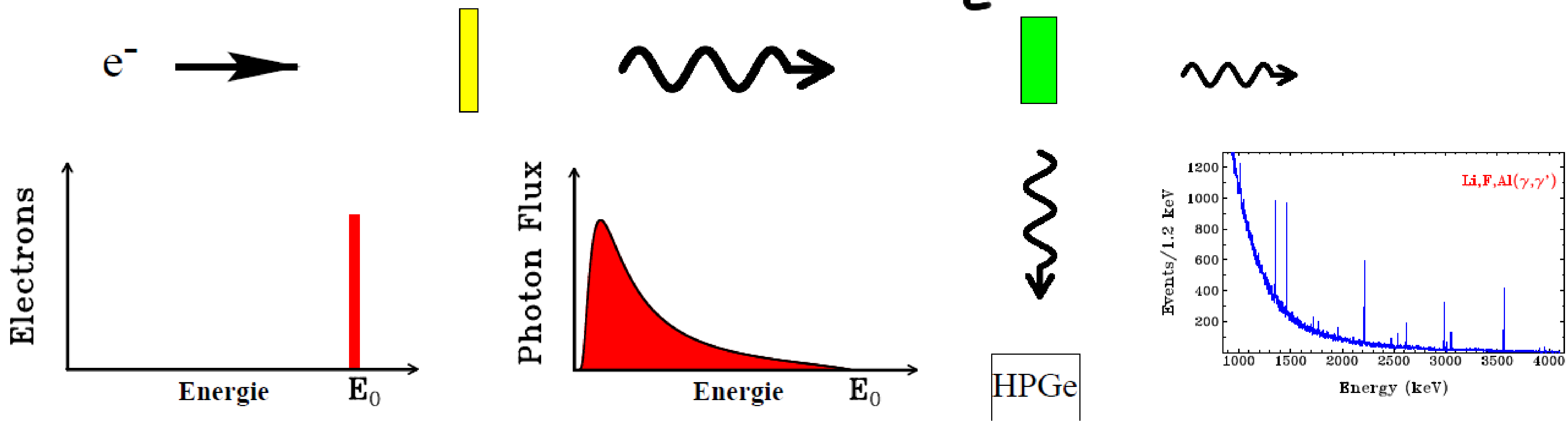
Nuclear Resonance Fluorescence

$\Pi\lambda$ −strengths

$\Delta J = 1{,}2$

high energy resolution





Connection to Lifetimes

In a nutshell – description of resonance: Breit-Wigner

$$\frac{d^2\sigma_{abs}(E)}{d\Omega dE} = \pi \lambda\!\!\!^{-2} \cdot \frac{2j+1}{2(2j_0+1)} \cdot \frac{\Gamma_0 \Gamma_f}{(E-E_r)^2 + \frac{1}{4}\Gamma^2} \cdot \frac{W(\theta)}{4\pi}$$

Integrate that over solid angle and the resonance:

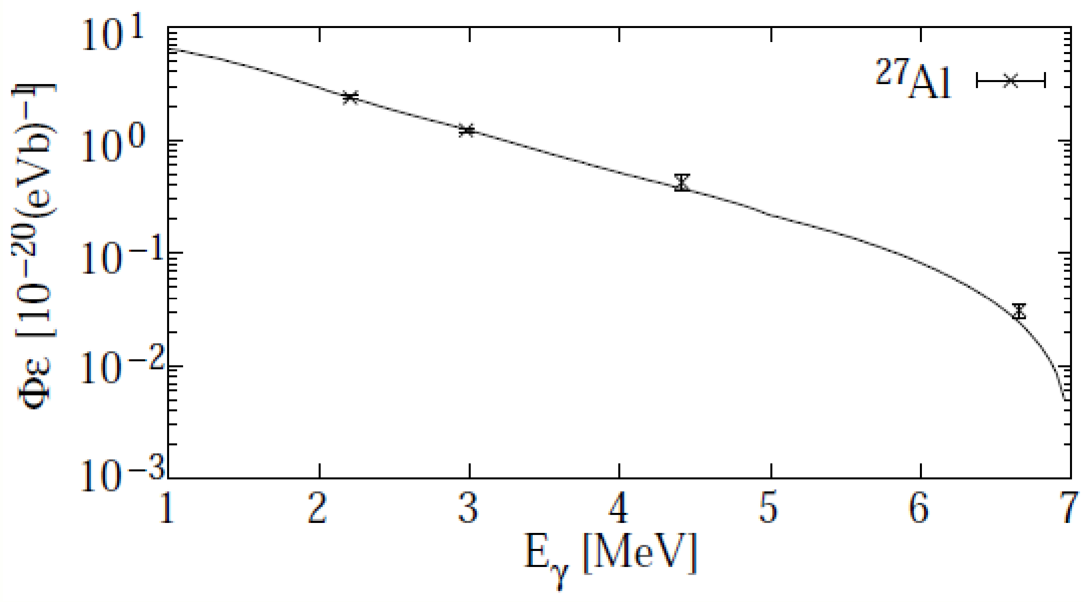
$$I_{s,f} \quad = \quad \pi^2 \lambda\!\!\!^{-2} \cdot \frac{2J+1}{2J_0+1} \cdot \frac{\Gamma_0 \Gamma_f}{\Gamma}$$

Integrated cross-section from size of the observed peak to „f”inal state.

Photon Flux from Standard

Measurement of x-sections always relative to a standard!
For example, ^{27}Al / ^{11}B have well-known cross-sections.

Measure Al/B states, measure / simulate detector efficiency
=> Photon Flux / Cross-section calibration



Connection to Lifetimes

Extract: $$\frac{\Gamma_0^2}{\Gamma} = \frac{2j_0+1}{2j+1} \cdot \left(\frac{E_\gamma}{\pi\hbar c}\right)^2 \cdot I_{s,0}$$

Resonance width: $$\Gamma = \frac{\Gamma_0^2}{\Gamma} \cdot \left(1 + \sum_{f>0} \frac{\Gamma_f}{\Gamma_0}\right)^2$$

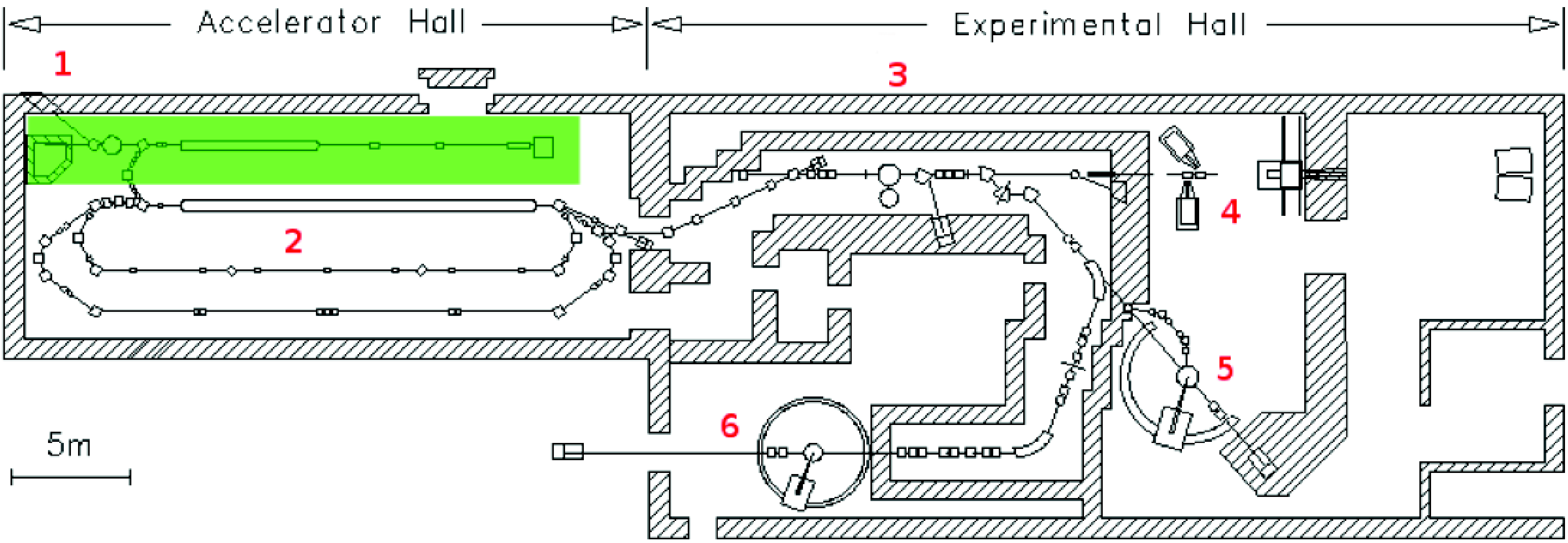
(if branchings known)

And the relation to lifetimes is: $$1/\tau = \Gamma = \sum_{f\geq 0} \Gamma_f$$

Typical lifetimes for strongly dipole-excited states: ***femto- / attoseconds !***

NRF is a model-independent way to measure lifetimes!

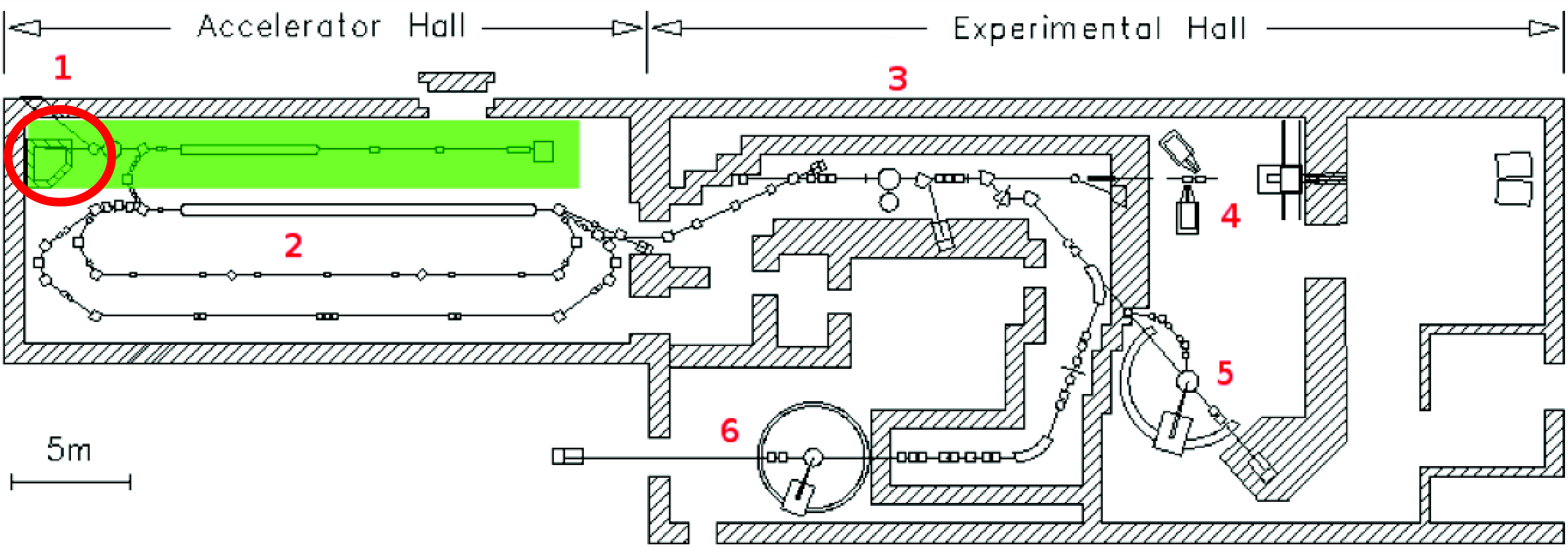
Superconducting DArmstadt LINear ACcelerator



Continuous Bremsstrahlung beams allow to identify dipole-excited states!
Parity determination is possible via polarimetry, but difficult.
(Figures of merit of polarimeters are not favorable, especially at high energies.)

Target ~ 4 g enriched 76Se

Superconducting DArmstadt LINear ACcelerator



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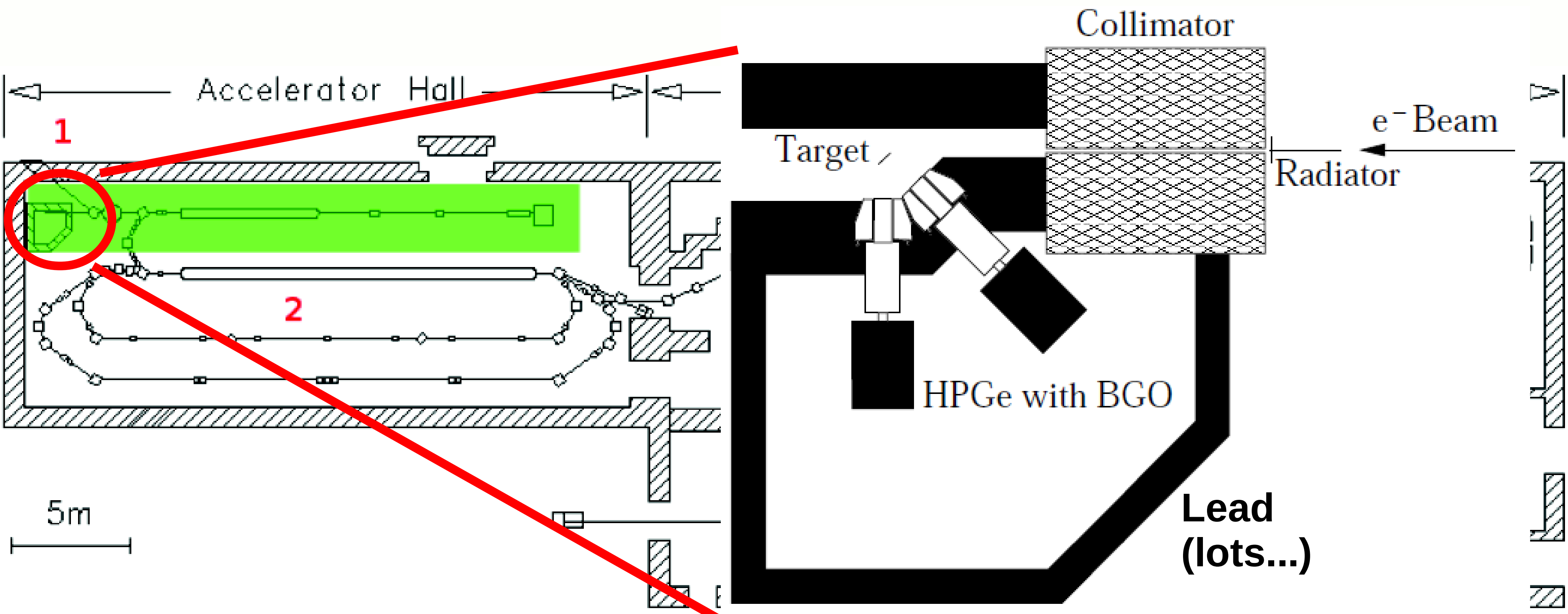

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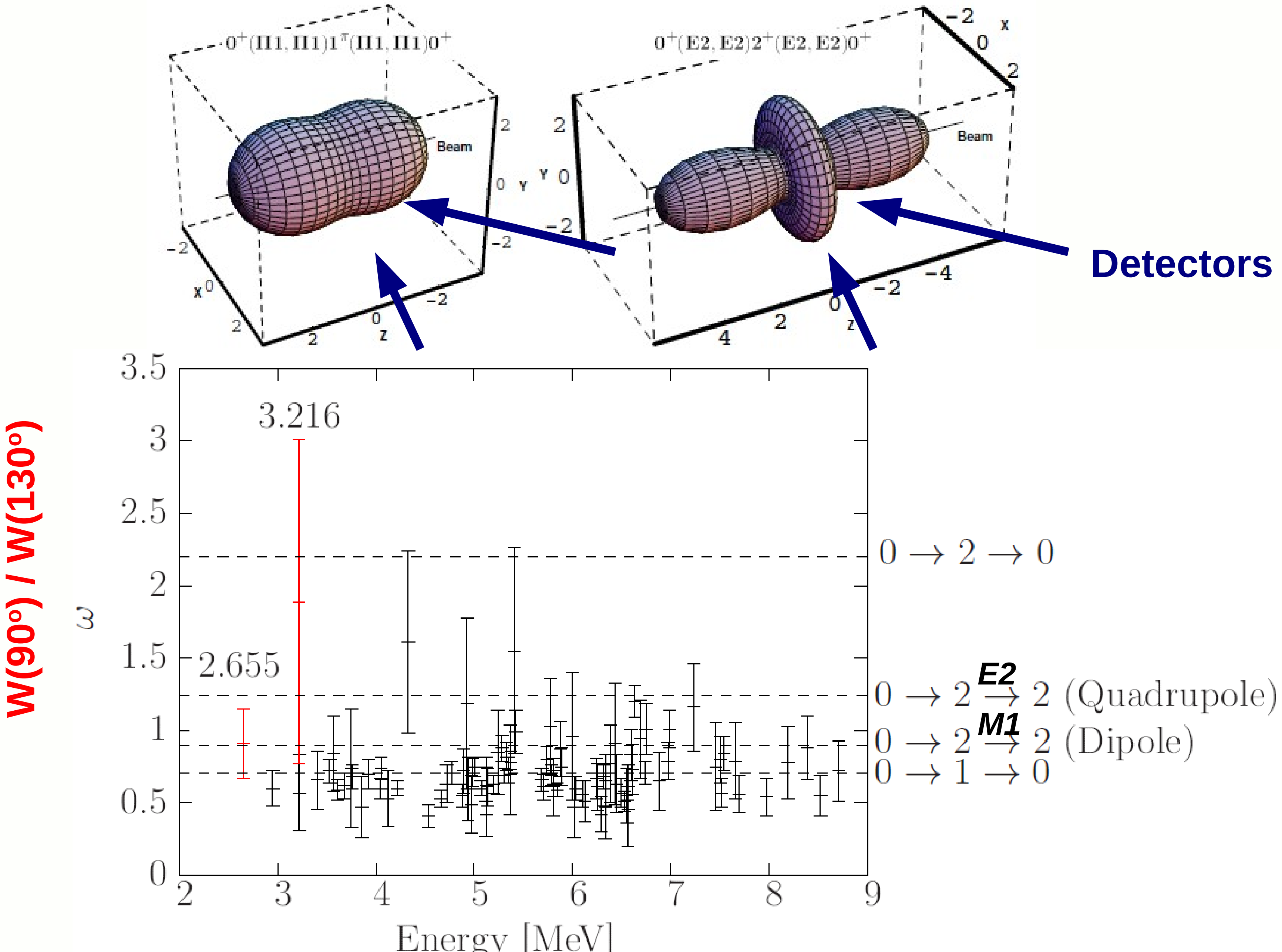
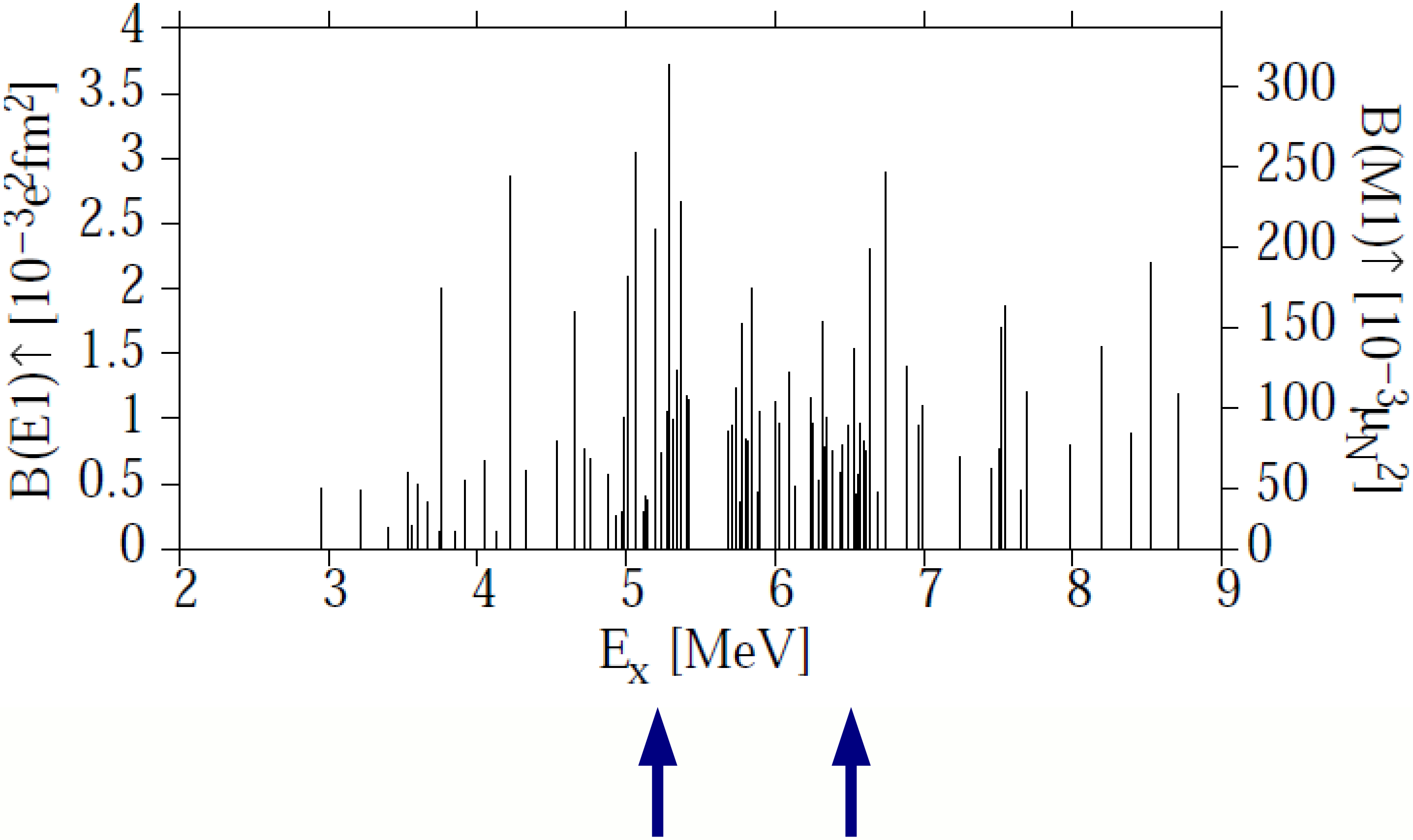
Spin Determination



Absolute X-Sections

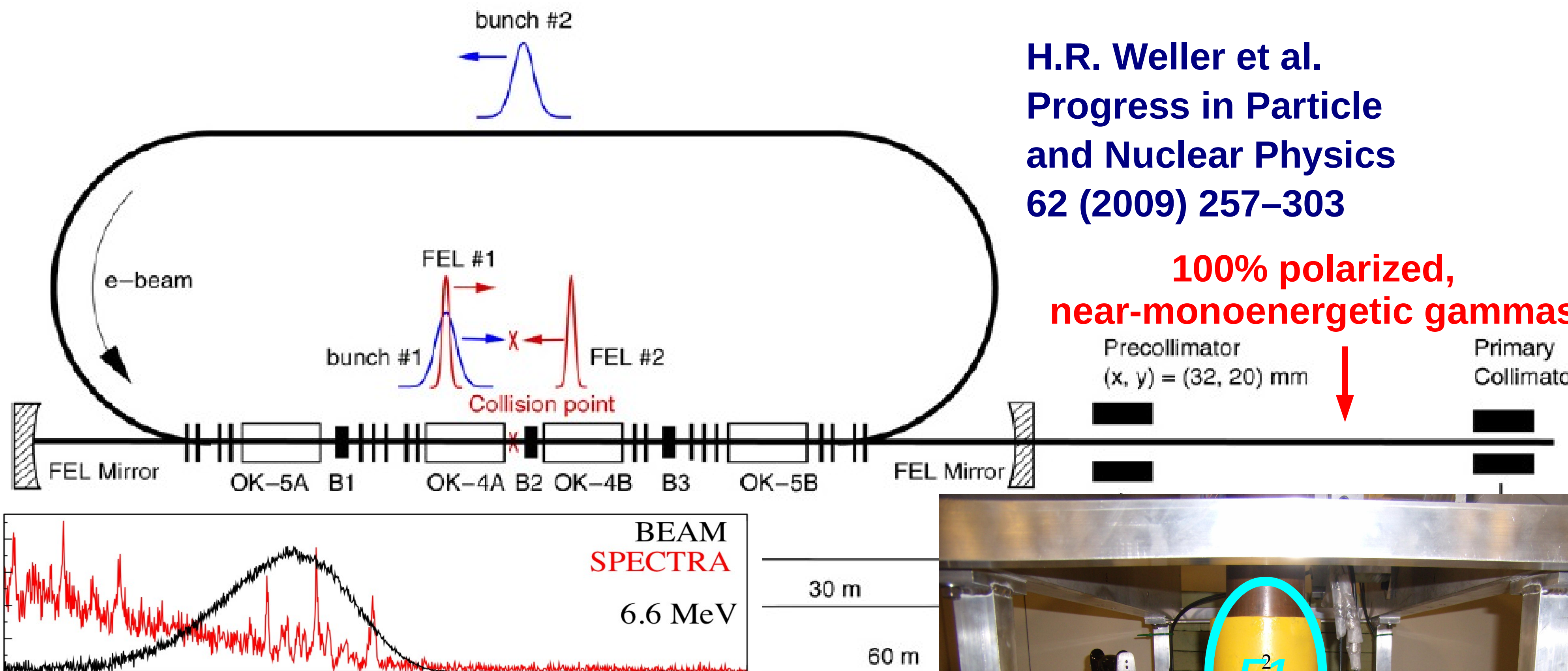


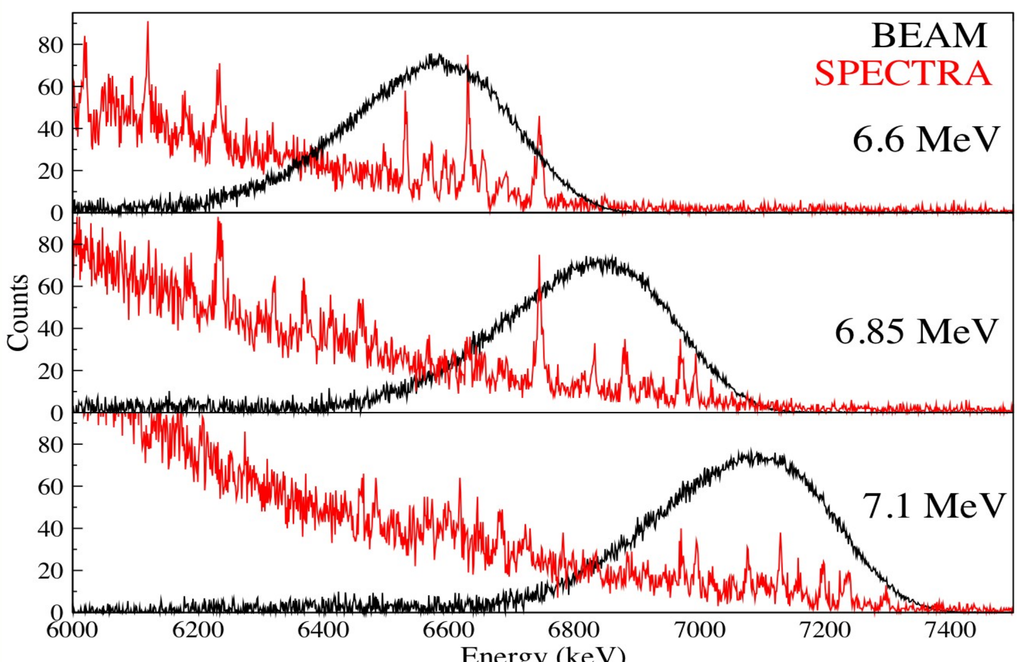
Strength concentrations – E1?

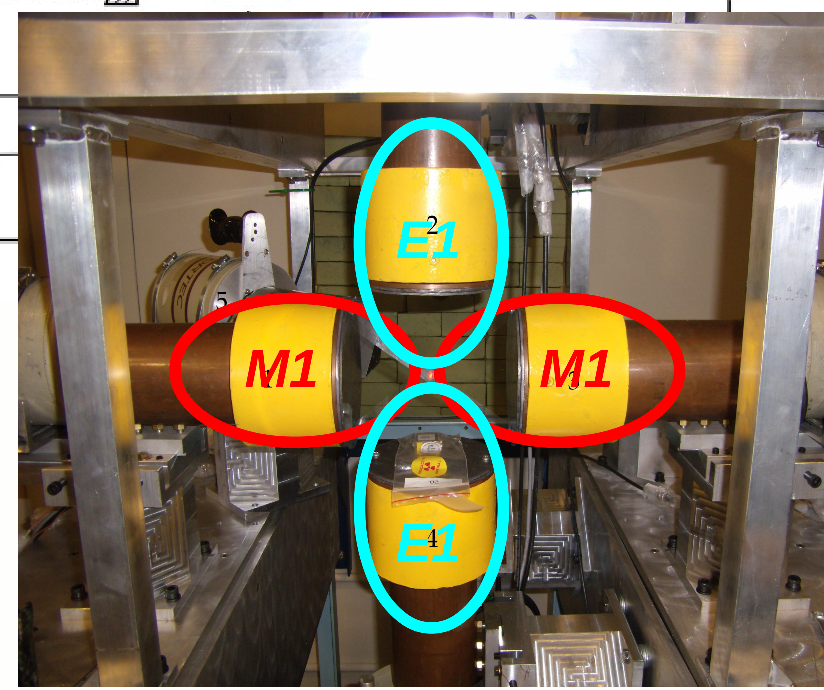
HIGS (Free Electron Laser)

H.R. Weller et al.
Progress in Particle and Nuclear Physics 62 (2009) 257–303

100% polarized, near-monoenergetic gammas

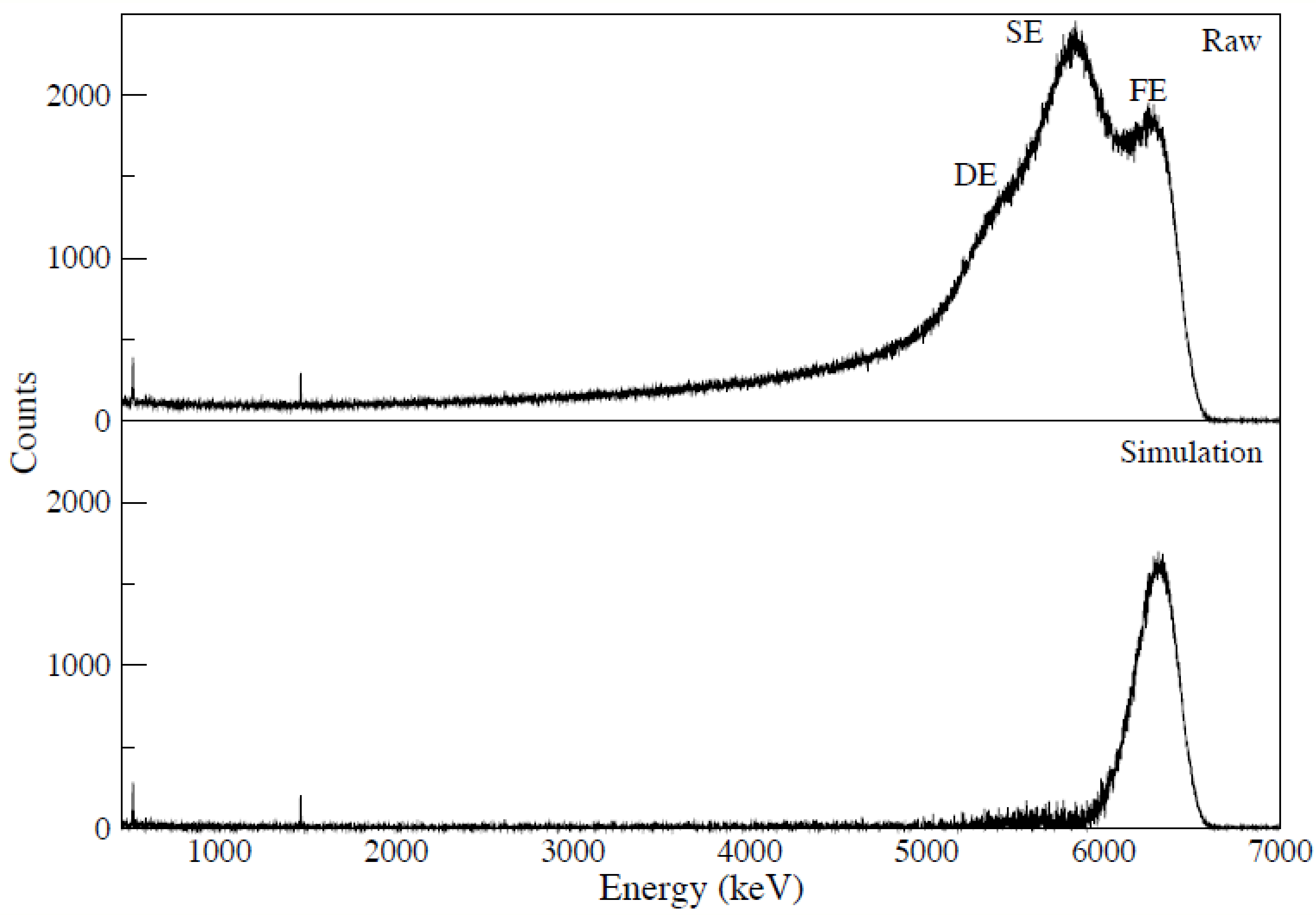




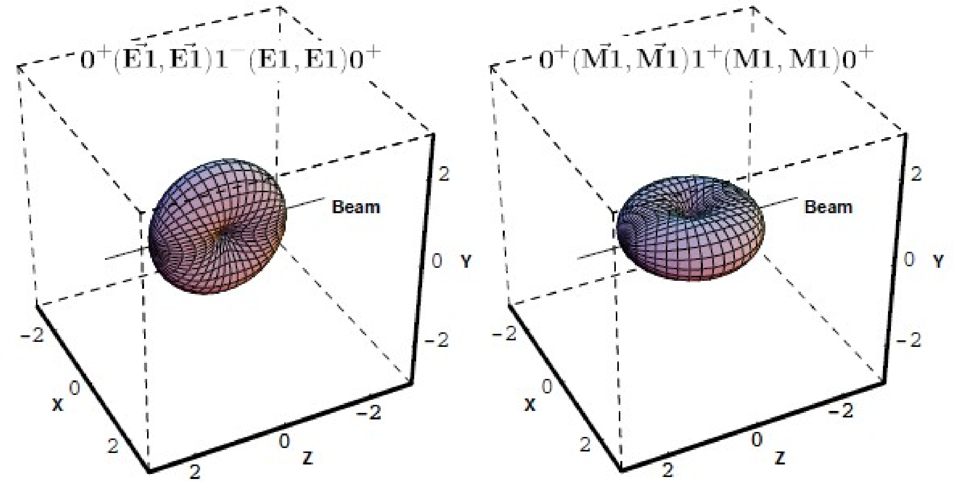


HIGS Beam Profile

Actually beam profile derived from 0º HPGe spectrum and GEANT simulation.

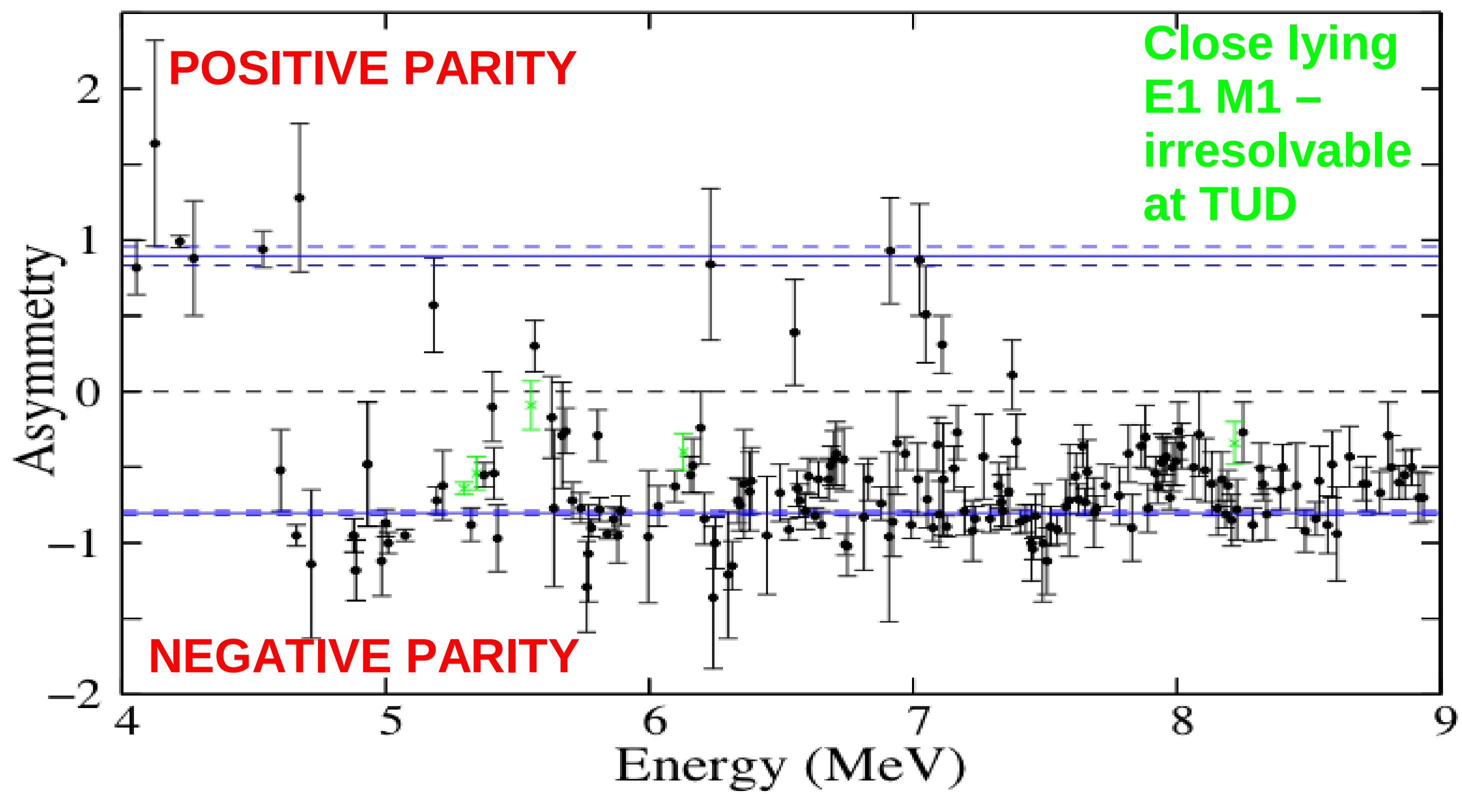


Polarization => Parity



Clear (and easy) identification Of E1 excited states through asymmetry horizontal/vertical

$$P_{ana} = \frac{W^{hor} - W^{ver}}{W^{hor} + W^{ver}}$$



M1

almost all: E1

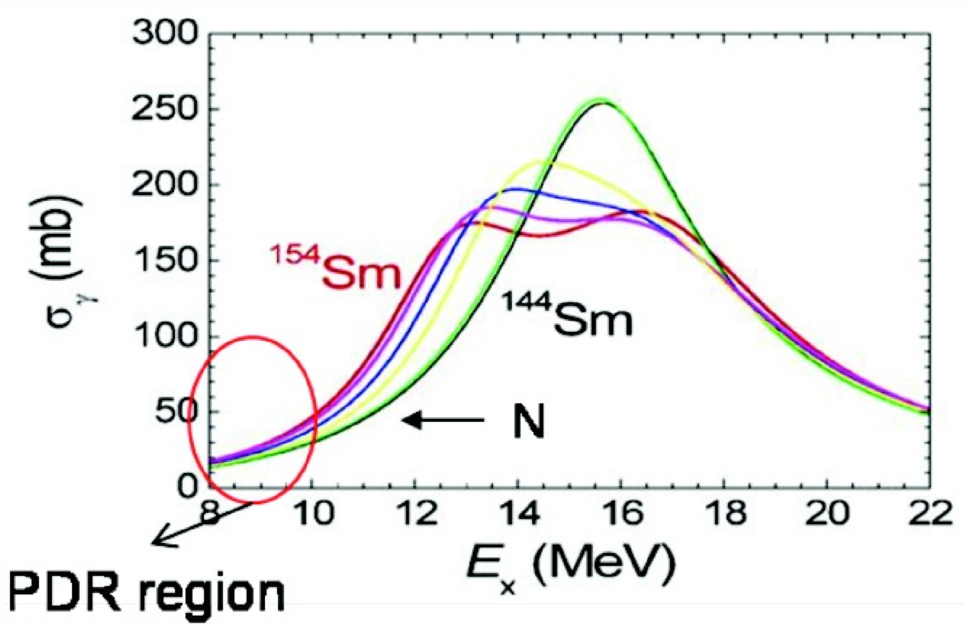
Combined HIGS & TUD Data

Between ~ 4-9 MeV: Cross sections from TU Darmstadt, parities from HIGS

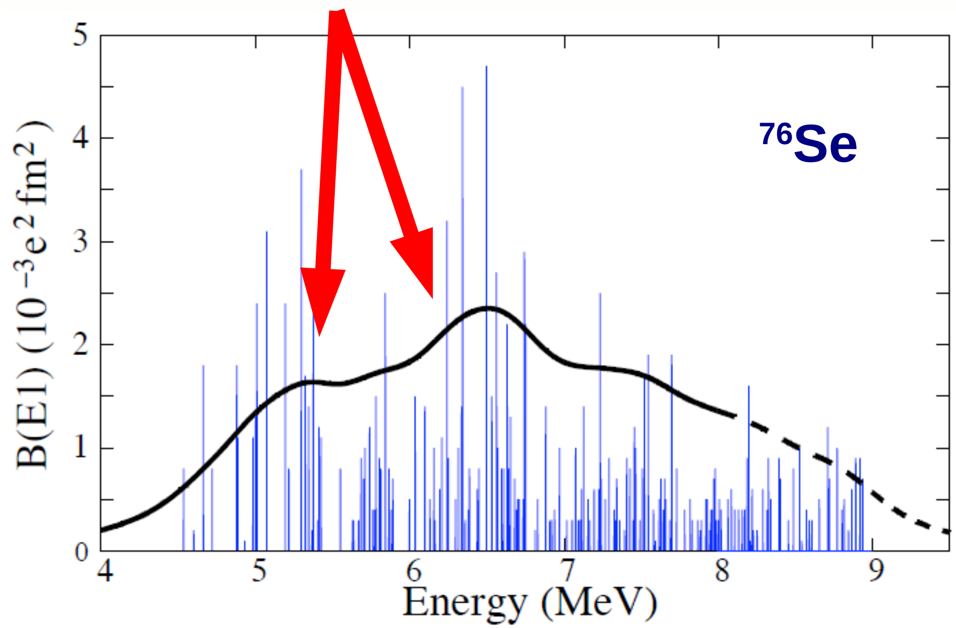
Nathan Cooper, Yale
submitted to PRC

Phil Goddard, Yale/Surrey
MPhys thesis, in prep. for PRC

Deformation splitting of the GDR (oscillations with respect to two ellipsoid axes)

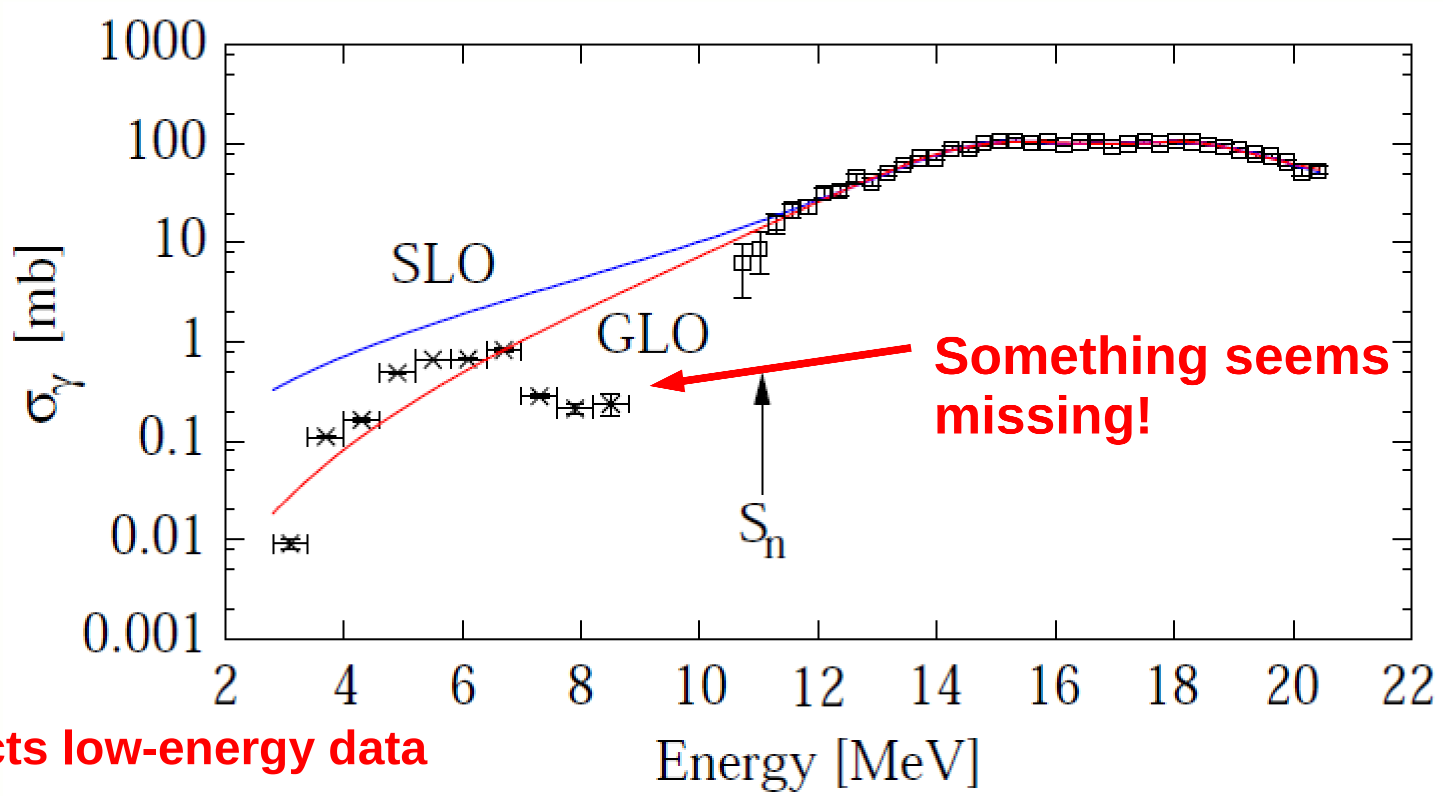


E1 strength distribution suggests that Pygmy strength is split. Splitting due to β-deformation?



Anything on the GDR Tail ??

Data from Bremsstrahlung only!
Two Lorentzians fitted because ^{76}Se is deformed (β~0.31)



Overpredicts low-energy data

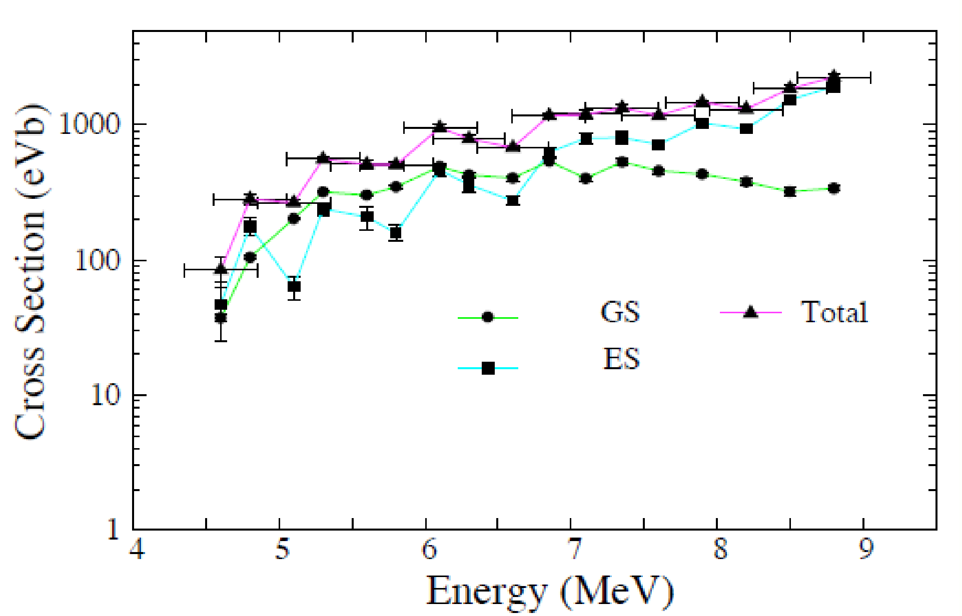
$$\sigma^{SLO} \propto \frac{E^2\Gamma^2}{(E^2 - E_0^2)^2 + E^2\Gamma^2}$$

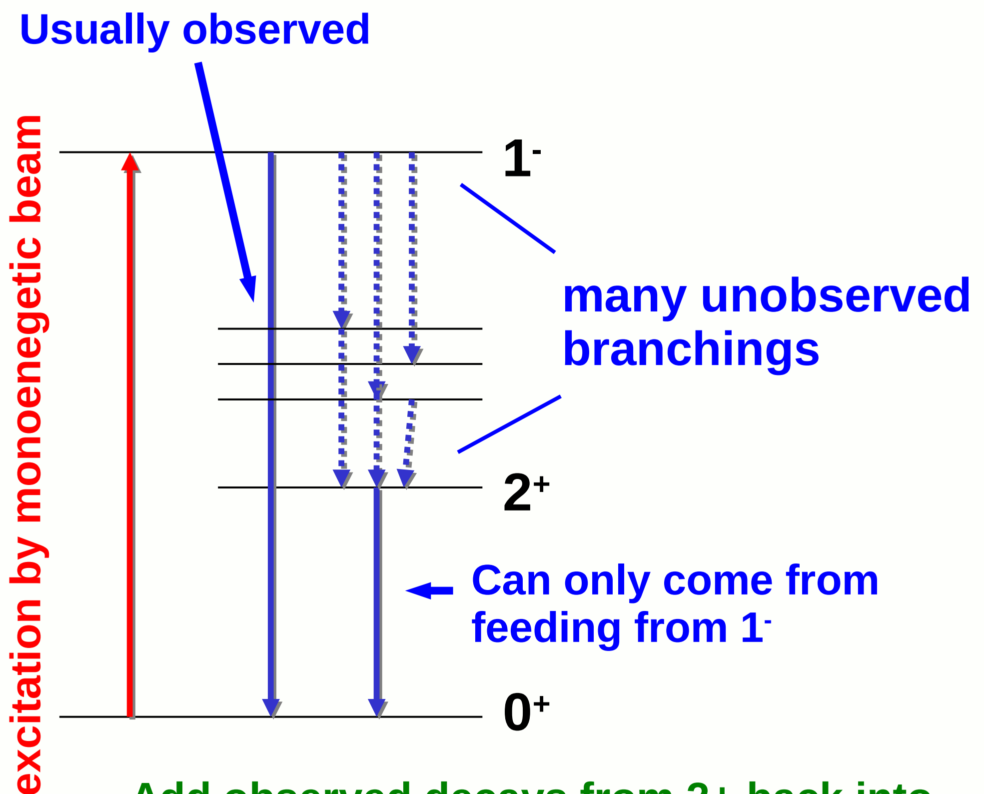
$$\sigma^{GLO} \propto E\Gamma\left[\frac{E\Gamma(E)}{(E^2 - E_0^2)^2 + E^2[\Gamma(E)]^2}\right]$$

Much E1 Strength is Hidden

Now including HIGS Data:

Higher-lying states decay stronger to excited states – corrections to total E1 excitation strength!



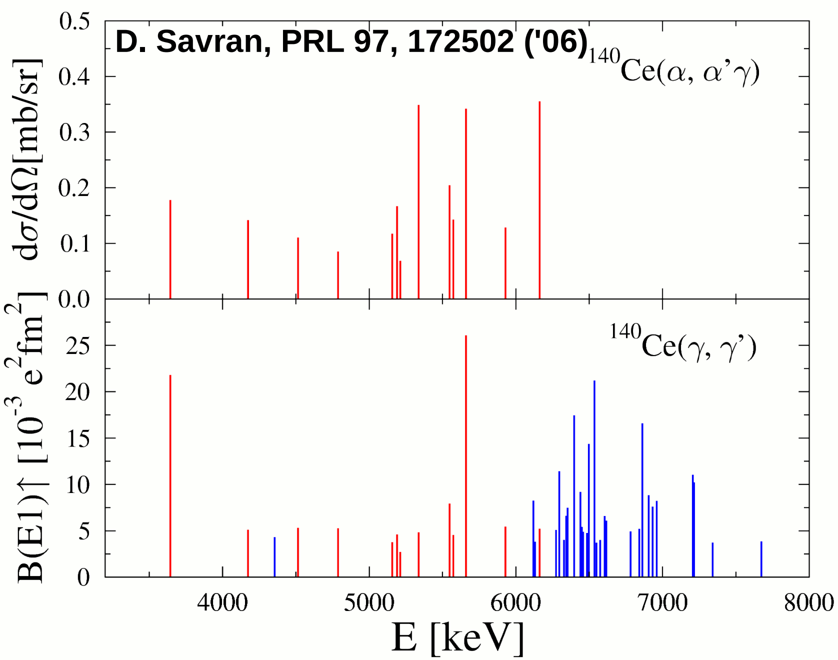


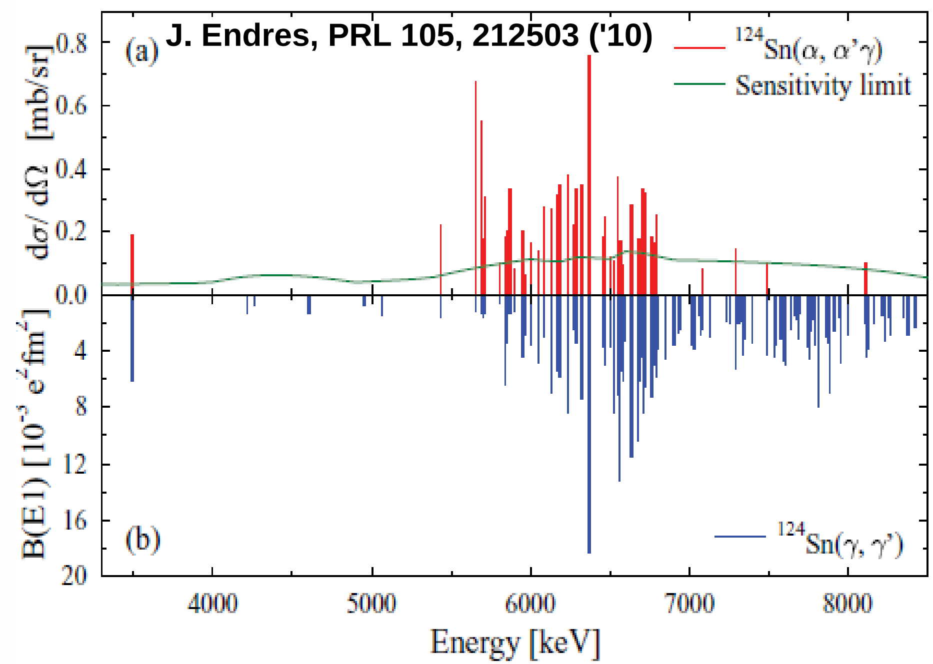
Add observed decays from 2+ back into excitation cross section

- **Could be an effect of structure of the higher (> 7 MeV) states -> GDR**
- **In Pygmy region: affects sum strength by a factor of 2 or more**

Isovector / Isoscalar Components

Another way of splitting the PDR





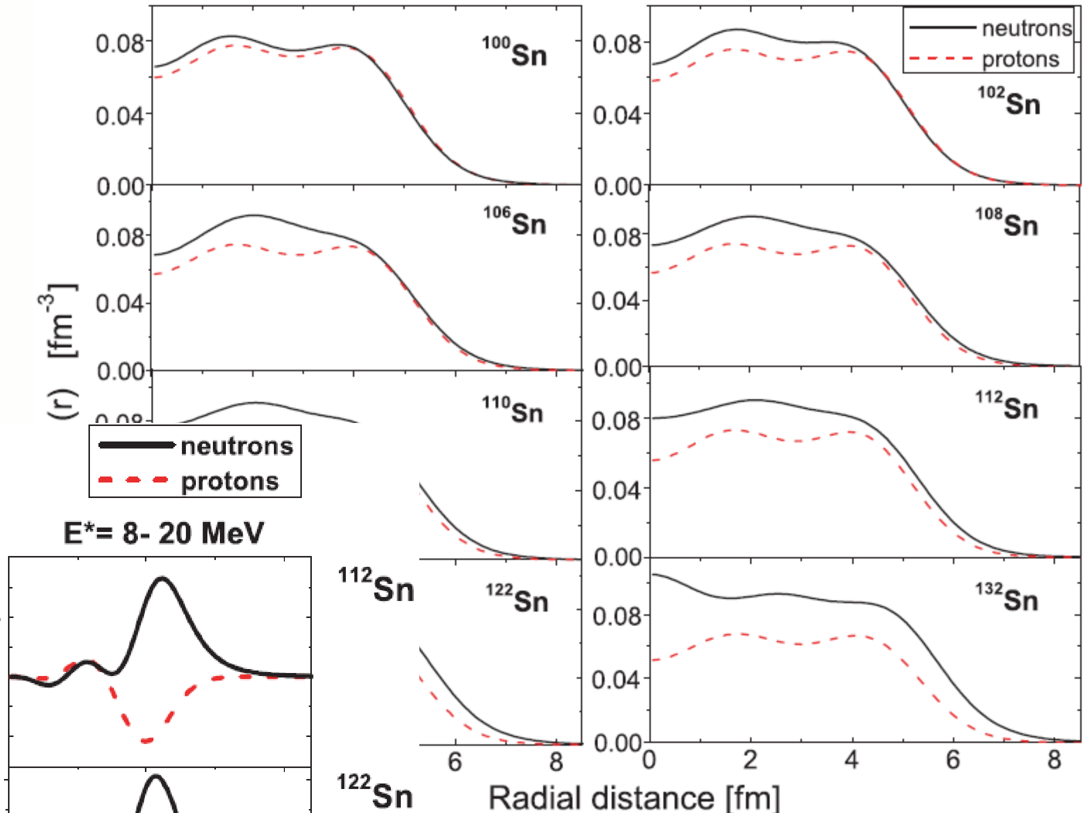
Higher lying states <u>not</u> excited in α-scattering

⇒ Different underlying structure

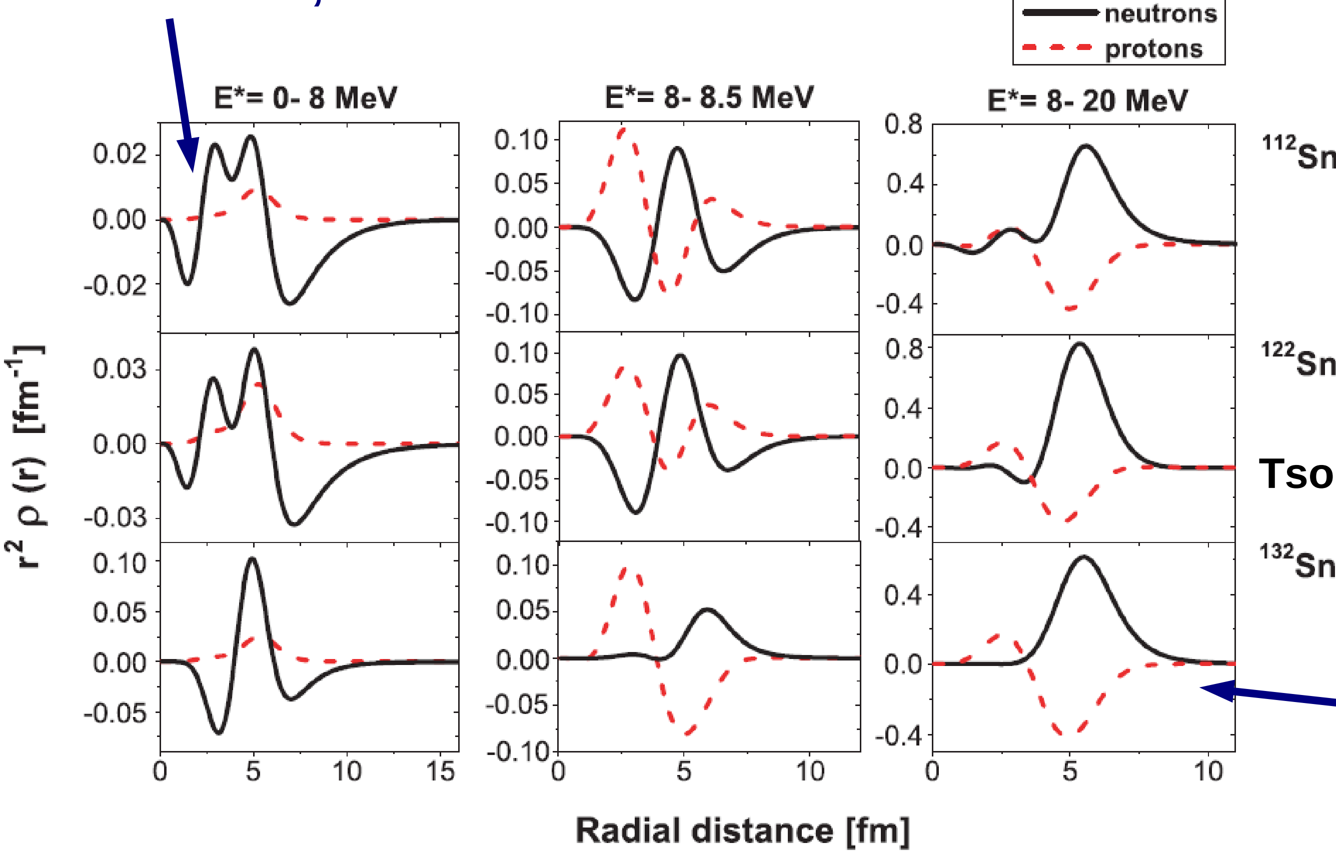
(isoscalar / isovector part)

Switch from PDR to GDR ?

Sn isotopes:
Calculated proton / neutron densities
-> neutron skin



Transition densities:
Isoscalar, n-oscillation on surface



Tsoneva / Lenske, PRC 77, 024321 ('08)
HFB + QPM

isovector -> GDR

What's next?

First: finish all corrections from HIGS data and refit Lorentzians!

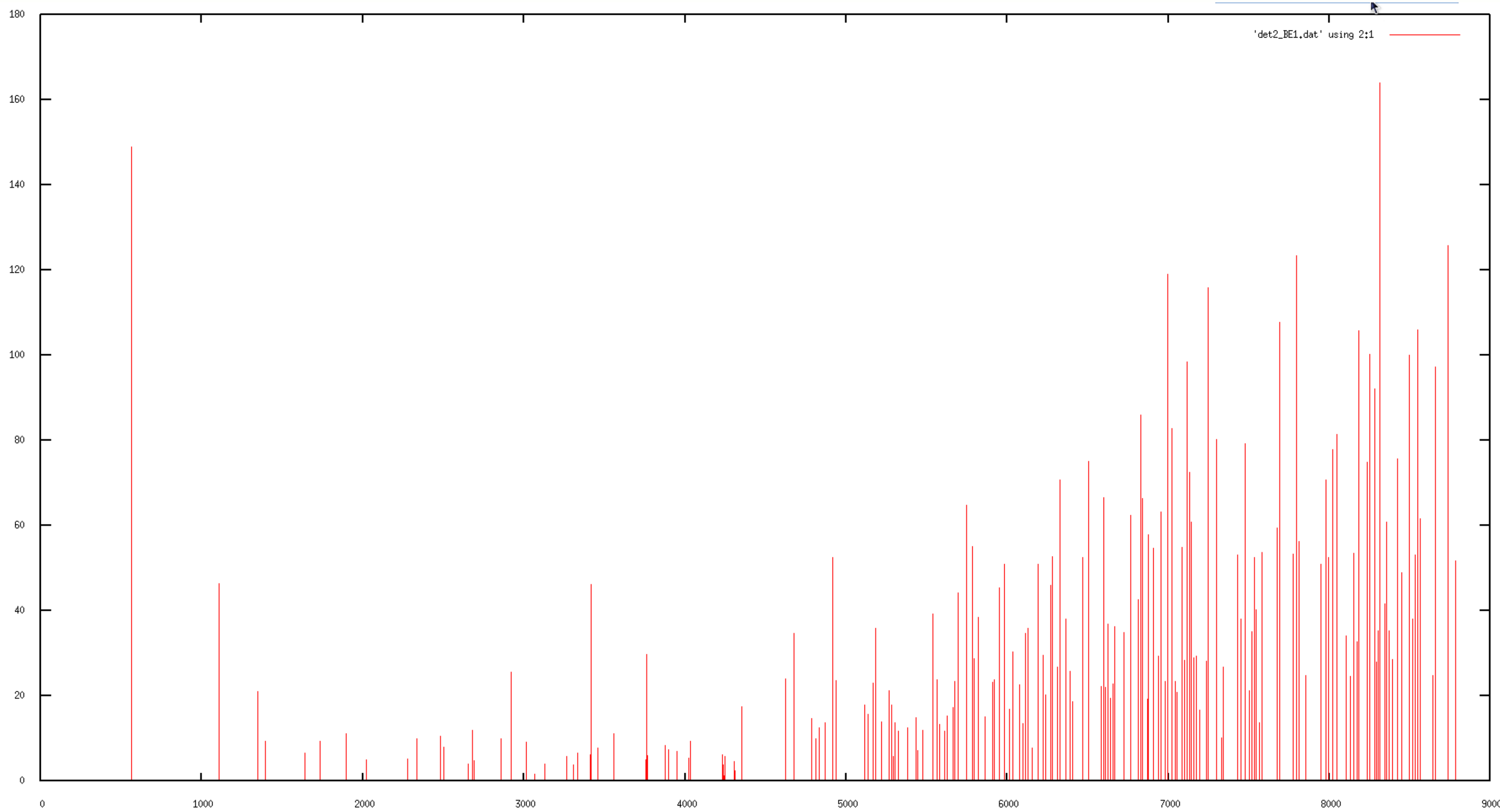
Comparison to 2β-decay partner ^{76}Ge

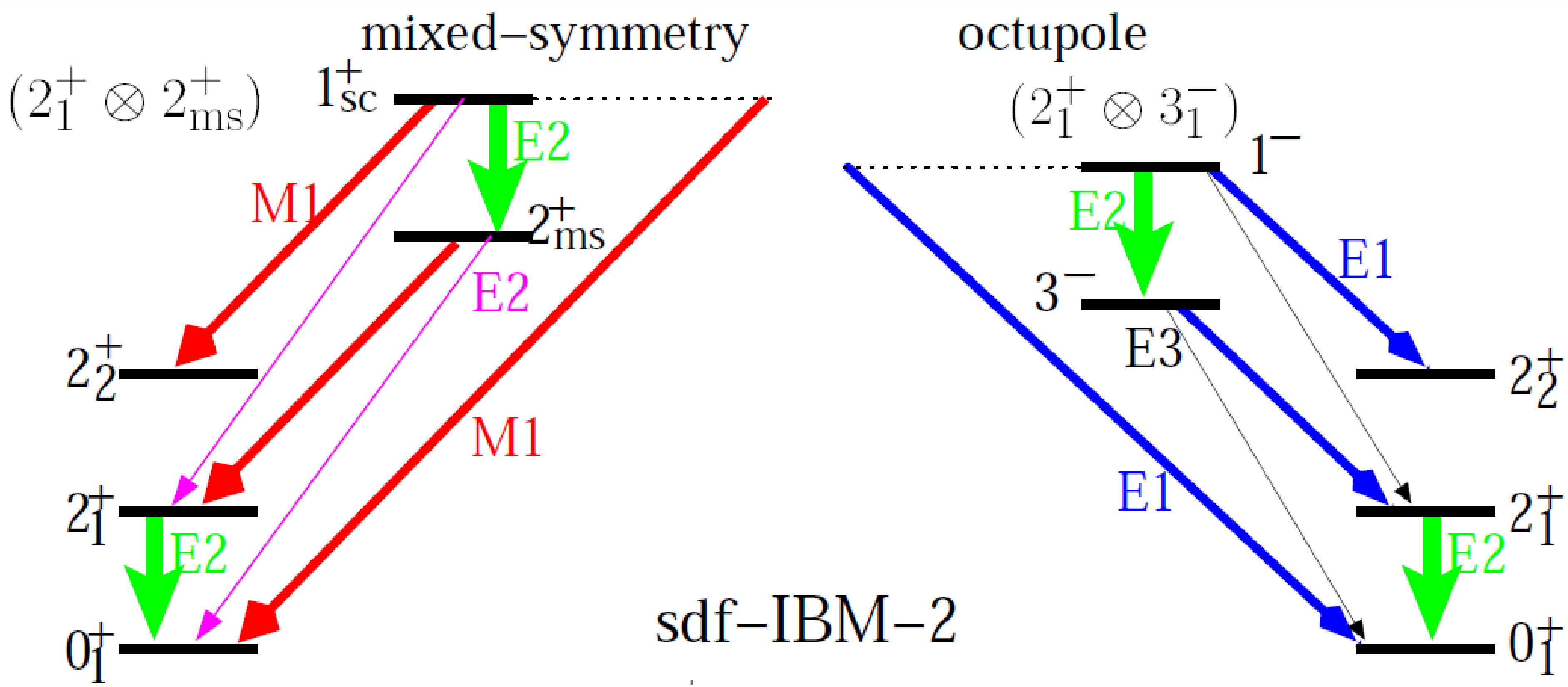
We need a means of observing the intermediate transitions,
Directly !

Same holds for other excitation modes, few examples follow...

First Glimpse ^{76}Ge

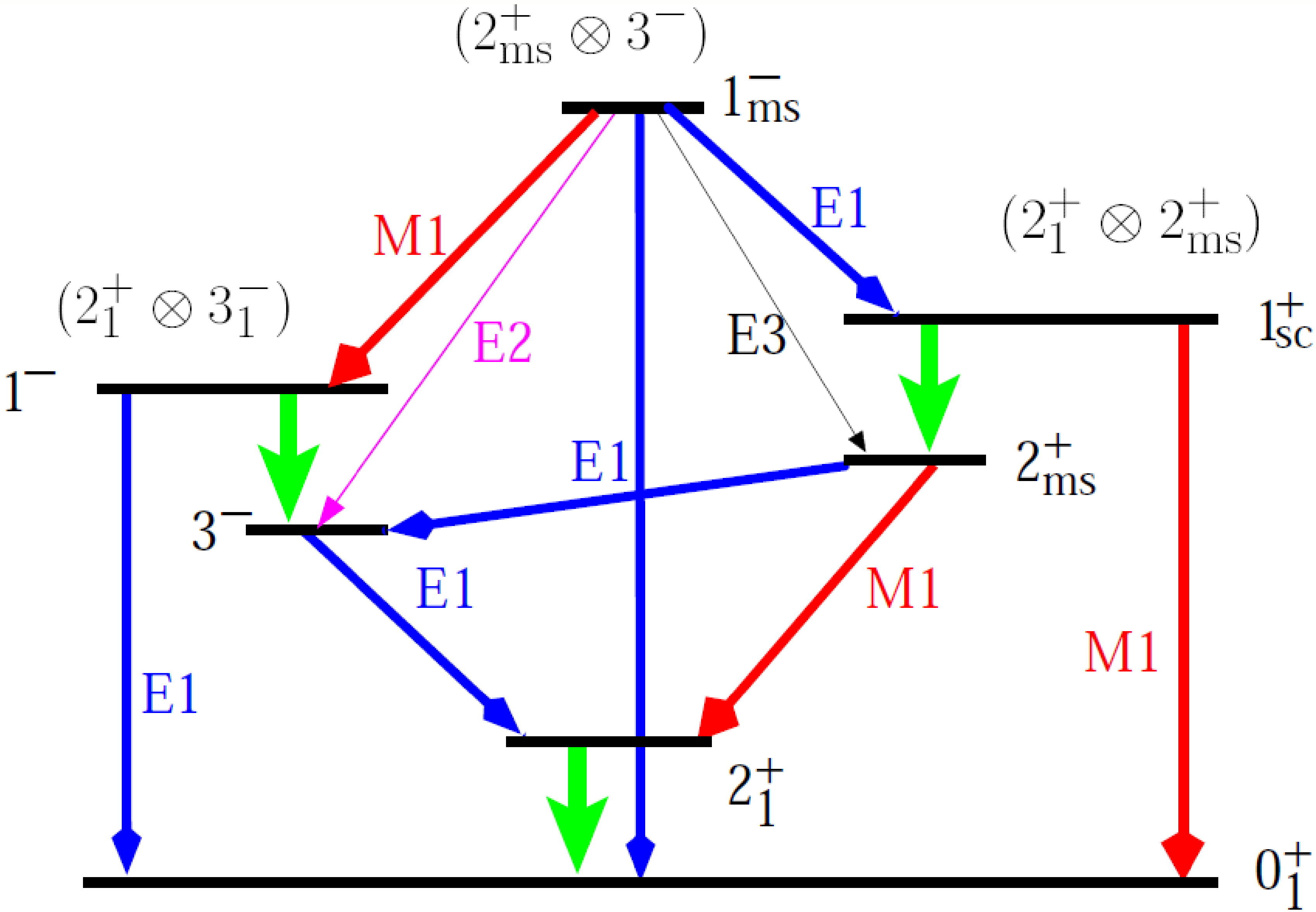
Pete Humby, Yale/Surrey, very first plot





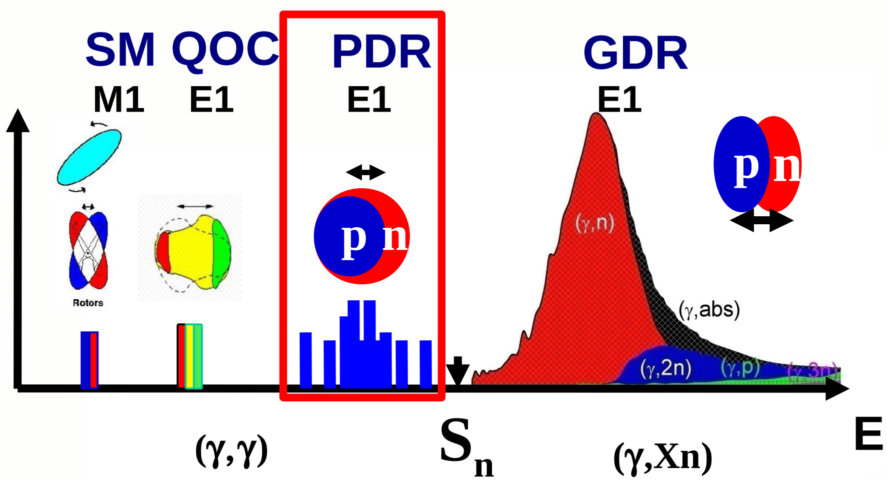
mixed–symmetry
$(2_1^+ \otimes 2_{ms}^+)$
1_{sc}^+
E2
M1
2_{ms}^+
E2
M1
2_2^+
2_1^+
E2
0_1^+
octupole
$(2_1^+ \otimes 3_1^-)$
1^-
E2
E1
3^-
E3
E1
2_2^+
2_1^+
E2
0_1^+
sdf–IBM–2

Q-O MS Coupling Scheme



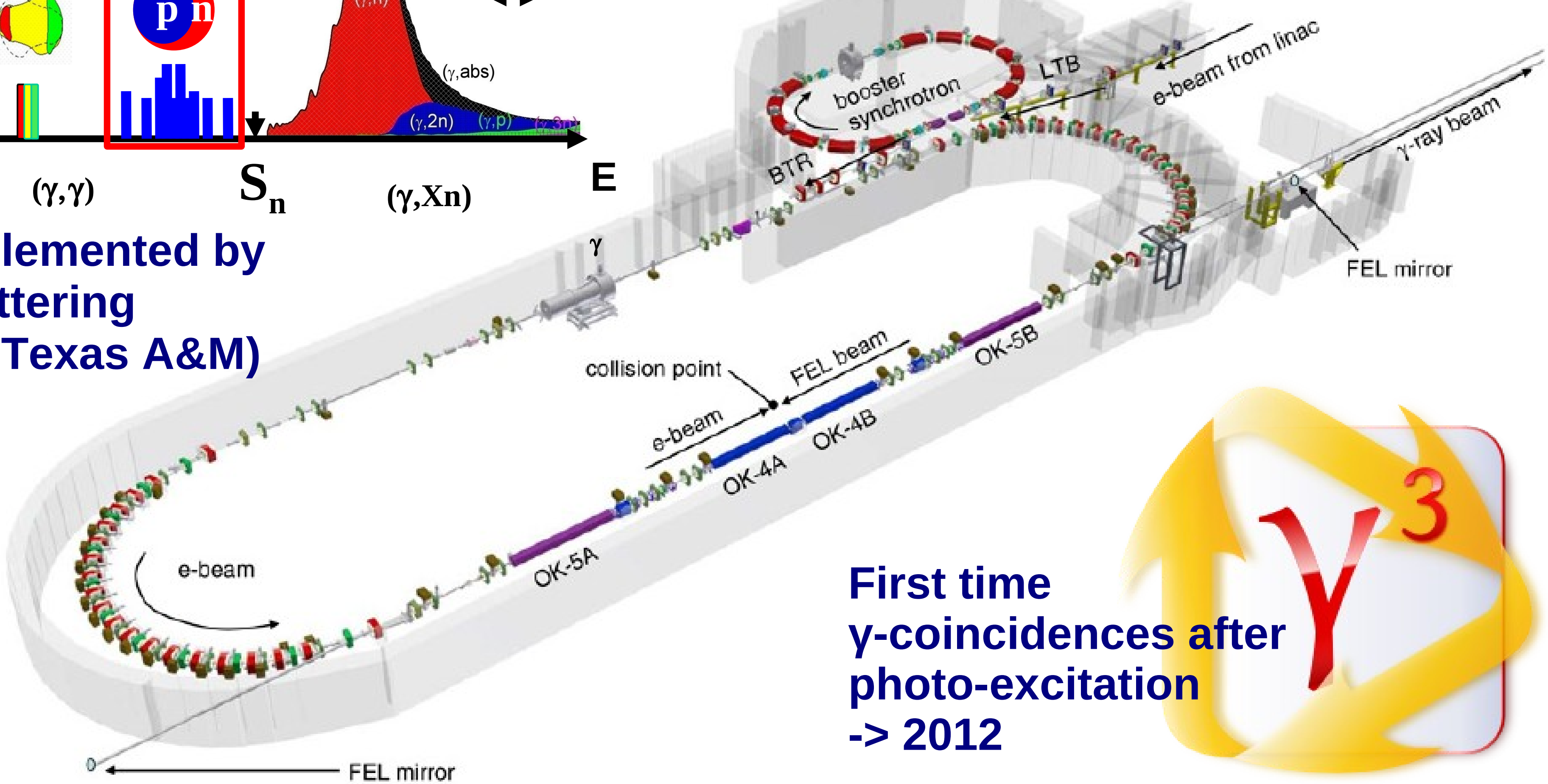
Smirnova et al., NPA 678, 235 (2000)

Missing so far: 3^-_{ms} state -> M. Scheck



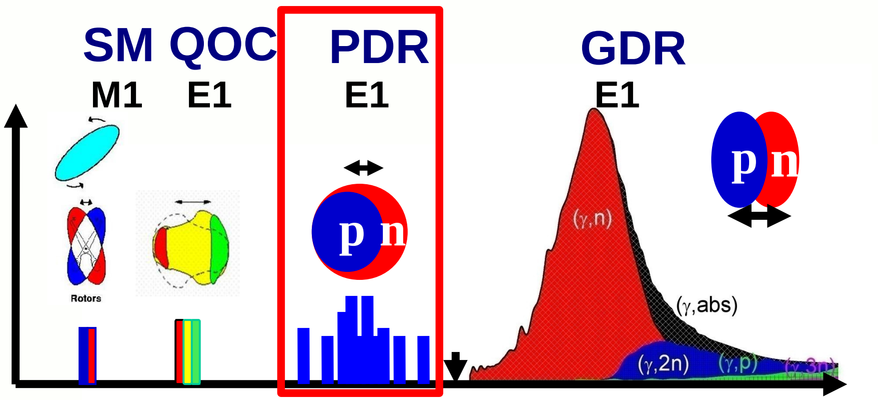
Study of the Pygmy Dipole Resonance
-> Neutron Skins
Study of Multi-Phonon States

Complemented by α-scattering (KVI / Texas A&M)



First time γ-coincidences after photo-excitation -> 2012

A new project coming up: Extreme Light Infrastructure (ELI) in Europe (Collide highly-intense electron beam high-power lasers)



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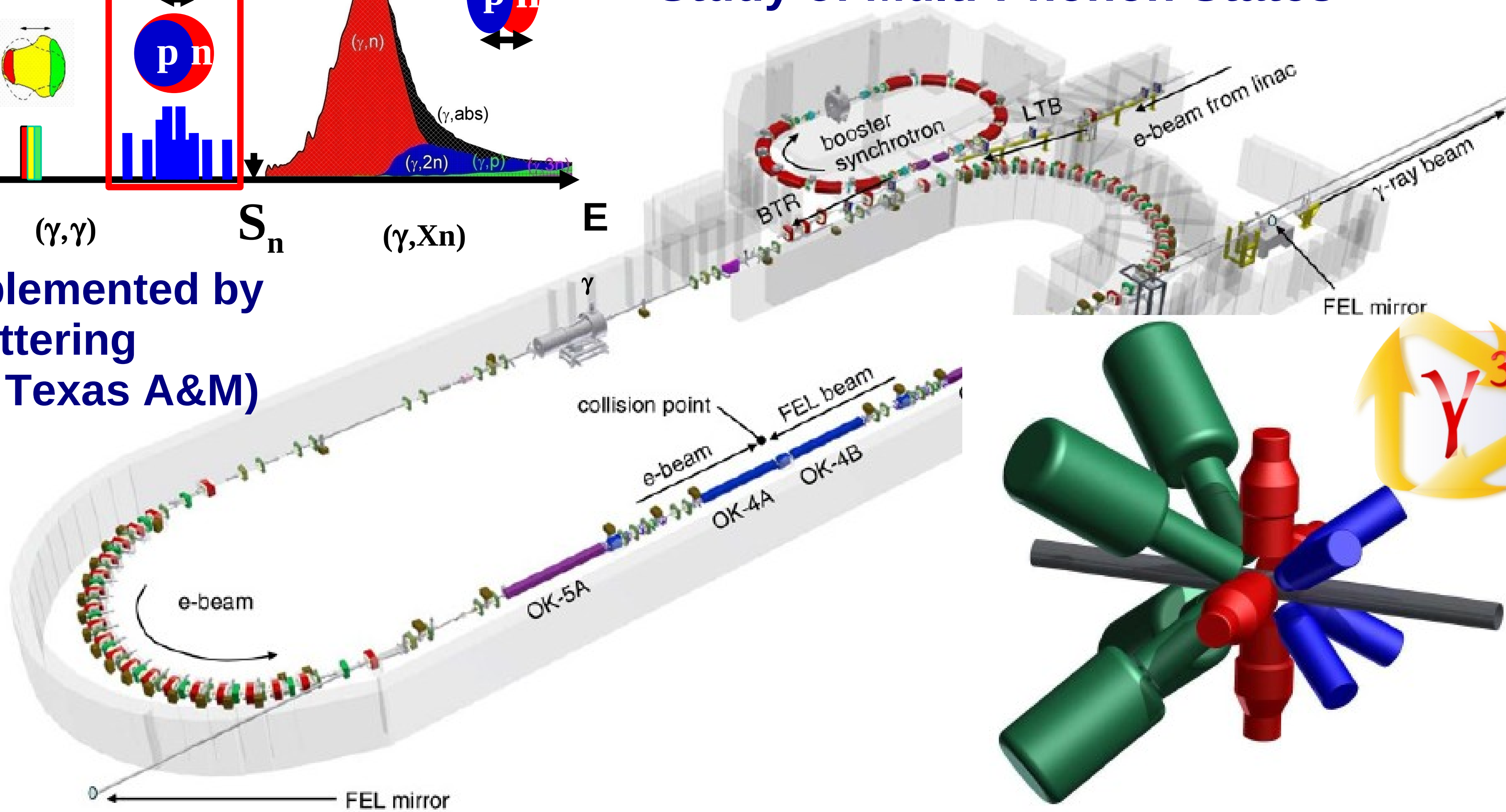

A new project coming up: Extreme Light Infrastructure (ELI) in Europe (Collide highly-intense electron beam high-power lasers)

The Yale Nuclear Structure Group 2012

Farheen Naqvi, PD

Nathan Cooper, GS

Volker Werner, PI

Rick Casten, Prof.

Christian Bernards, PD

+ Peter Humby (MPhys Surrey) !!