New Developments on the Recoil-Distance Doppler-Shift Method

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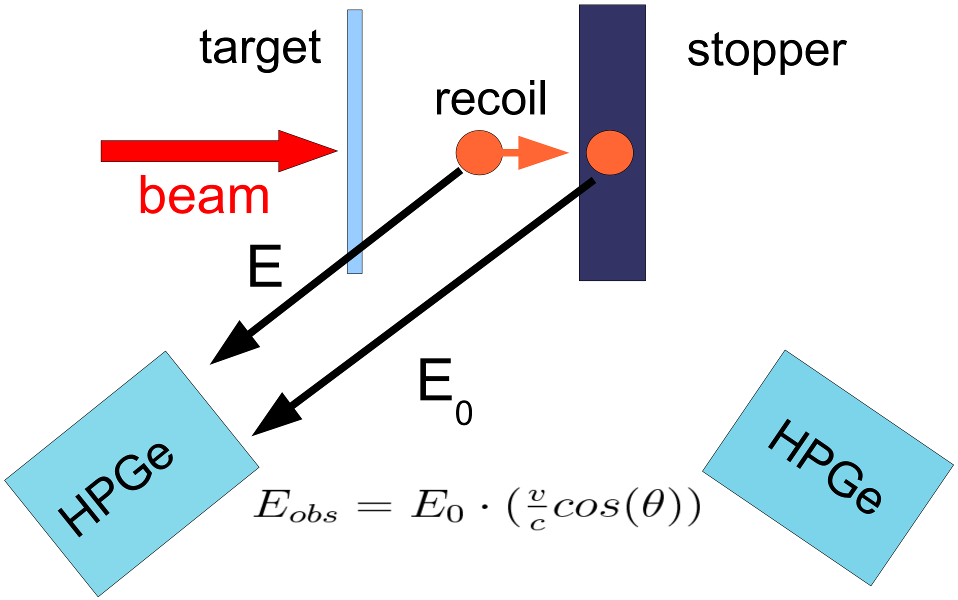
Outline

- Fusion, direct reaction or Coulex with radioactive beams in inverse kinematics: lifetimes determination with RDDS
- RDDS after Coulex in inverse kinematics: example ^{128}Xe
- The new Cologne plunger for radioactive ion beams
- Recent experiments at NSCL
- Outlook: planned experiments at GSI, Darmstadt

The recoil distance Doppler-shift method (RDDS)



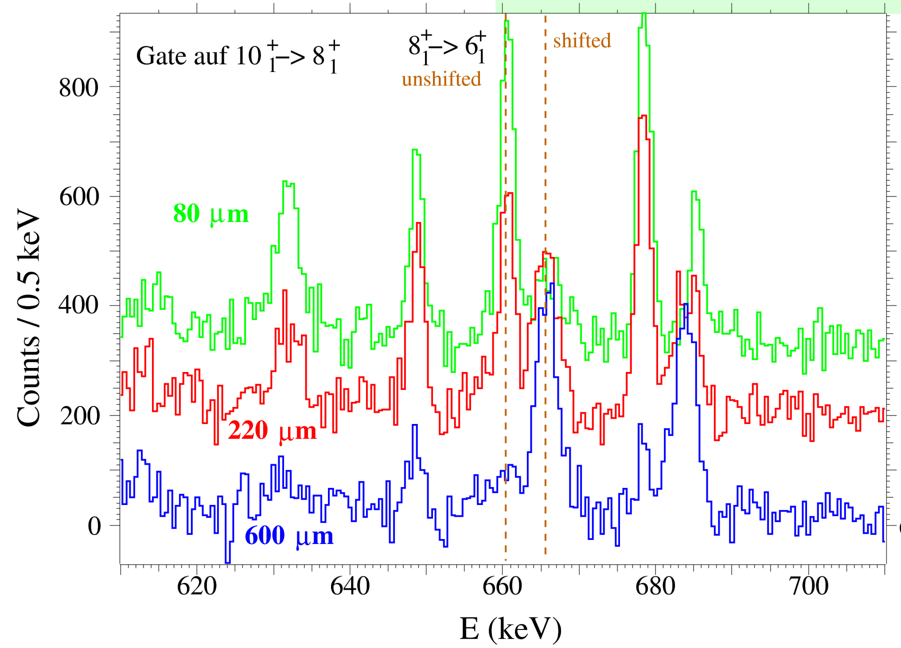
$$E_{obs} = E_0 \cdot (\frac{v}{c} cos(\theta))$$

$$\tau(t_k) = \frac{I^{us}(t_k)}{\frac{d}{dt} I^{sh}(t_k)}$$

I^{us} = Intensity of the unshiftet γ-ray line

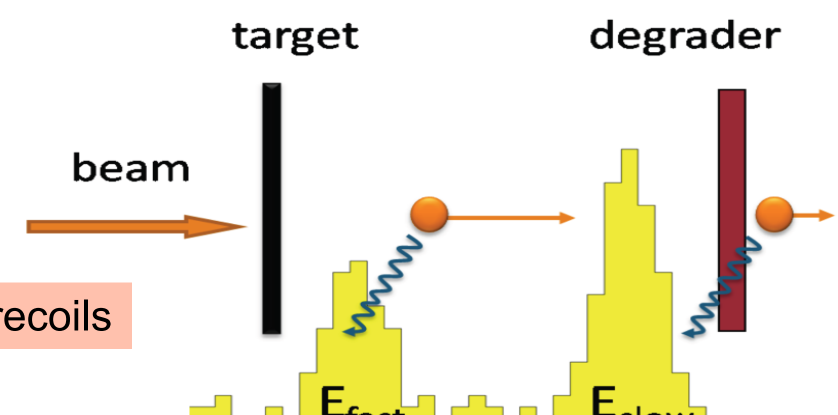
I^{sh} = Intensity of the Doppler-shifted component

$^{92}Mo(^{10}B,3np)^{98}Pd$

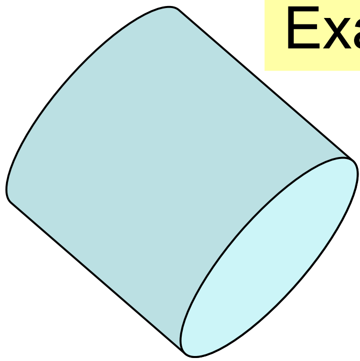


Differential Plunger

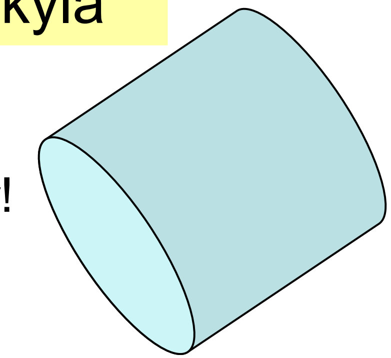
Use degrader instead of stopper to allow identification of recoils

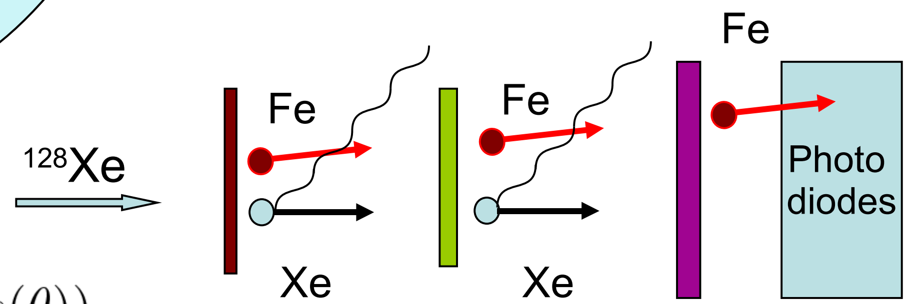


Inverse Kinematics Coulomb Excitation: Example: ^{128}Xe measured at Jyväskylä



Gating on target recoils:
do not observe Coulex on degrader!





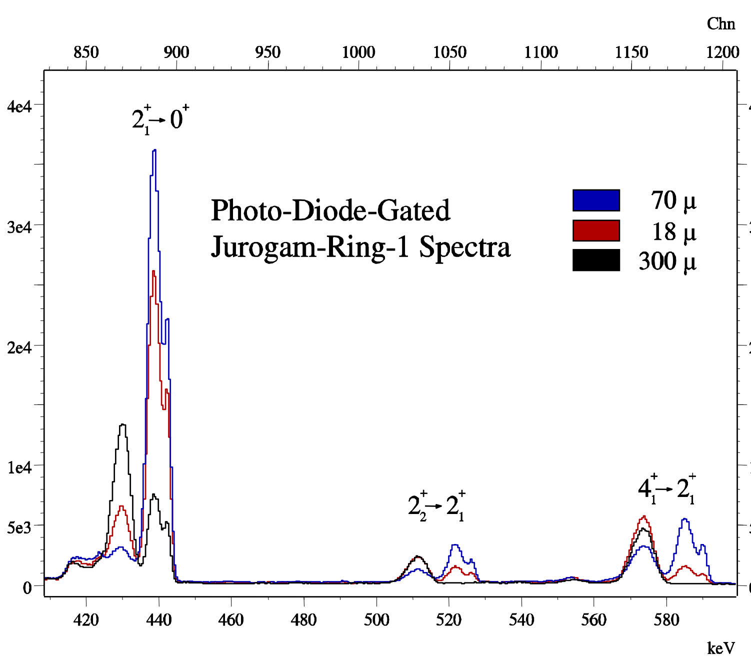
Measure target like recoils
protect detector from beam

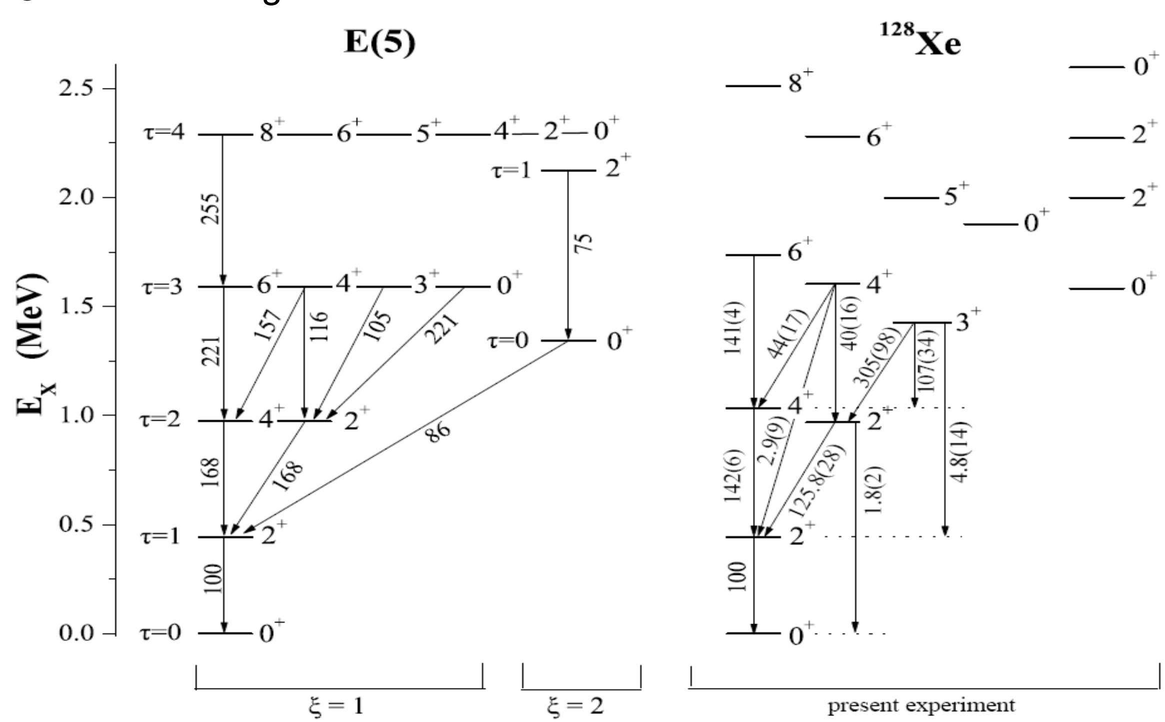
$$E_{obs} = E_0 \cdot \left(\frac{v}{c} cos(\theta)\right)$$

Fe target 1mg/cm²

Nb degrader 5mg/cm²

Au beam stopper 19 mg/cm²





Deorientation

Hyperfine interaction:
Original spin alignment diminished
as function of interaction time

Decay described by attenuation function

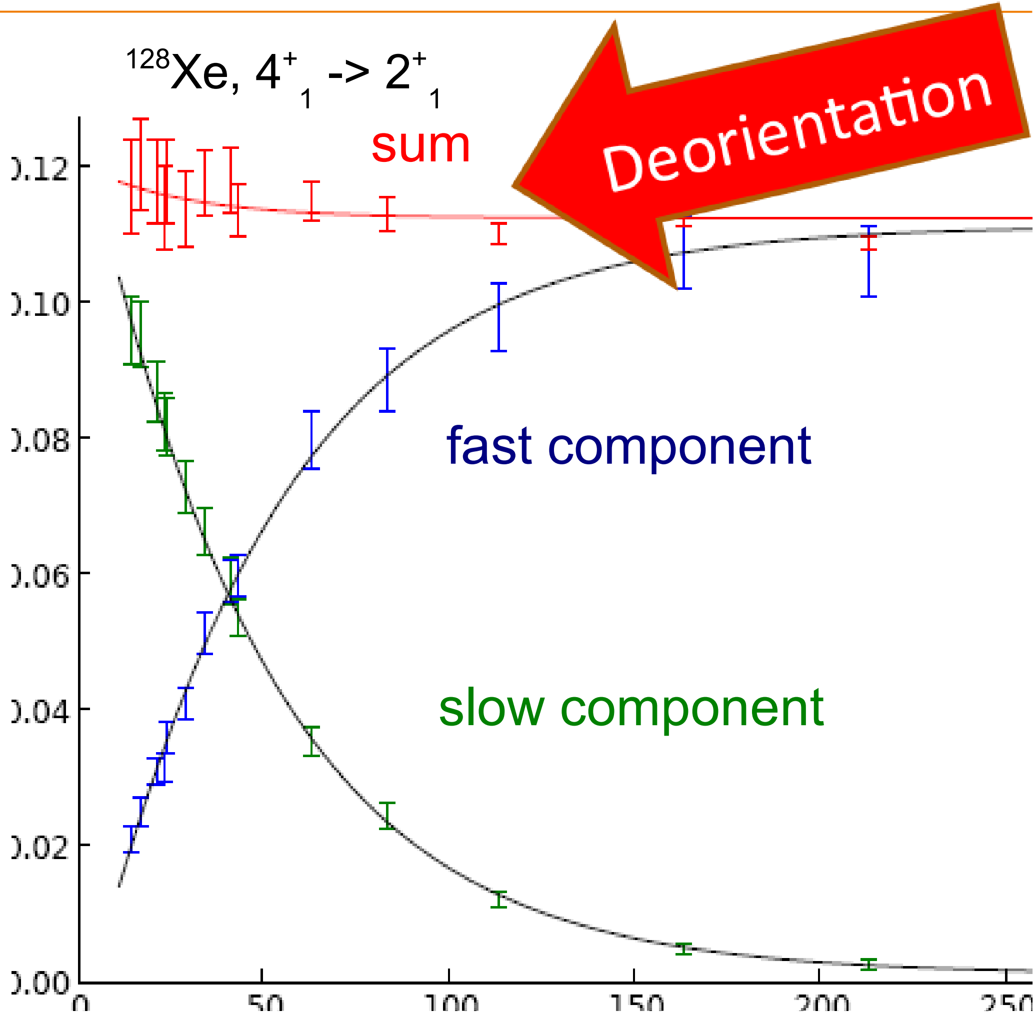
$$\omega(d) = 1 + pe^{-d/T_D}$$

T_D relaxation time
After projectile leaves foil,
angular distribution decays into isotropy

Intensities of fast and slow components:

$$\tilde{R}_i^{\dot{s},f} = \omega(d) R_i^{\dot{s},f}$$

Integrate from 0 to d (target – degrader)
for (f) and
from d to infinity (behind degrader) for (s)

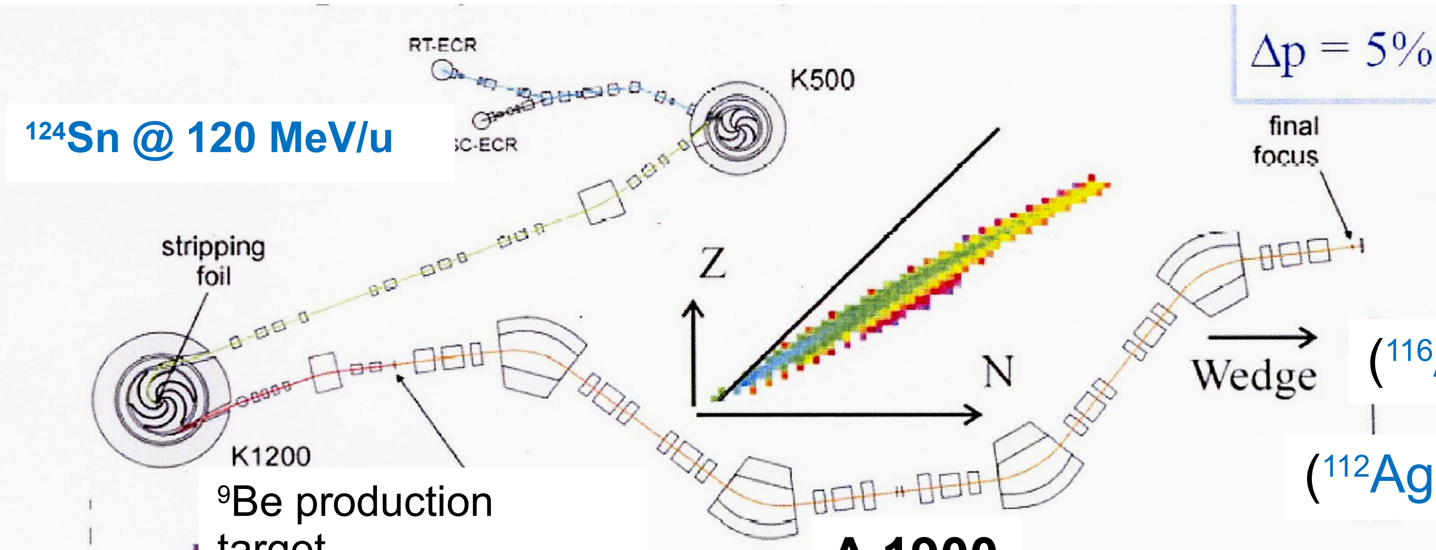


Sum of components not constant!

A new plunger device for radioactive beams at NSCL, MSU

target/ degrader diameter: 4 cm
target/ degrader separations: 0-2,5 cm
precision : ~ 1 μm
target/ degrader thickness: ~ 1μm -1mm

Plunger for radioactive ion beams: NSCL coupled cyclotron facility + A1900; MSU



^{124}Sn @ 120 MeV/u

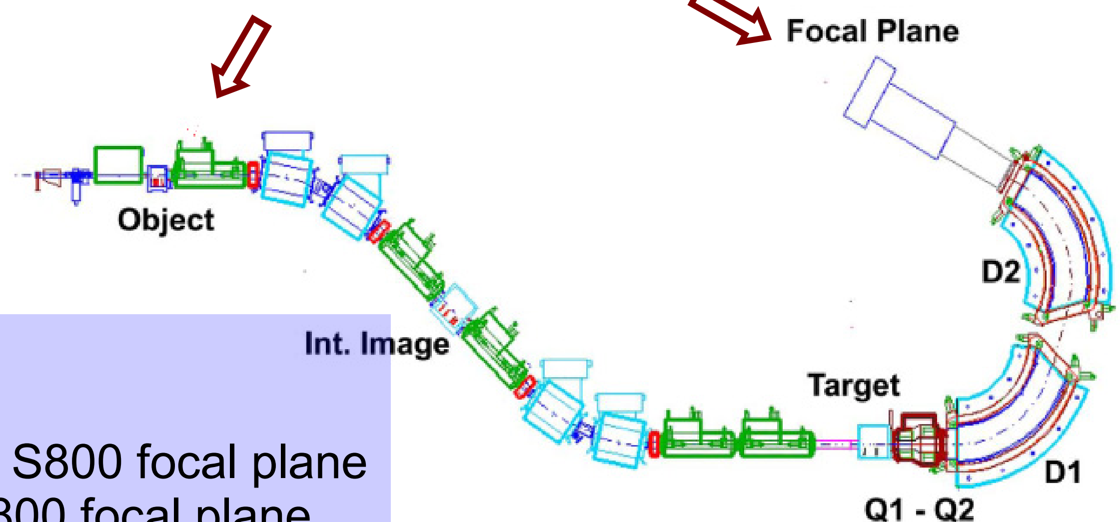
^{9}Be production target

A 1900

(^{116}Ag, ^{112}Rh, ^{114}**Pd**)

(^{112}Ag, ^{108}Rh, ^{110}**Pd**)

Diamond – FP S800



A1900: mass separation
Identification of incoming beam:
TOF between K1200 and Diamond

Mass and charge of reaction products:
from TOF and energy loss.
TOF between Diamond and scintillator in S800 focal plane
energy loss with ionization chamber in S800 focal plane

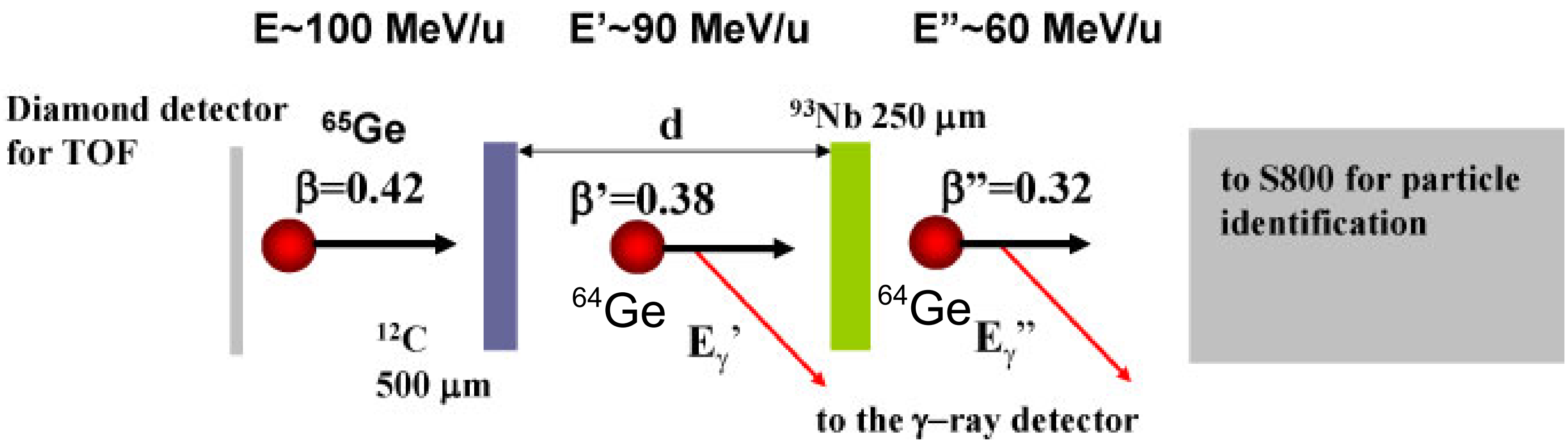
Plunger lifetime measurements using secondary knock-out reactions or coulomb excitation

Knock-out reaction

Investigation of the N=Z nucleus ^{64}Ge (and ^{62}Zn) at NSCL

K. Starosta et al, Phys. Rev. Lett. 99, 042503 (2007)

beam: ~5% 65Ge, ~25% 64Ga, ~70% 63Zn, ~2% 62Cu



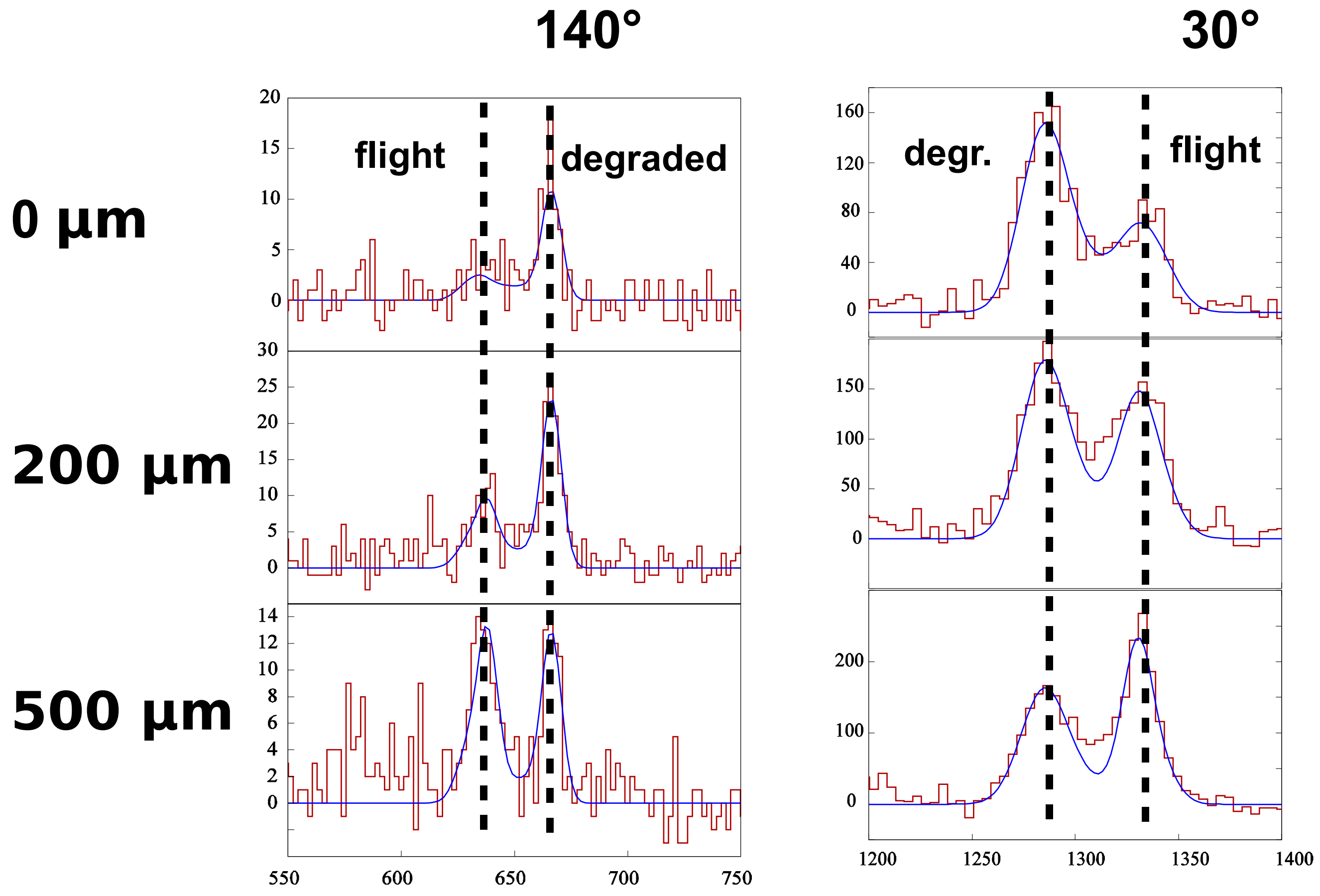
d: 0 – 500μm

Knockout or fragmentation: access of states beyond the 2^+_1

relativistic Coulex: practically only 2^+_1

Analysis using decay function and lineshape

^{62}Zn : ($2^+ \rightarrow 0^+$) transition measured at different target – degrader separations



Lifetime determined for 2_1^+ in ^{62}Zn:
τ = 4.2(7) ps
including lineshape analysis

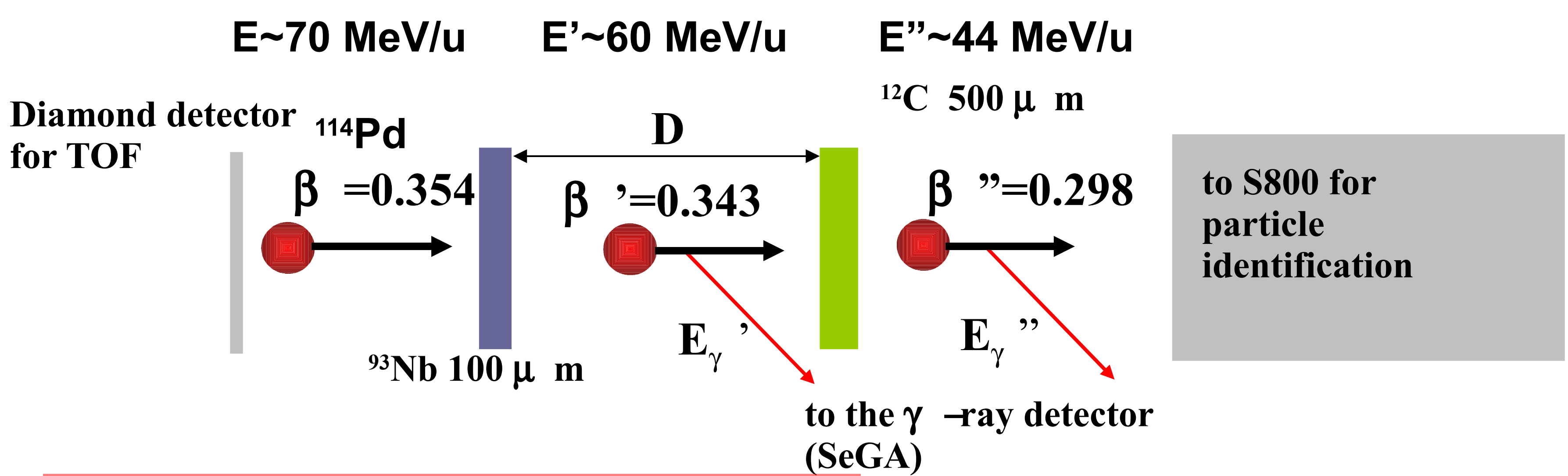
Nucl.Data Sheets 91(2000)

τ = 4.2(3) ps

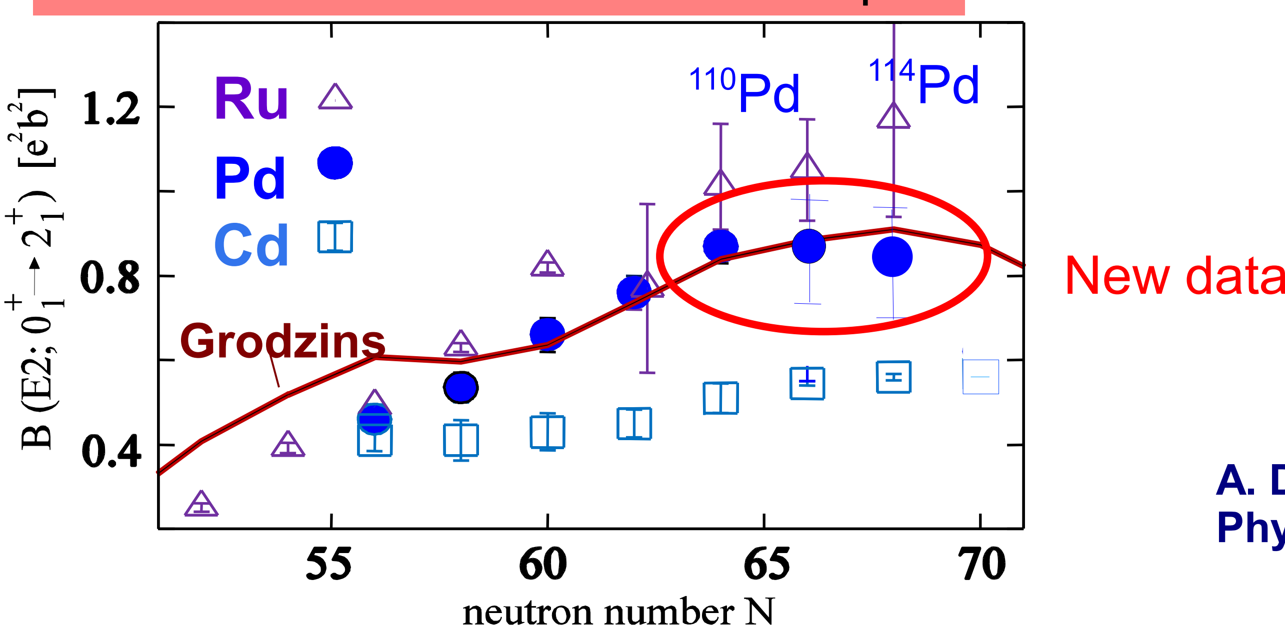
- Stopping power fixed by using velocities measured after the target and after the degrader
- Relativistic effects were considered
- Parameter: degrader excitation (40%)
  width of the velocity distribution
- Free parameter: lifetime, normalisation factor

→ 90% of intensity of 2^+_1 decay in ^{62}Zn from fast feeding. Knockout reaction excellent tool for lifetime measurements!

Plunger technique at intermediate-energy for ^{110}Pd and ^{114}Pd with coulex



New data for neutron rich Pd isotopes



^{114}Pd:
τ =118 (20) ps

^{110}Pd:
τ=67 (8) ps

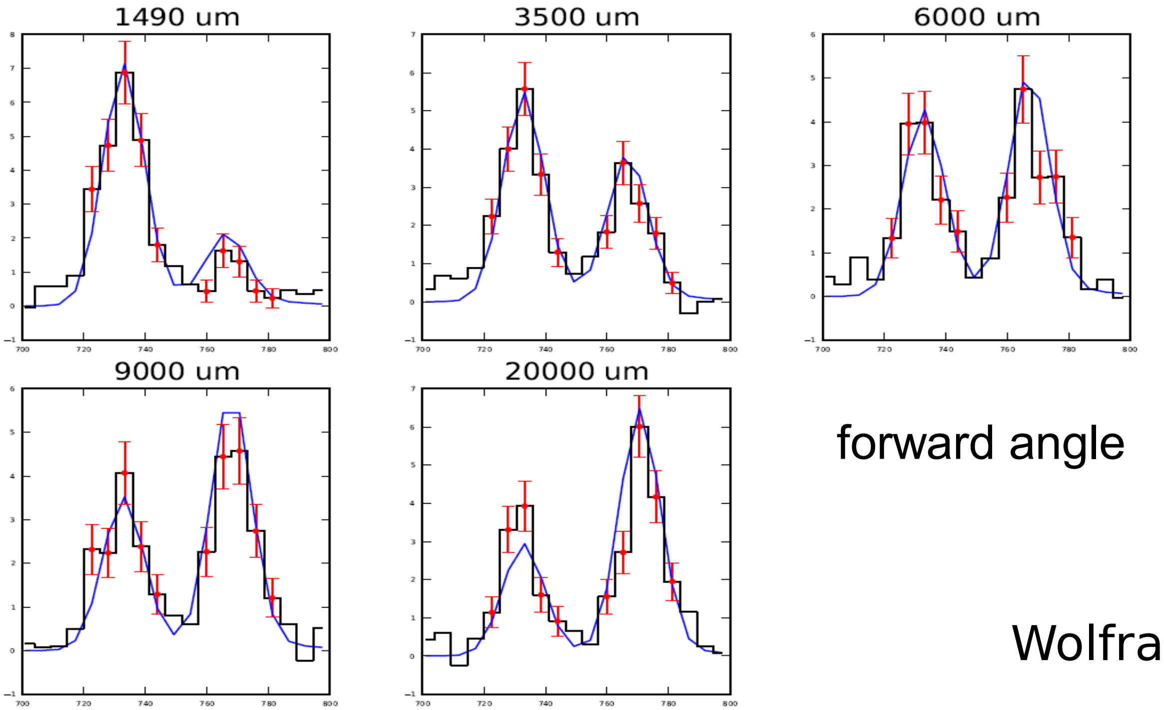
A. Dewald et al,
Phys. Rev C 78, 051302(R), 2008

Investigation of n-rich Fe isotopes @ NSCL, MSU

RDDS after Coulex in inverse kinematics

A	Beta	Energy [MeV/u]	pps	Au –Target	Nb-Degrader
62	0.43	100	36k	0.3 mm	0.3 mm
64	0.42	95	6k	0.3 mm	0.4 mm
66	0.40	85	1k	0.3 mm	0.3 mm

Example: lineshape analysis ^{66}Fe

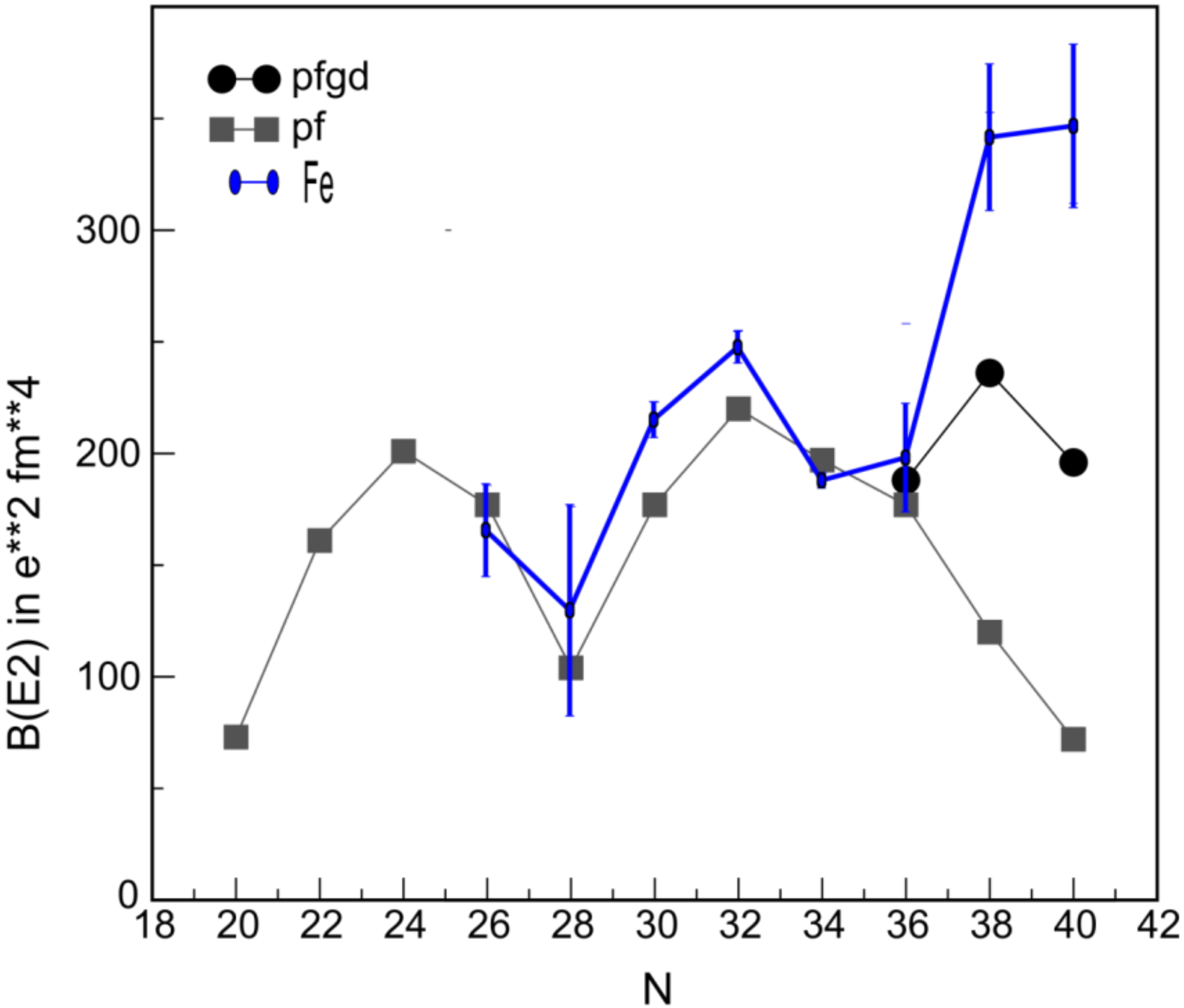


^{66}Fe, $2_1^+ \rightarrow 0_1^+$

forward angle

Wolfram Rother, IKP Cologne

$B(E2, 2_1^+ \rightarrow 0_1^+)$ systematics for Fe isotopes



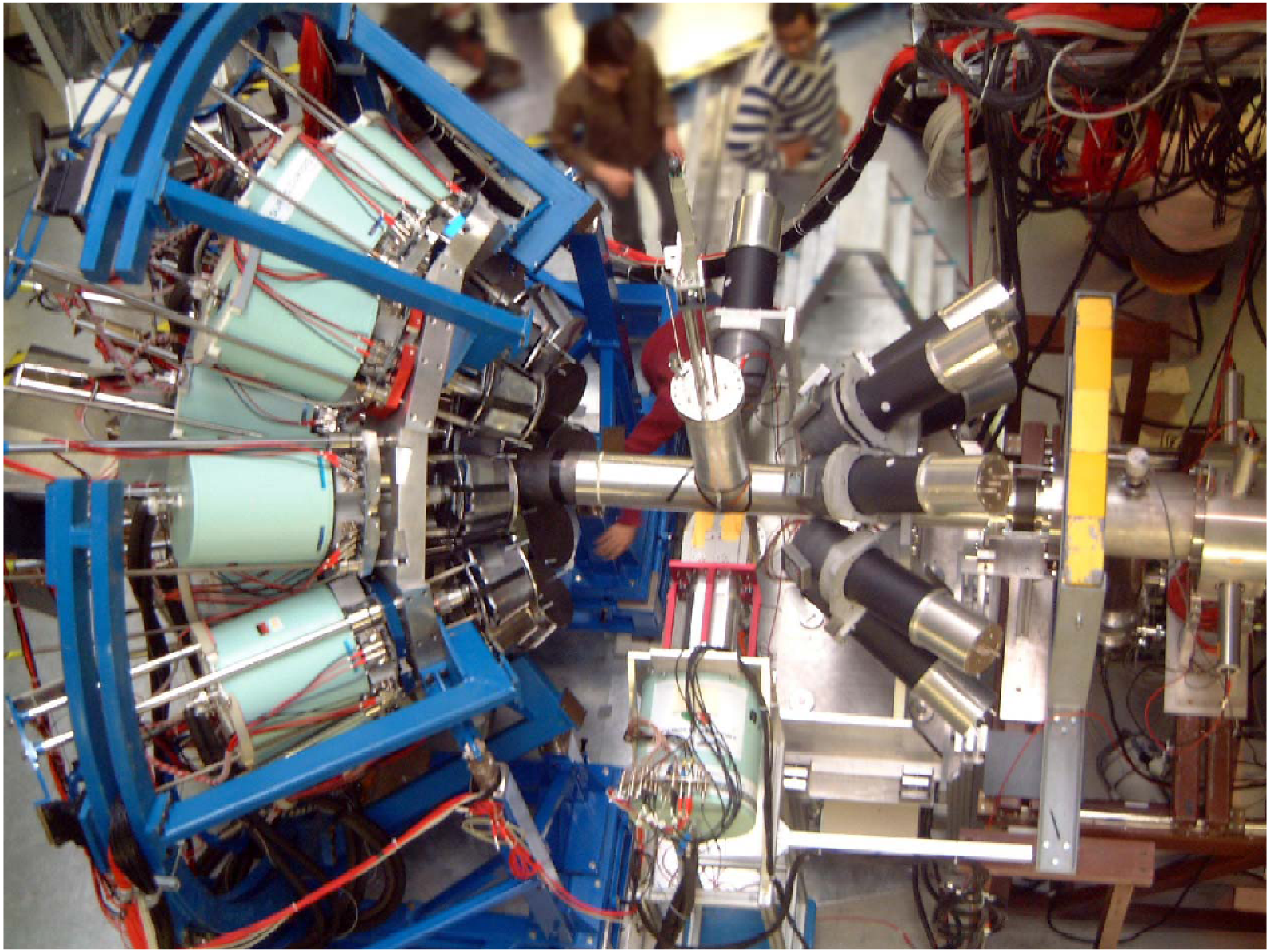
Fe: N=26 – 34 from Nuclear Data Sheets

N=36,38,40 Wolfram Rother, new data

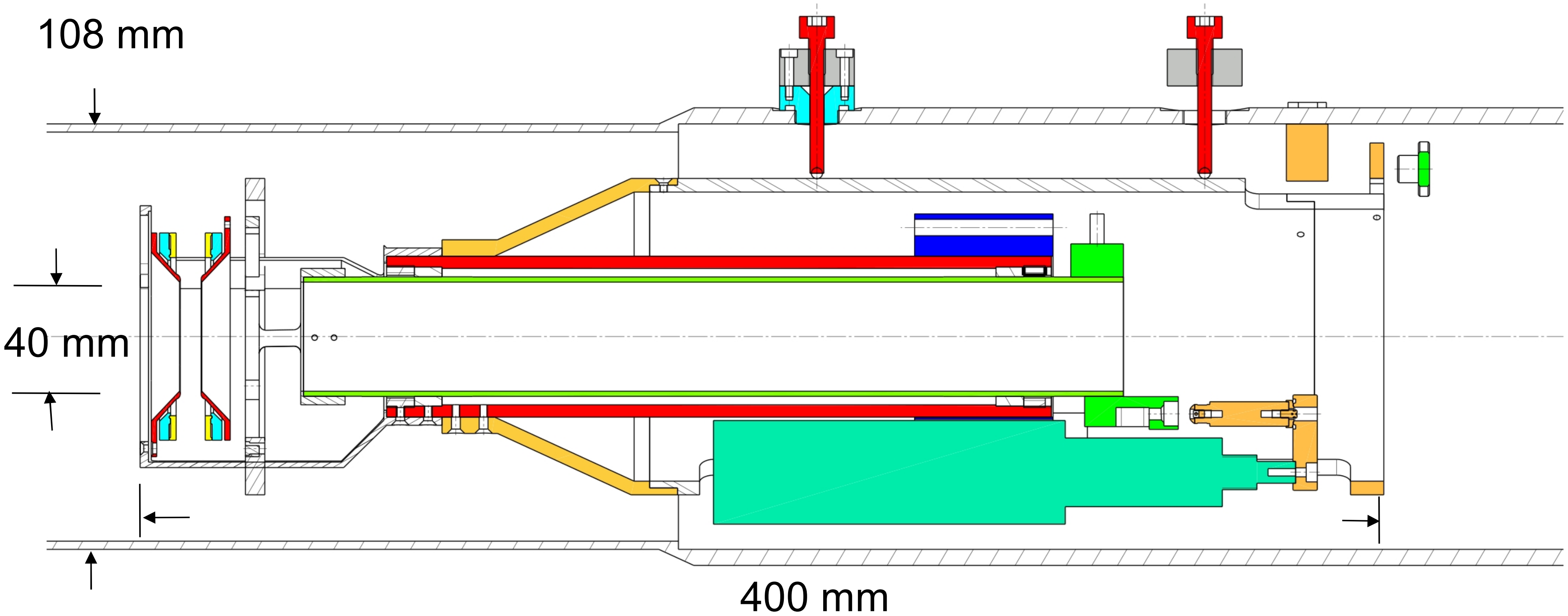
Calculations in pfgd and pf shells:
E. Caurier et al., Eur. Phys. J. A15, 145 (2002)

Wolfram Rother, IKP Cologne

Plunger at GSI: PRESPEC/LYCCA -> HISPEC

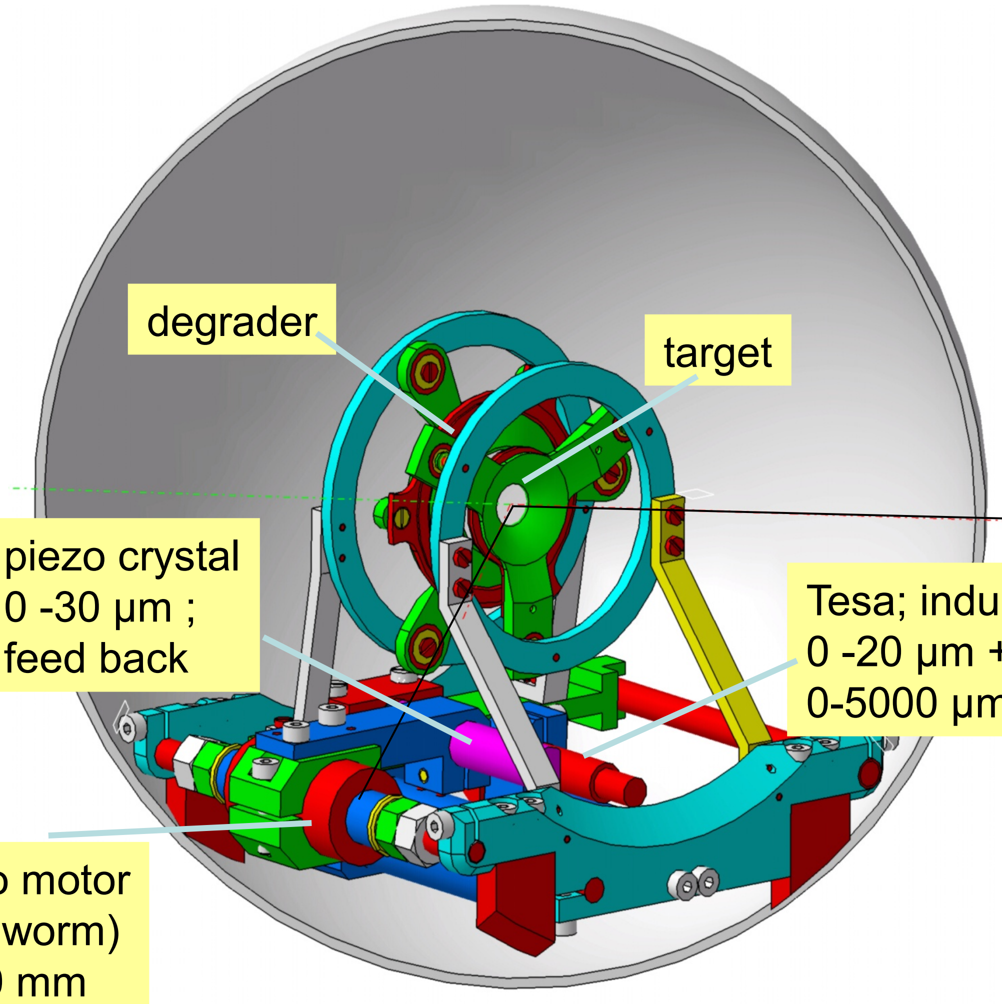


Plunger for radioactive beam experiments @ MSU



Required for GSI plunger:
- larger target/degrader diameter 70 – 80 mm ✓
- larger beam pipe diameter 6“ = 152.4 mm ✓
- two piezo motors necessary ✓
- less material in front of target (beam halo) ✗

A dedicated plunger for deep inelastic reactions: PRISMA @ LNL, VAMOS @ GANIL



Modifications for use at PRESPEC:
- Construction not stable enough for large (Ø = ~80 mm) and heavy targets (~1 g/cm^2)
  ► fundamental changes to mechanics needed.
- two inchworm motors necessary
- large target chamber needed.

Advantage of construction: nearly no material in front of target

Outlook: Investigation of neutron rich Cd isotopes at GSI with RDDS and the new AGATA array at PRESPEC

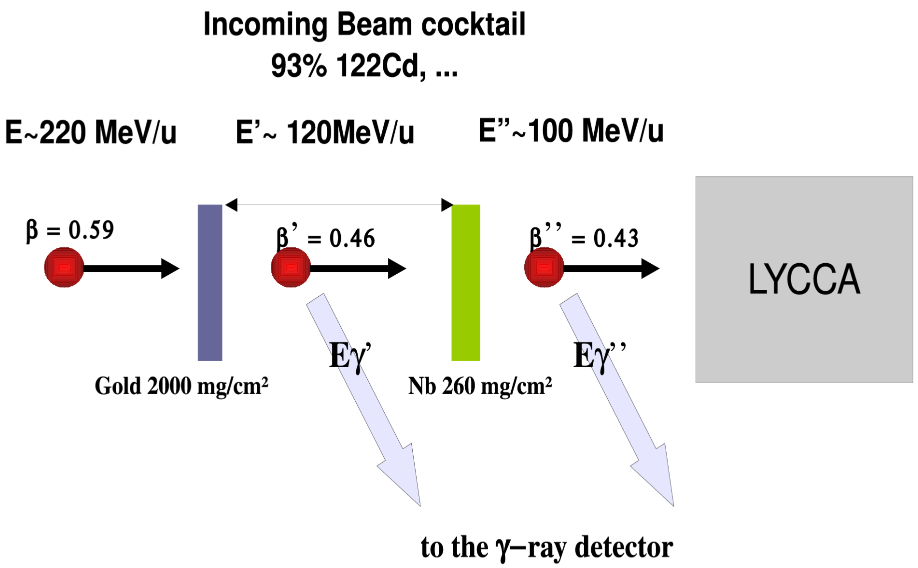
1. Commissioning experiment on ^{122}Cd with new Cologne differential plunger

Aim: application of Cologne differential plunger for lifetime measurements at HISPEC/PRESPEC with Coulex in inverse kinematics

Measure $B(E2,0_1^+ \rightarrow 2_1^+)$ in ^{122}Cd:

Determine from lifetimes measured with plunger

Compare to $B(E2,2_1^+ \rightarrow 0_1^+)$ from Coulex

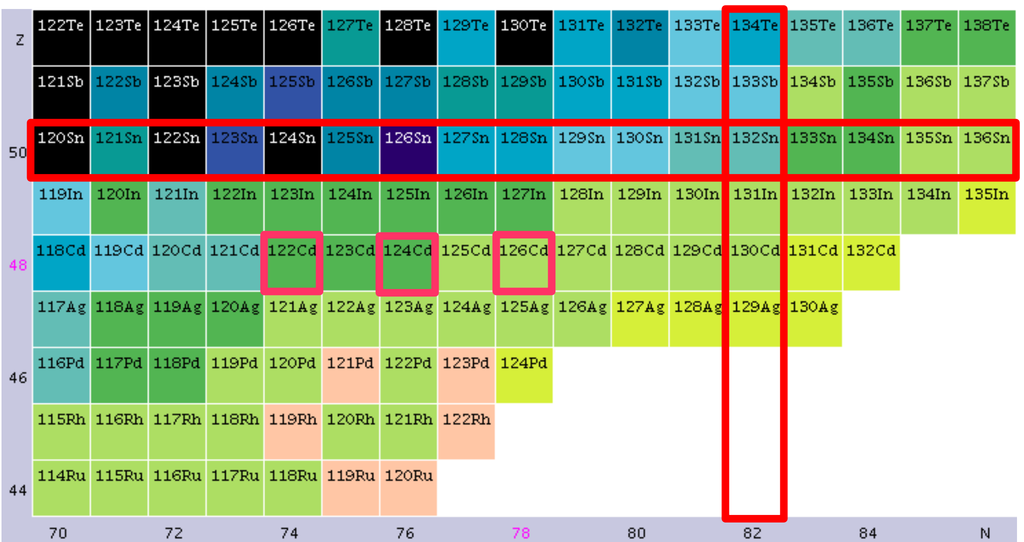


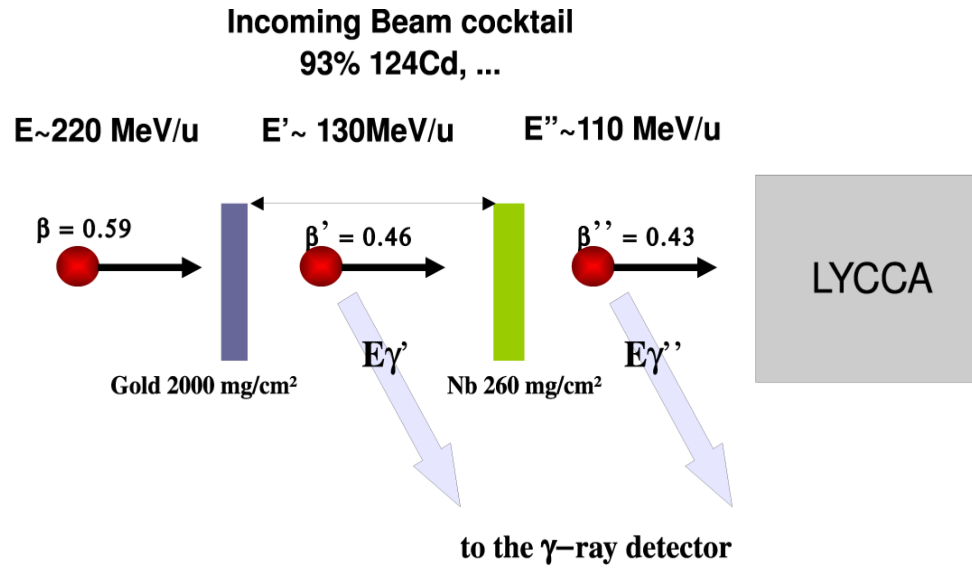
Lifetime τ [ps]	14.4
Doppler-shiftet γ-ray energy after plunger-target at 15° [keV]	914.2
PRESPEC γ-ray energy resolution [%]	4
Averaged cross section for Coulex in target [mb]	300
Cross section for Coulex in degrader [mb]	140
Number of detected good PRESPEC-LYCCA coincidences/h	172
Shifts per single target-degrader data point	1
Estimated number of shifts	3

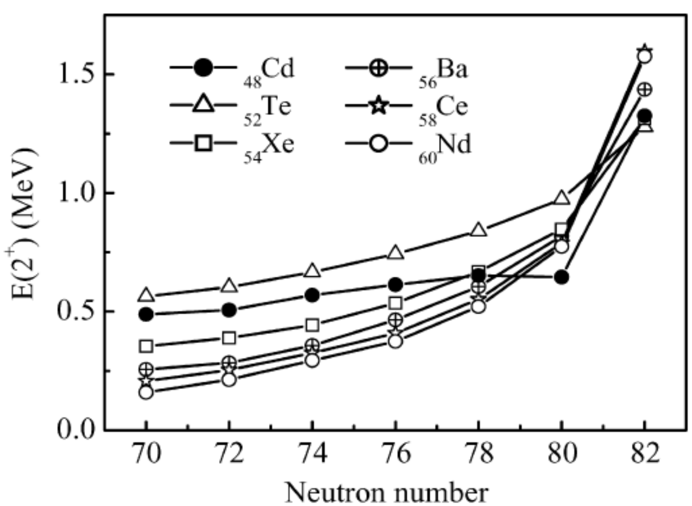
Approved parasitic experiment
21 parasitic shifts (Spring 2011)

Outlook: Investigation of neutron rich Cd isotopes at GSI with RDDS and the new AGATA array at PRESPEC

2. Letter of Intent:
measurement of B(E2) in ^{124,126}Cd in inverse kinematics
Coulex with differential plunger







- Investigate collectivity when approaching N=82
- $B(E2,2_1^+ \rightarrow 0_1^+)$ related to nuclear quadrupole deformation
- Milestone in understanding properties of these nuclei
- Anomalous behavior of 2_1^+ in n-rich Cd

Need precise data on $B(E2,2_1^+ \rightarrow 0_1^+)$

Conclusion

Differential plunger is a very profitable instrument for lifetime measurements in inverse kinematics:

- New results on stable ^{128}Xe from JYFL
- Examples for measurements with radioactive ion beams at NSCL/MSU
- Outlook: Experiments planned at FRS/GSI with radioactive beams and AGATA

Collaboration:

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J. Jolie, K. O. Zell

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P. Voss, D. Weisshaar

INRNE, Bulgaria
P. Petkov

GSI, Darmstadt, Germany
M. Gorska and the PRESPEC Collaboration

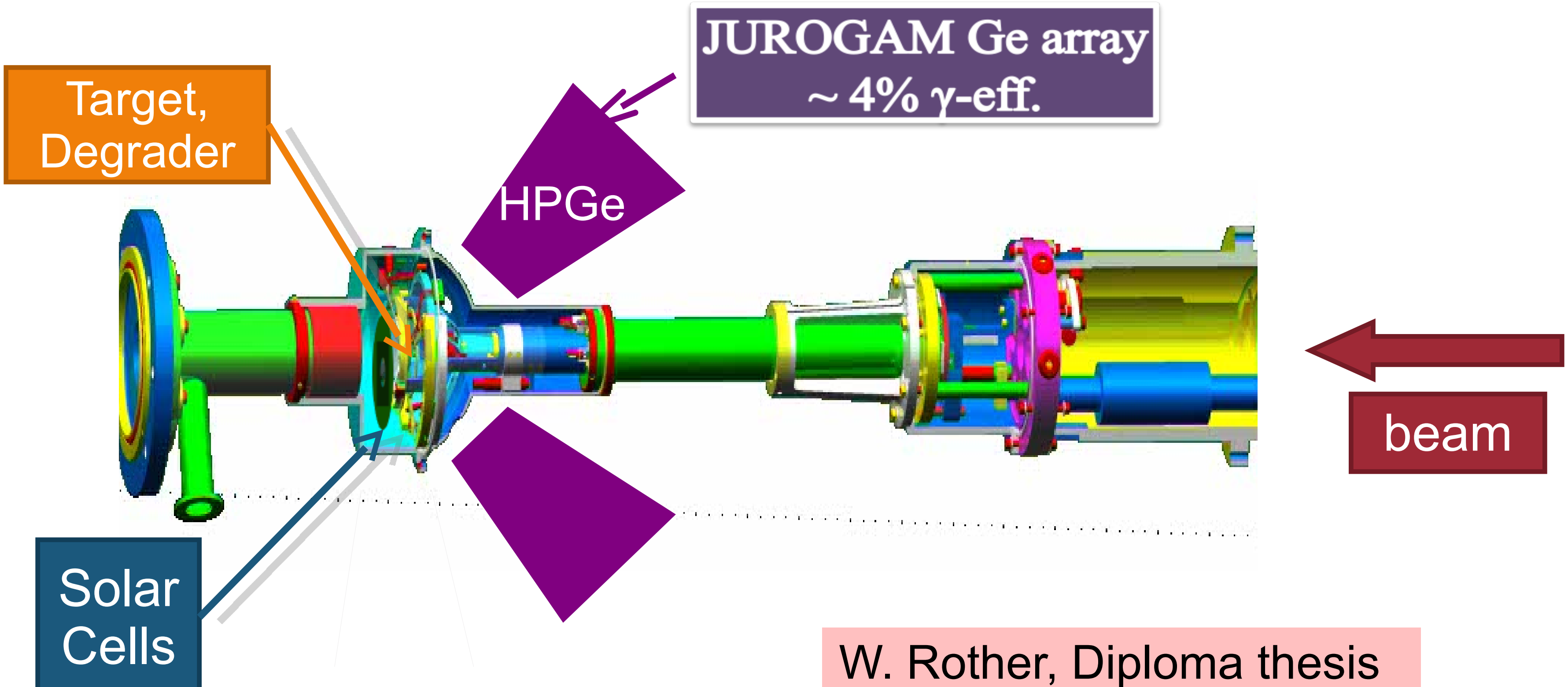
Athens, Greece
S. Harrisoupulos, T. Konstaninopulos

Example: experiment on ^{128}Xe at Jyväskylä

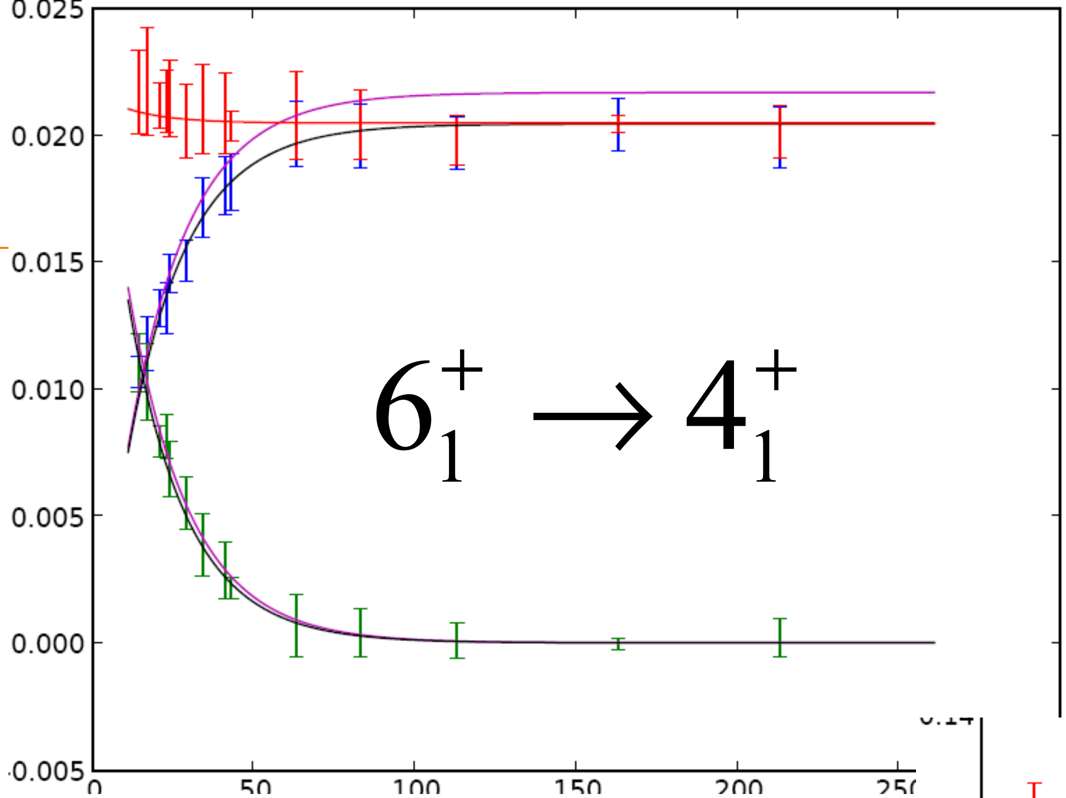
- ^{128}Xe candidate for E(5)
  critical point in transition from vibrator to gamma-soft

- Experiment performed in Coulex in inverse kinematics with differential plunger

- Experimental method, data analysis, setup

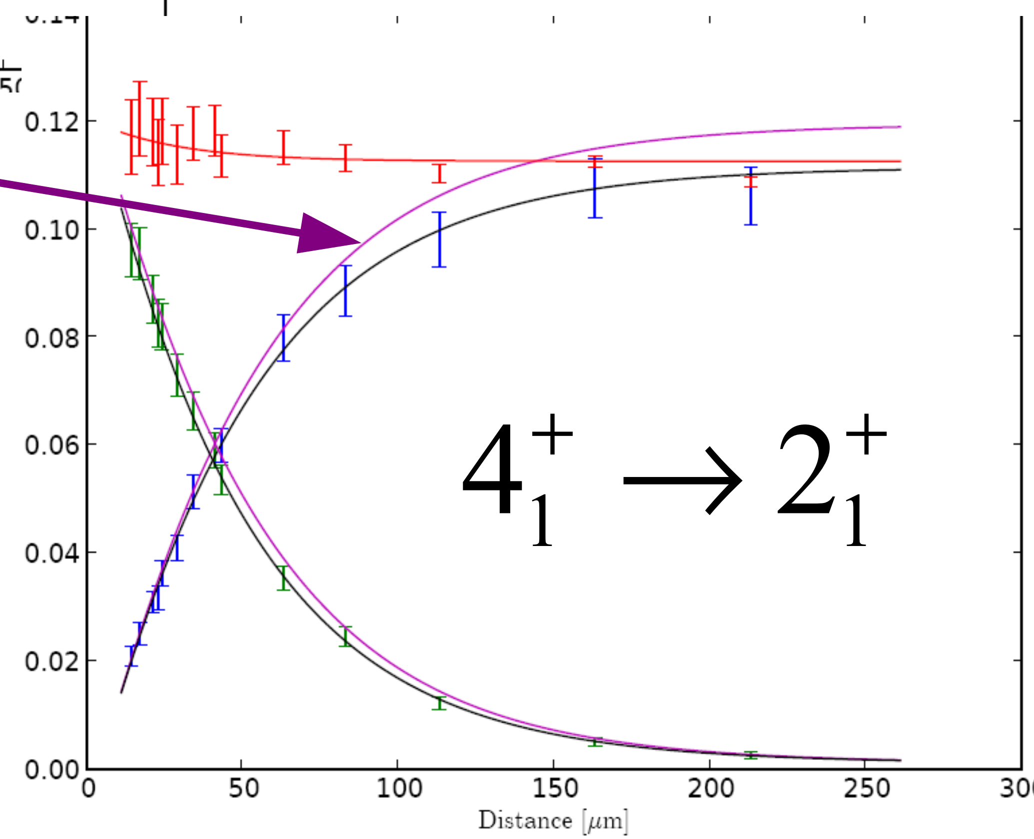


W. Rother, Diploma thesis
University of Cologne 2009



$$\tau_{6_1^+} \approx 1.95(1)\,\mathrm{ps}$$
$$v/c = 3.24(1)$$
$$\tau_{4_1^+} \approx 4.7(2)\,\mathrm{ps}$$

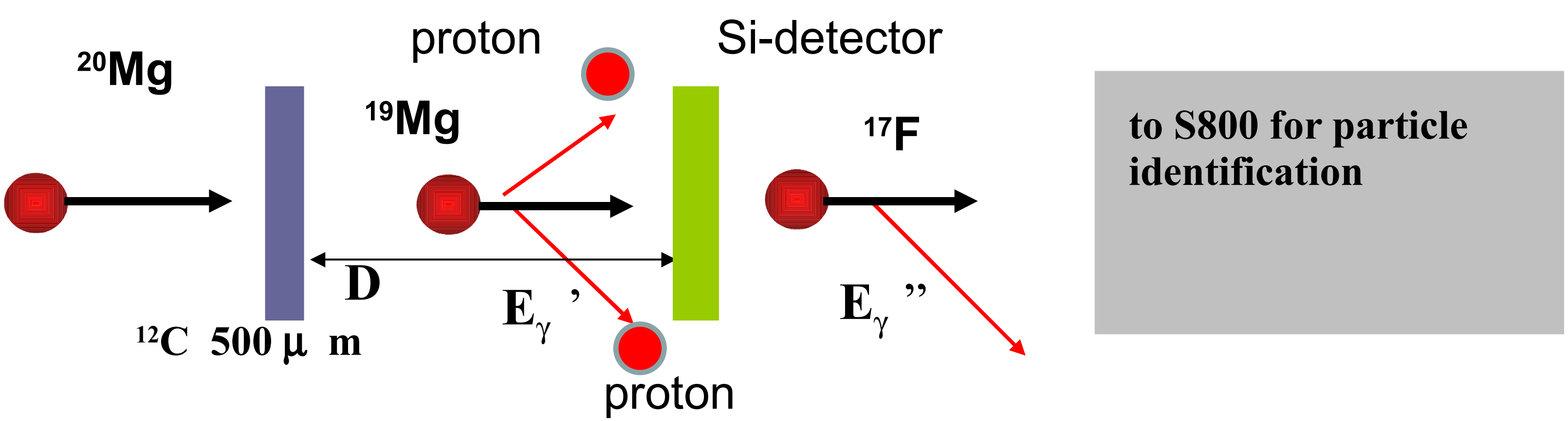
Bateman equations: correct for deorientation

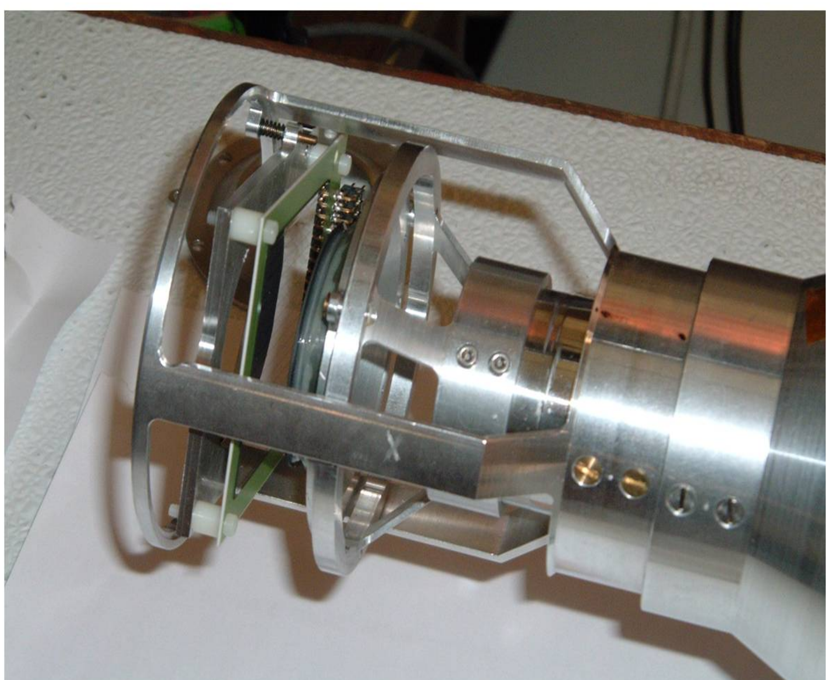


$$\omega(d) = 1 + p\, e^{-d/D_D}$$
$$\widetilde{R^f_{ik}}(d) = \int_0^d dd'\, \omega(d')\, \dot{R}^f_{ik}(d')$$
$$\widetilde{R^s_{ik}}(d) = \omega(d) \int_d^\infty dd'\, \dot{R_{ik}}^s(d')$$

A New Application of the Recoil Distance Method Probing Exotic, Particle-Decay Isotopes

P. Voss[1,2], P. Adrich[1], T. Baumann[1], D. Bazin[1], A. Dewald[3], D. Enderich[1,2], H. Iwasaki[3], D. Miller[1,2], R. P. Norris[1,2], S. Progovac[1,2], A. Ratkiewicz[1,2], A. Spyrou[1], K. Starosta[1,2], M. Thoennessen[1,2], C. Vaman[1]
NSCL/MSU ; IKP Köln





Plunger with a 500μm carbon target and a double sided, 16x16 strip, 300μm silicon detector on a ceramic mount from Micron Semiconductor.

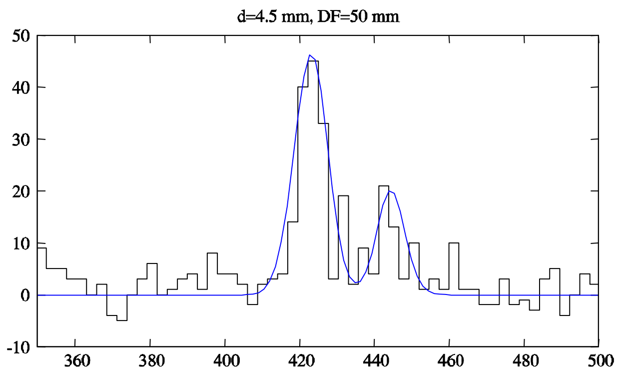
Table 1: Experimental details

	^{122}Cd	^{124}Cd	^{126}Cd
Primary beam	^{136}Xe	^{136}Xe	^{136}Xe
Energy [MeV/u]	700	675	675
Intensity [pps]	$1 \cdot 10^9$	$1 \cdot 10^9$	$1 \cdot 10^9$
^{9}Be target [mg/cm^2]	1622	1622	1622
S1 wedge Al [mg/cm^2]	2000	–	–
S2 wedge Al [mg/cm^2]	5000	6400	5500
Secondary beam	^{122}Cd	^{124}Cd	^{126}Cd
Purity [%]	93	93	90
S2 intensity	$9.80 \cdot 10^4$	$4.50 \cdot 10^4$	$1.30 \cdot 10^3$
Transmission through FRS for nucleus of interest	15.86%	22.09%	23.98%
Beamspot size at plunger-target X-plane [mm]	±20	±20	±15
Incoming beam energy on plunger-target [MeV/u]	220	220	280
Incoming velocity on plunger-target [c]	0.59	0.59	0.64
Total/^{12X}Cd incoming beam intensity on plunger target [pps]	770/727	230/209	34/31
Number of particles registered by LYCCA [pps]	700/651	200/186	30/27
Thickness Au plunger target [g/cm^2]	2.0	2.0	3.5
Outgoing beam energy plunger target [MeV/u]	120	120	130
Outgoing velocity plunger target [c]	0.464	0.464	0.480
Thickness plunger-degrader (Nb) [μm]	300	300	300
Outgoing beam energy plunger-degrader [MeV/u]	100	100	110
Outgoing beam velocity plunger-degrader [c]	0.430	0.430	0.447
Change in beam velocity target-degrader [c]	0.034	0.034	0.033
State of interest	2_1^+	2_1^+	2_1^+
Transition of interest	$2_1^+ \rightarrow 0_1^+$	$2_1^+ \rightarrow 0_1^+$	$2_1^+ \rightarrow 0_1^+$
γ-ray energy of interest [keV]	562	612	652
Assumed lifetime τ [ps]	14.4	16.4	16.4
Flight-path corresponding to τ [mm]	2.1	2.4	2.4
Doppler-shiftet γ-ray energy of interest after plunger-target at 30° [keV]	843.4	907.5	979.0
Doppler-shiftet γ-ray energy of interest after plunger-target at 15° [keV]	914.2	983.7	1066.5
Doppler-shiftet γ-ray energy of interest after plunger-degrader at 30° [keV]	819.2	881.5	951.6
Doppler-shiftet γ-ray energy of interest after plunger-degrader at 15° [keV]	879.4	946.4	1026.4
Change in Doppler-shifted energy at 30° [keV]	24.2	26.0	26.6
Change in Doppler-shifted energy at 15° [keV]	34.8	37.4	40.1
PRESPEC γ-ray energy resolution [%]	4	4	4

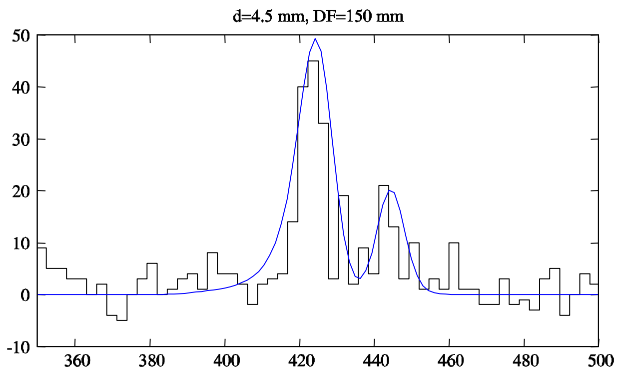
Table 2: Continuation of Tab. 1

	^{122}Cd	^{124}Cd	^{126}Cd
Averaged cross section for Coulex in target [mb]	300	300	400
Number of Coulomb excitations on target [1/s]	1.19	0.24	0.14
Cross section for Coulex on degrader [mb]	140	140	140
Number of excitations on degrader [1/s]	0.15	0.05	0.008
Photopeak efficiency for three rings of PRESPEC at forward angles [%]	4	4	4
Number of detected good PRESPEC-LYCCA coincidences [1/s]	0.0477	0.0096	0.0056
Number of detected good PRESPEC-LYCCA coincidences per hour	172	35	20
Number of shifts per single target-degrader data point	1	3	6
Estimated number of shifts to complete the measurement	3	9	18

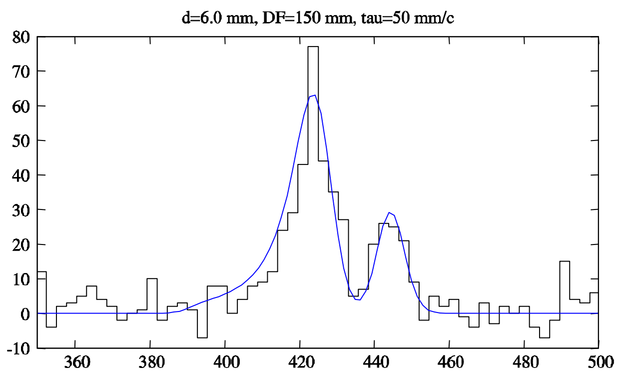
114Pd : (2+ →0+) transition measured at different target – degrader separations



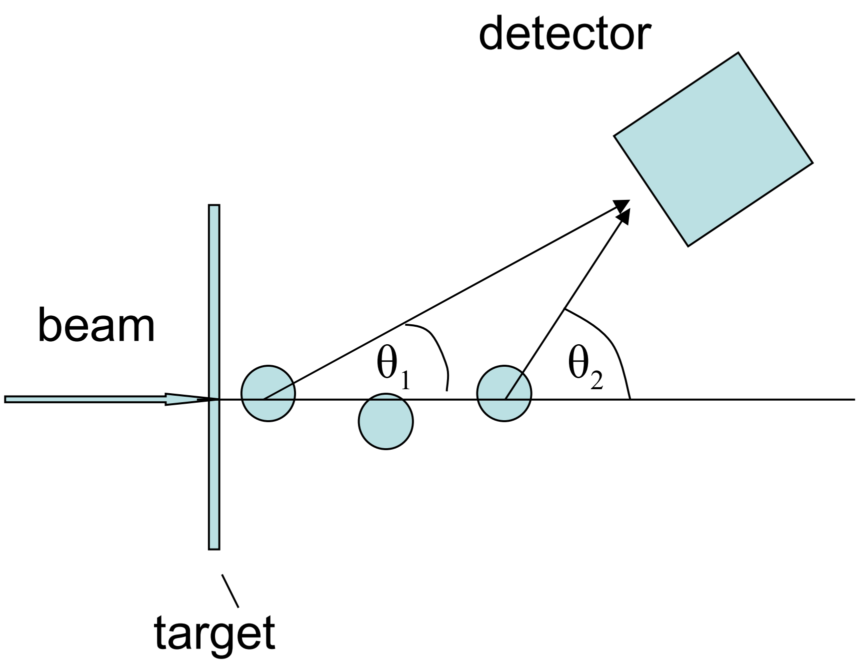
Emission only up to 5cm downstream of the degrader considered



Emission up to 15cm downstream of the degrader considered



Assumption of a longer lifetime



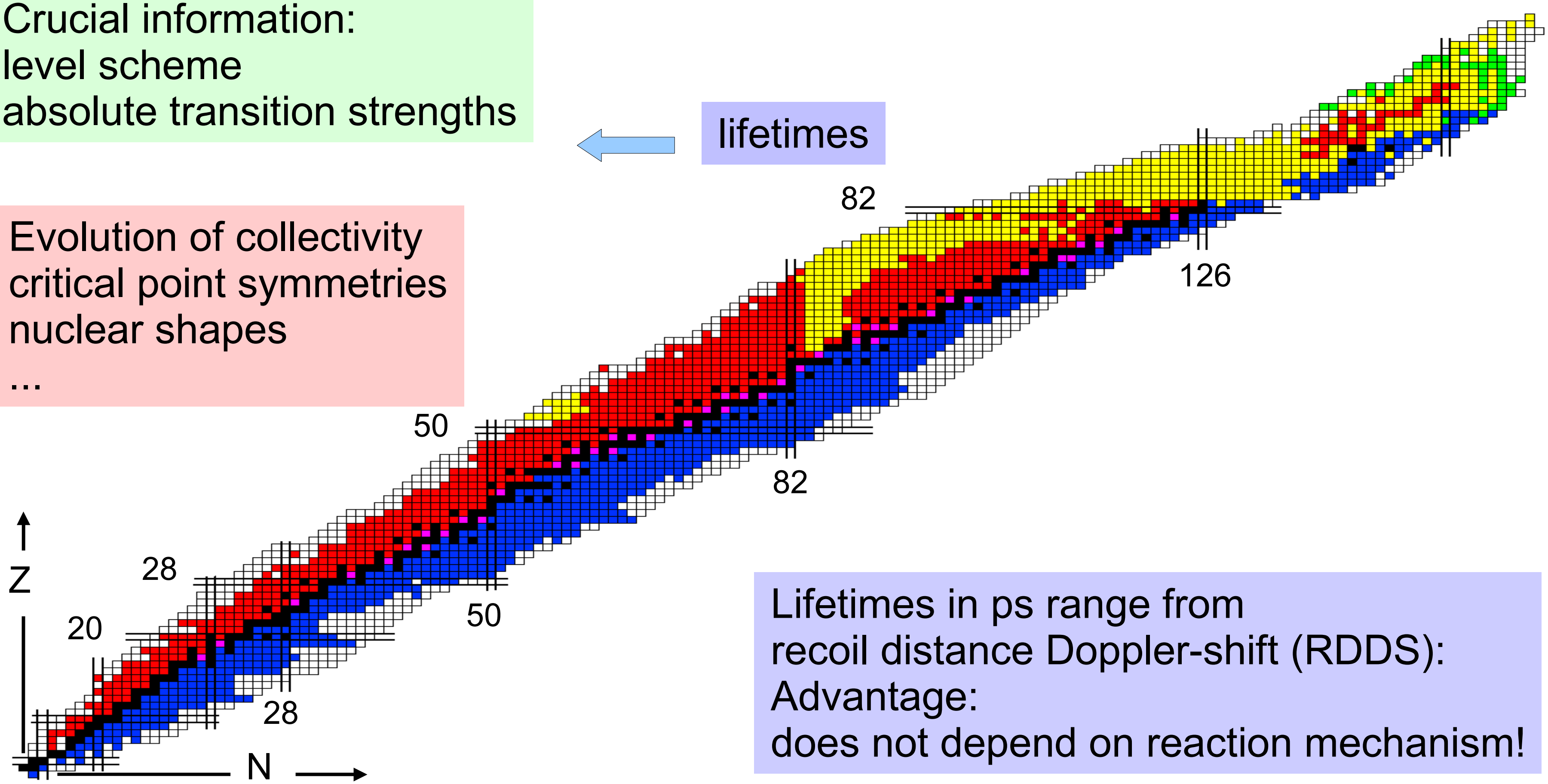
Motivation

Present nuclear physics:
focus on nuclei far from stability

Crucial information:
level scheme
absolute transition strengths

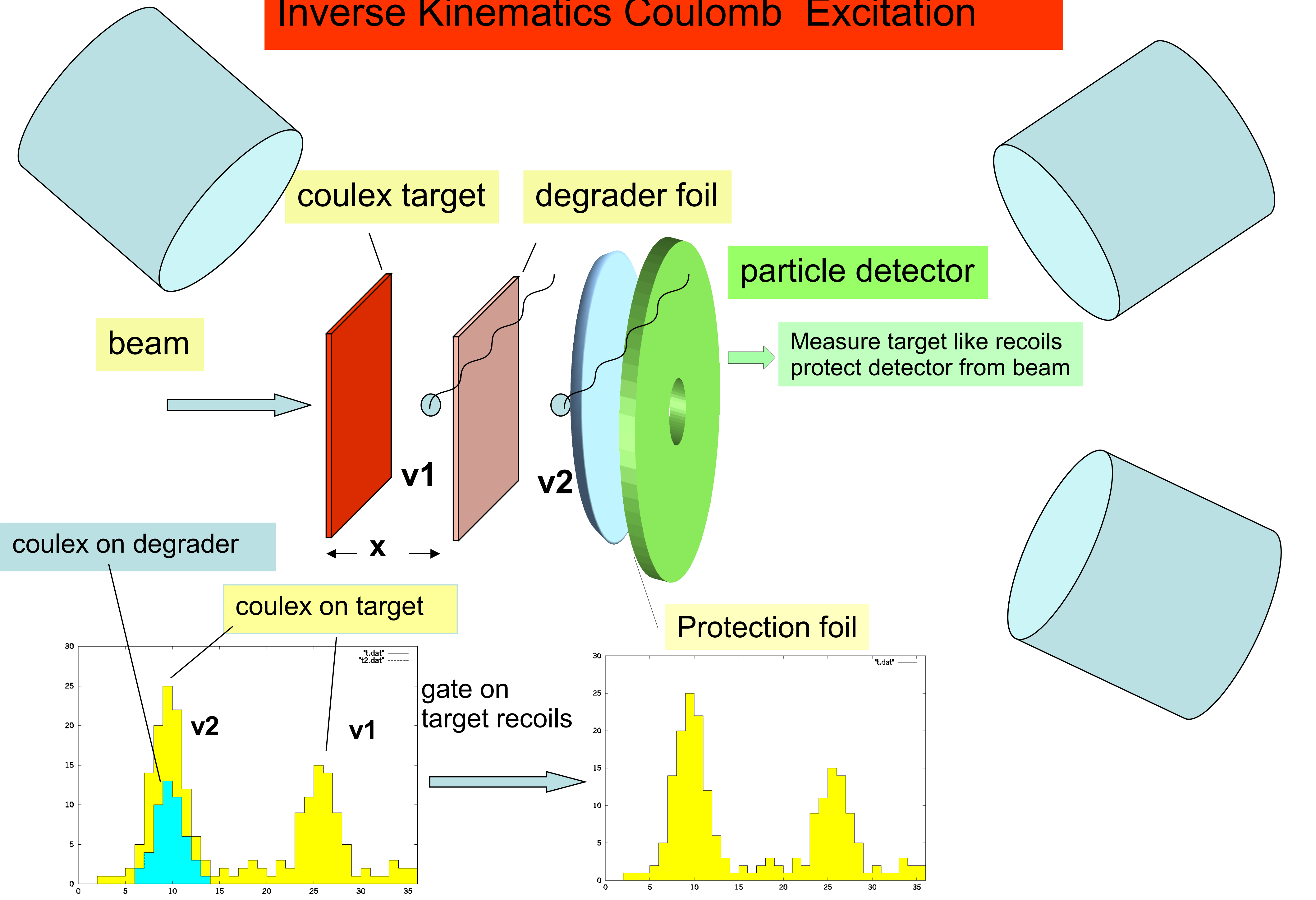
lifetimes

Evolution of collectivity
critical point symmetries
nuclear shapes
...

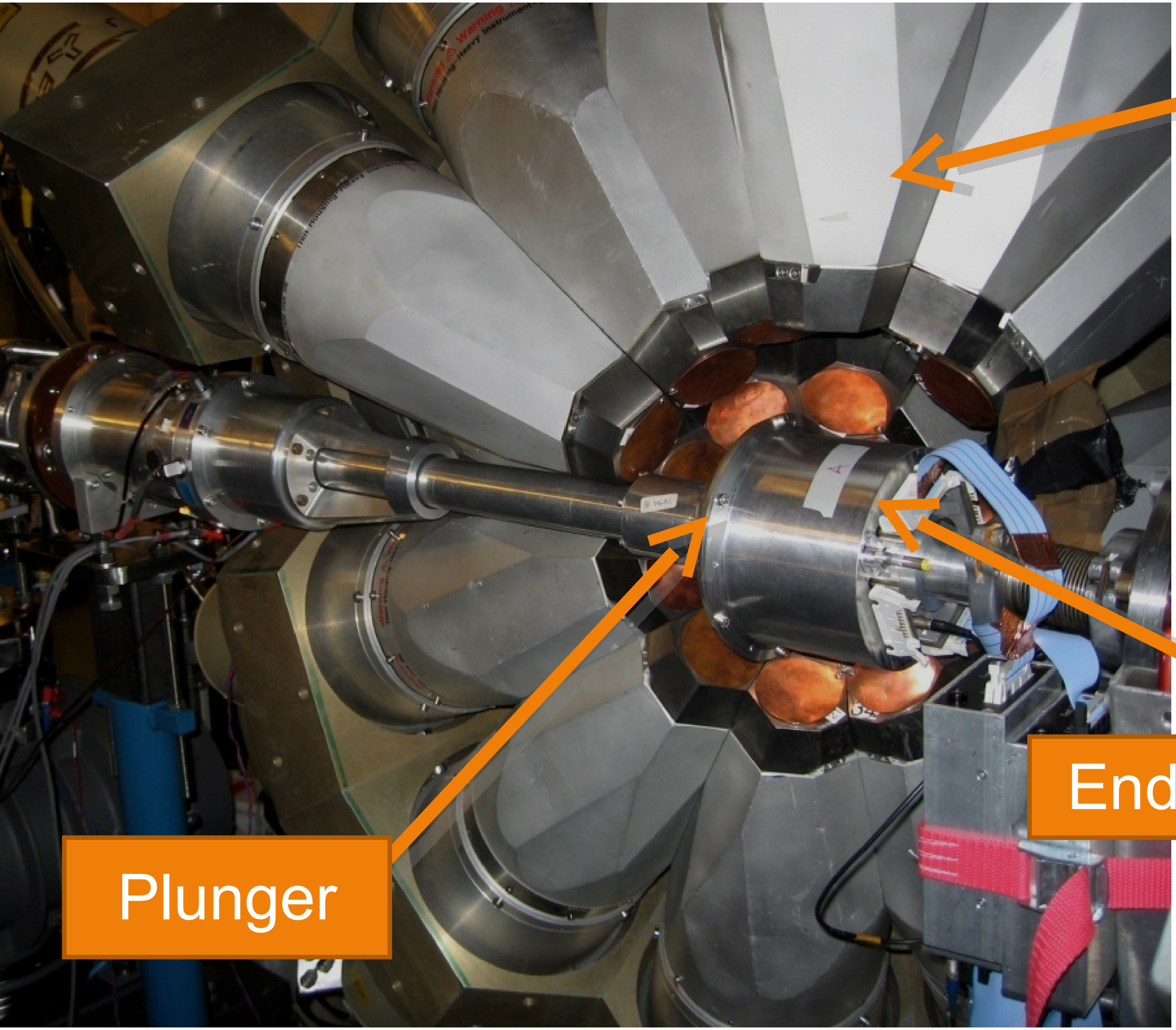


Lifetimes in ps range from
recoil distance Doppler-shift (RDDS):
Advantage:
does not depend on reaction mechanism!

Inverse Kinematics Coulomb Excitation



Plunger@Jyväskylä



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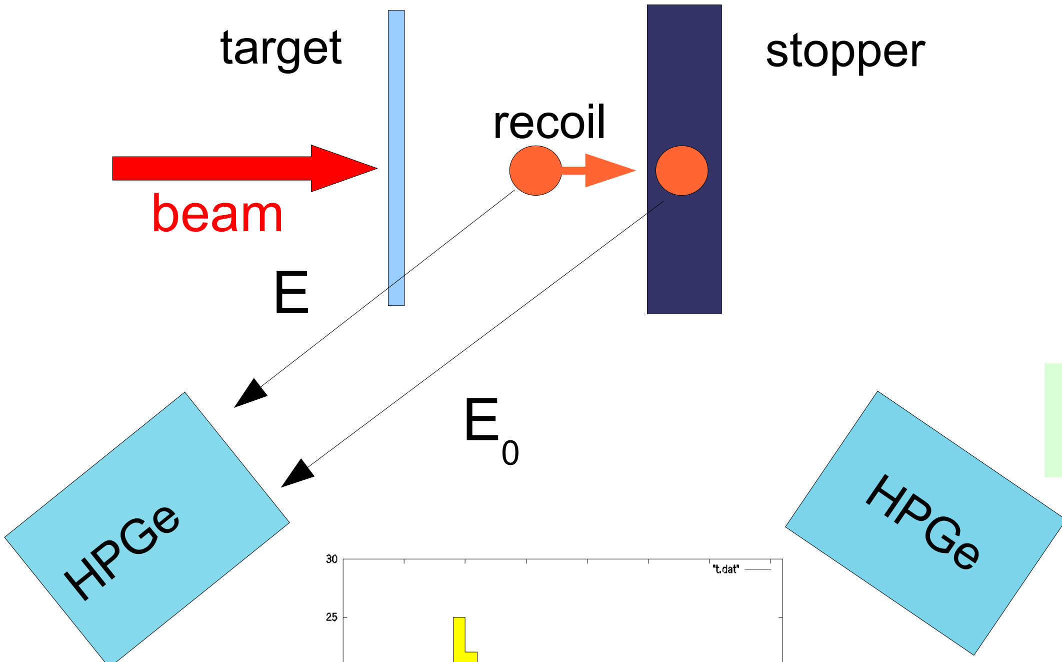
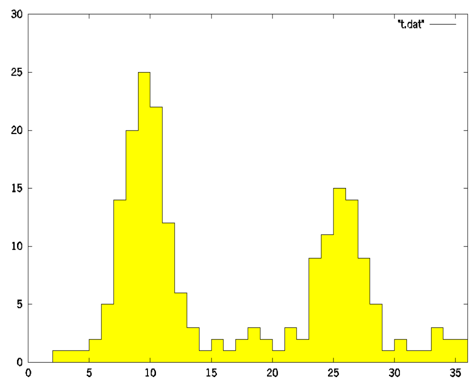




$$E_{obs} = E_0 \cdot (\frac{v}{c} cos(\theta))$$

$$\tau(t_k) = \frac{I^{us}(t_k)}{\frac{d}{dt} I^{sh}(t_k)}$$

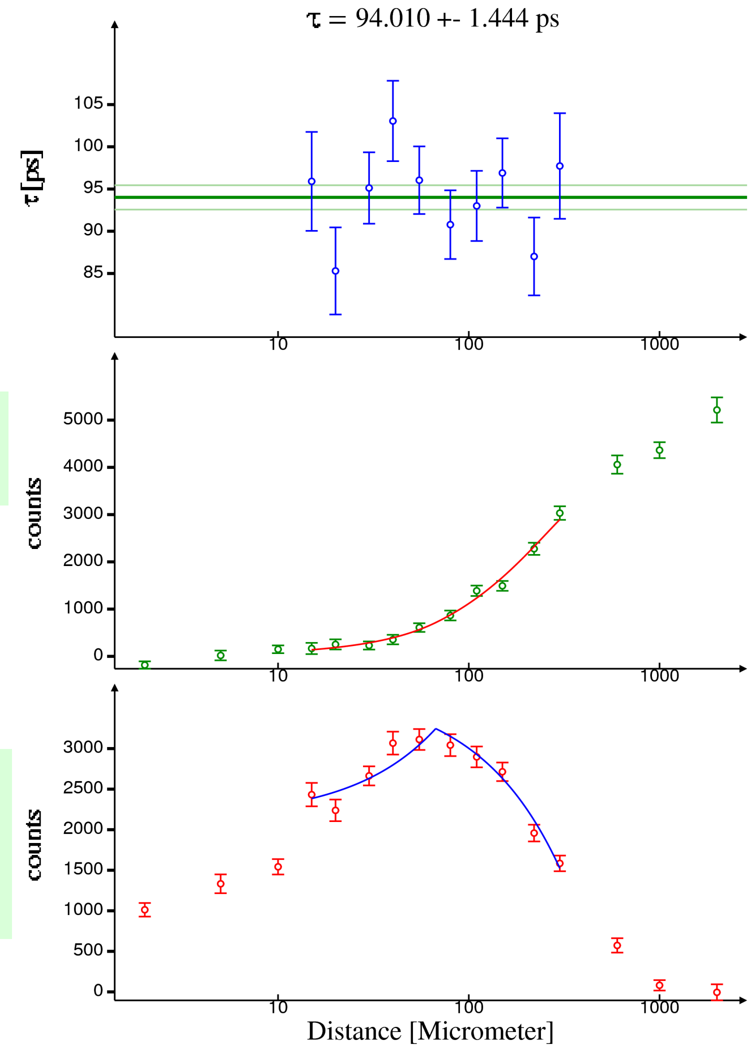
I^{us} = Intensity of the unshiftet γ-ray line

I^{sh} = Intensity of the Doppler-shifted component

t-curve

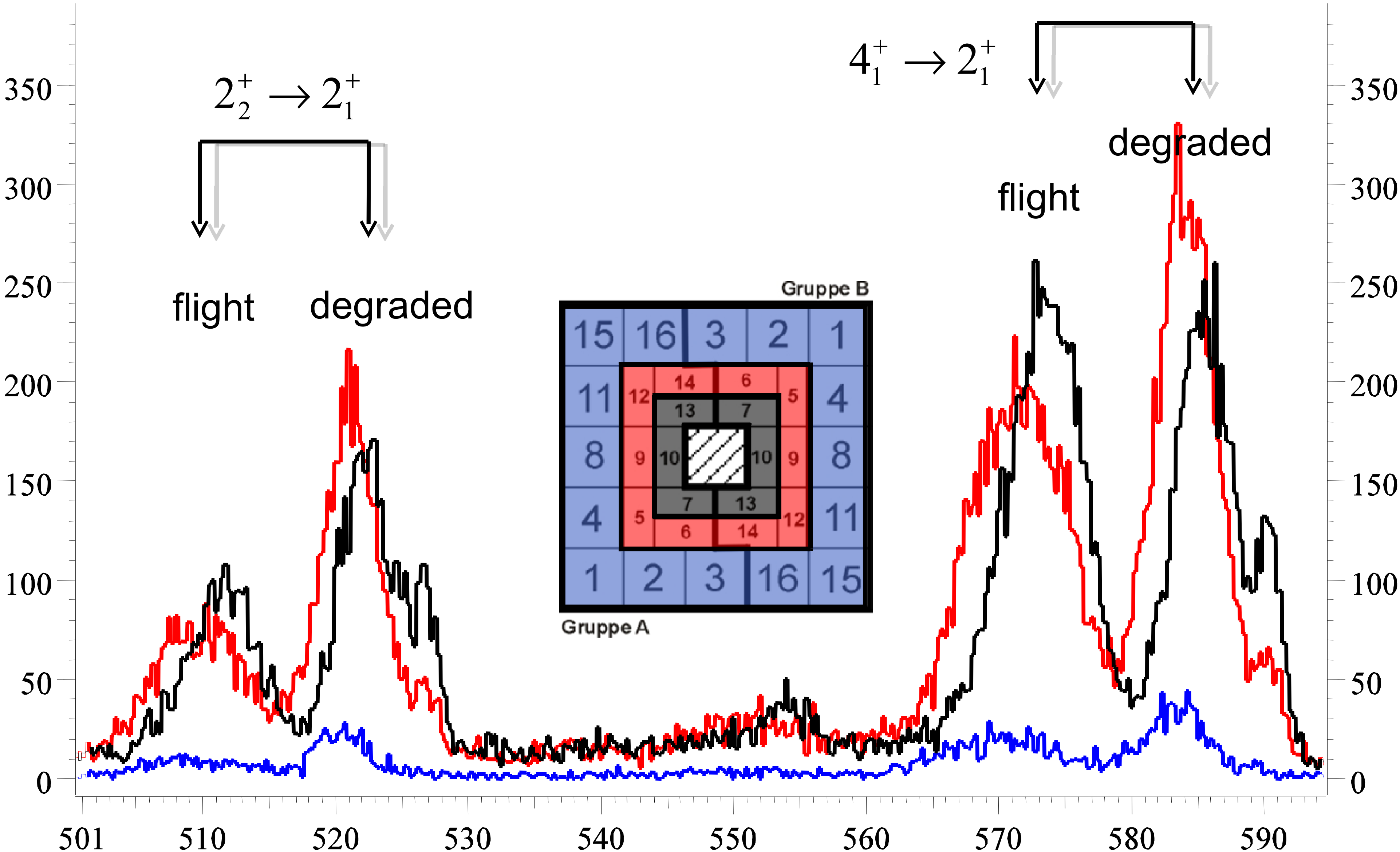
Flight peak intensity

I^{us};
d/dt $I^{sh}(t)$
derivative of
flight peak intensity



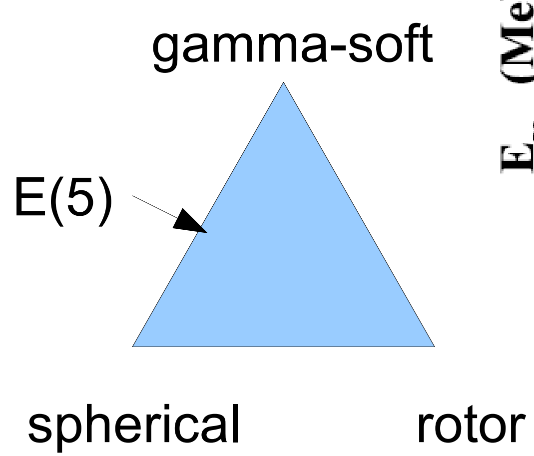
$^{92}Mo(^{10}B,3np)^{98}Pd$

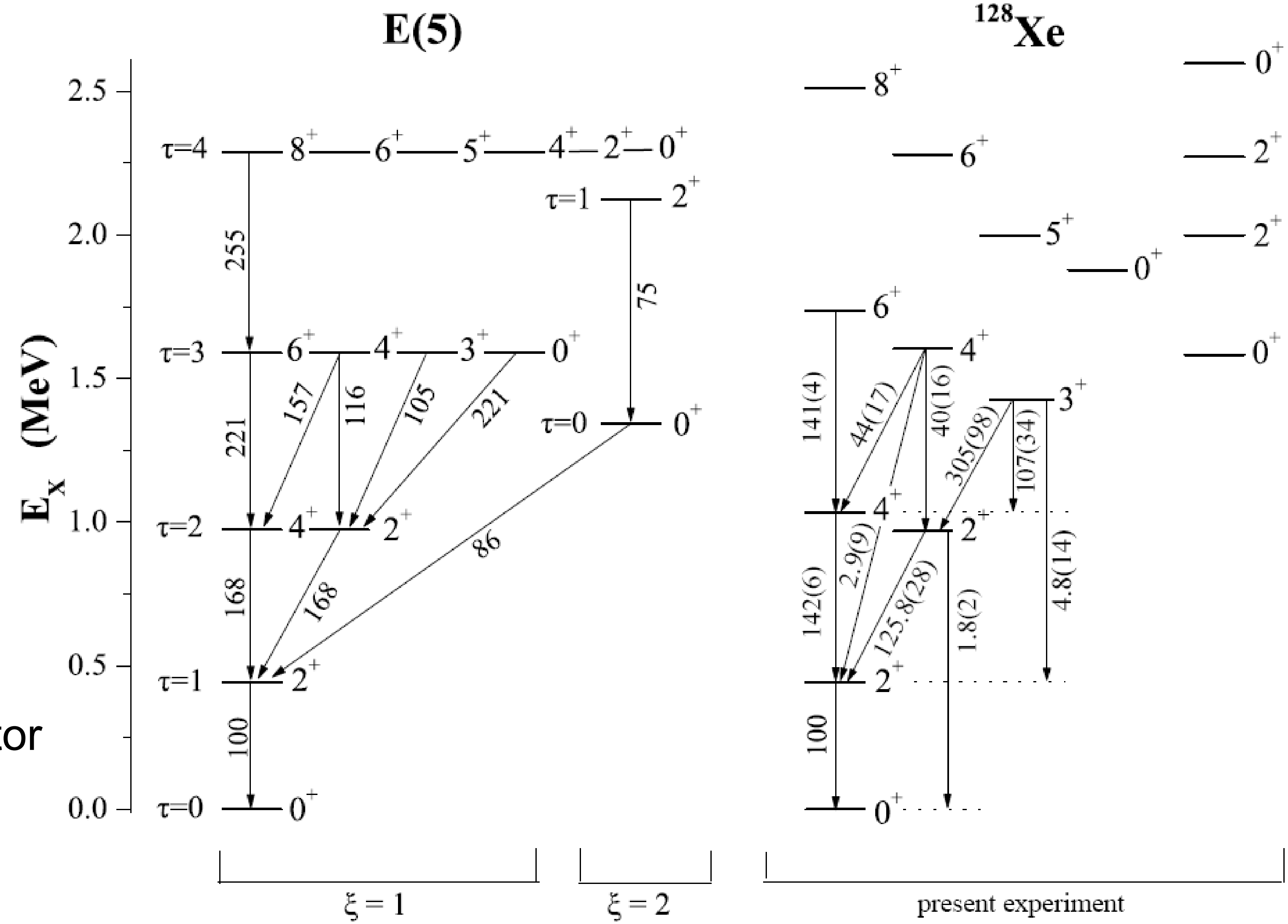
Gamma-ray singles gated on target recoils @ 30µm



^{128}Xe E(5) ?

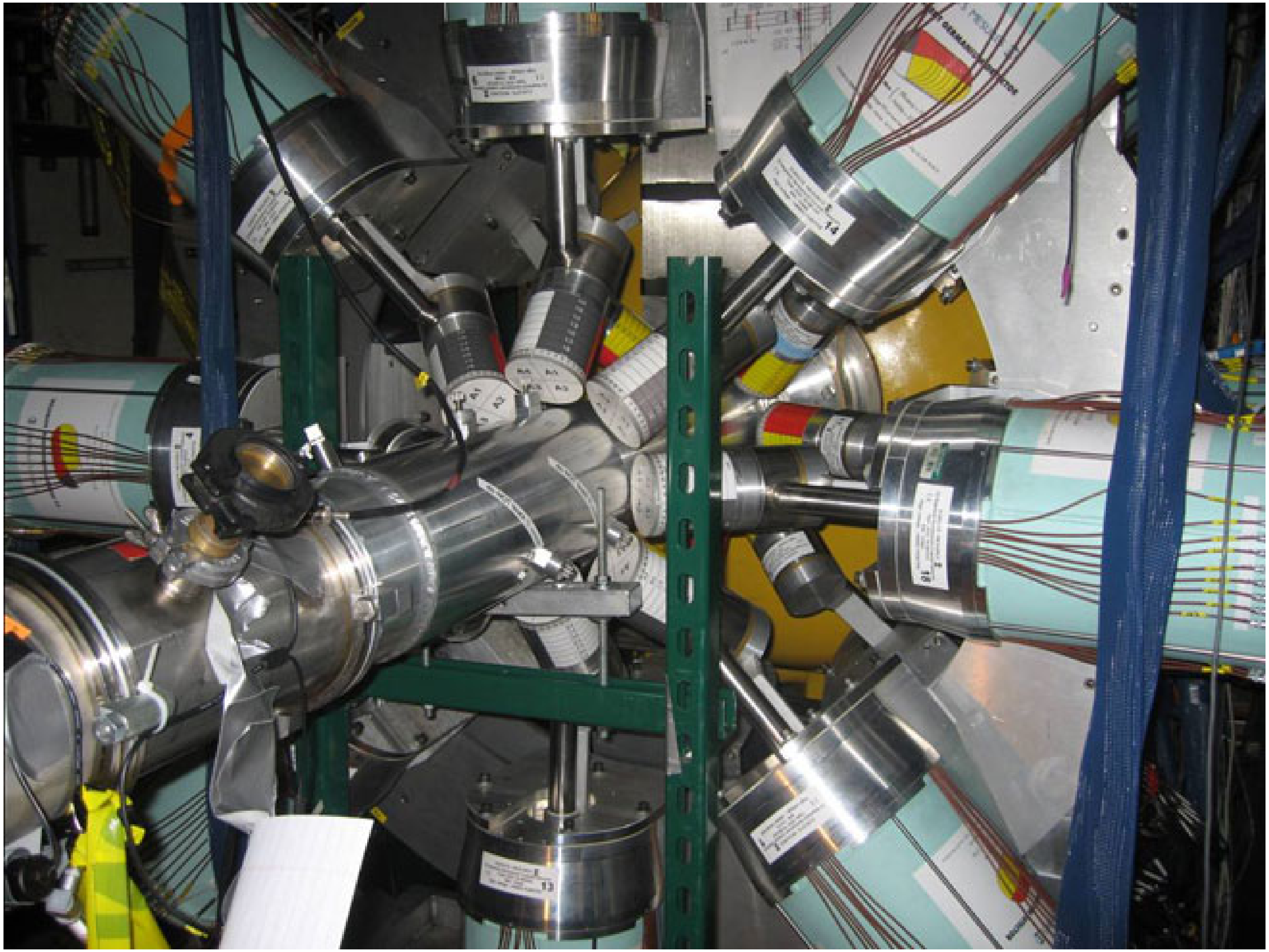
E(5): exact solution of Bohr hamiltonian at critical point of shape phase transition from spherical vibrator to gamma-soft nuclei





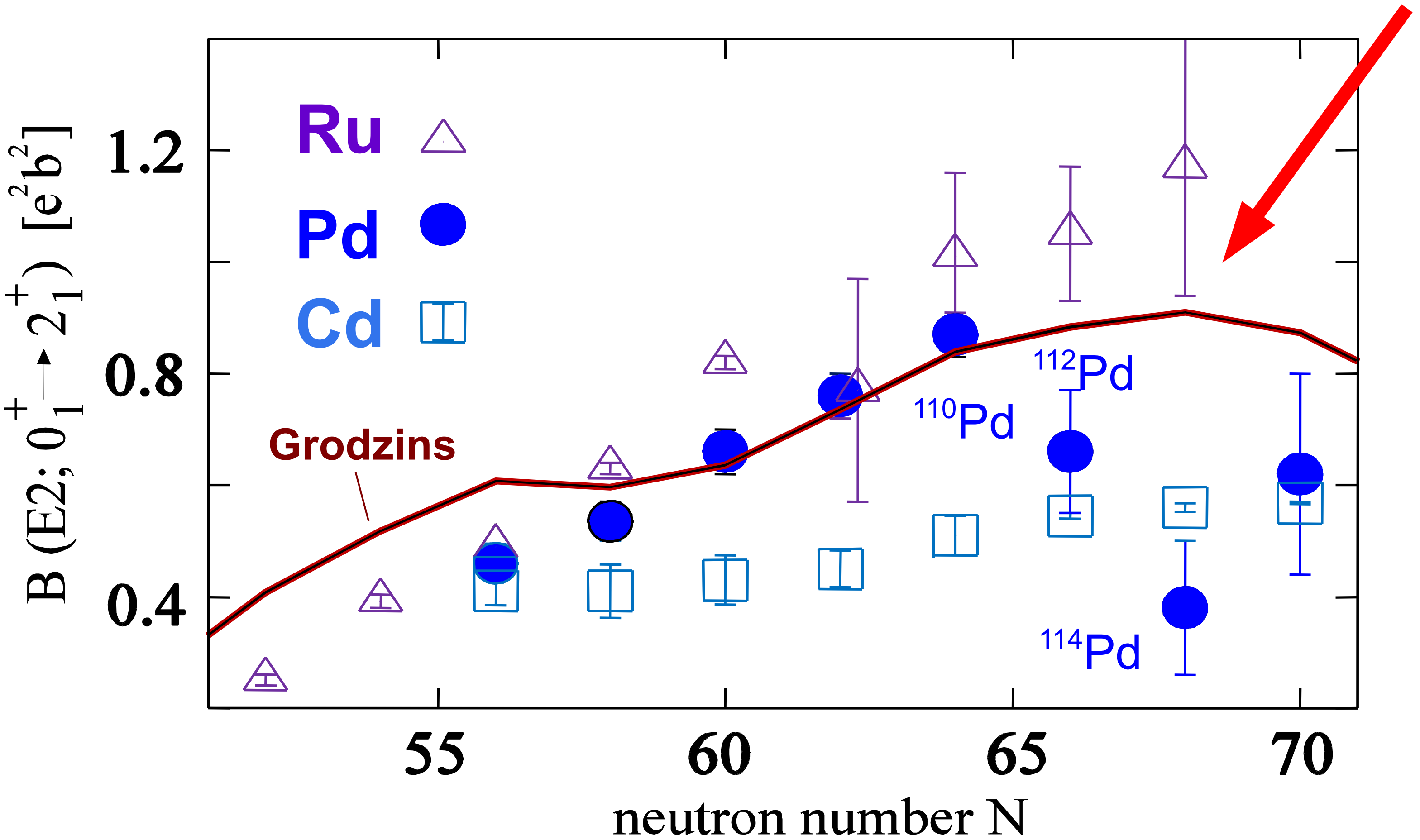
F. Iachello:
Phys. Rev. Lett. 85, 3580 (2000)

Plunger + SEGA @ S800



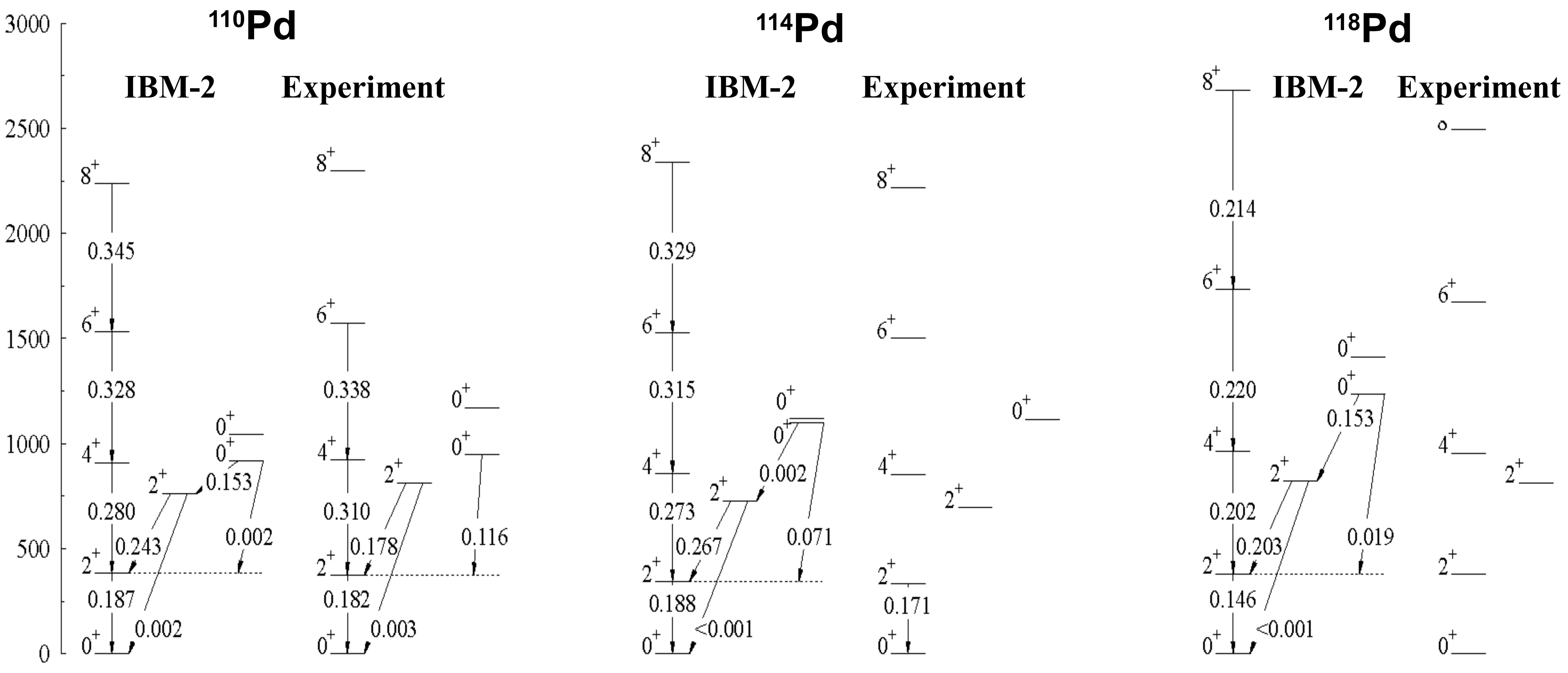
B(E2)-Systematics for Pd Isotopes and Neighbours: old

Old data: strong deviation of neutron rich Pd isotopes from Grodzins rule



Grodzins rule: $$E(2^+) \cdot B(E2, 2^+ \rightarrow 0_1^+) = \frac{Z^2}{A}(24.6 \pm 8.2)\mathrm{MeV e^2 fm^4}$$

IBM-2 calculations ⬄ Experiment



$\beta \approx 0.24$ $\beta \approx 0.24$ $\beta \approx 0.21$

$e_\pi = 12\ fm^2$

$e_\nu = 10\ fm^2$

H. Kim et al., Nucl. Phys. A604, 163 (1996)