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Exploring exotic nuclei using the plunger technique

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EGAN Workshop 2012, Orsay

Outline

1. Introduction: recent experiments with the plunger
2. Experiments with the compact plunger at Legnaro (AGATA, PRISMA) and at GANIL (EXOGAM, VAMOS)
3. Plunger device for medium energy radioactive beams: the Köln-NSCL plunger
4. A new plunger for relativistic radioactive beams: the GSI plunger for PRESPEC/HISPEC

Motivation: structure studies of exotic nuclei

Many-body problems for strongly-interacting system with protons and neutrons

Stable nuclei

Shell structure

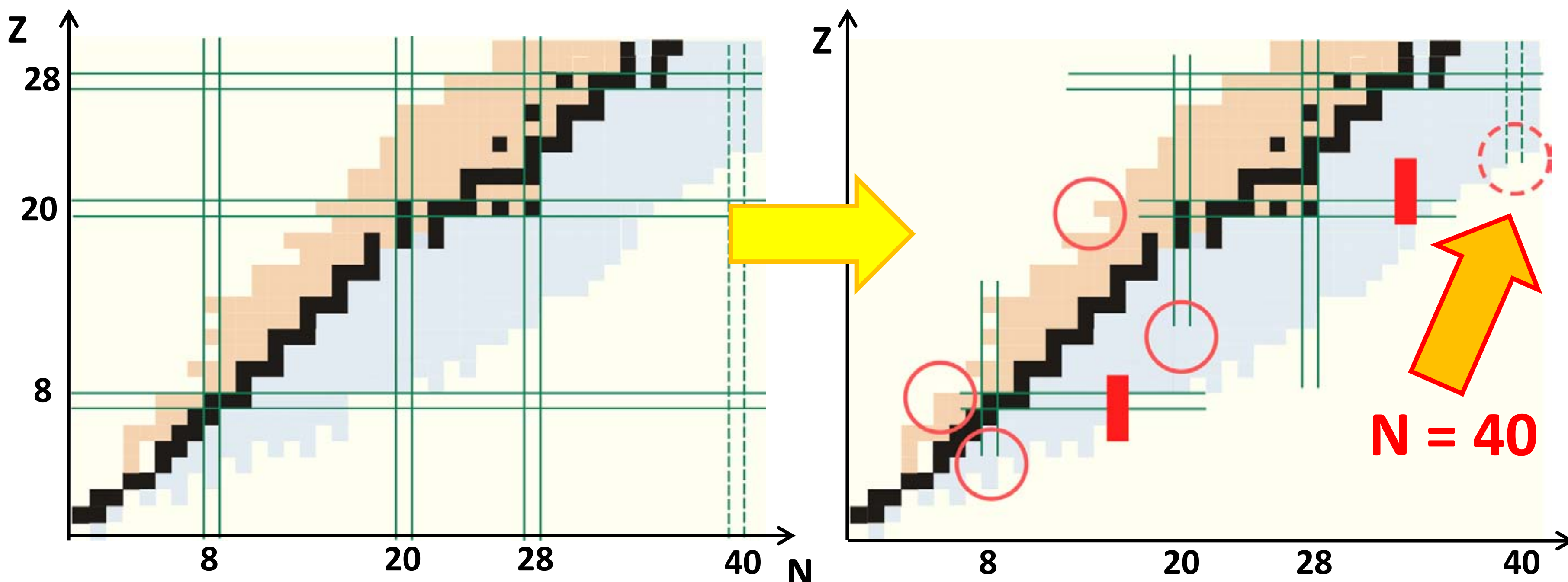
magic number (2,8,20…)

Exotic nuclei

Drastic change of shell structure

disappearance (N=8,20,..) and

appearance(16,34) of magic numbers

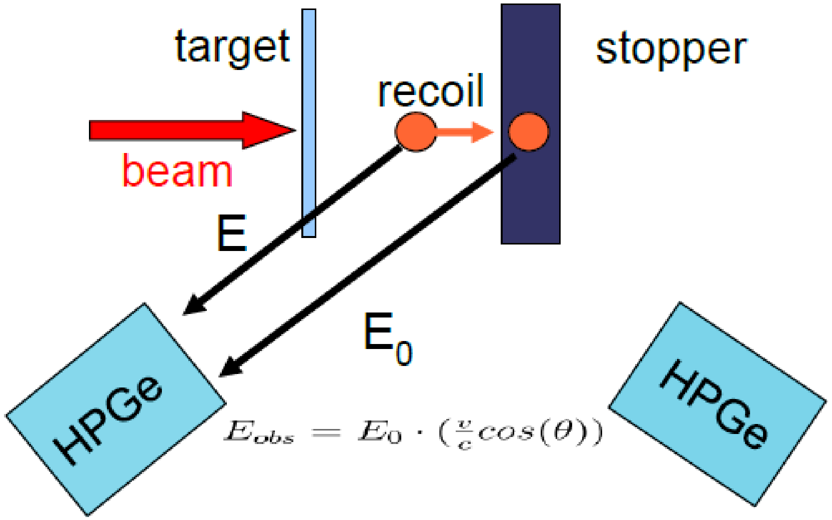


What is the driving force responsible for the shell evolution?

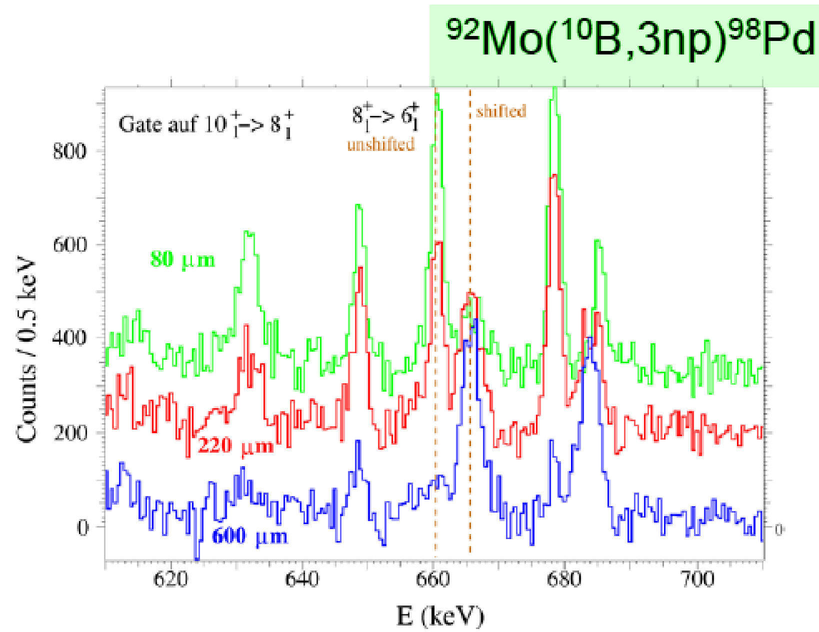
Can we characterize the structure changes in a simple manner?

→ Measure absolute transition strengths

The plunger technique



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



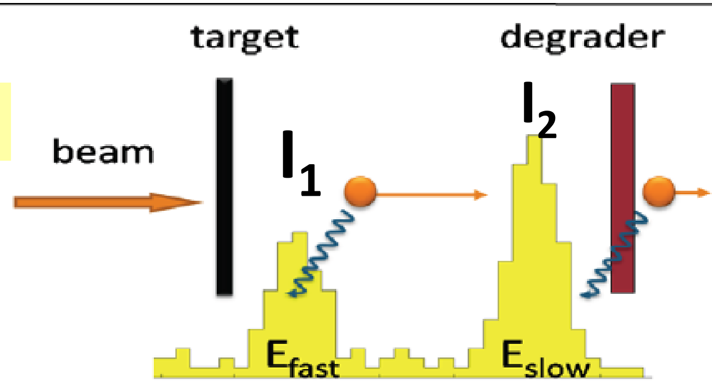
$$\tau(t_k) = \frac{I^{us}(t_k)}{\frac{d}{dt} I^{sh}(t_k)}$$

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

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

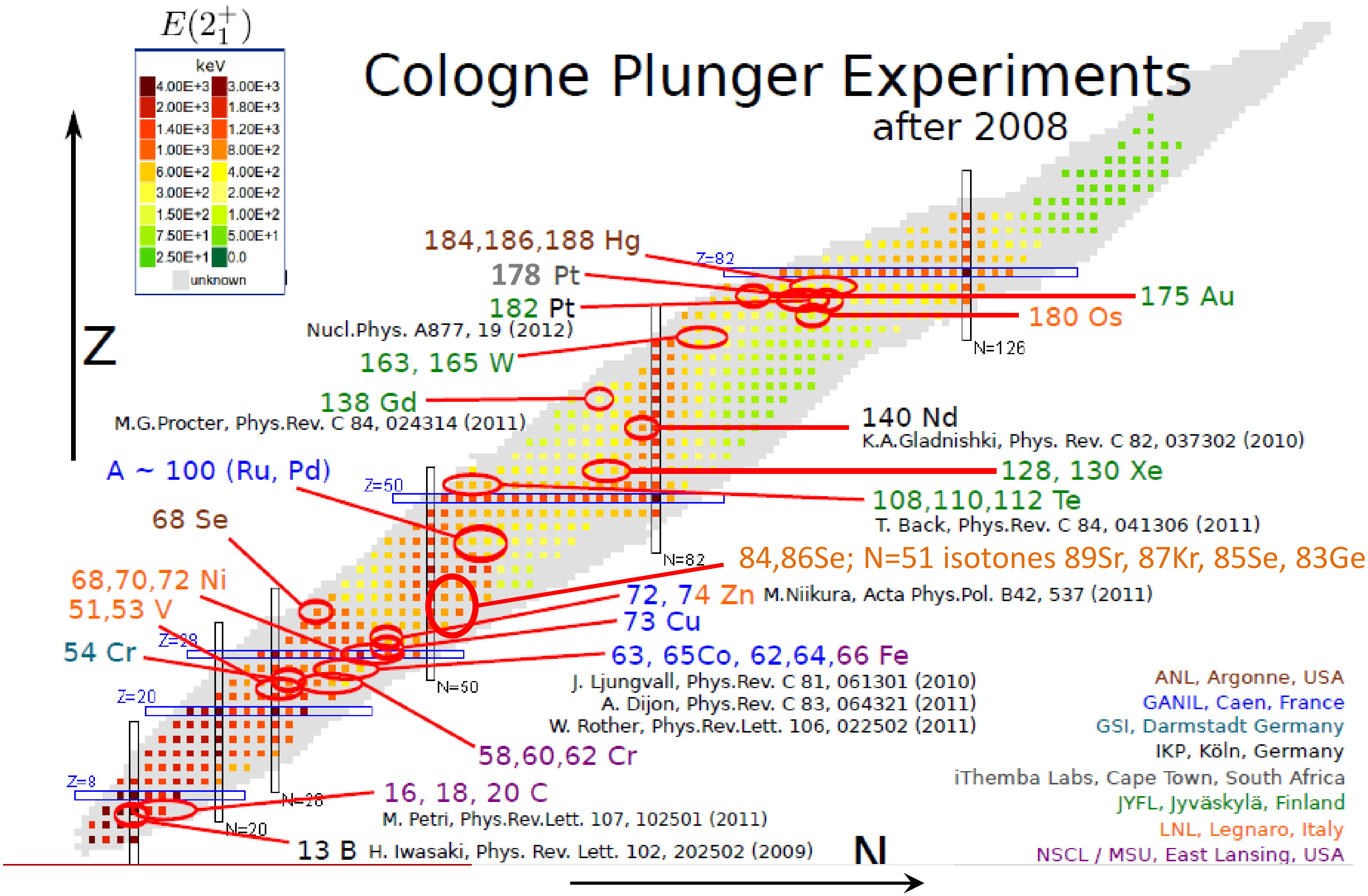
Differential Plunger

Use degrader instead of stopper to allow identification of recoils



Particle ident.:
LYCCA
S800 (MSU)

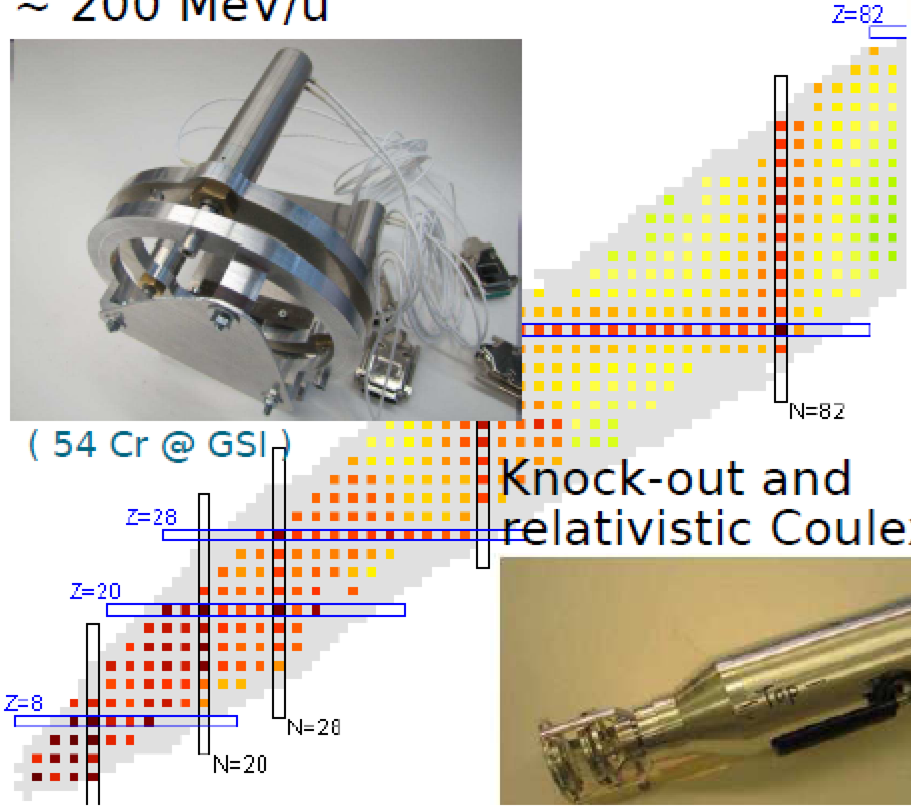
Overview: plunger experiments



Different plunger devices…

relativistic Coulex
~ 200 MeV/u

(54 Cr @ GSI)



Fusion-evaporation
Safe Coulex inverse kinematics

Jyväskylä, Finnland: Der Plunger mit Solarzellen in JUROGAM

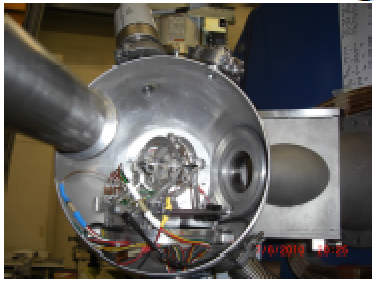
178Pt
@iThemba

184,186,188 Hg @ ANL
128, 130 Xe @ Jyfl

Knock-out and
relativistic Coulex ~ 100 MeV/u

58,60,62 Cr
@ NSCL

Deep-inelastic scattering



63, 65Co, 62,64 Fe @ GANIL

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Plunger experiments with AGATA and PRISMA at LNL: examples

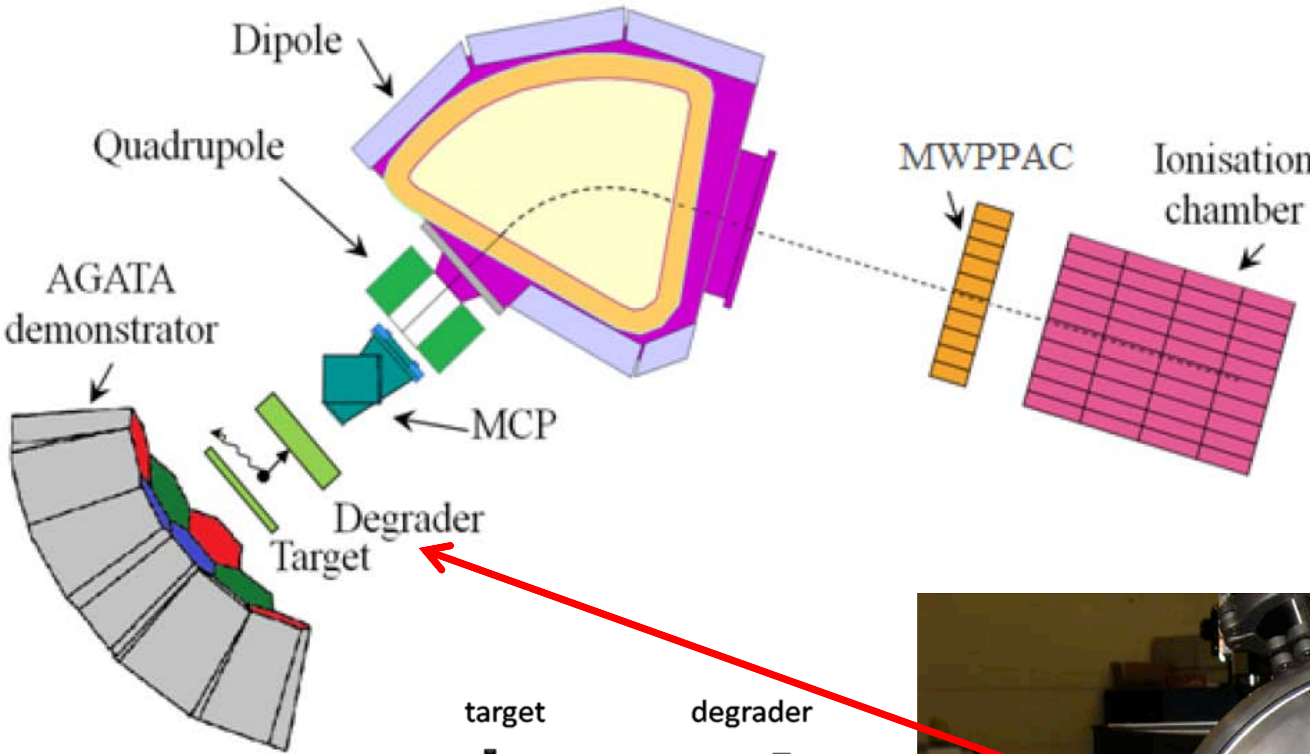
1. ^{84,86}Se: J. Litzinger, C. Fransen (Cologne)

2. Structure of n-rich N=51 nuclei in the vicinity of ^{78}Ni:
   D. Verney (Orsay), G. Duchene (Strasbourg)
   → presentation by G. Duchene, Wednesday, 3 30 pm

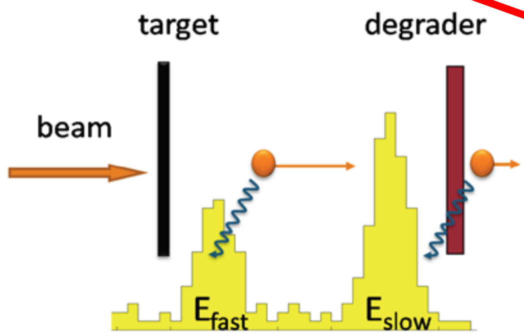
3. Lifetimes in N=20 isotones of Si, P, S: A. Goasduff (Strasbourg)

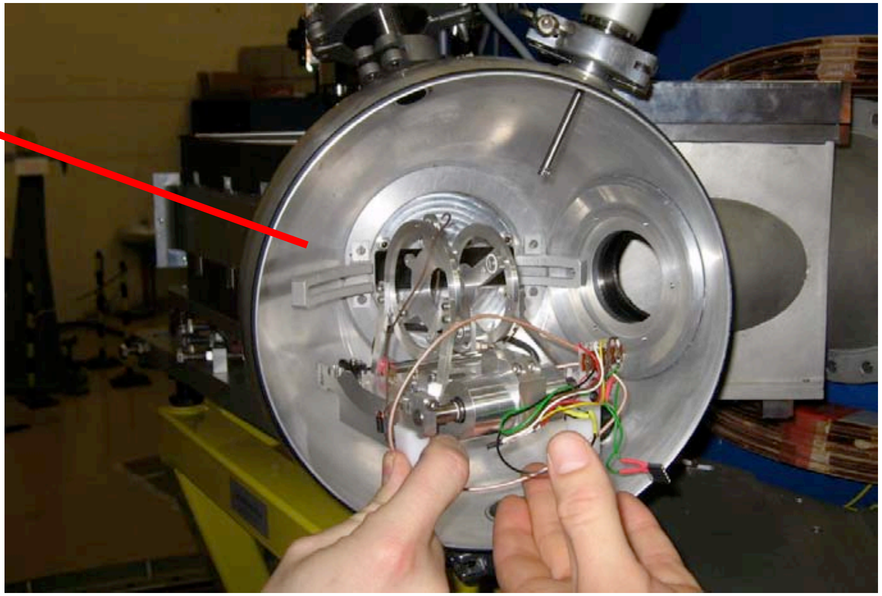
4. Collectivity in Zn region: C. Louchart (Saclay)

The Cologne compact plunger @ PRISMA



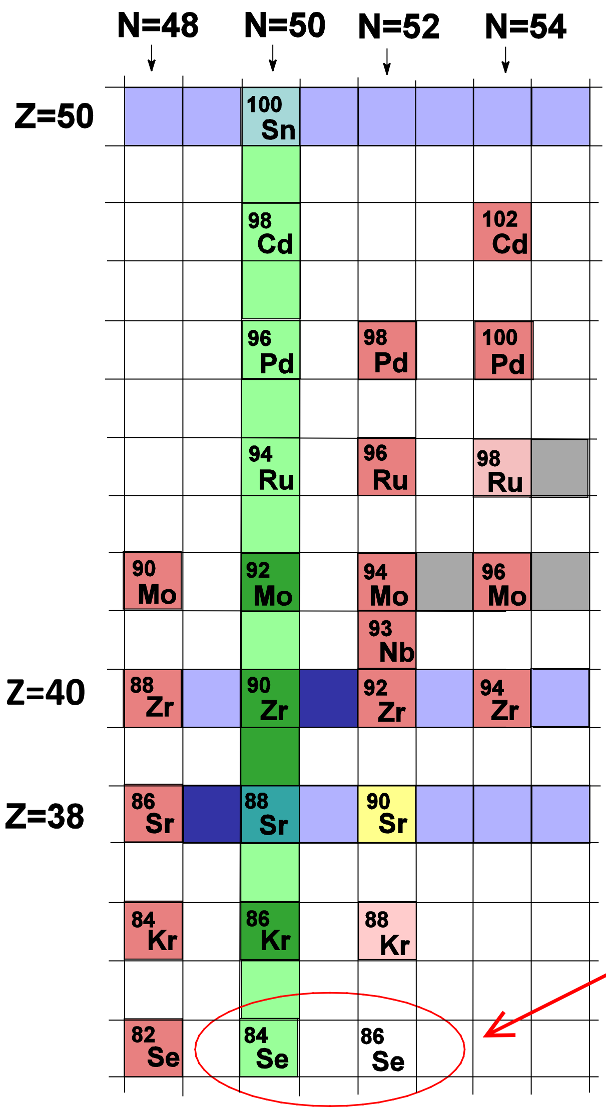
Compact plunger successfully used at LNL and GANIL for grazing angles up to 60 degrees





Proof of principle with fixed Plunger @ PRISMA/CLARA
(J.J. Valiente-Dobon et al., PRL 102, 242502 (2009)
2010/2011: AGATA demonstator @ PRISMA

Plunger experiment on ^{84,86}Se with AGATA/PRISMA: 1.Motivation ^{86}Se

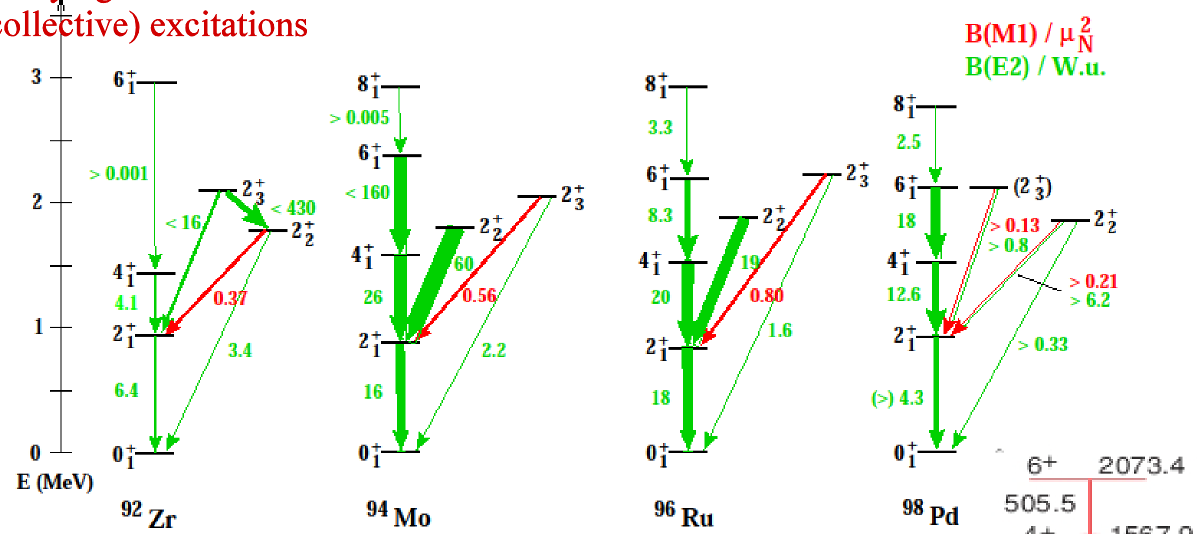


detailed data on low-lying (collective) excitations

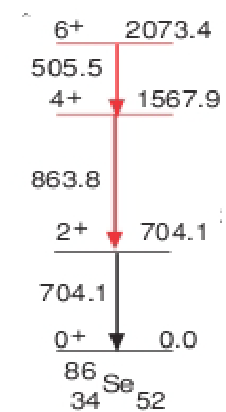
this proposal

Systematics of yrast and non-yrast states of heavier N=52 isotones

Mo-Pd: Filling of proton $g_{9/2}$ shell



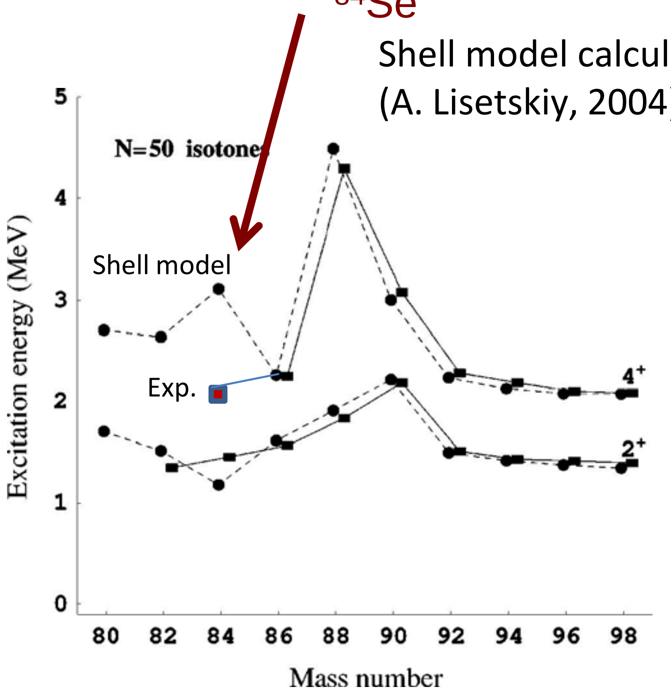
^{86}Se:
no transition strengths,
lowest yrast levels known
E.F. Jones et al., PRC 73, 017301 (2006)



Plunger experiment on ^{84,86}Se with AGATA/PRISMA:
2. Motivation ^{84}Se

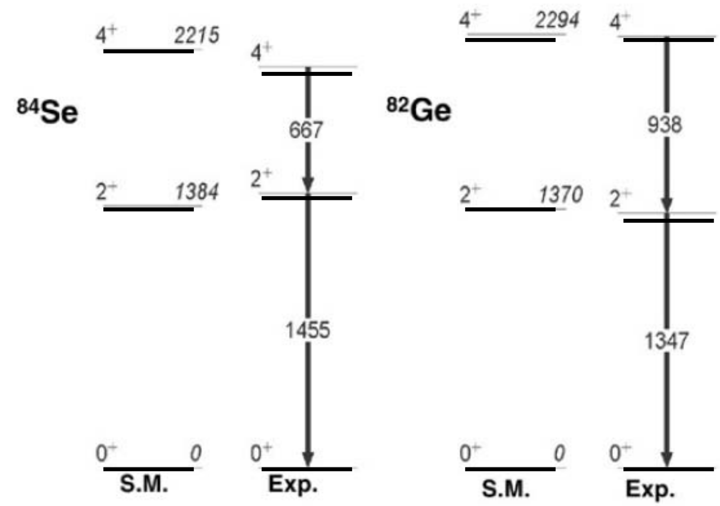
^{84}Se

Shell model calculation
(A. Lisetskiy, 2004)



A. Lisetskiy et al., PRC 70, 044314 (2004)

Program OXBASH
Neutrons: lowest orbital p3/2
followed by f5/2, p1/2, g9/2
Protons: lowest orbital f5/2
But: for ^{84}Se disagreement for 4_1^+
(not known at that time)



G. de Angelis, Prog. Part. Nucl. Phys. 59, 409 (2007)

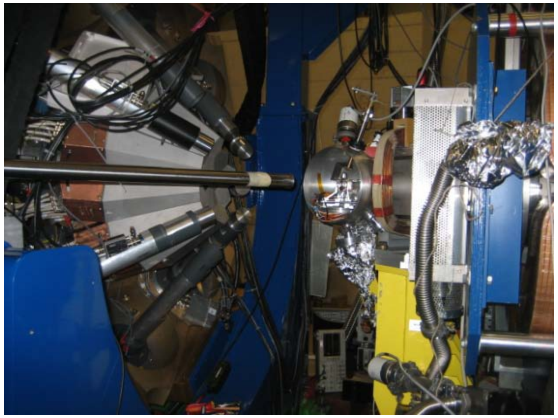
Shell model calc.: B.A. Brown et al., MSU-NSCL Report 524 (1985):
Same interaction as in calculation by Lisetskiy,
but better agreement for 4_1^+

Real test and tuning of interaction can only be
done by measuring transition strengths

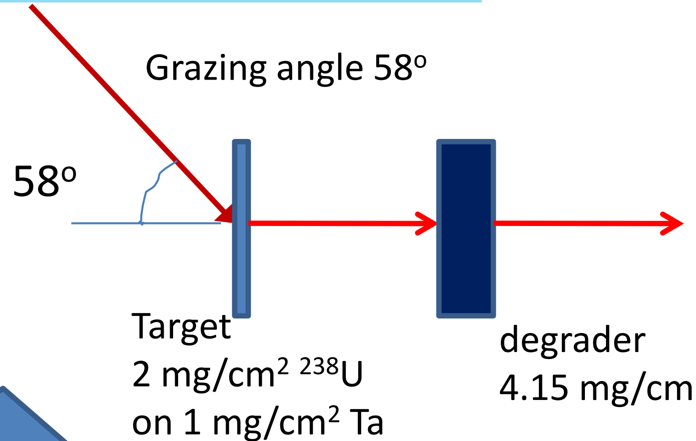
In addition: Collectivity of 2p-2h band in ^{114}Sn (Z=50)
proven from E2 transition strengths
(J. Gableske et al., Nucl. Phys. A 691 551 (2001))

^{84}Se: N=50
Existence of similar collective structures possible

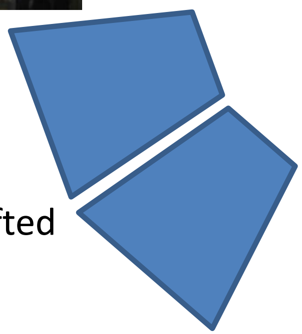
Plunger experiment on ^{84}Se and ^{86}Se



E(^{82}Se) = 558 MeV (on ^{238}U)
from XTU Tandem + ALPI



PRISMA
Recoil identification



AGATA demonstrator
5 AGATA triples
Observation of Doppler-shifted
Gamma-rays

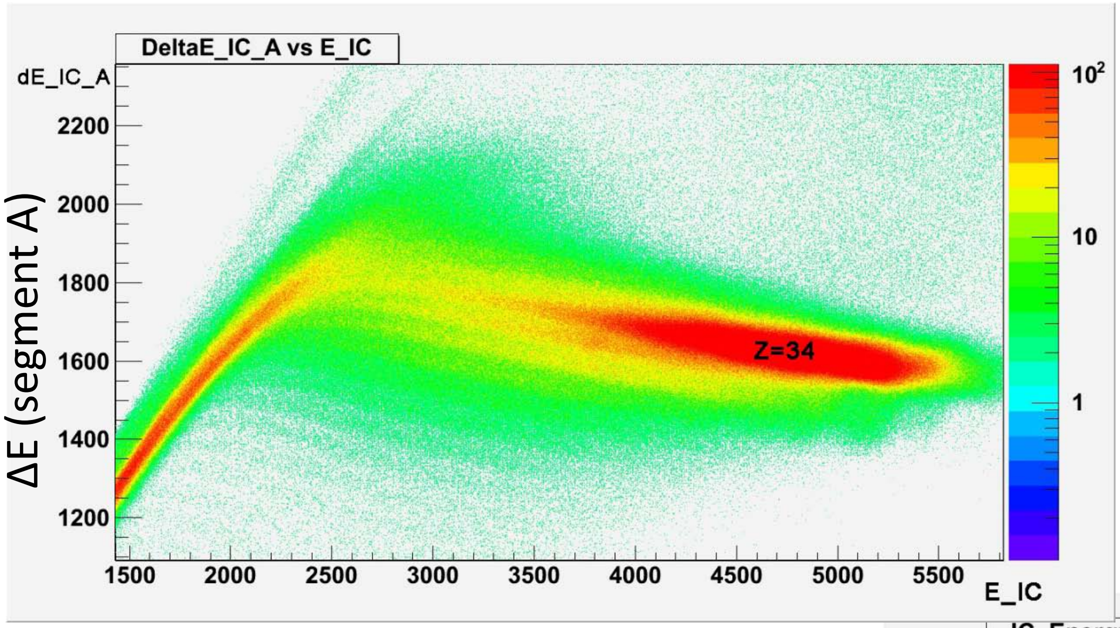
3 target-degrader distances:
20.7 µm , 207 µm, 414 µm

Reaction: ^{82}Se + ^{238}U → ^{84}Se, ^{86}Se (2n and 4n transfer reactions)
Reaction cross sections (GRAZING):

$E(^{82}\mathrm{Se})$	^{82}Se + ^{208}Pb 480 MeV	^{82}Se + ^{238}U 490 MeV	^{82}Se + ^{238}U 510 MeV
Nucleus	σ (mbarn)	σ (mbarn)	σ (mbarn)
^{84}Se	58.6	68.9	62.9
^{86}Se	3.33	3.02	4.07
^{82}Ge	0.47	1.48	1.31

Experiment performed in combination with measurements on N=51 isotones ^{89}Sr, ^{87}Kr, ^{85}Se, ^{83}Ge (D. Verney, G. Duchene)

Recoil identification with PRISMA: Z, q



ΔE (segment A)

E (segments ABCD)

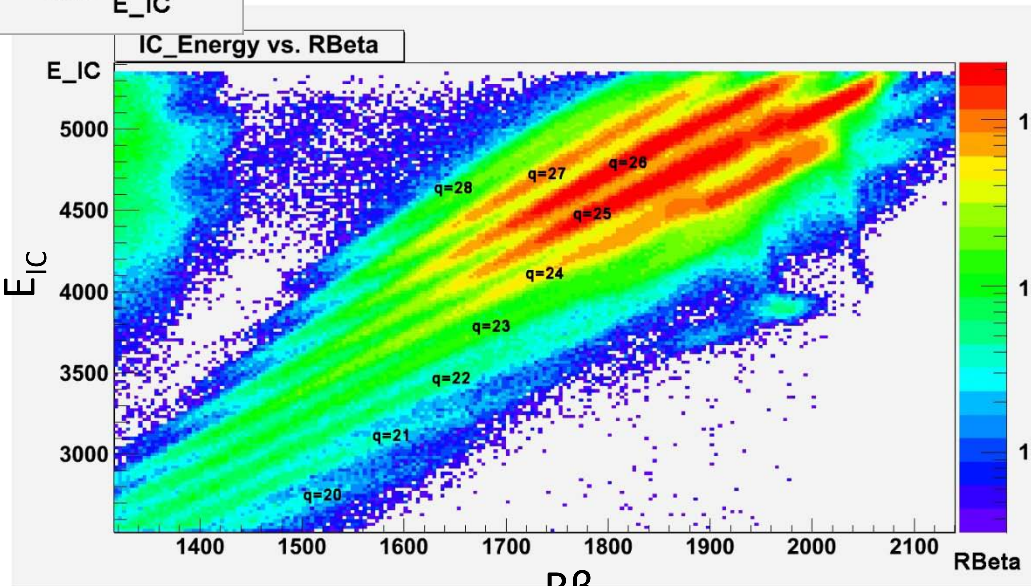
ΔE-E plot: Z identification with IC

$\Delta E/E \propto Z^2$

Rv-E_{IC} plot: q identification

$$E_{IC} = \frac{1}{2}mv^2, \quad \frac{mv^2}{R} = qvB$$

$$\Rightarrow \frac{E_{IC}}{Rv} \propto q$$

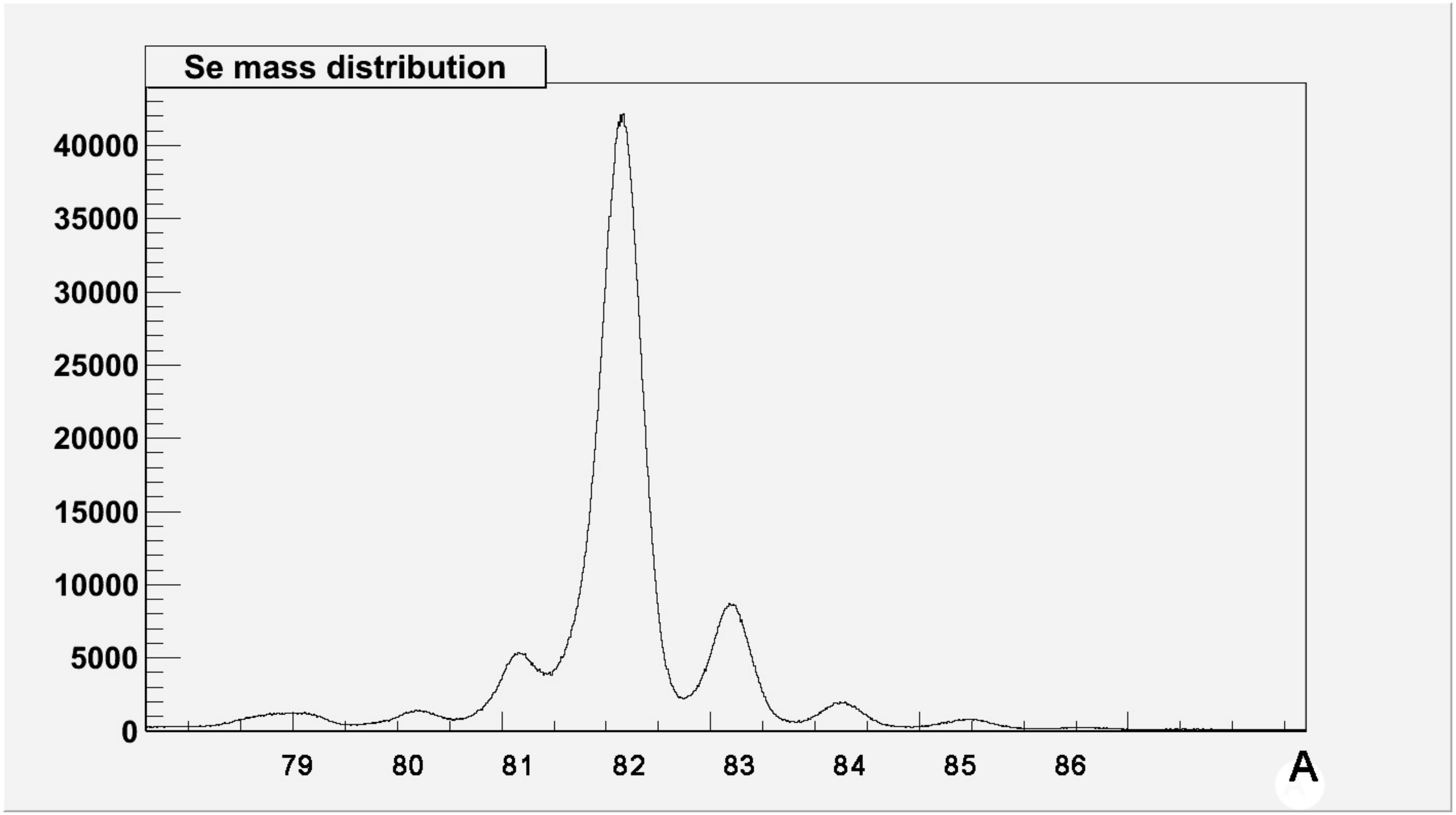


E_{IC}

Rβ

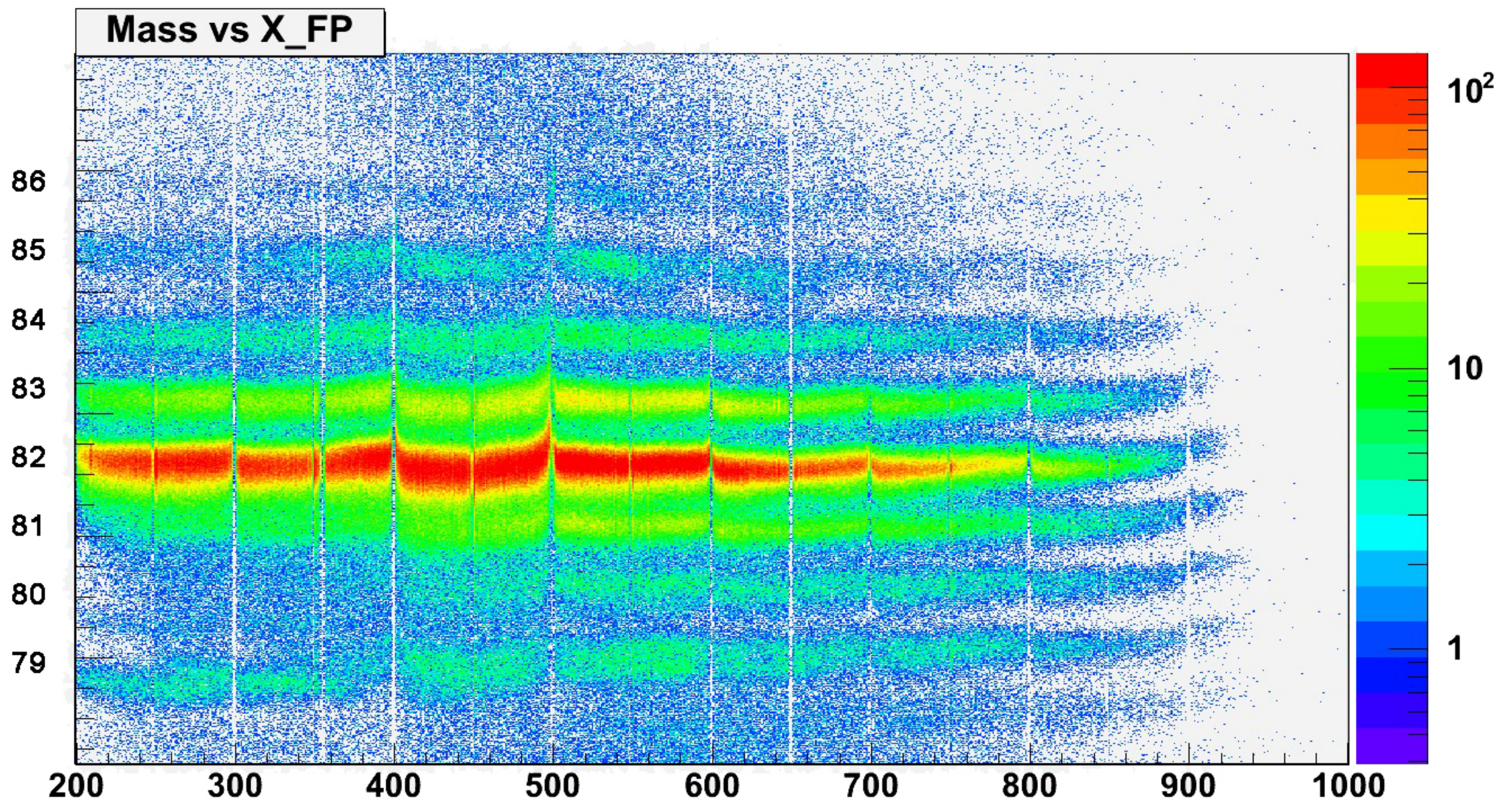
Data analysis:
J. Litzinger, Cologne (under progress)

Recoil identification with PRISMA: Se mass distribution



Data analysis:
J. Litzinger, Cologne (under progress)

Recoil identification with PRISMA: Se mass distribution

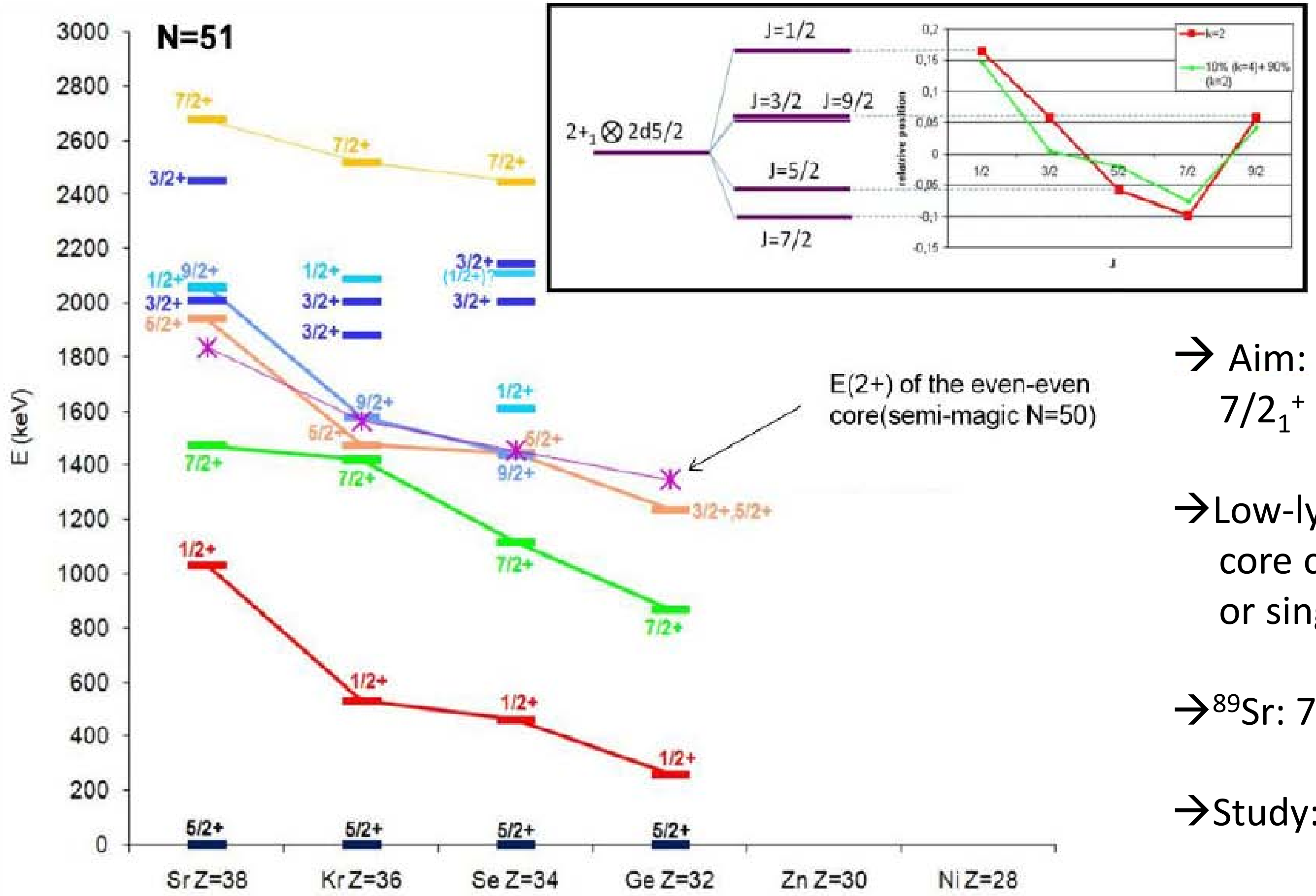


Data analysis:
J. Litzinger, Cologne (under progress)

Observe 84Se and 86Se
→ To do: set particle gates to get γ ray spectra

Structure of neutron rich N=51 nuclei in the vicinity of 78Ni

D. Verney, G. Duchene



→ Aim: determine nature of the $7/2_1^+$ state in ^{83}Ge, ^{85}Se, ^{87}Kr (N=51)

→ Low-lying states in N=51 isotones: core coupled configuration or single particle conf.

→ ^{89}Sr: $7/2_1^+$ state: core coupled conf.

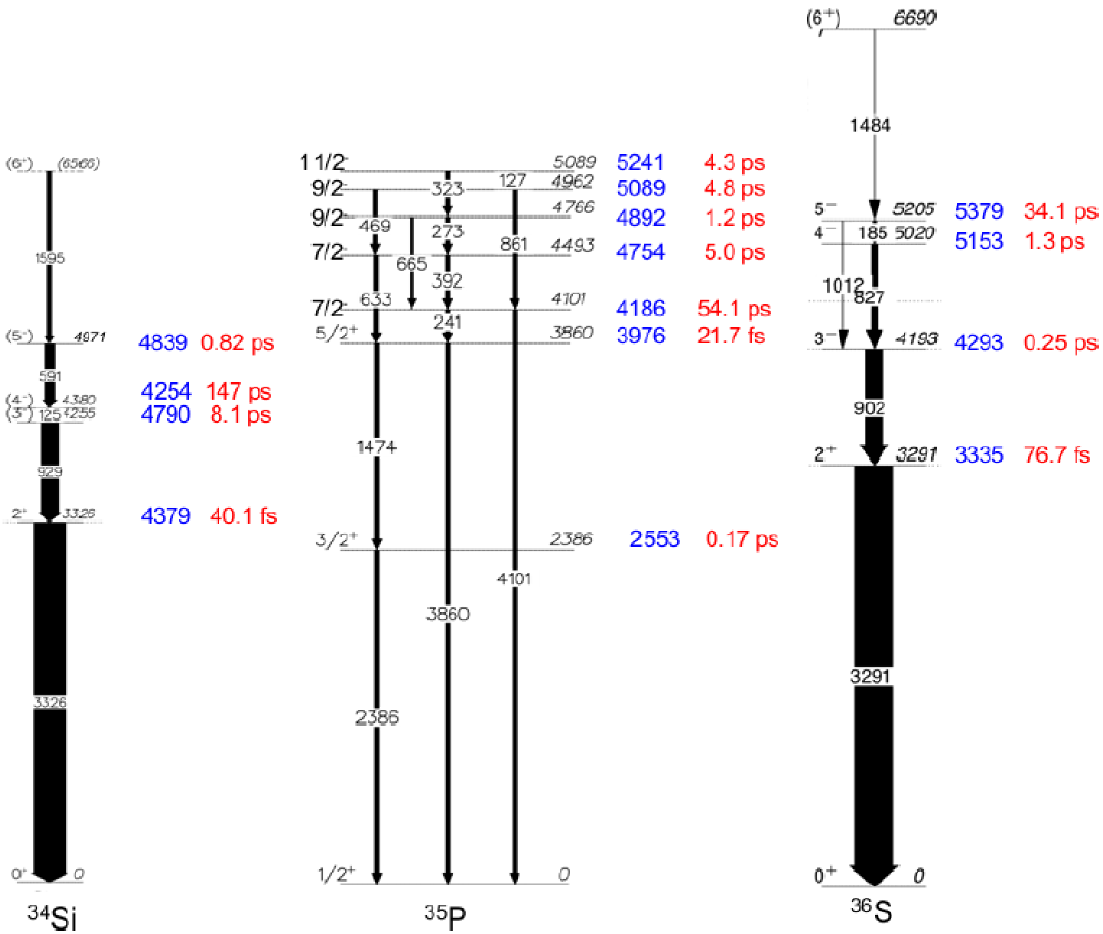
→ Study: constrain theoretical models

Nucleus	Relative production rate	$E(7/2^+_1)$ Exp	$E(7/2^+_1)$ Th	$\tau_{1/2}(7/2^+_1)$ $2^+ \otimes \nu 2d_{5/2}$	$\tau_{1/2}(7/2^+_1)$ $0^+ \otimes \nu 1g_{7/2}$
89Sr	4.5	1473 keV	1559 keV	0.11 ps	10.3 ps
87Kr	27	1578 keV	1598 keV	0.13 ps	16.1 ps
85Se	36	1115 keV	1226 keV	0.29 ps	55.1 ps
83Ge	1	867 keV	1035 keV	0.70 ps	214 ps

Talk by G. Duchene, Wednesday, 3 30 pm

Lifetimes in N=20 isotones of Si, P, S: Motivation, experiment

Alain Goasduff, IPHC Strasbourg



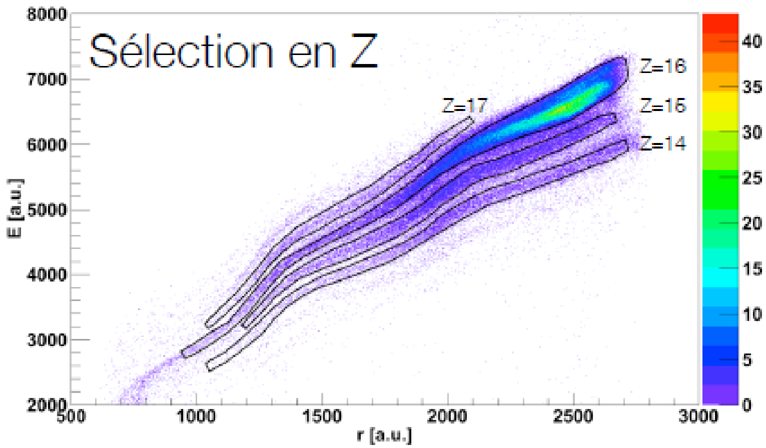
Shell model predictions (Antoine, PSDPF) and experiments with CLARA/PRISMA

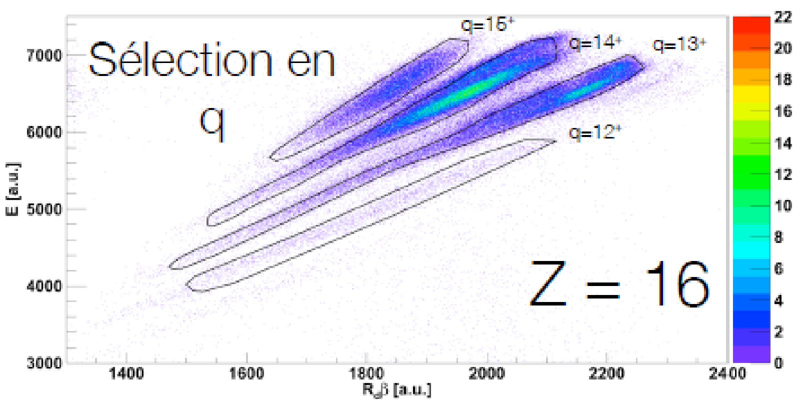
Experiment:
AGATA-PRISMA-Plunger

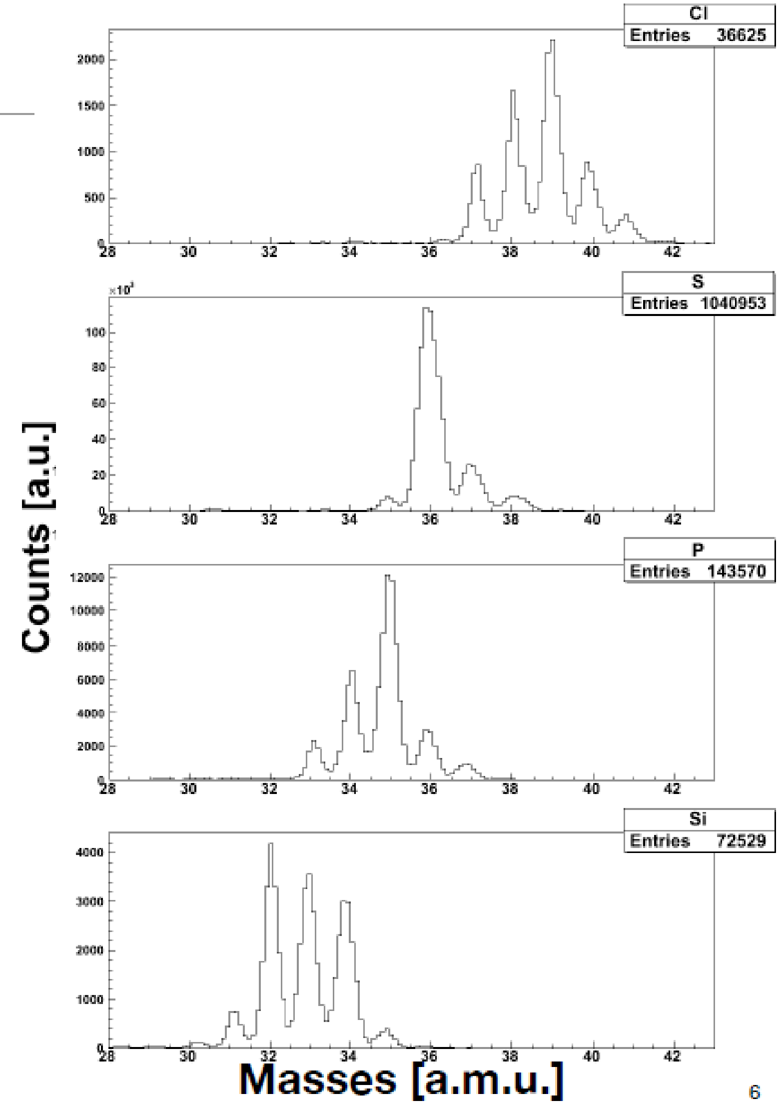
- → beam: $^{36}S^{9+}$, 6.3 AMeV (Tandem+ALPI)
- → plunger target: 1 mg/cm^2 ^{208}Pb + 1 mg/cm^2 ^{93}Nb backing
- → degrader: 3 mg/cm^2 ^{93}Nb
- → 5 distances 7, 20, 35, 65, 120 µm
- → AGATA demonstrator with 5 triples
- → distance to target: 18 cm
- → PRISMA under 59 degrees

Lifetimes in N=20 isotones of Si, P, S: Recoil identification

Identification des reculs







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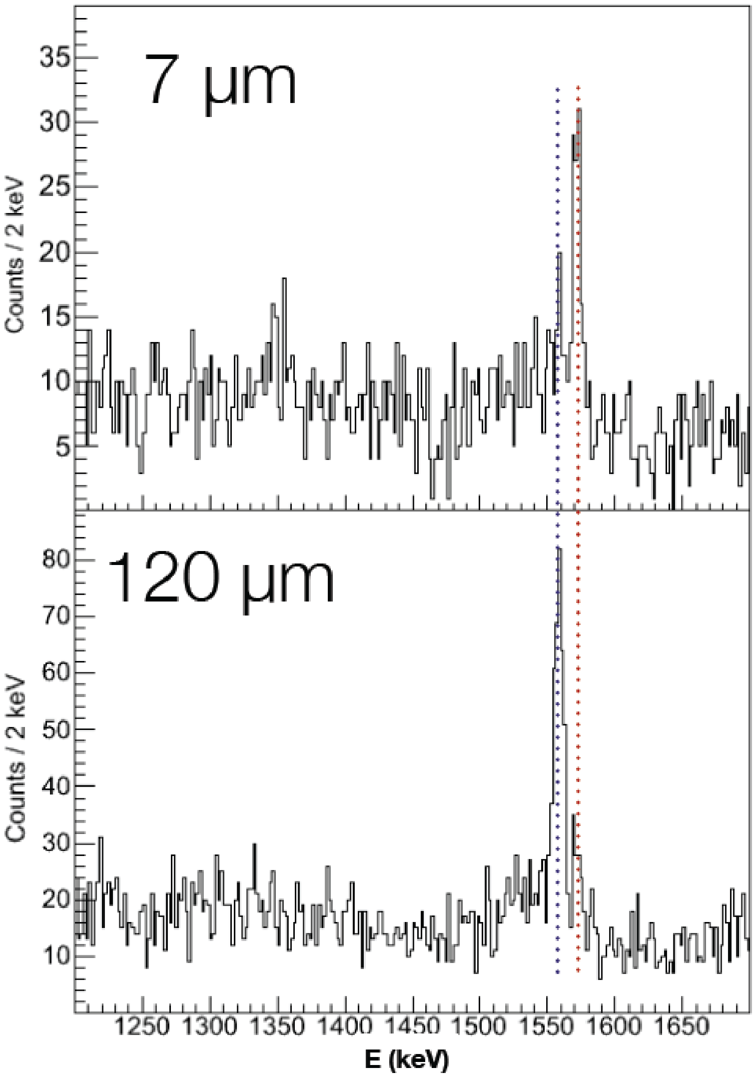
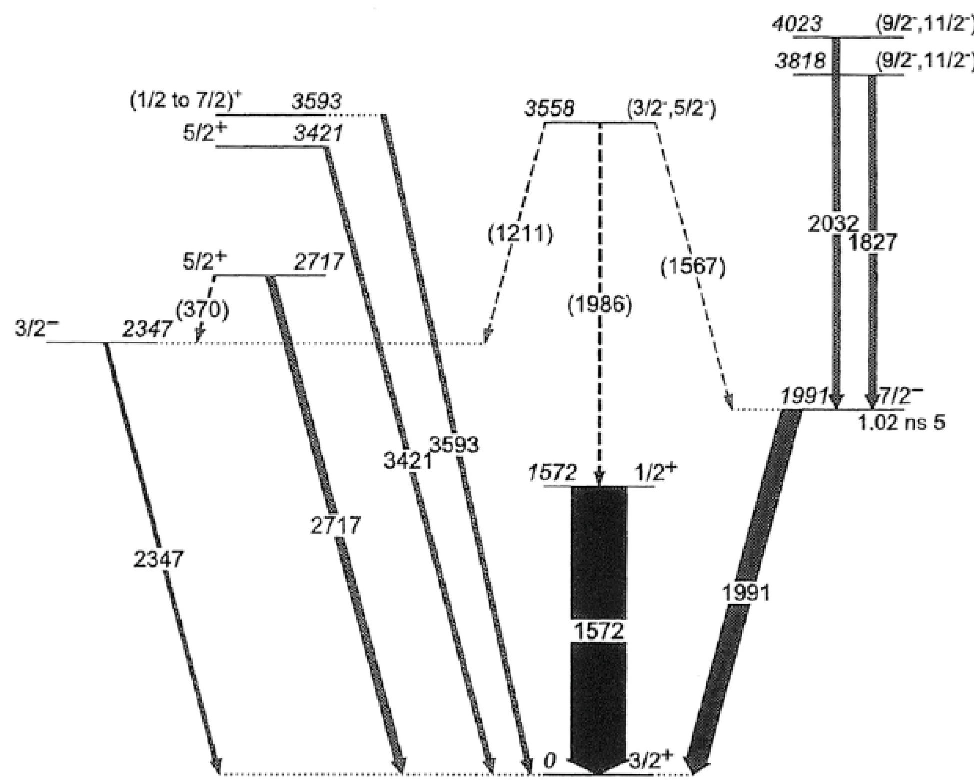
Alain Goasduff, IPHC Strasbourg

Lifetimes in N=20 isotones of Si, P, S: First results for $^{35}S_{19}$



Alain Goasduff, IPHC Strasbourg

- Example of ^{35}S first excited state $1/2^+$:



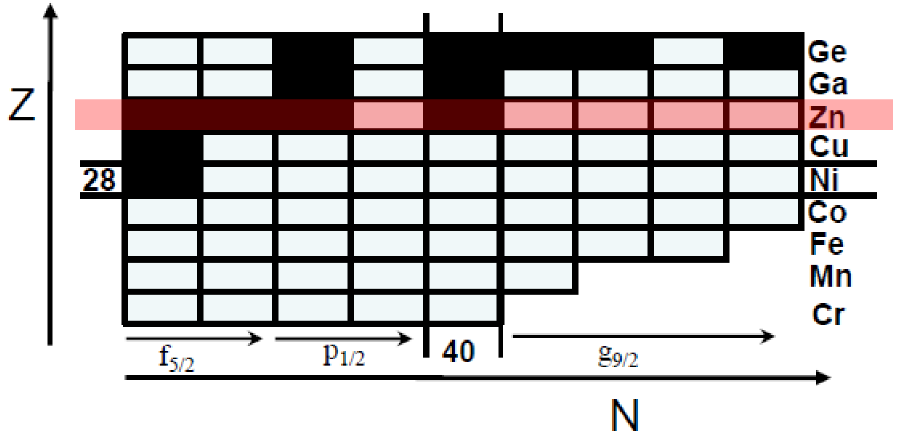
T_{lit}=3.3 (5) ps (Warburton et al., PRC 7, 1120 (73)

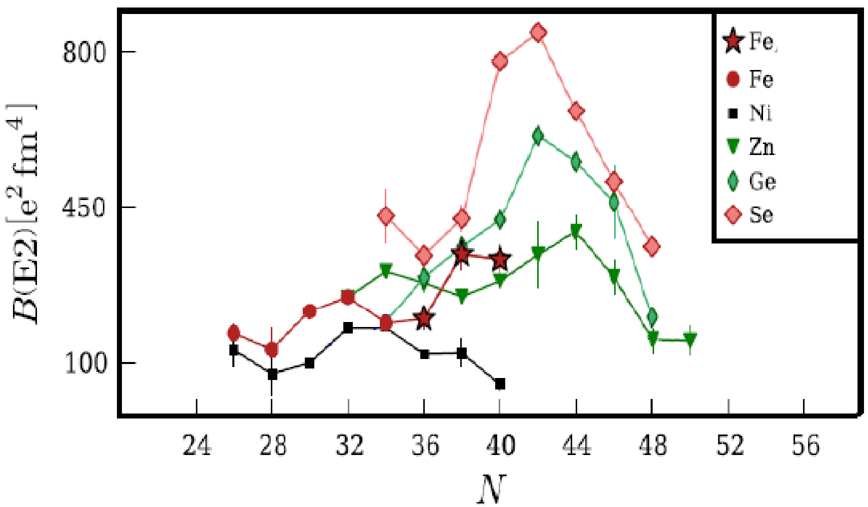
Shell model pred.: τ = 2.0 ps

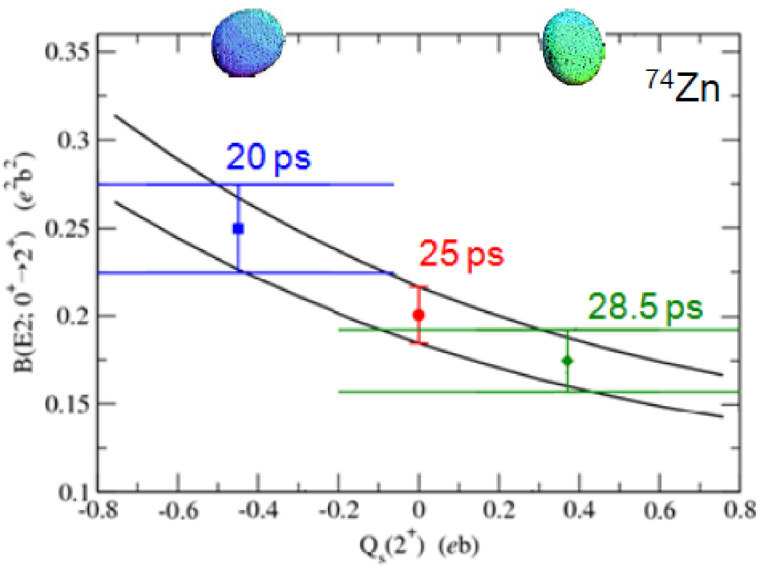
Prelim. this work: τ = 2.26(12) ps

Lifetimes of excited states in n-rich Zn isotopes using the AGATA demonstrator
C. Louchart, Saclay

Onset of collectivity near N=40: investigate $^{70}Zn_{40}$, $^{72}Zn_{42}$, $^{74}Zn_{44}$







Ref: J. Van de Walle thesis

- Lifetime measurement to determine accurate B(E2) value for $2^+/4^+$ states
- Comparison with theory

Important role of ν $g_{9/2}$ and $d_{5/2}$ intruder orbitals

Lifetimes of excited states in n-rich Zn isotopes using the AGATA demonstrator: Experiment

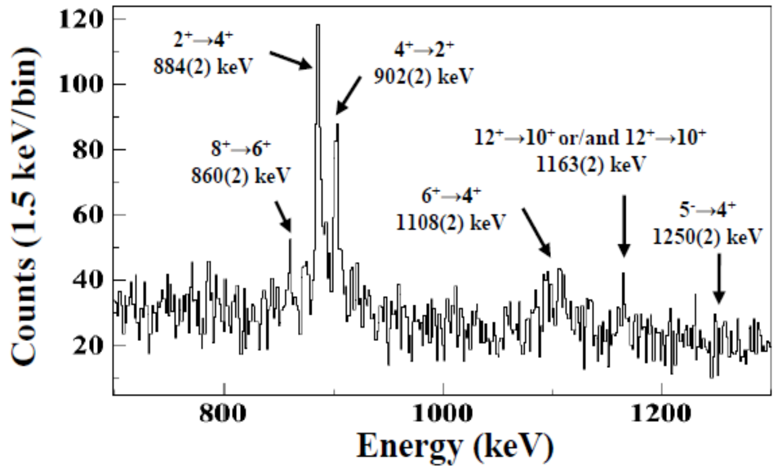
→multi-nucleon transfer:
^{76}Ge on 1.4 mg/cm^2 ^{238}U @ 577 MeV, 0.3 pnA

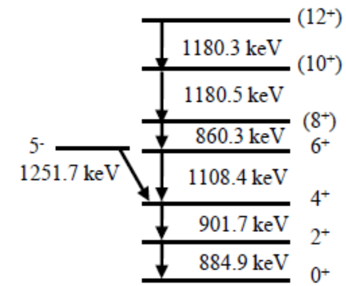
AGATA-PRISMA-Plunger

→5 distances 100, 200, 500, 1000, 1900 µm

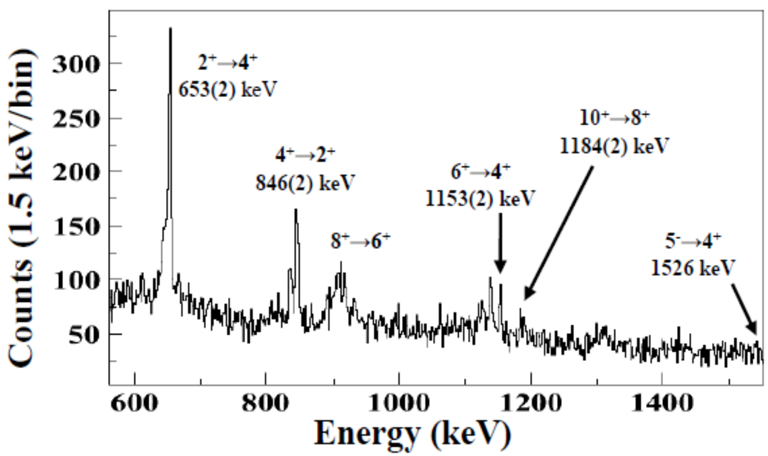
→ AGATA demonstrator with 4 triples

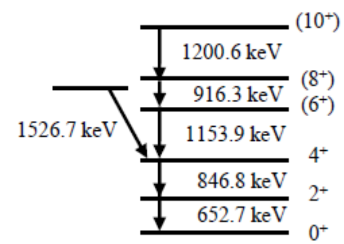
→PRISMA at 55°





^{70}Zn
100 µm



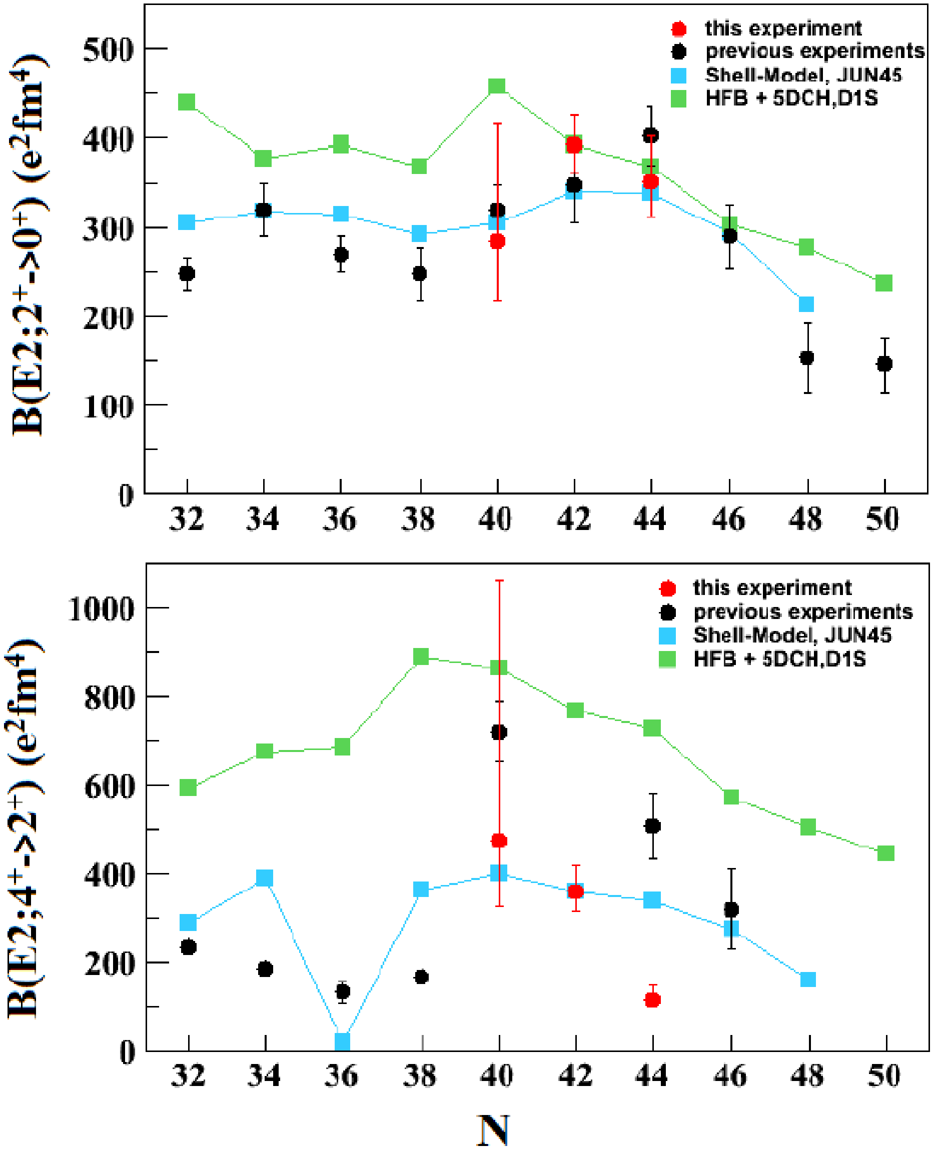


^{72}Zn
100 µm

From NNDC data base

C. Louchart, Saclay

Lifetimes of excited states in n-rich Zn isotopes using the AGATA demonstrator: Results for $^{70,72,74}Zn$



- B(E2; 2^+->0^+) values are in agreement with shell model calculations

- Beyond mean field calculation over estimate the collectivity

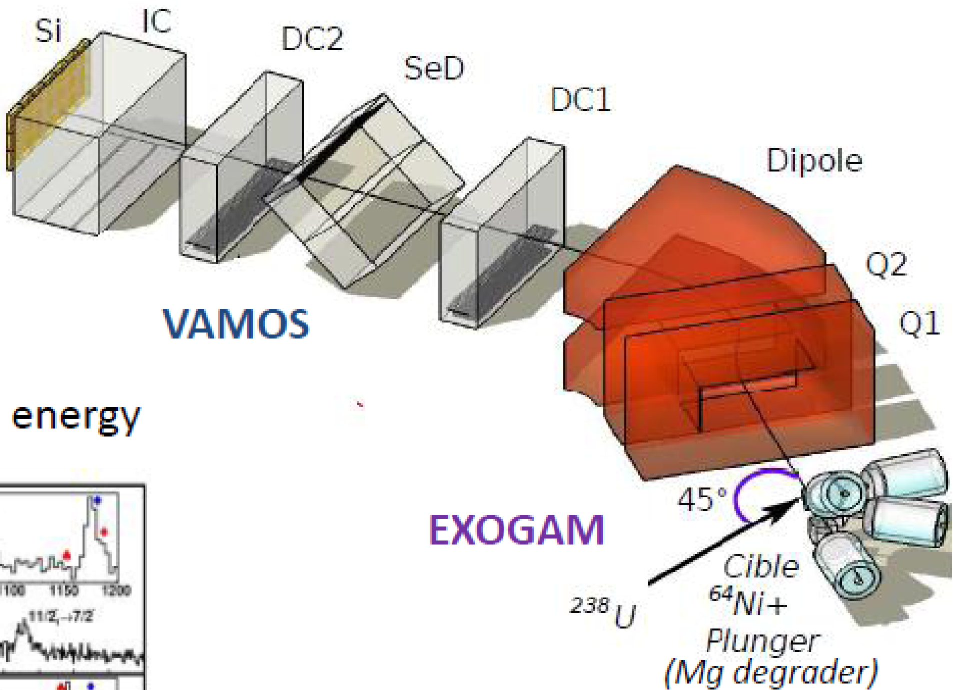
- Shell model predictions don't reproduce the trend of the systematics

C. Louchart, Saclay

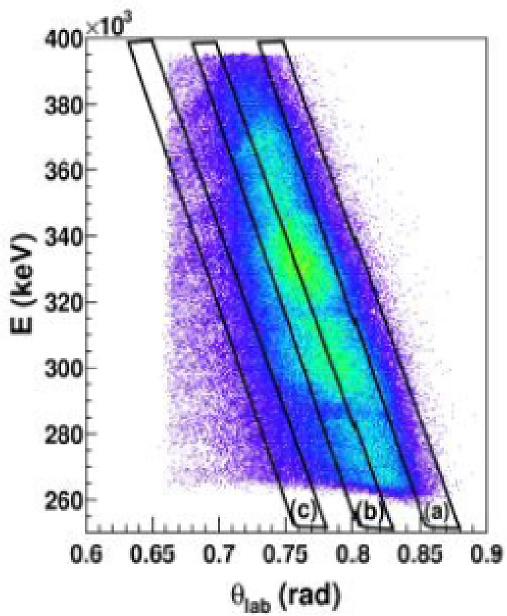
Lifetime measurements in odd-mass ^{63,65}Co at GANIL

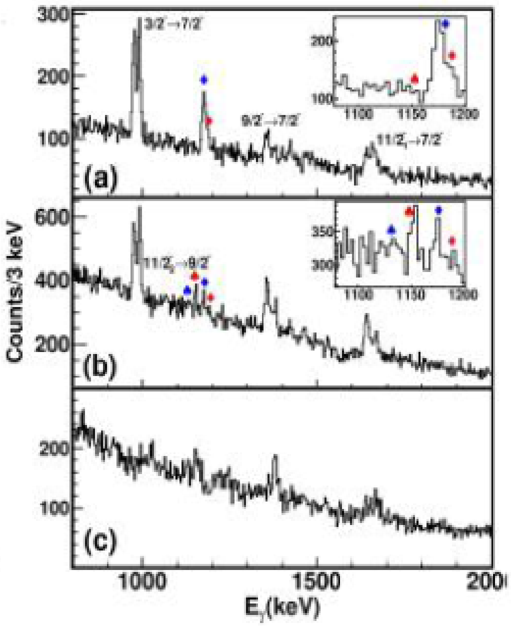
A. Dijon *et al.*, *PRC 83, 064321 (2011)*

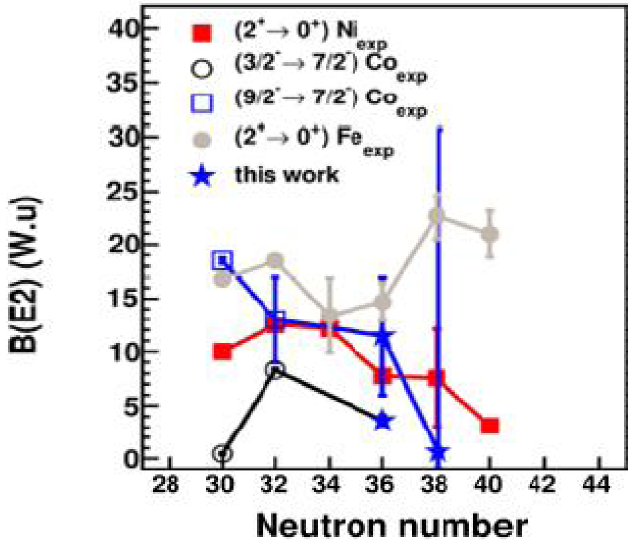
Objectifs :
- B(E2) measurement of 3/2$^-$, 9/2$^-$ states
- Core coupled state with even-even Ni isotone ?



→ lifetime extracted by selection in excitation energy







→Ni-like and Fe-like core coupled states in odd mass Co isotopes

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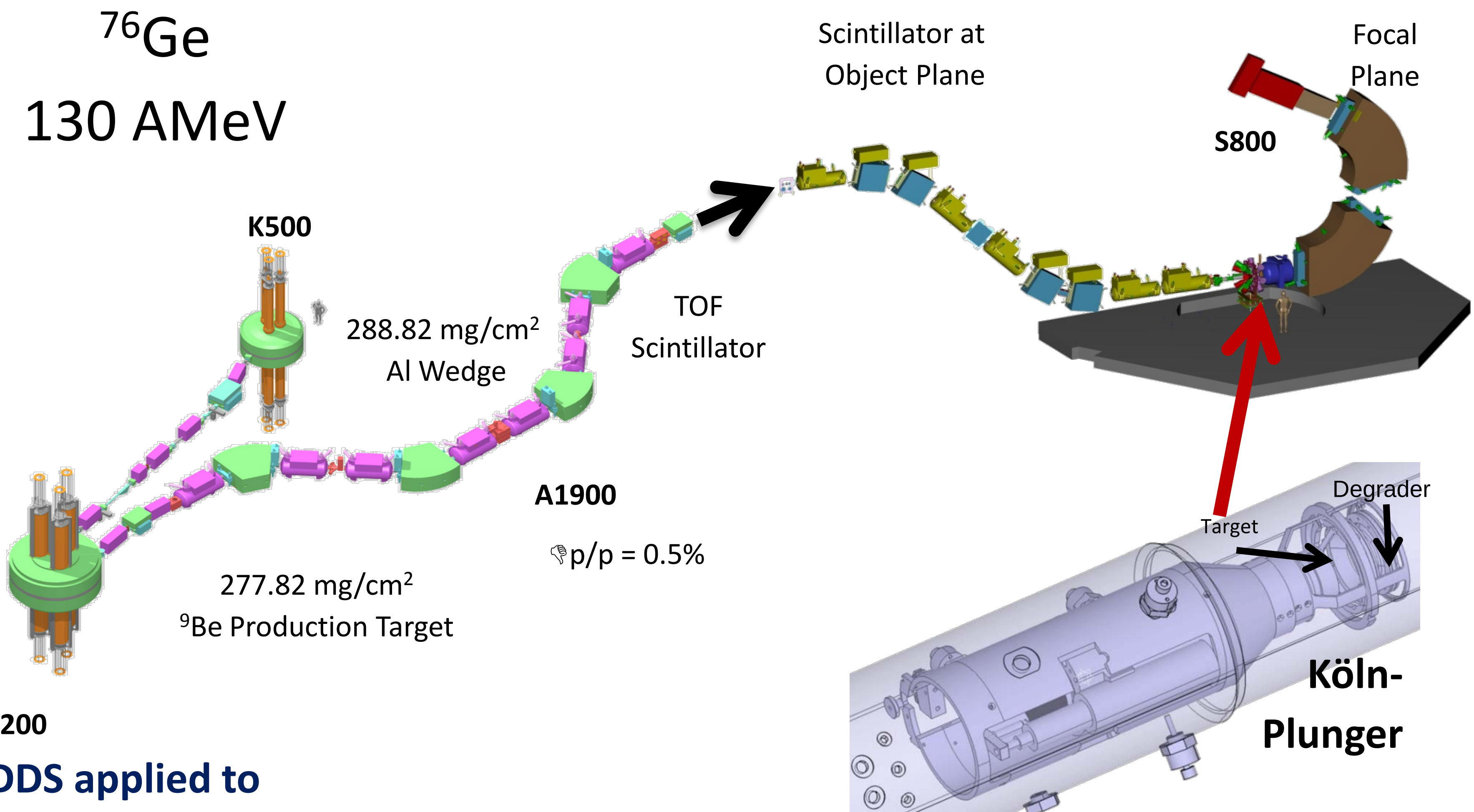
Example: $^{62,64,66}Fe$ lifetime measurement at NSCL, MSU

NSCL coupled cyclotron facility + A1900; MSU



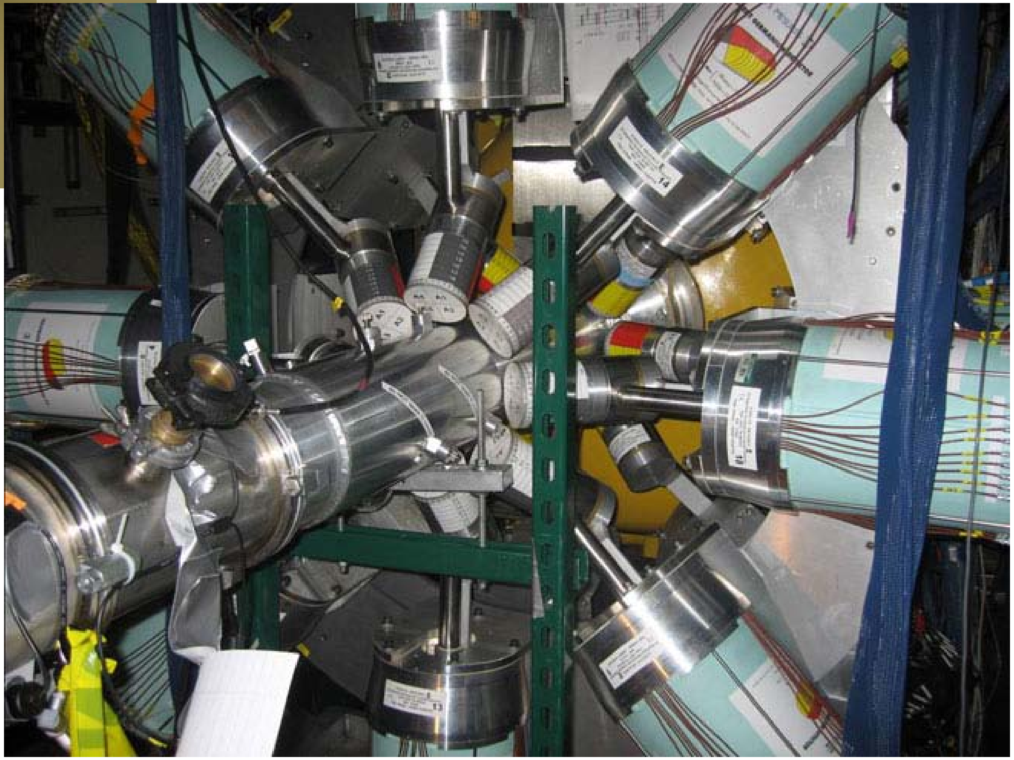
RDDS applied to projectile ($^{62,64,66}Fe$) Coulomb excitation reactions at intermediate energies (88-98 AMeV)

Köln/NSCL plunger

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

SeGA @ S800

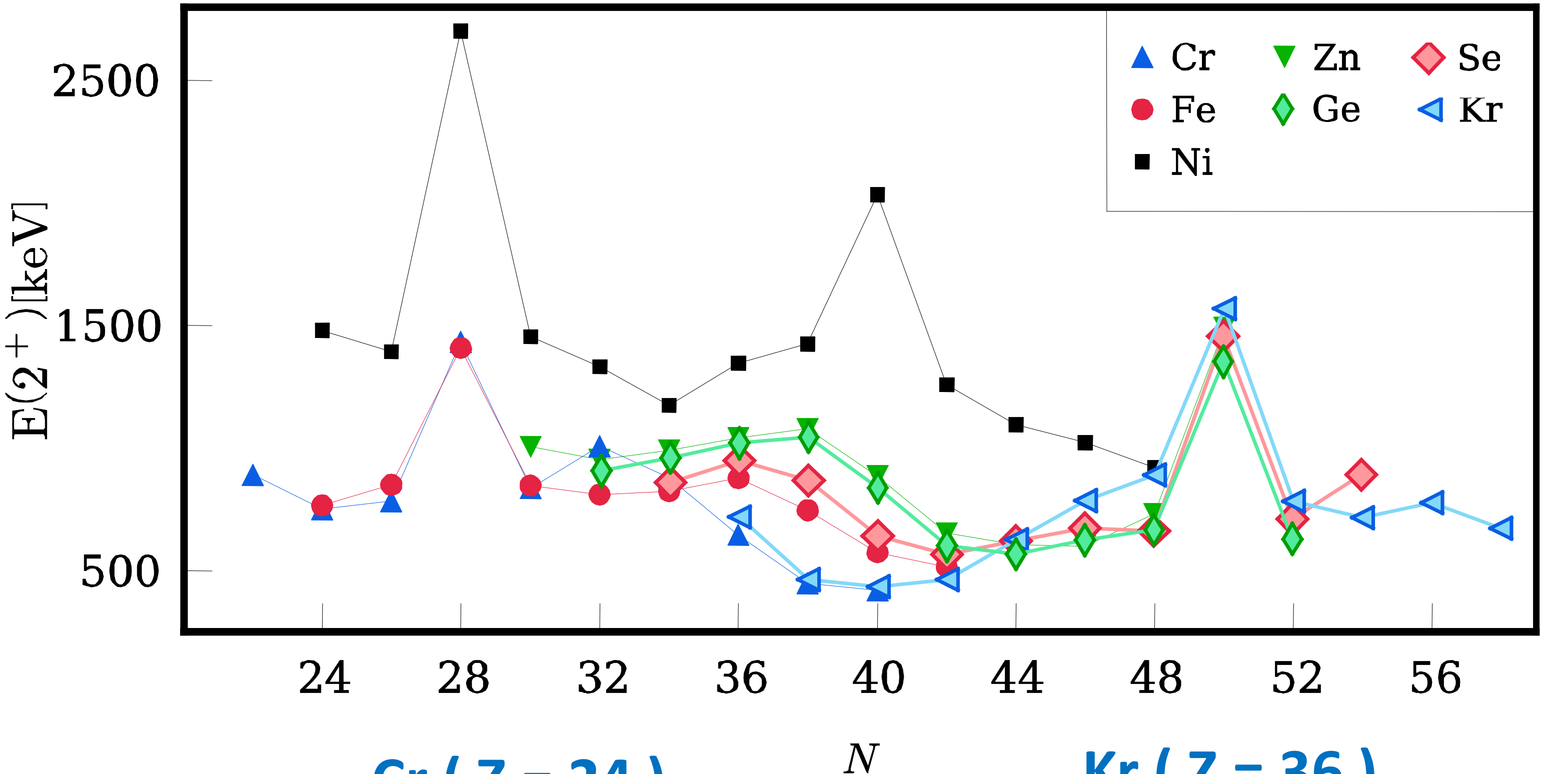
7 detectors
at forward angles (30 deg.)
8 detectors
at backward angles (140deg.)



Motivation: ^{62,64,66}Fe lifetime measurement at NSCL, MSU

Symmetry with respect to Z ≈ 30

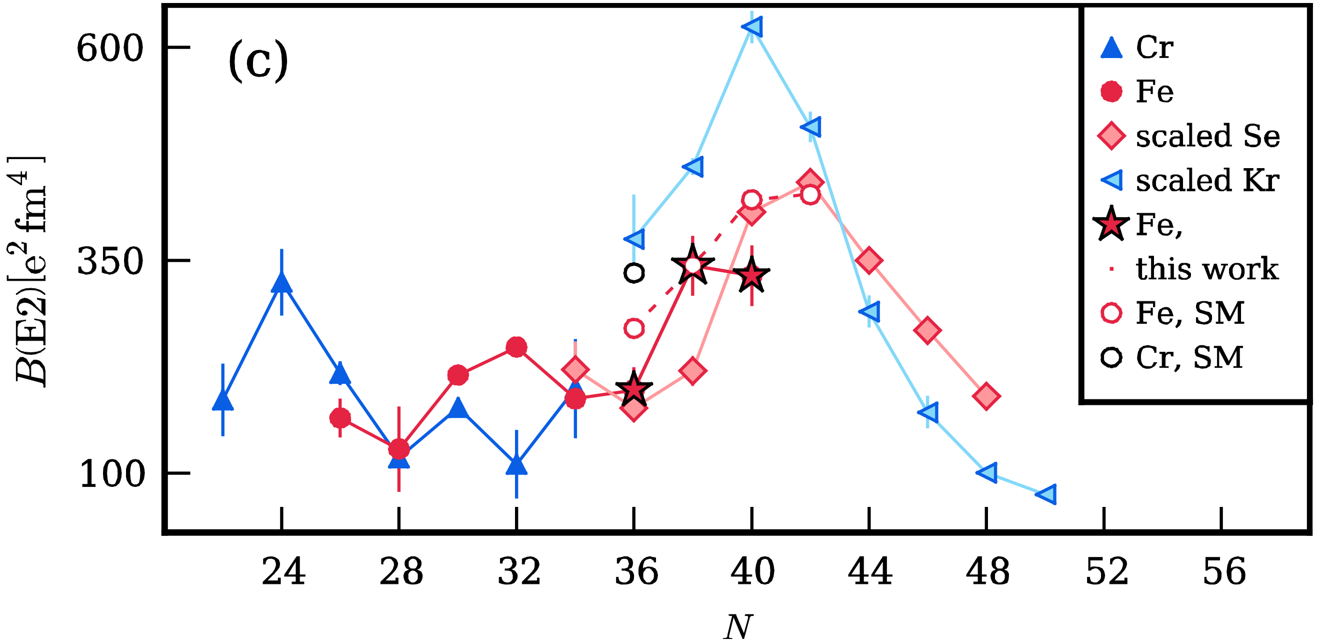
N.Hoteling et al., PRC 74 (2006) 064313



	Cr (Z = 24)		Kr (Z = 36)
pairs	Fe (Z = 26)	⟺	Se (Z = 34)
	Zn (Z = 30)		Ge (Z = 32)

Results

Symmetry with respect to Z ≈ 30, and shell evolution at N=40



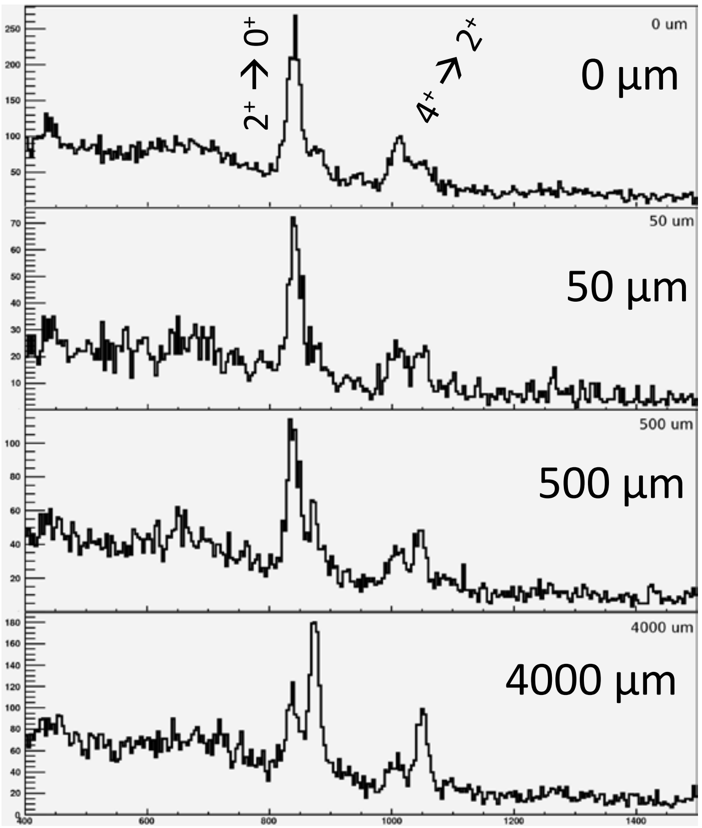
W. Rother et al., Phys. Rev. Lett. 106, 022502 (2011)

Recent shell model calculations
with new effective LNPS interaction (by S.M.Lenzi, F.Nowacki, A.Poves, K.Sieja)
well explain the trends of B(E2) for ^{62,64,66}Fe at N=40

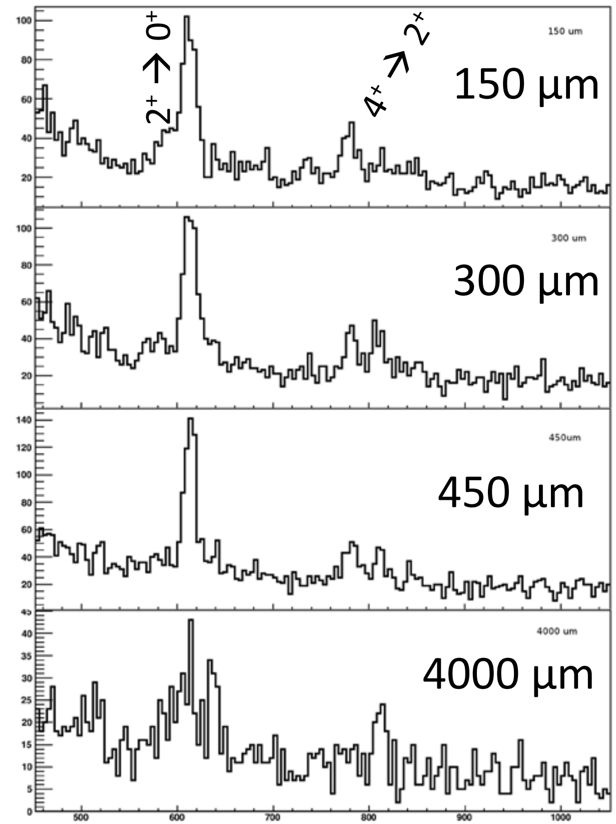
→Motivation of measurement of B(E2) values in ^{58,60,62}Cr
→Performed at NSCL in Dec. 2011 with 1p knockout, data analyzed at the moment

Spectra of ^{58,60,62}Cr

→ measurement of B(E2) values in ^{58,60,62}Cr
→ Performed at NSCL in Dec. 2011 with 1p knockout, secondary beam ^{59,61,63}Mn @ ~ 95 MeV/u
→ data analyzed at the moment (T. Braunroth, Cologne)



^{58}Cr

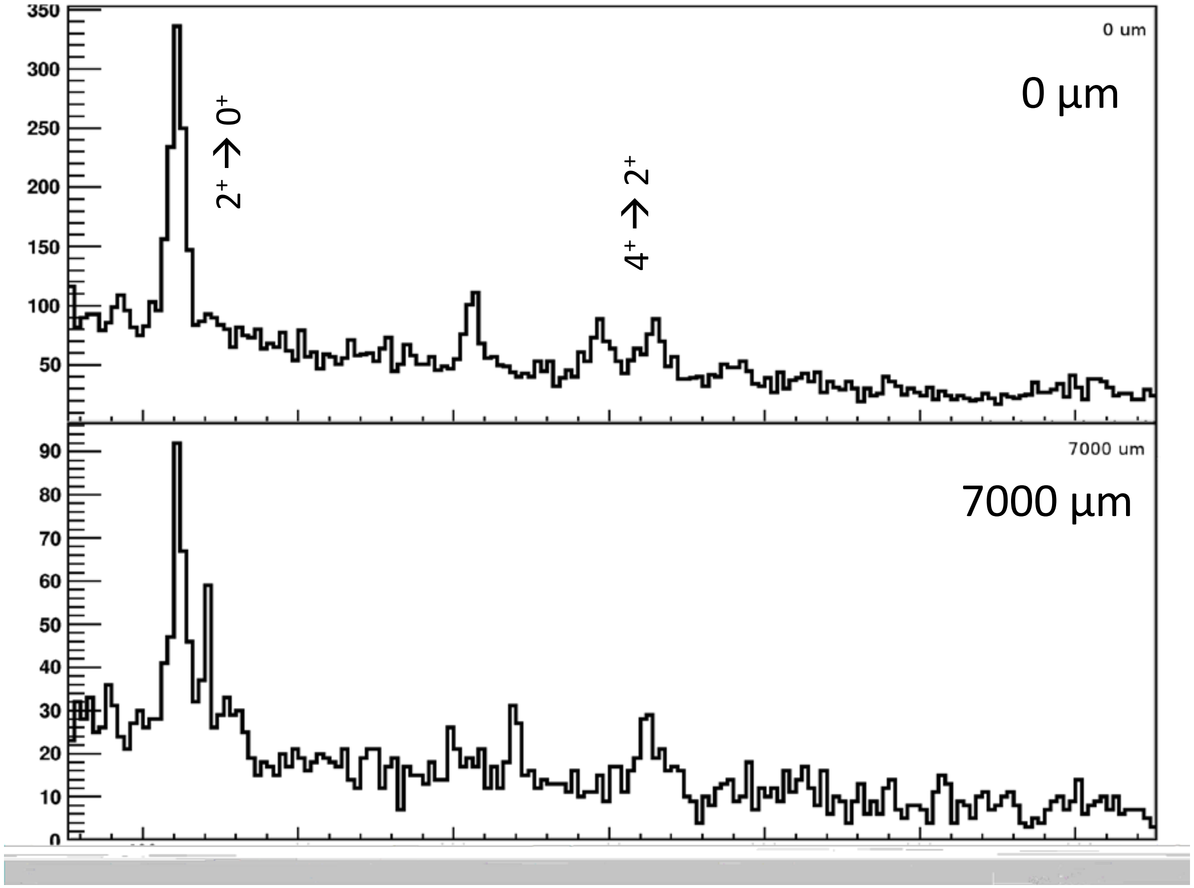


^{60}Cr

Spectra from online sorting

Spectra of $^{58,60,62}Cr$

→ measurement of B(E2) values in $^{58,60,62}Cr$
→ Performed at NSCL in Dec. 2011 with 1p knockout, secondary beam $^{59,61,63}Mn$ @ ~ 95 MeV/u
→ data analyzed at the moment (T. Braunroth, Cologne)



^{62}Cr

Outline

1. Introduction: recent experiments with the plunger
2. Experiments with the compact plunger at Legnaro (AGATA, PRISMA) and at GANIL (EXOGAM, VAMOS)
3. Plunger device for medium energy radioactive beams: the Köln-NSCL plunger
4. A new plunger for relativistic radioactive beams: the GSI plunger for PRESPEC/HISPEC

Plunger experiments at PRESPEC/HISPEC, GSI

Motivation

- Measure lifetimes of excited states of very exotic nuclei with radioactive ion beams at GSI
- At GSI: Access to neutron-rich and other exotic nuclei

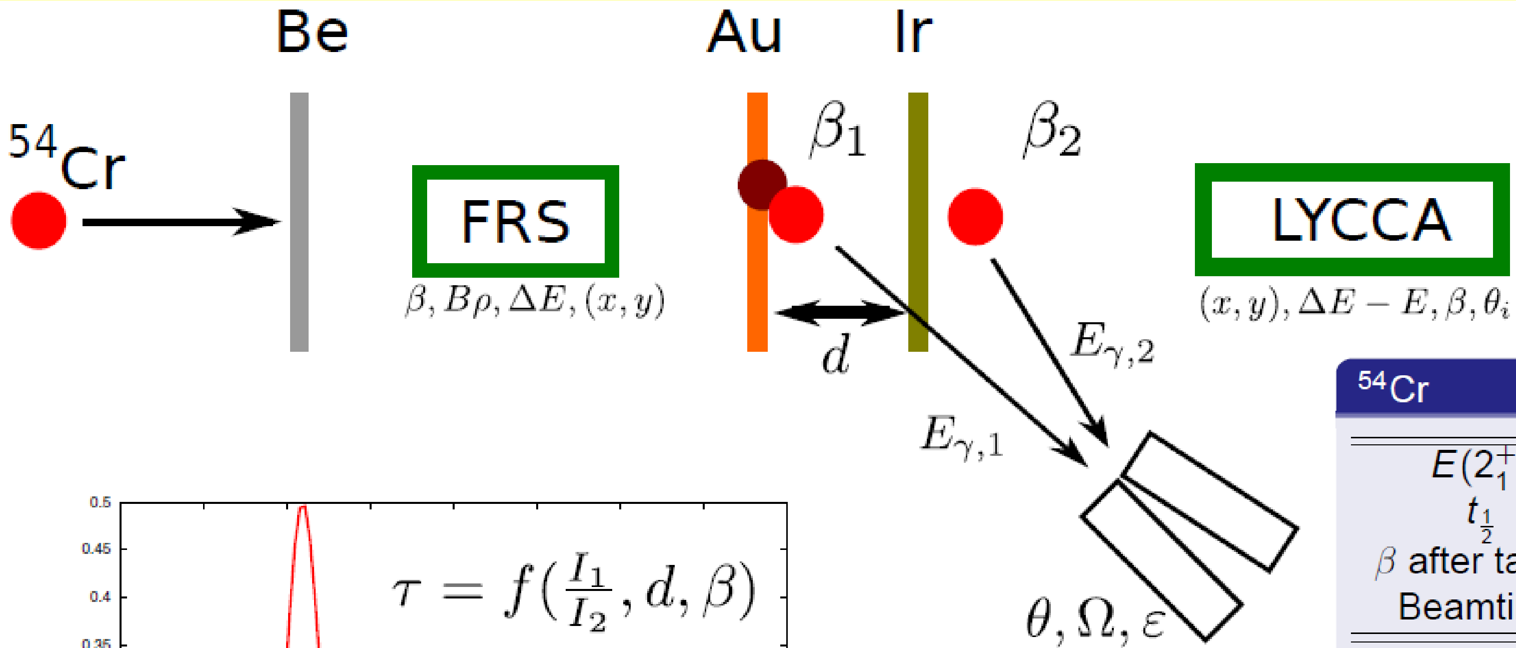
Challenges

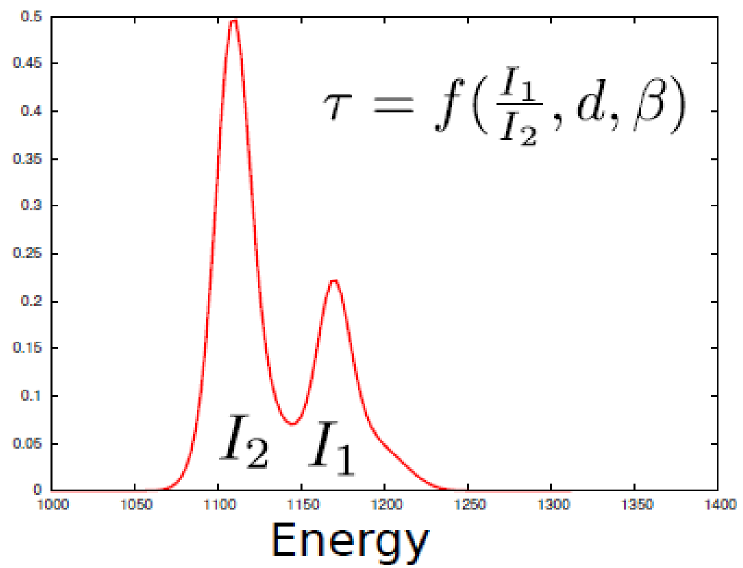
- Large beam - diameter (2 - 5 cm)
- Large recoil velocity ($v \approx .4c$)
- Thick foils (500 μm)
- Peak to background ratio
- Particle tracking

Experimental Means

- Coulomb excitation
- Knock-out reactions

Commissioning run with stable ^{54}Cr





^{54}Cr

$E(2_1^+)$	835 keV
$t_{\frac{1}{2}}$	7.9(3) ps
β after target	0.45
Beamtime	10 h

Test with stable beam

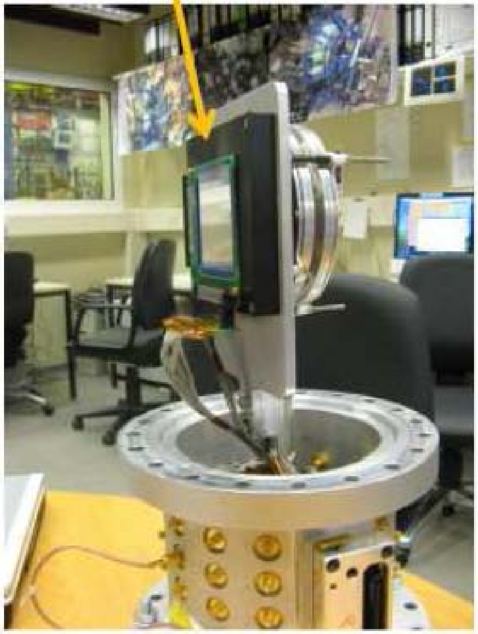
- ^{54}Cr
- 183 MeV/u at target position
- 1 mm Au, 0.5 mm Ir (lots of material)
- realistic conditions: primary Be-target for large distribution in p and x.

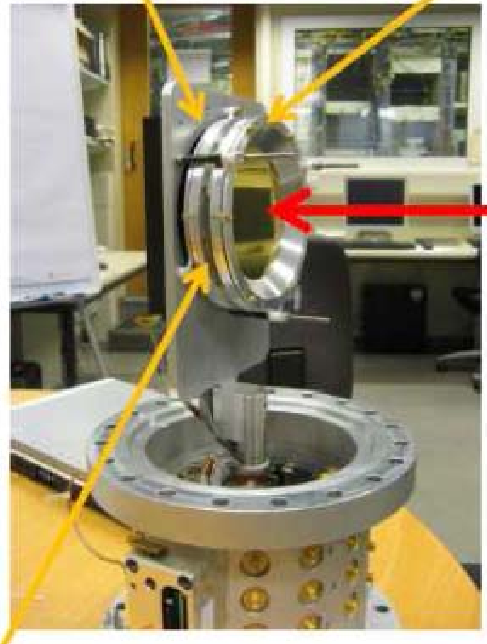
Commissioning run with fixed plunger

Target - DSSD

Ir Degrader (0.5 mm)

Au Target (1 mm)

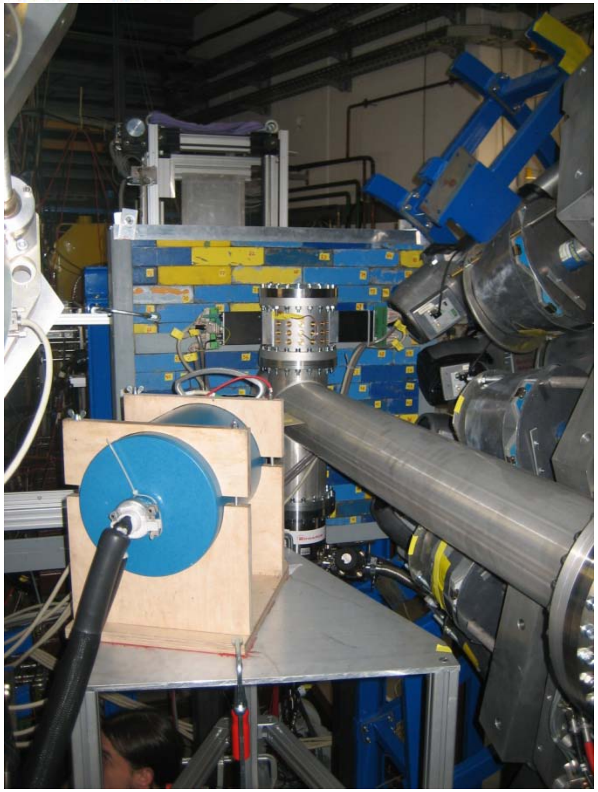




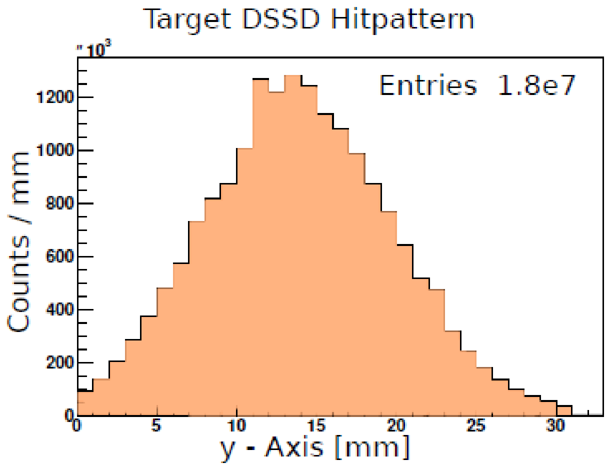
^{54}Cr, 182 MeV / u

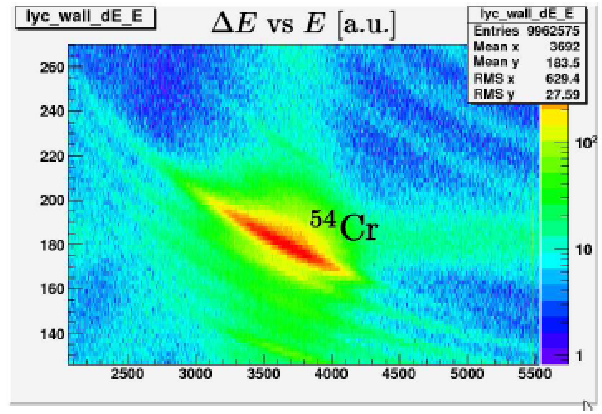
Distance: 700 µm

Fixed plunger mounted in RISING target chamber

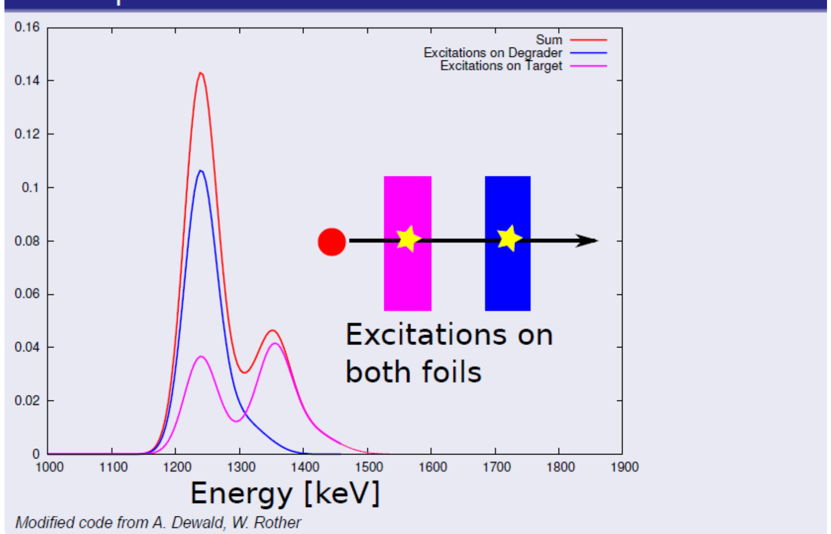


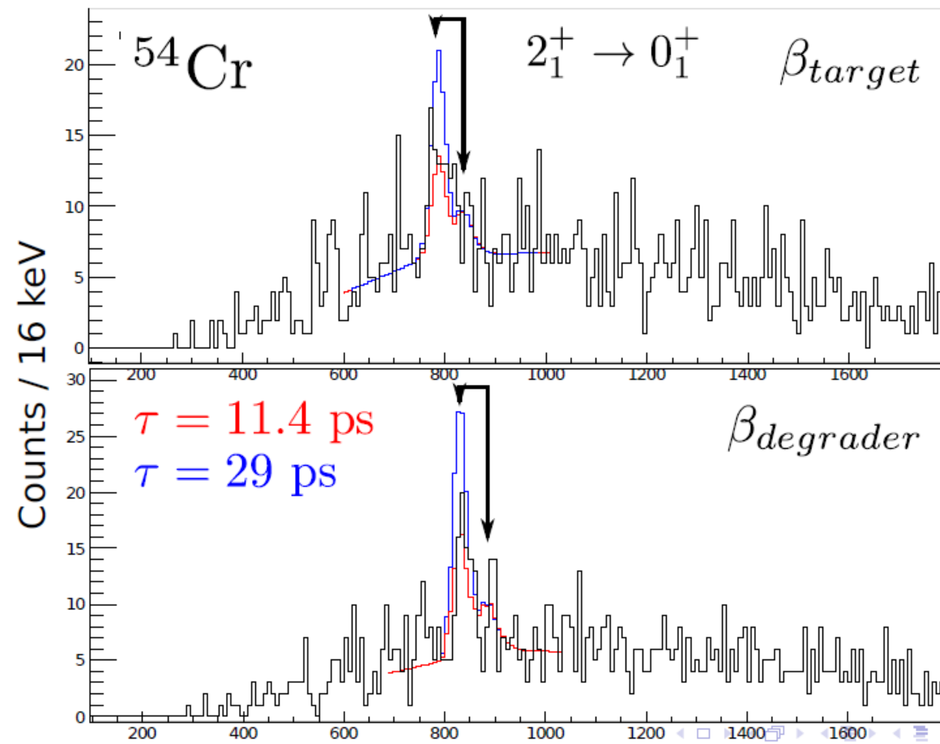
Commissioning run with fixed plunger at GSI: results





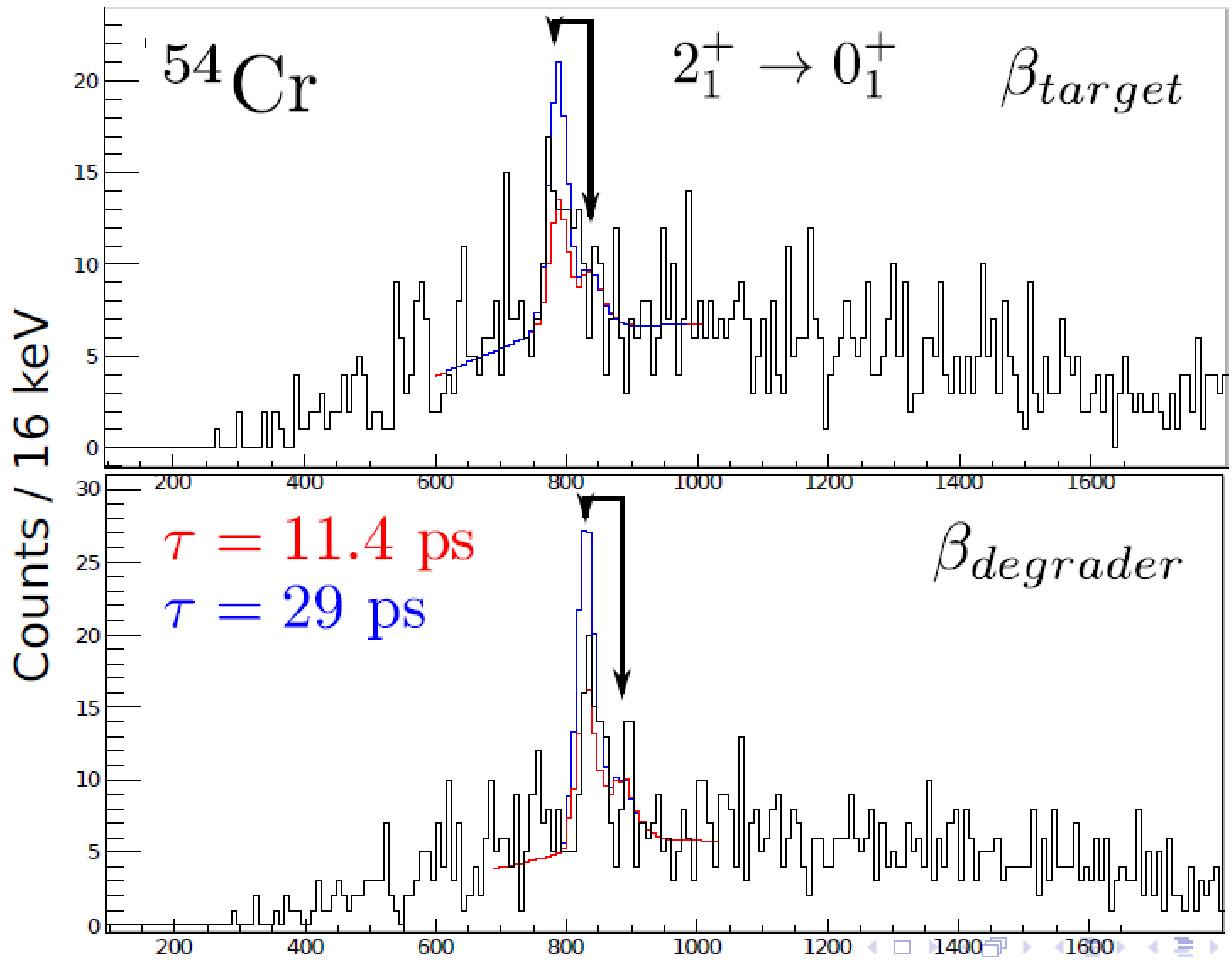
Lineshape simulation





Analysis: M. Hackstein, IKP Cologne

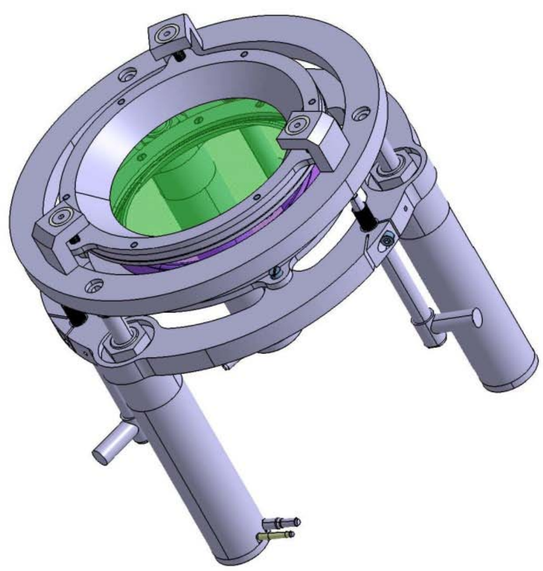
Commissioning run with fixed plunger at GSI: results

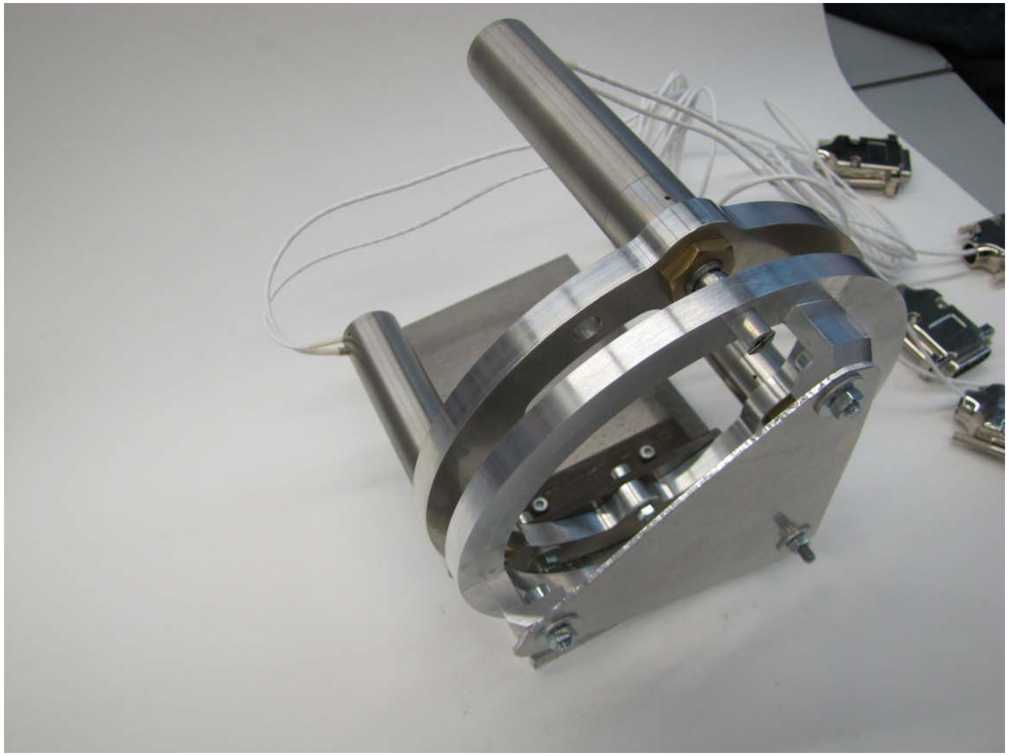


Analysis: M. Hackstein, IKP Cologne

New plunger device for PRESPEC/HISPEC

Target/degrader diameter: 75 mm





- Test device already built with 3 PI motors (type N381 vacuum proof)
- Software for parallel operation of 3 PI motors first version developed by T. Braunroth, IKP Cologne

Conclusion

→ Several experiments with the plunger method
successfully performed on exotic nuclei in different regions, e.g.,
GANIL: VAMOS + EXOGAM
LNL: AGATA + PRISMA
NSCL: A1900 fragment separator + S800 magnetic spectrometer + SeGA
GSI: commissioning run at FRS + RISING/PRESPEC

→ Plunger devices existing for different experimental conditions:
low-energy beams (few MeV/u) up to relativistic beams with 100 MeV/u.

→ Development ongoing to access even more exotic nuclei, e.g.,
at GSI with PRESPEC/HISPEC

Collaboration

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TU Darmstadt, Germany: G. Guastalla, E. Merchan, O. Möller, N. Pietralla, M. Reese, D. Ralet

INFN and University of Milano, Italy: G. Benzoni, A. Bracco, N. Blasi, F. Camera, F. Crespi, B. Million, O. Wieland

Physics Dept. University of Jyväskylä, Finland: R. Julin, T. Grahn, P. Greenless, P. Rahikila, C. Scholey

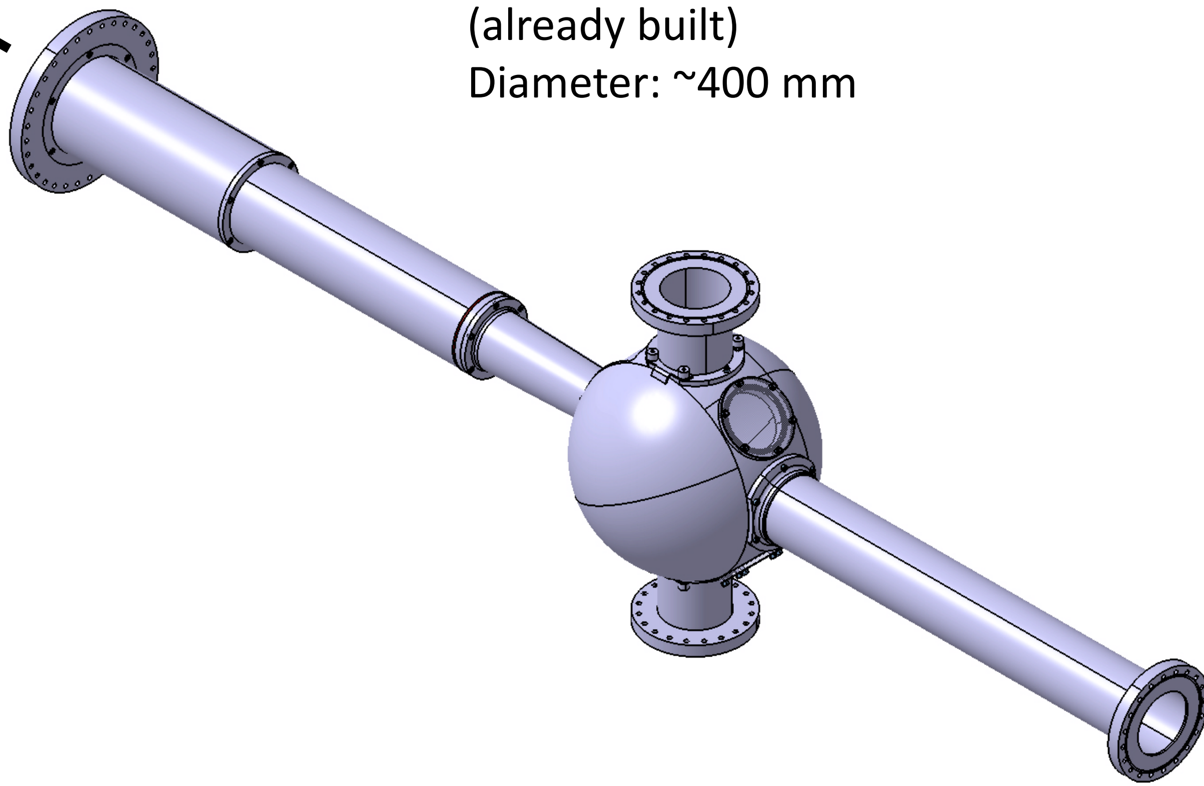
INP, N.C.S.R. Demokritos, Athens, Greece: S. Harissopulos, T. Konstaninopoulos, A. Lagoyannis

Additional transparencies

New developments for experiments at PRESPEC/HISPEC, GSI

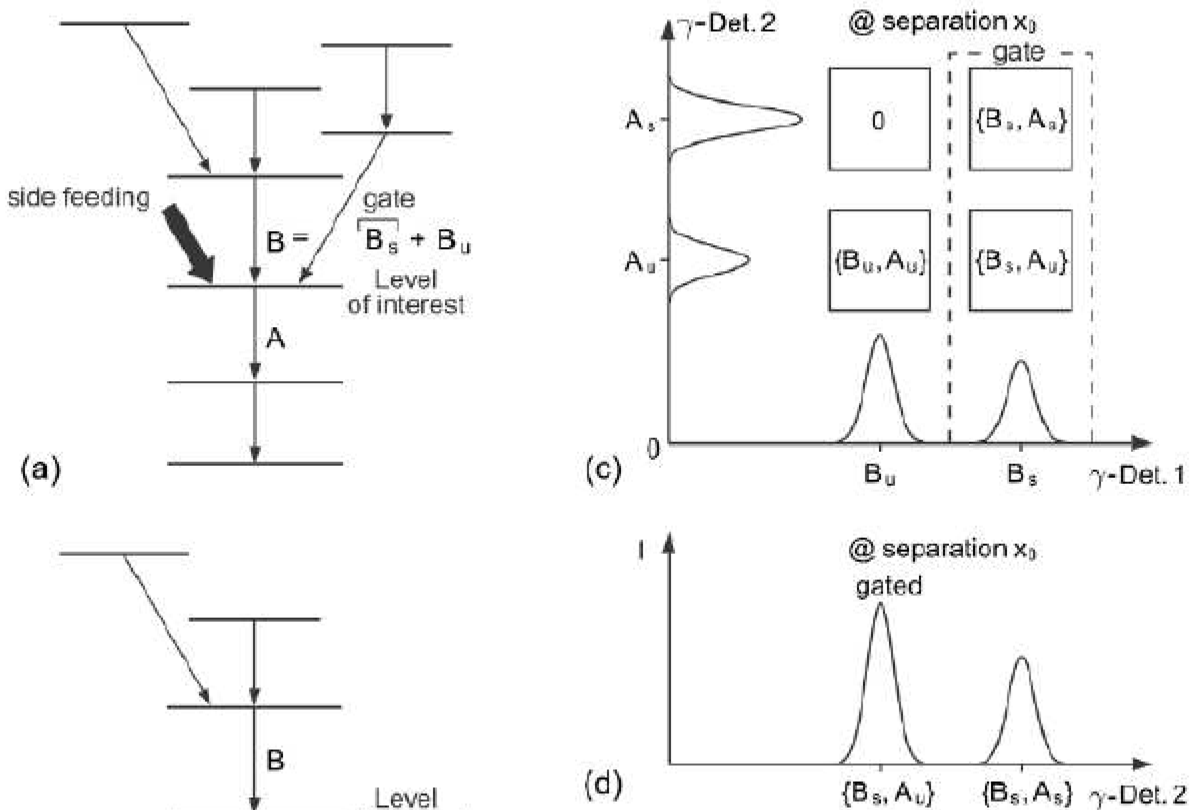
To LYCCA

New target chamber for AGATA at PRESPEC
(already built)
Diameter: ~400 mm



Radioactive beam from FRS

Differential Decay Curve Method - Coincidences



$$\Longrightarrow \quad \tau = -\frac{\{B_s, A_u\}(x_0)}{\Delta\{B_s, A_s\}(x_0)} \cdot \frac{\Delta x}{v},$$

where $\Delta\{B_s, A_s\}(x_0) =$
$\{B_s, A_s\}(x_0) - \{B_s, A_s\}(x_0 + \Delta x)$.

Neutron-rich Fe isotopes at N = 40

In the vicinity of N=40,
only Ni isotopes show
a typical signature of magicity
with high $E(2^+)$ and small B(E2) .

Low $E(2^+)$ for other isotopes
indicate a fragility of
the N=40 (sub) shell closure.

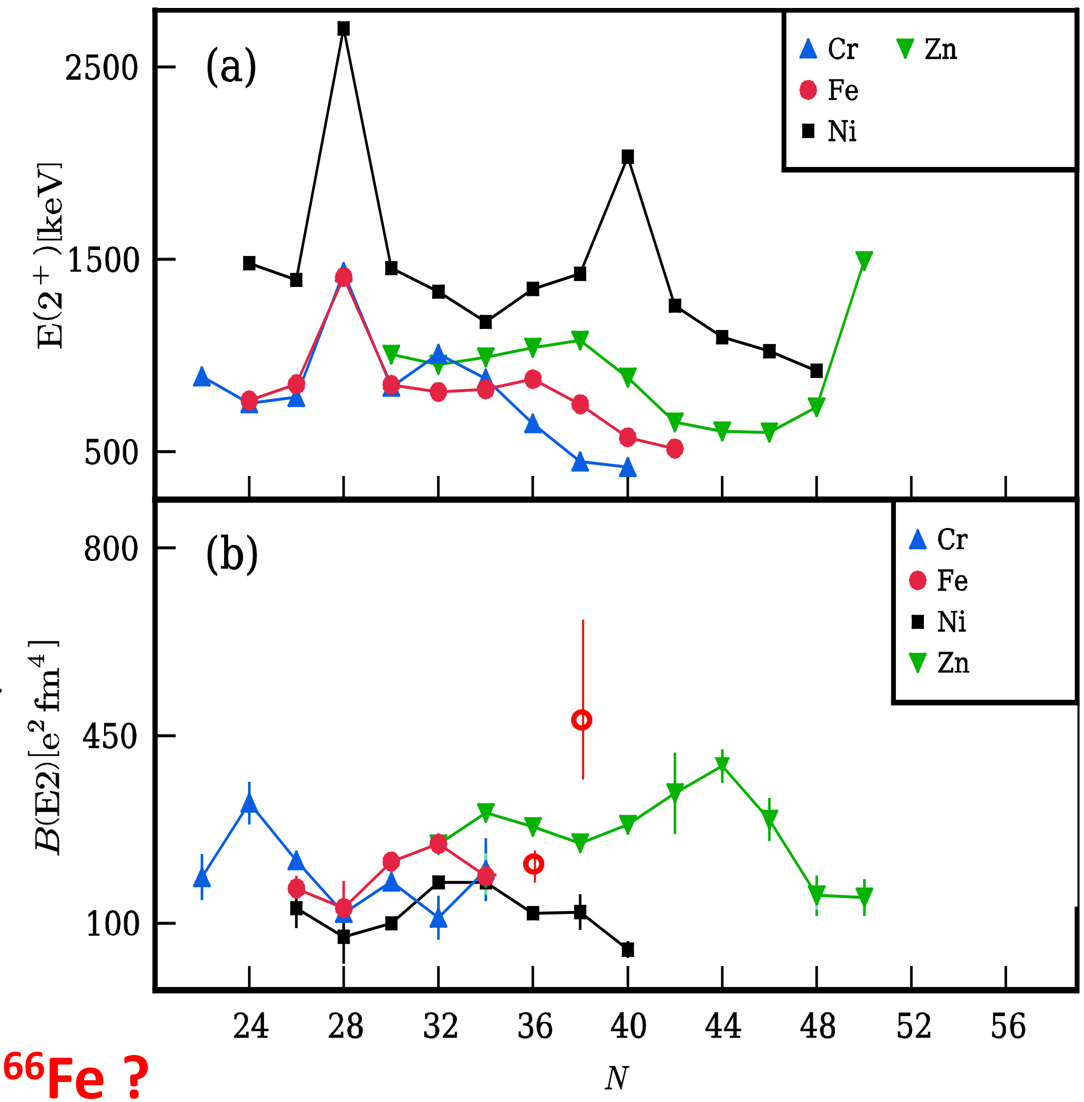
Collectivity at N=40 seems to
be increased toward lighter
isotopes (Ni → Fe → Cr).

(E(2+) ^{66}Fe : M.Hannawald et al., PRL82(99)1391
^{64}Cr : A.Gade et al., PRC81(10)051304R)

But, B(E2) data are still scarce.

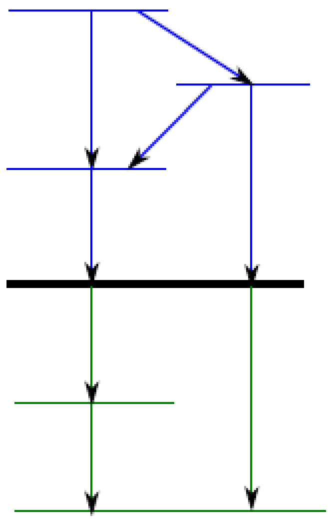
A recent B(E2) data on ^{62,64}Fe
(J.Ljungvall et al., PRC81(10)061301R)
suggest an increse of collectivity
towards N=40.

Systematics $E(2^+)$ and B(E2)



How about ^{66}Fe ?

Differential Decay Curve Method



DDCM

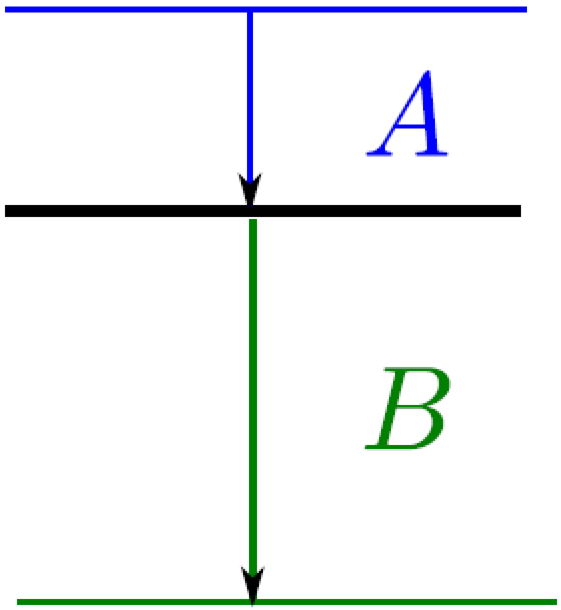
$$\dot{n}_i(t) = -\lambda_i n_i(t) + \sum_h \lambda_h b_{hi} n_h(t)$$

Solutions: Bateman equations. Or: Differential Decay Curve Method (DDCM)[1]

$$\tau_i = \frac{1}{\lambda_i} = \frac{-n_i(t) + \sum_k b_{kh} n_k(t)}{\frac{\mathrm{d}}{\mathrm{d}t} n_i(t)}$$

[1] A. Dewald et al, Z. Phys. A AtomicN uclei 334, 163-175 (1989)

Differential Decay Curve Method - Coincidences



DDCM - coincidences

Direct Feeder:

$$\tau_i = \frac{I^{BA}_{(u,s)}(t)}{\frac{\mathrm{d}I^{BA}_{(s,s)}(t)}{\mathrm{d}t}} \qquad (1)$$

$I^{BA}_{(u/s,s)}$: Coincidences of unshifted / shifted A + shifted B (=Flight of B).

- No sidefeeding
- No problem with unknown feeding
- Model independently (no assumptions)

Structure of neutron rich N=51 nuclei in the vicinity of 78Ni

→Talk by Gilbert Duchene (Wednesday, 3 30 pm)

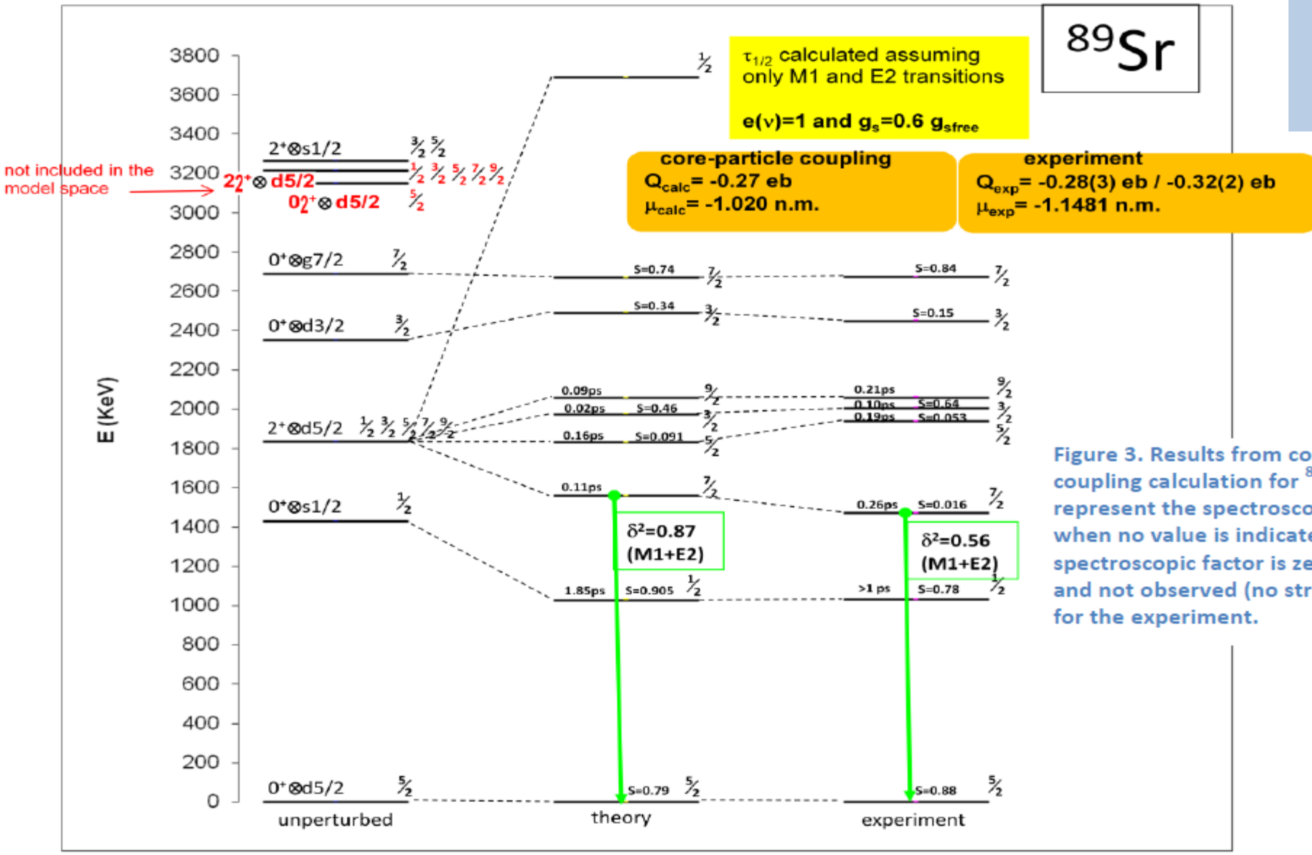


Figure 3. Results from core-particle coupling calculation for ^{89}Sr. S represent the spectroscopic factors, when no value is indicated the spectroscopic factor is zero for theory and not observed (no stripped state) for the experiment.

Table 1 Calculated $7/2^+_1$ half-lives using the core-particle coupling model. Column 5 contains the values obtained for a $7/2^+_1$ calculated as originating from 2*d5/2 and column 6 from 0*g7/2 ("forced" single-particle state situation).

Nucleus	Relative production rate	$E(7/2^+_1)$ Exp	$E(7/2^+_1)$ Th	$\tau_{1/2}(7/2^+_1)$ $2^+ \otimes \nu 2d_{5/2}$	$\tau_{1/2}(7/2^+_1)$ $0^+ \otimes \nu 1g_{7/2}$
89Sr	4.5	1473 keV	1559 keV	0.11 ps	10.3 ps
87Kr	27	1578 keV	1598 keV	0.13 ps	16.1 ps
85Se	36	1115 keV	1226 keV	0.29 ps	55.1 ps
83Ge	1	867 keV	1035 keV	0.70 ps	214 ps

D. Verney,
G. Duchene,
G. de Angelis et al.

Outline

1. Introduction: recent experiments with the plunger
2. Plunger technique: a short overview
3. Experiments with the compact plunger at Legnaro (AGATA, PRISMA) and at GANIL (EXOGAM, VAMOS)
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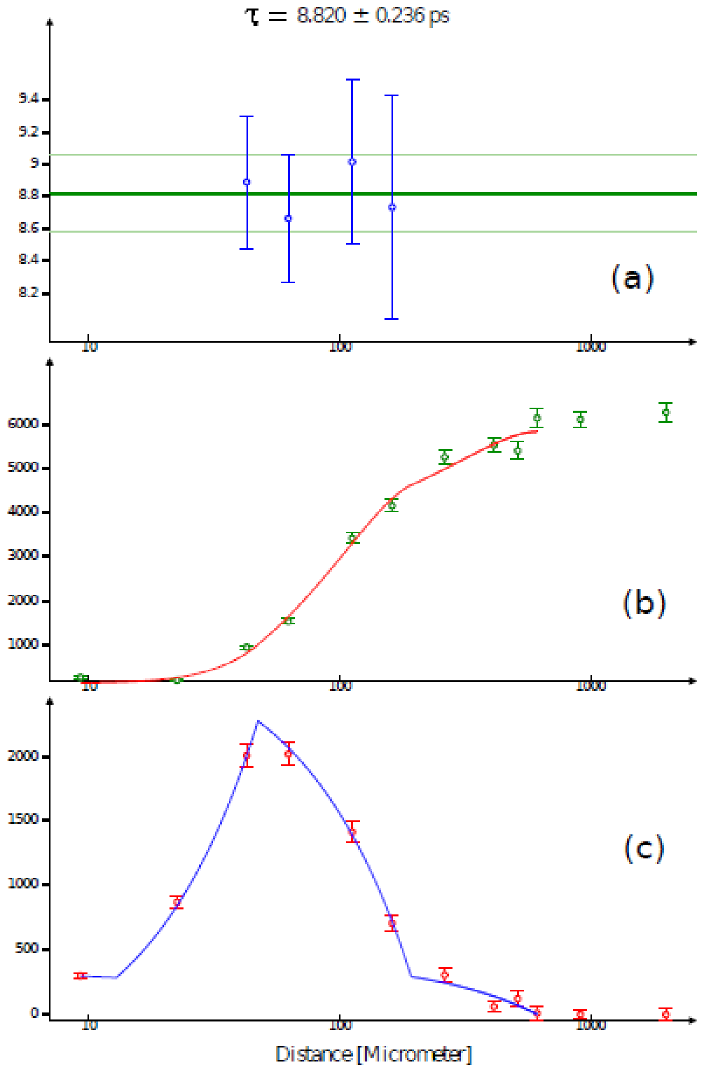
The plunger technique



- Plot ratio $I_1/I_1 + I2$ vs distance
- Every distance d_i gives $\tau_{d_i} = f_{d_i}(\frac{I_1}{I_1+I_2})$
- More reliable*: **D**ifferential **D**ecay **C**urve **M**ethod
- Differential: $\frac{d}{dt} = \frac{d}{dx}\frac{dx}{dt} = v\frac{d}{dx}$

* Depending on statistics and distances measured.