# Spectroscopy of very heavy elements (II)

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# Outlook

- Interest and motivations
- Limits of stability : macroscopic aspects
- Decay modes
- Discovery of the heaviest elements

①

- Production
- Stability : microscopic aspects
- Decay spectroscopy
  - Technique, alpha decay, atomic effects, K-isomers

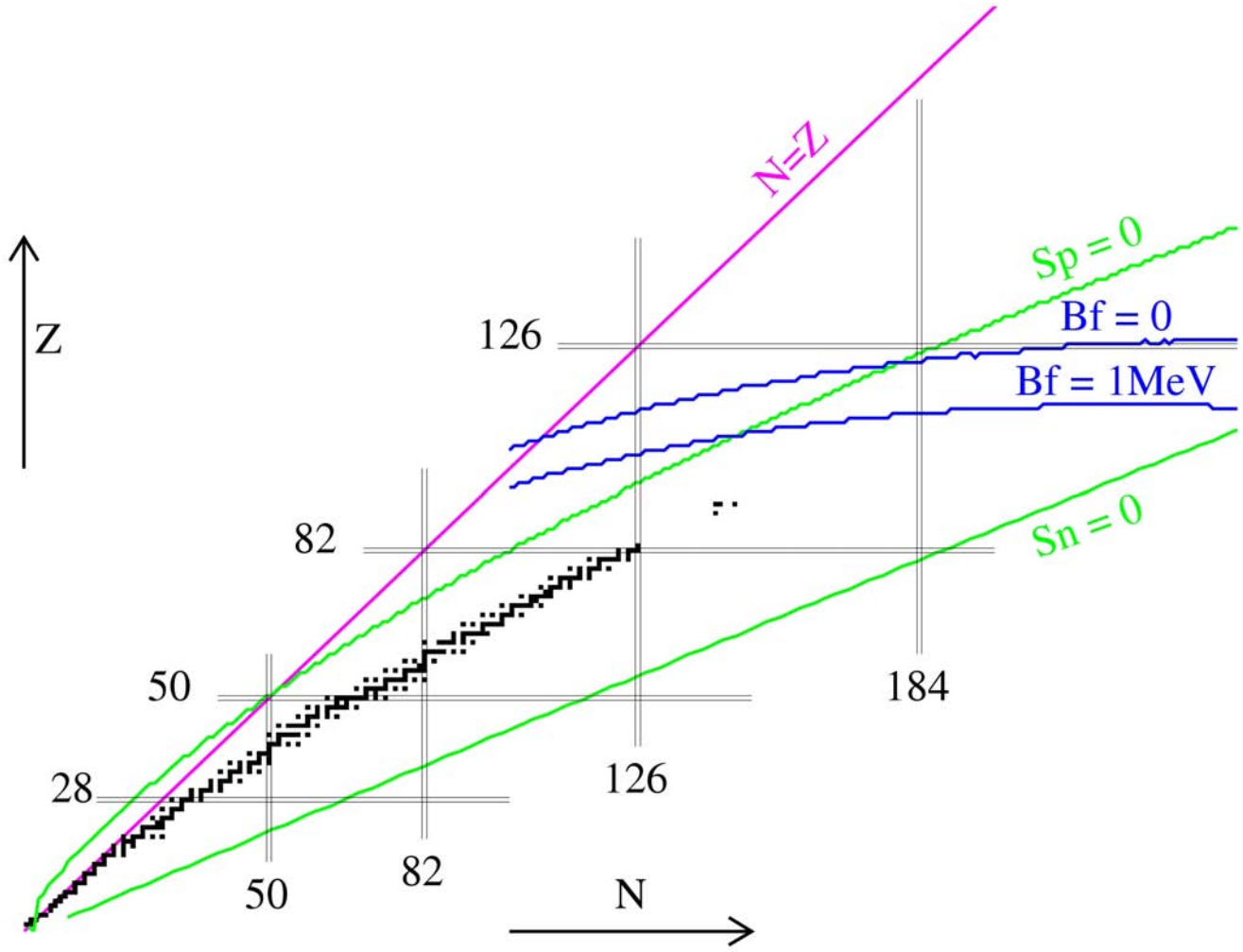
②

③

- Separators, spectrometers and focal plane devices
- Prompt spectroscopy
  - Recoil Decay Tagging
  - Gamma and electron spectroscopy
- Pushing the limits : facilities and devices

④

# Limits of stability from liquid drop model



# Magic numbers

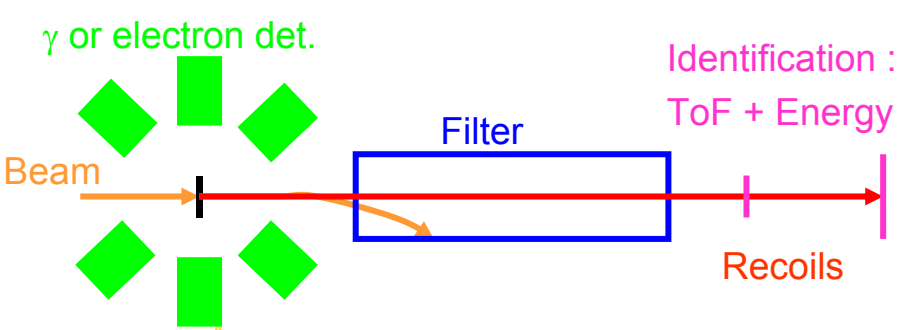
| | Z | N |
|---|---|---|
| W.S | 114 | 184 |
| HFB | 126 | 184 |
| RMF | 120 | 172 |

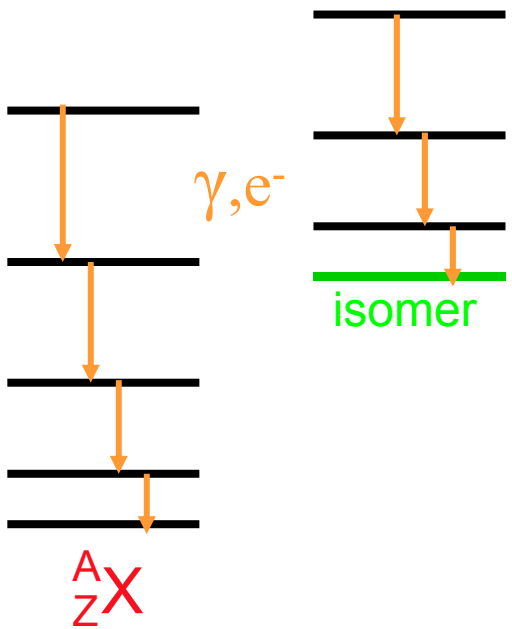
Note 1 :Up to $^{208}$Pb : proton and neutron magic numbers identical.

Note 2 : Models rely on extrapolations –parameters are adjusted on known cases

# Experimental techniques

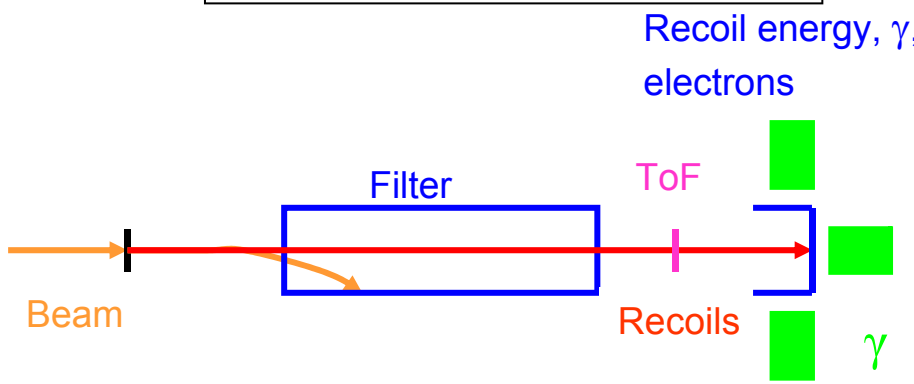
## Prompt spectroscopy

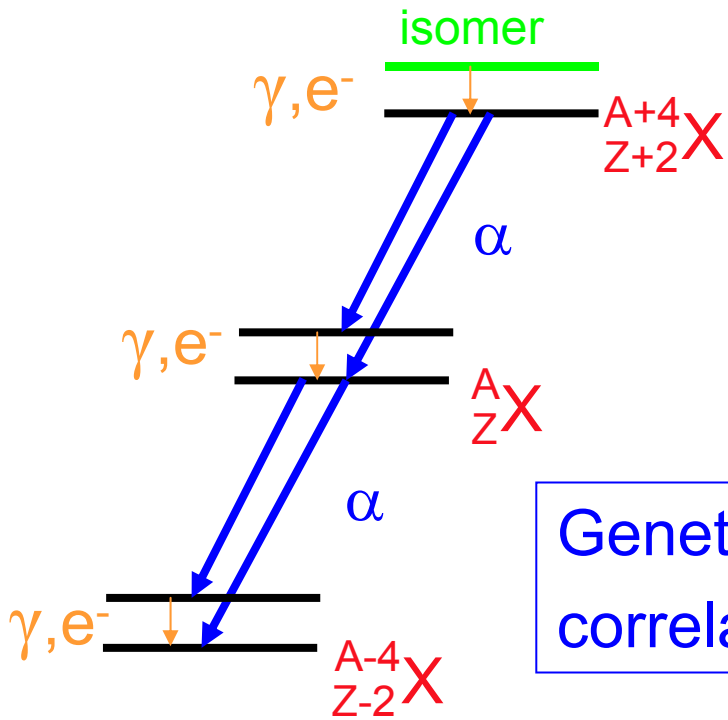



Recoil (decay) Tagging

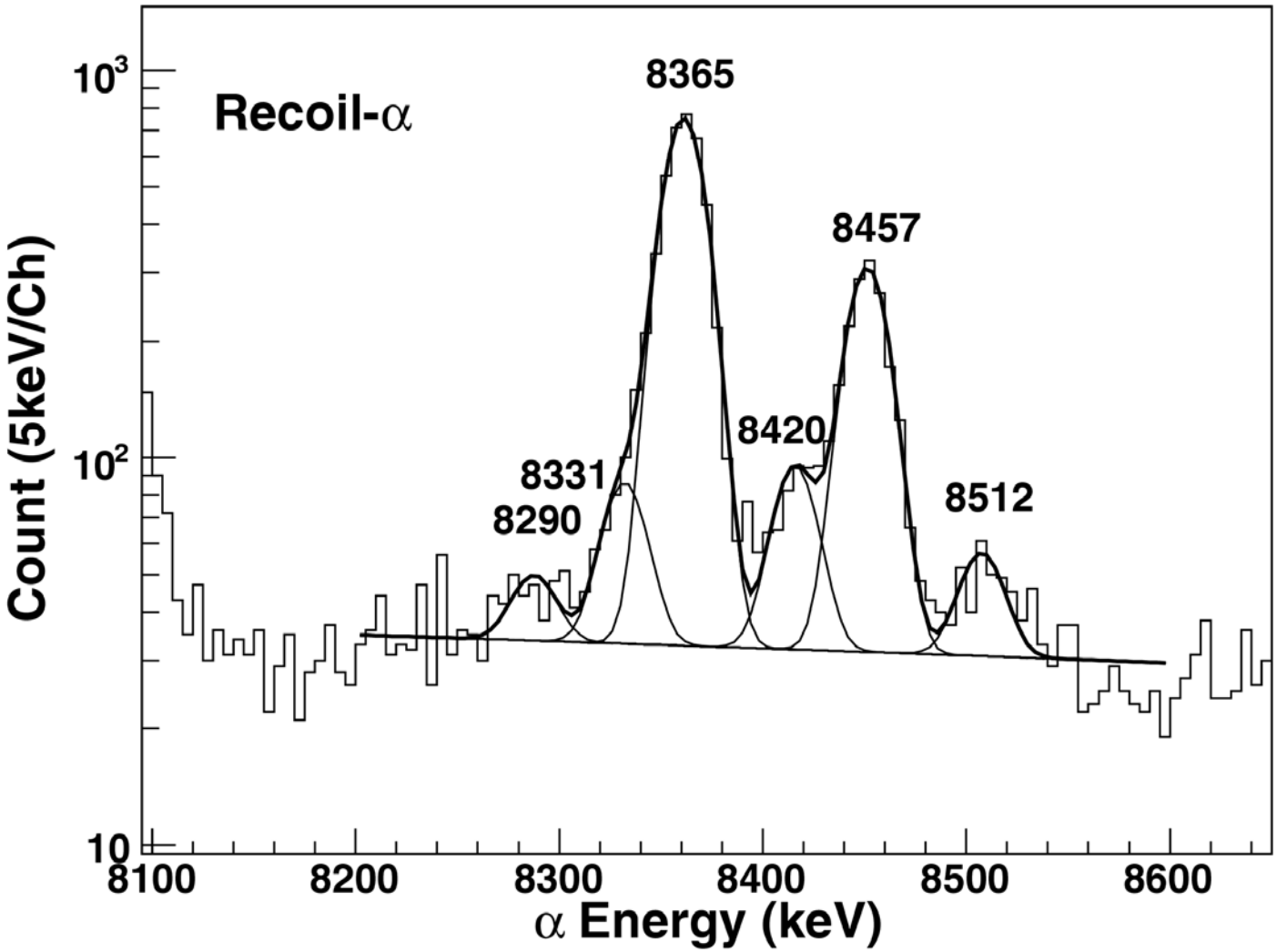
## Decay spectroscopy

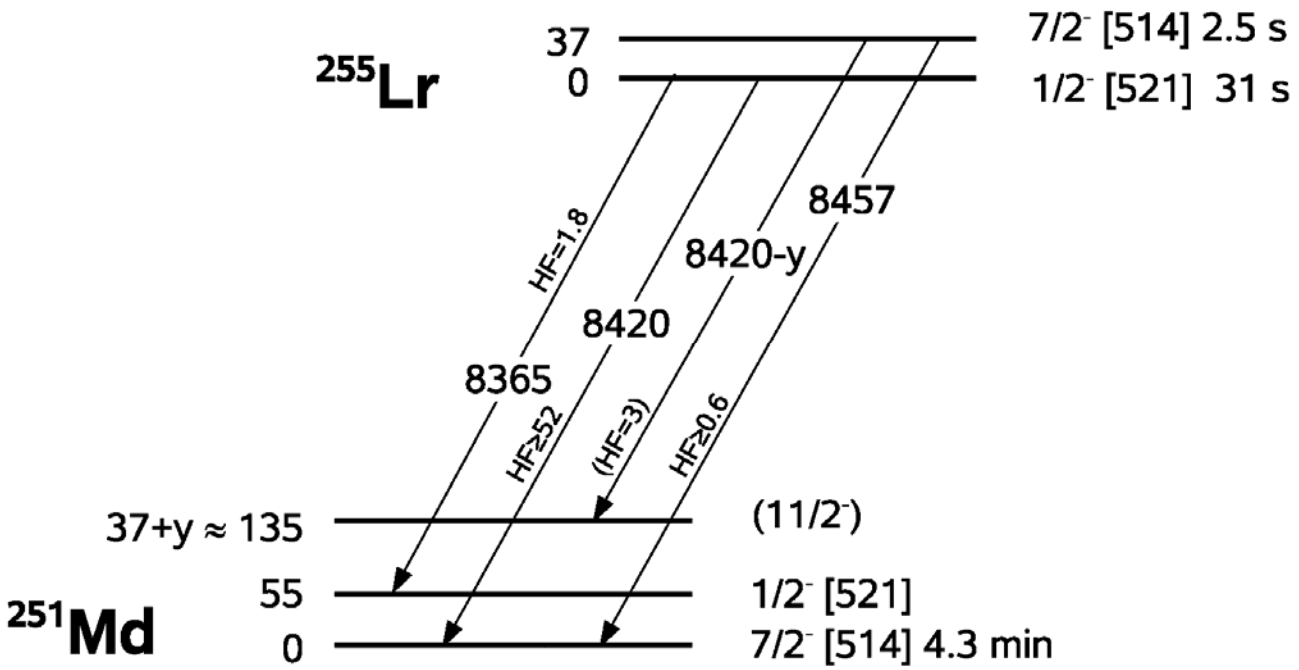



Genetic correlations

# Example 2 : alpha decay $^{255}Lr \rightarrow ^{251}Md$



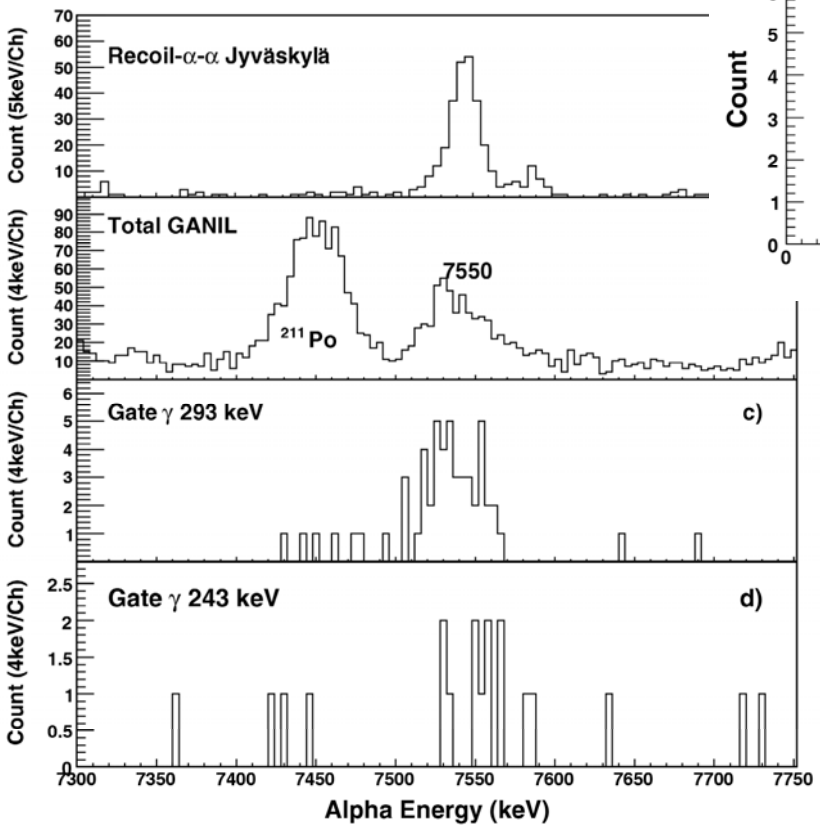


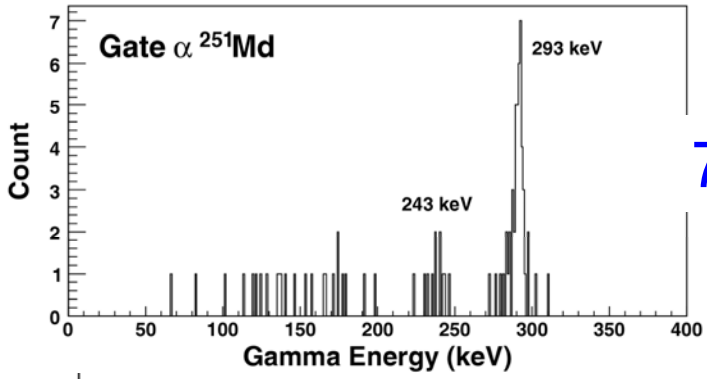

A. Chatillon et *al*., EPJA 30 (2006) 397

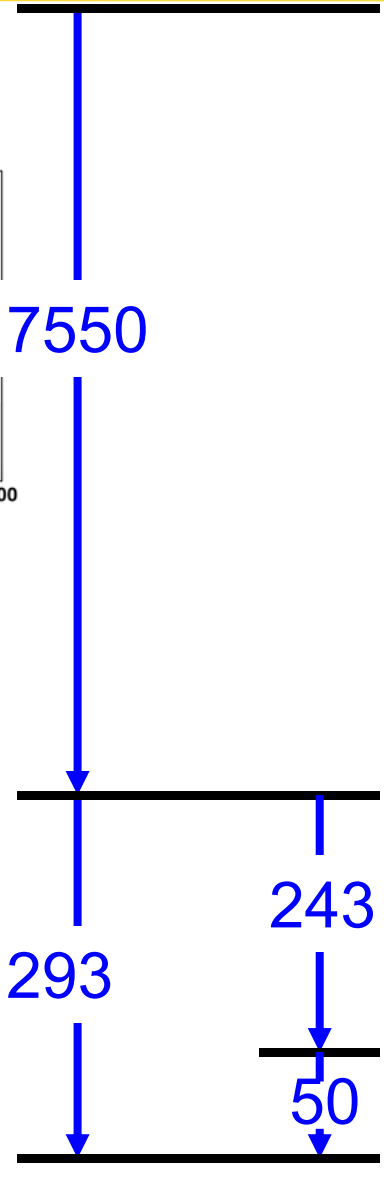
# Electromagnetic decay

Alpha-gamma and alpha-electron coincidences

Example :



# Electromagnetic decay

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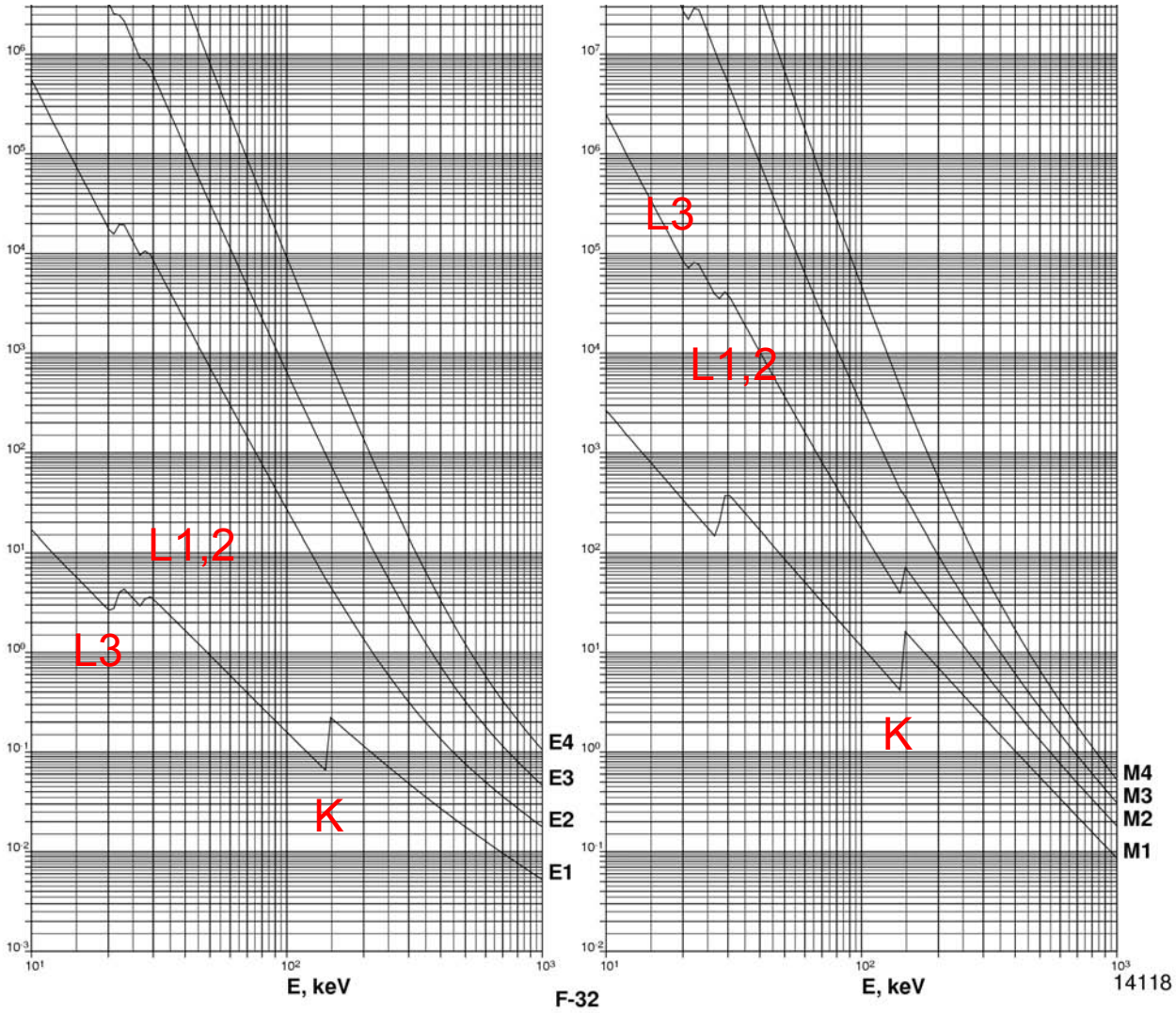
Electron conversion is high !



$E_{electron} = E_{transition}$ – Electron binding energy

Conversion coefficient $\alpha = I(electron)/I(\gamma)$

$\alpha \uparrow$ when $Z \uparrow$

$\alpha \uparrow$ when $E \downarrow$

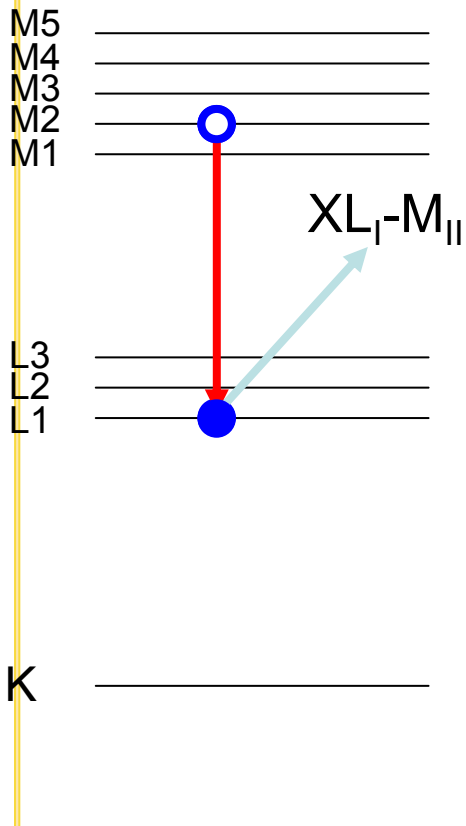
$\alpha \uparrow$ when $\Delta I \uparrow$

- Example : 50 keV transition, Z = 100

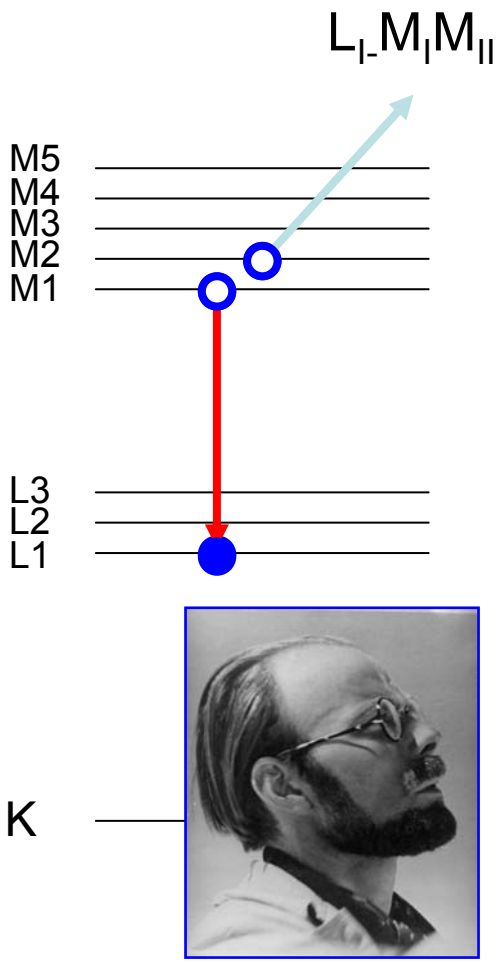
| | E1 | E2 | M1 | M2 |
|---|---|---|---|---|
| Total | $9.47\ 10^{-1}$ | $7.28\ 10^{2}$ | $8.78\ 10^{1}$ | $3.67\ 10^{3}$ |
| K | - | - | - | - |
| L | $7.03\ 10^{-1}$ | $5.16\ 10^{2}$ | $6.49\ 10^{1}$ | $2.59\ 10^{3}$ |
| M | $1.80\ 10^{-1}$ | $1.48\ 10^{2}$ | $1.61\ 10^{1}$ | $7.72\ 10^{2}$ |

# Atomic effects

## X-Ray

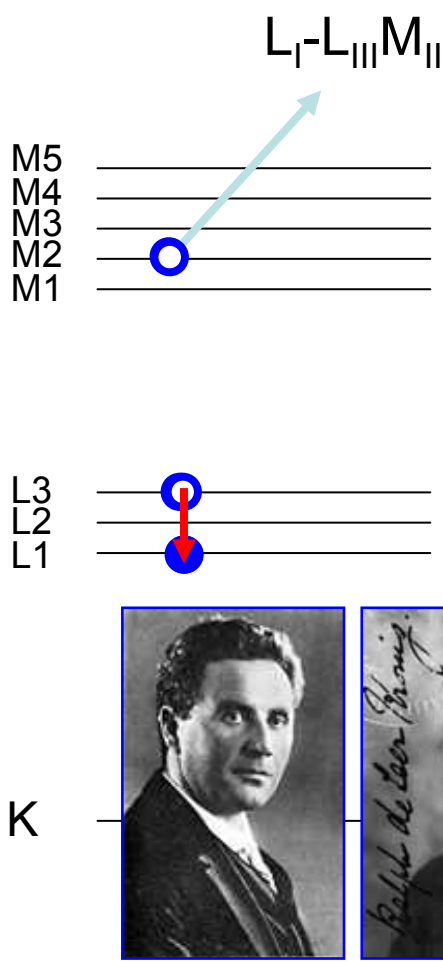



## Auger

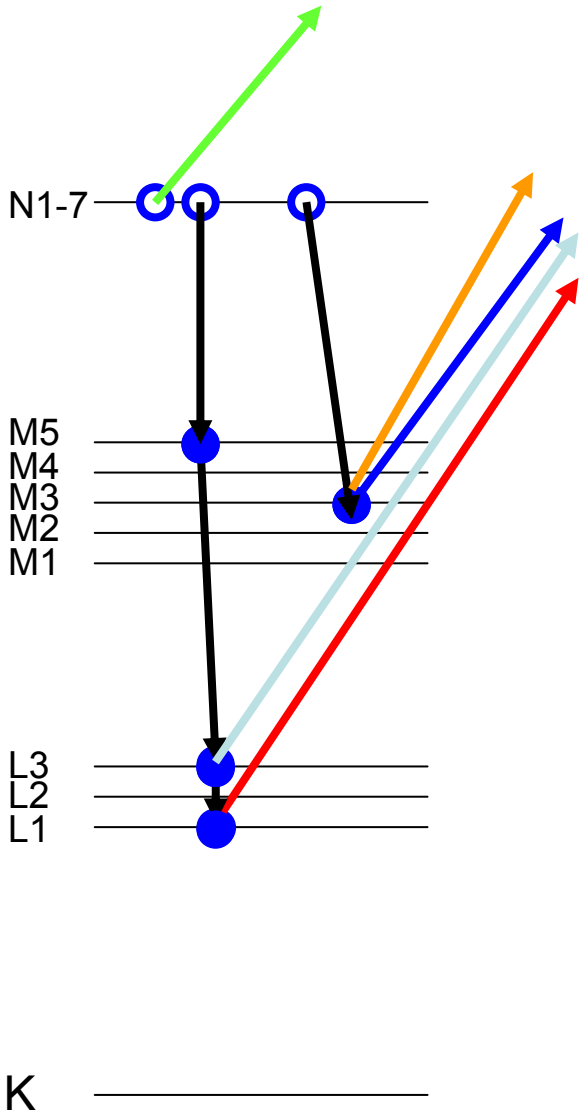





## Coster-Kronig



# Example (Z=99 Conversion 50 keV M1)




1 Conversion $L_I$ 23.2

2 Coster-Kronig $L_I$-$L_{III}M_{III}$ 1.1

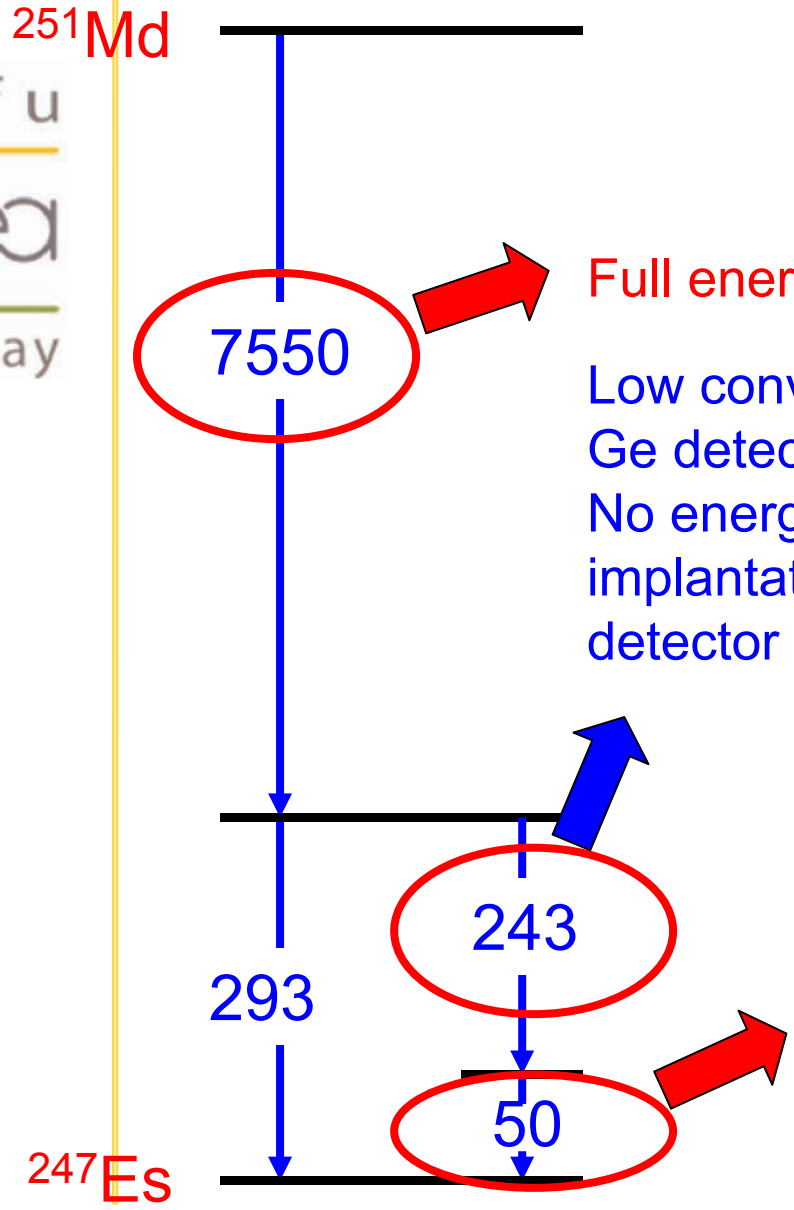
3 X $L_{III}$-$M_V$ 16.0

4 X $M_{III}$-$N_I$ 3.4

5 Auger $M_V$-$N_VN_{VII}$ 2.9

And so on…

# Electron summing



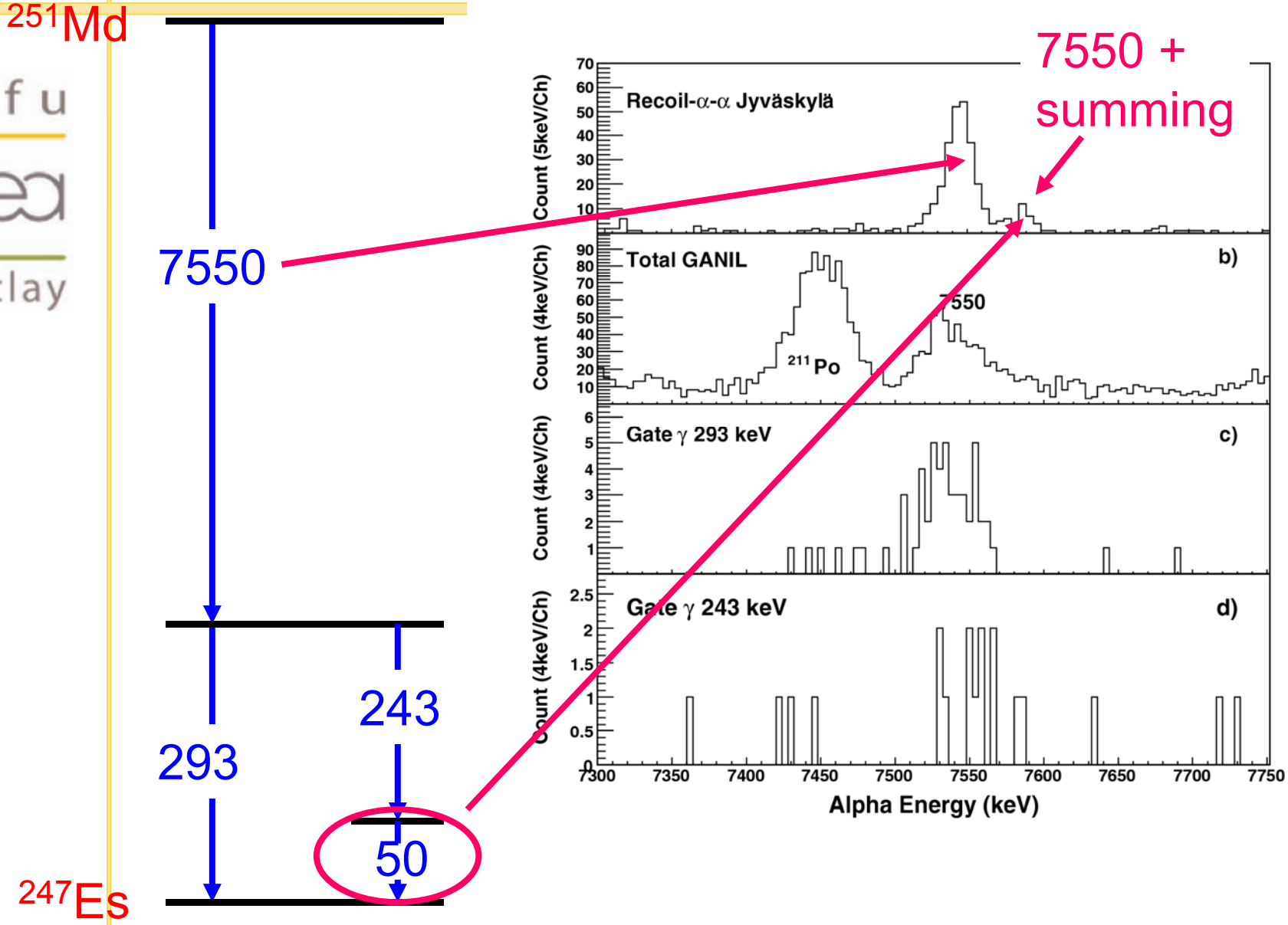

Full energy in implantation detector

Low conversion.
Ge detector
No energy in implantation detector

Summing
Edet =
7550 + energy<50)

High conversion → conversion electron, low energy X-ray and auger electron deposit energy in implantation detector

# Electron and X-ray summing



# Summing

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Needs simulations to understand alpha spectra

Some alpha line do not correspond to a mother – daughter alpha transition, but result from the summing of alpha lines and atomic processes

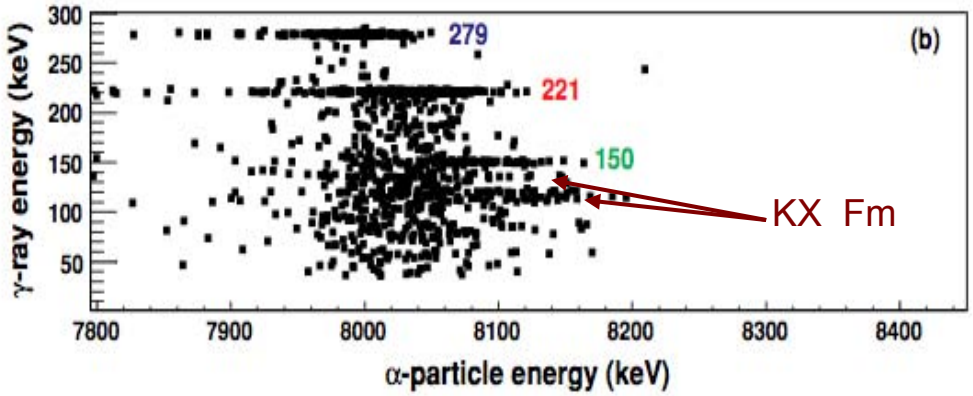
(for details see Theisen, Lopez-Martens, Bonnelle NIM A 580 (2008) 230)

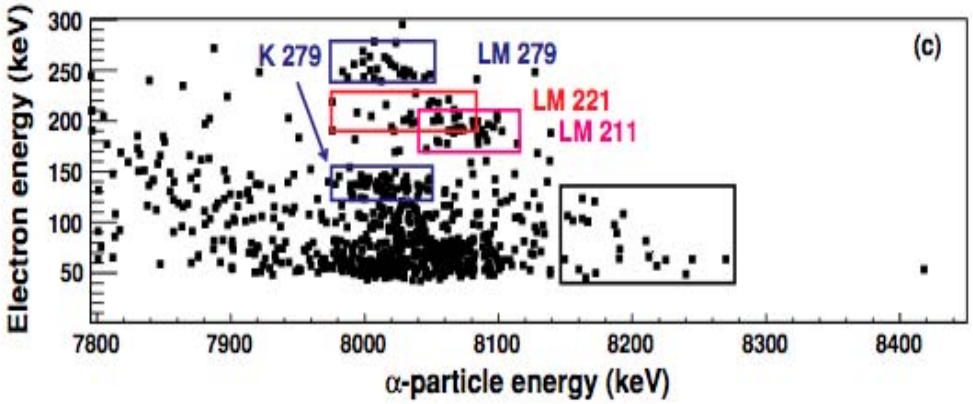
Alpha spectra have to be taken with care !

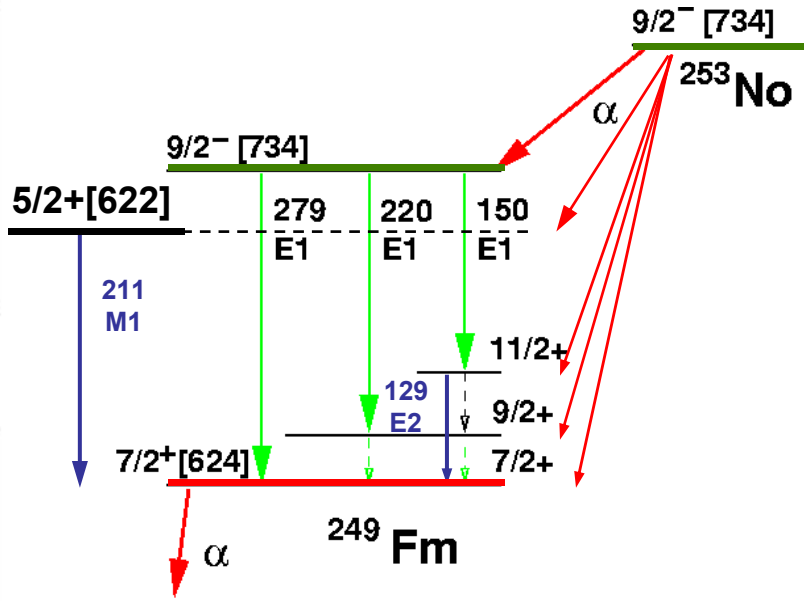
# Alpha – gamma and electrons correlations

$^{207}Pb(^{48}Ca,2n)^{253}No \rightarrow ^{249}Fm$

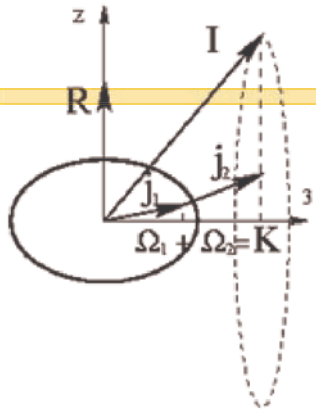
A. Lopez-Martens et al., Phys. Rev. C 74 (2006) 044303

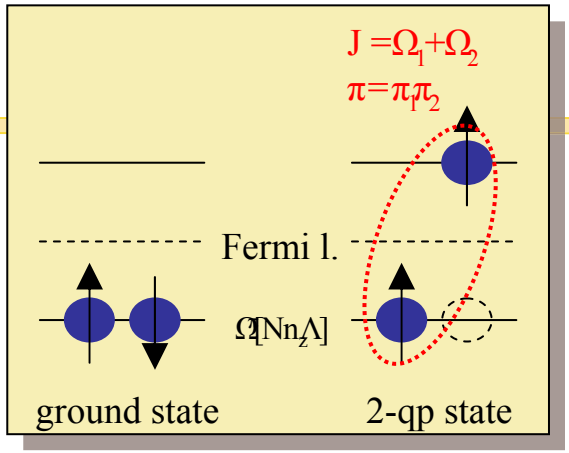


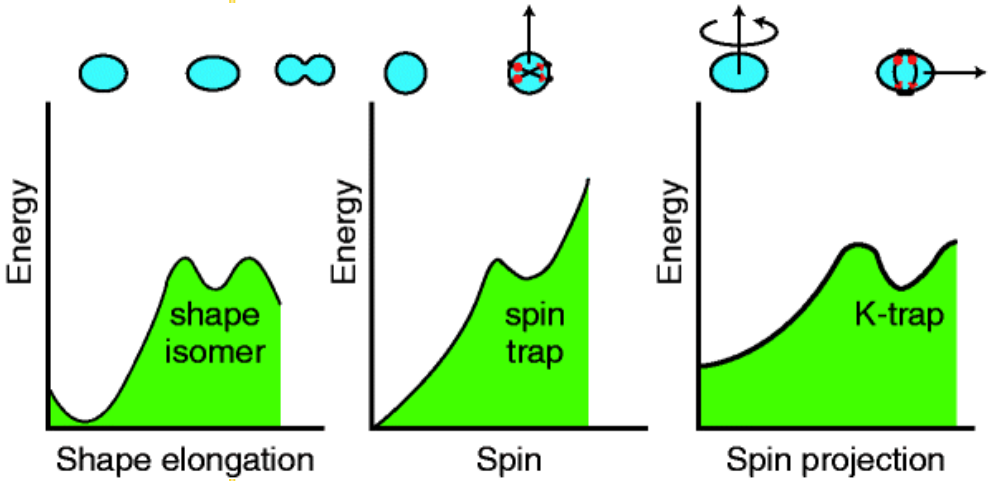



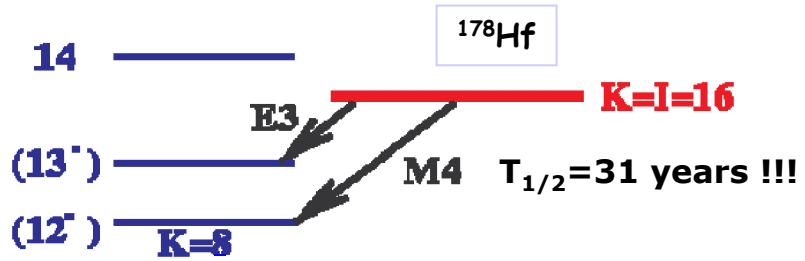
# K-isomer




**Example of Isomeric transition**



# K-isomer

- Degree of K forbidness $\nu = \Delta K - \lambda$

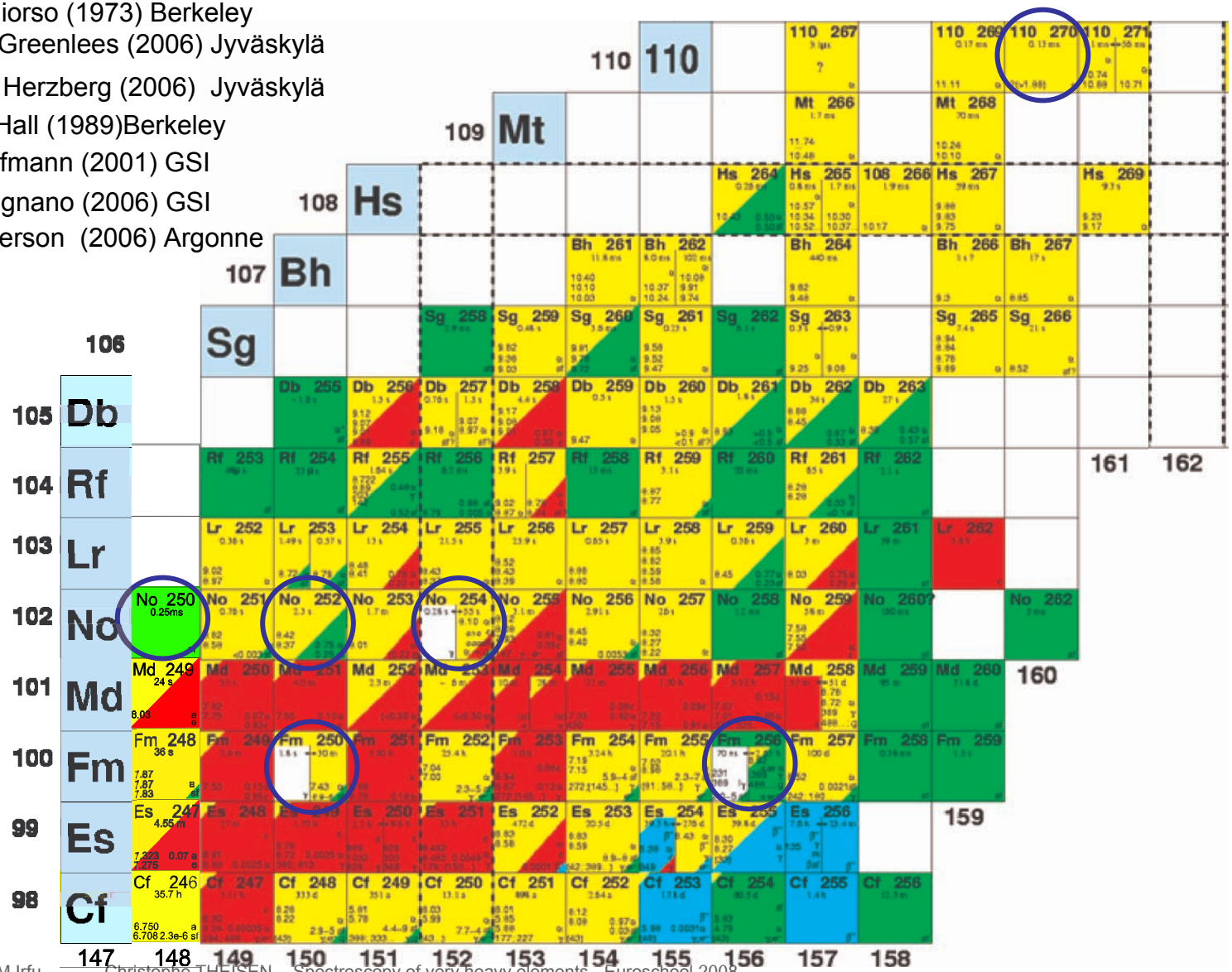
- Empirical rule : $F_W = \dfrac{T^{\gamma}_{1/2}(\text{experiment})}{T^{\gamma}_{1/2}(\text{Weisskopf})} \sim 100^{\upsilon}$

- ie each degree of forbidness increases the lifetime by a factor of 100 compared to Weisskopf estimates

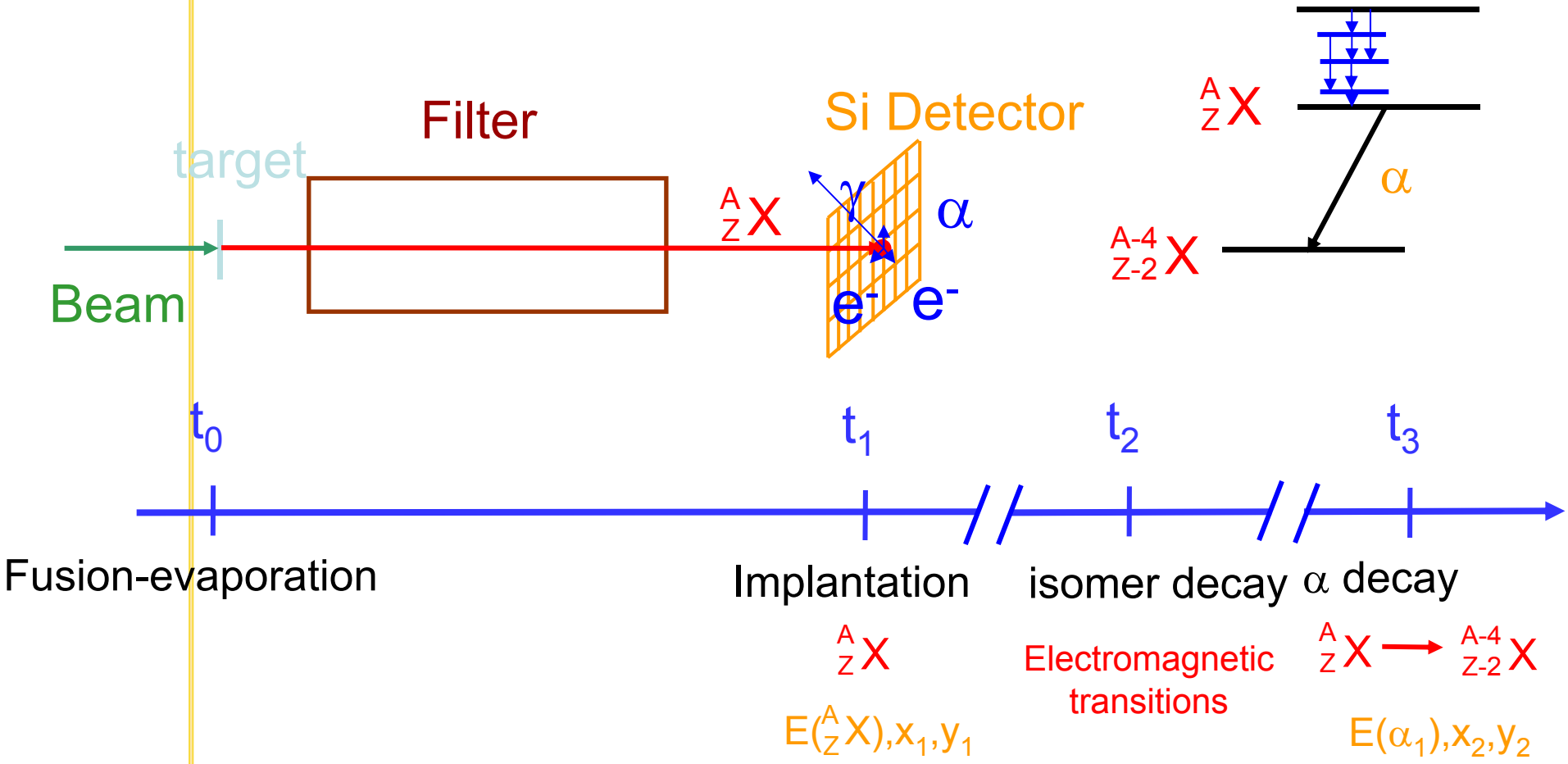
Löbner, PL 26B (1968) 369
Walker J. Phys. G 16 (1990) L233

# K-isomer in even-even nuclei

A. Ghiorso (1973) Berkeley
P. T. Greenlees (2006) Jyväskylä
R.-D. Herzberg (2006) Jyväskylä
H. L. Hall (1989)Berkeley
S. Hofmann (2001) GSI
B. Sulignano (2006) GSI
D. Peterson (2006) Argonne



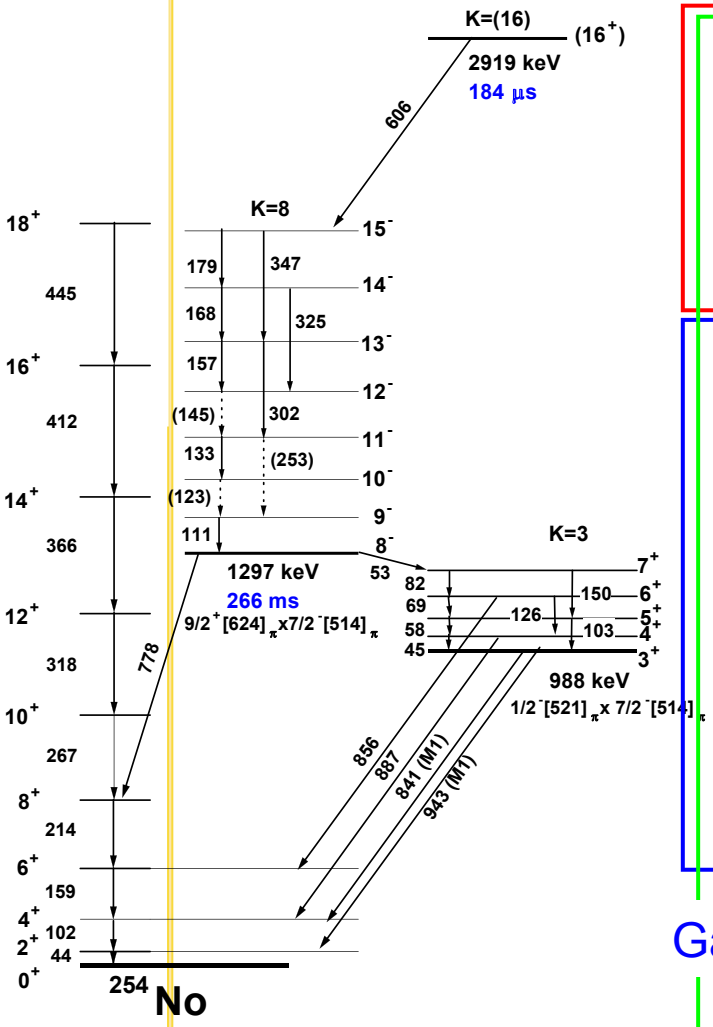
# Isomer tagging



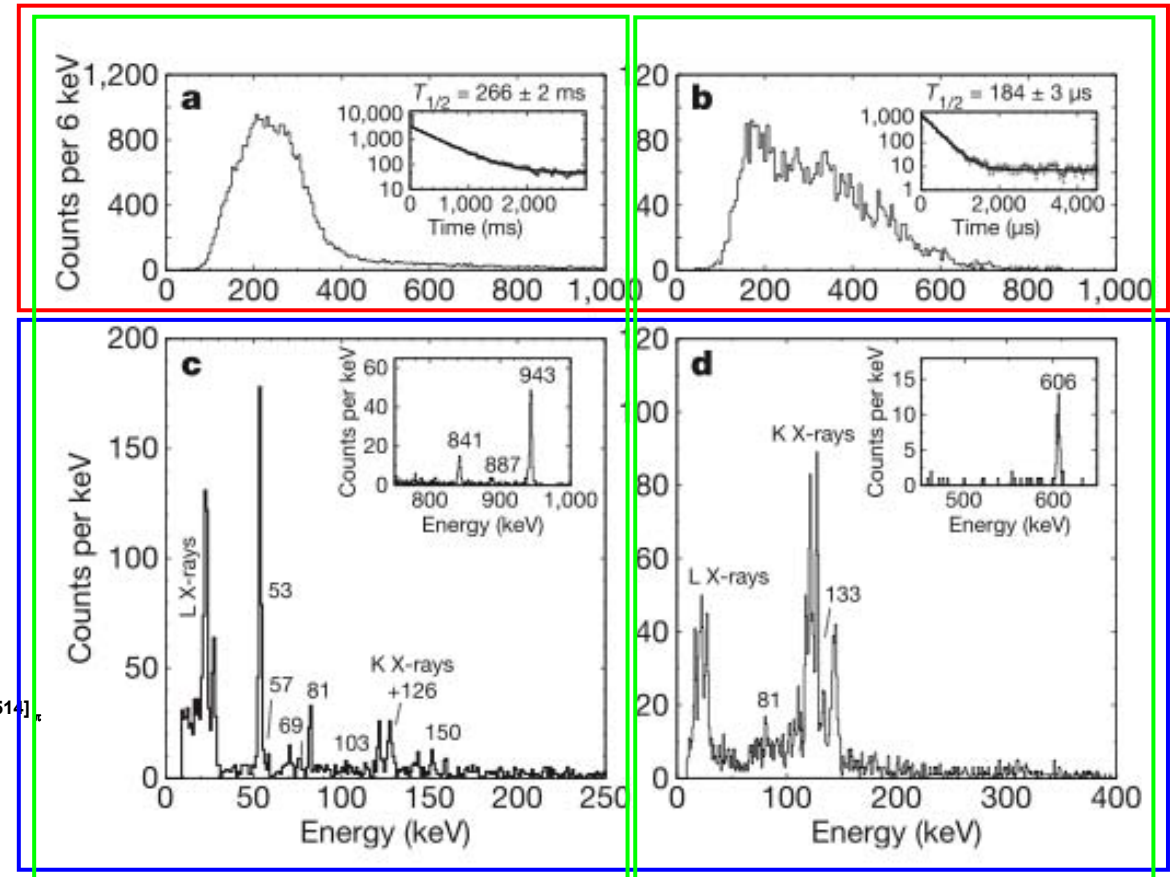

Calorimeter technique :
isomer tagging using the implantation detector
G.D. Jones, Nucl. Instr. And Meth. A 488 (2002) 471

$\Delta t = t_2 - t_1$
$\Rightarrow t_{1/2}$(isomer)

# $^{254}$ No K-isomers




Electrons, implantation det.




Gammas, Delayed ER-gamma-electron coincidences

Long isomer

Short isomer

R.-D.Herzberg et al Nature 442 (2006) 896

# K-isomer

How to assign the configuration (proton or neutron) of a 2qp state (even even nucleus) ?

# Comparison experiment - theory

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General remarks

- Comparison of a given nucleus with theory is usually not very instructive. A more general view is needed e.g. comparison of isotopic or isotonic chain
- Accuracy of models not better than ~200 keV. Comparison of absolute energy like level ordering may be not instructive
- Collective vibrations or other degree of freedom like triaxiality may not be included in models (because of complexity)
- On the other side, trends, evolution in isotonic or isotopic chain is instructive.

# Comparison with theory Es isotopes (I)

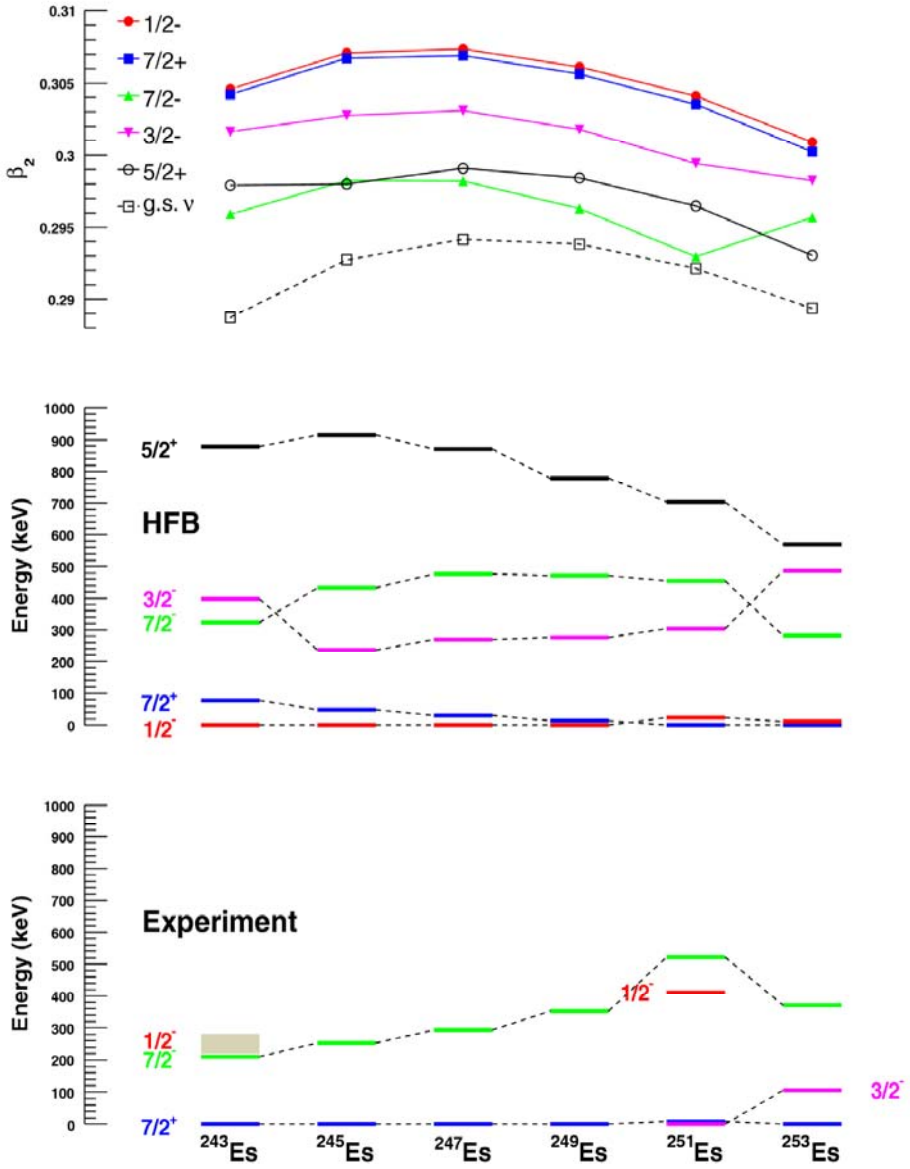
Trace separation of states from 4 spherical shells:

$\pi[521]1/2^-$ $(2f_{5/2})$

$\pi[514]7/2^-$ $(1h_{9/2})$

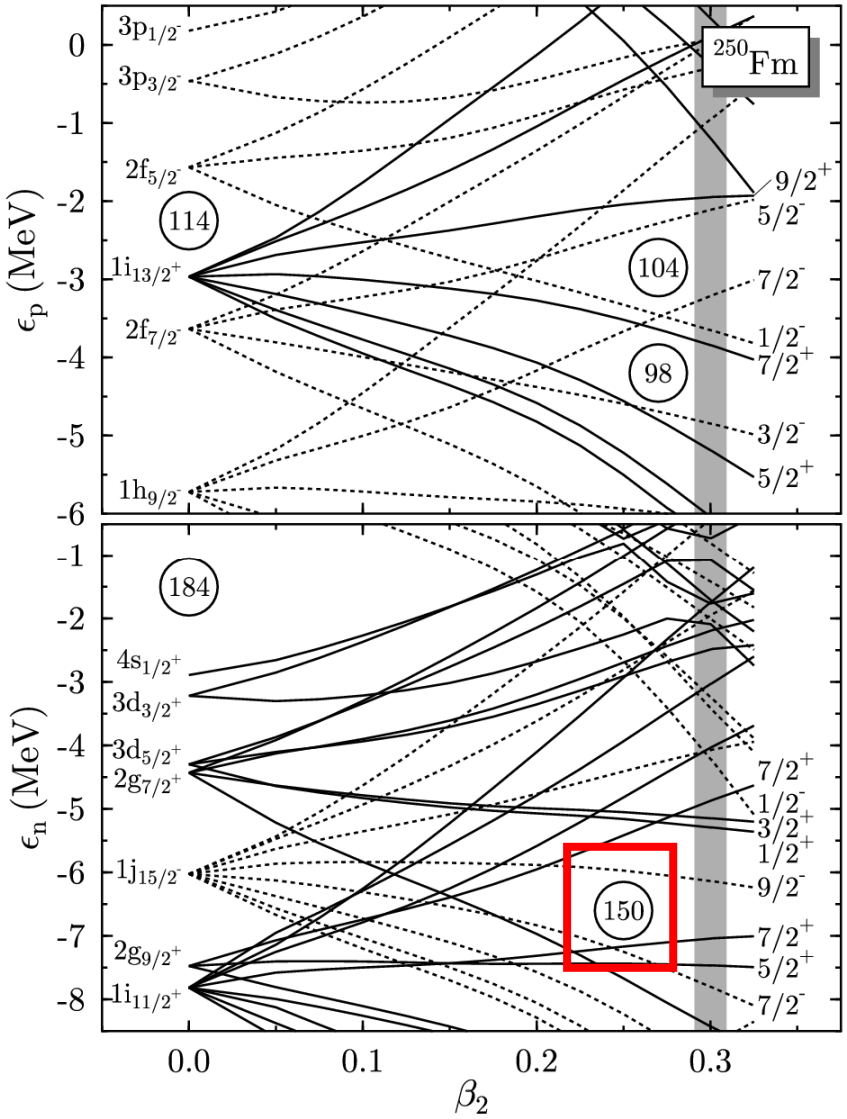
$\pi[633]7/2^+$ $(1i_{13/2})$

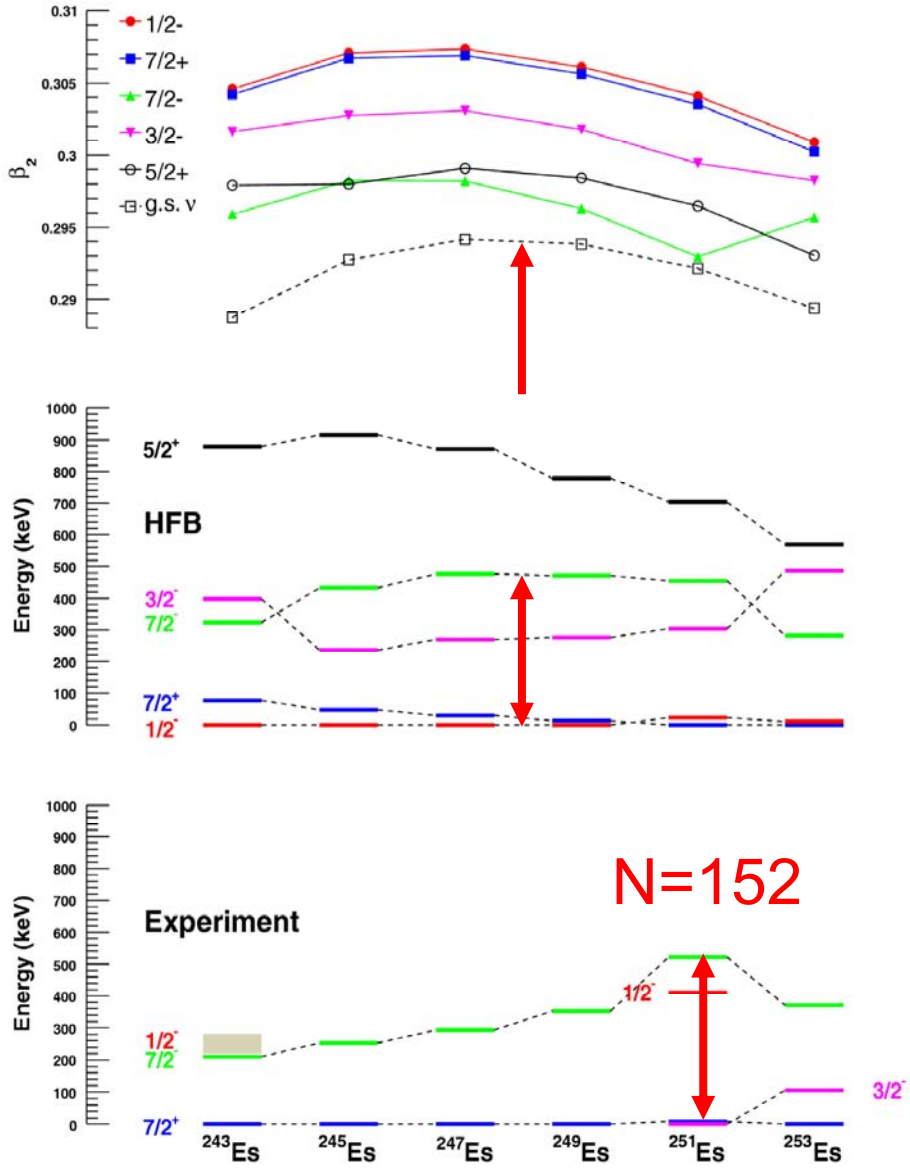
$\pi[521]3/2^-$ $(2f_{7/2})$



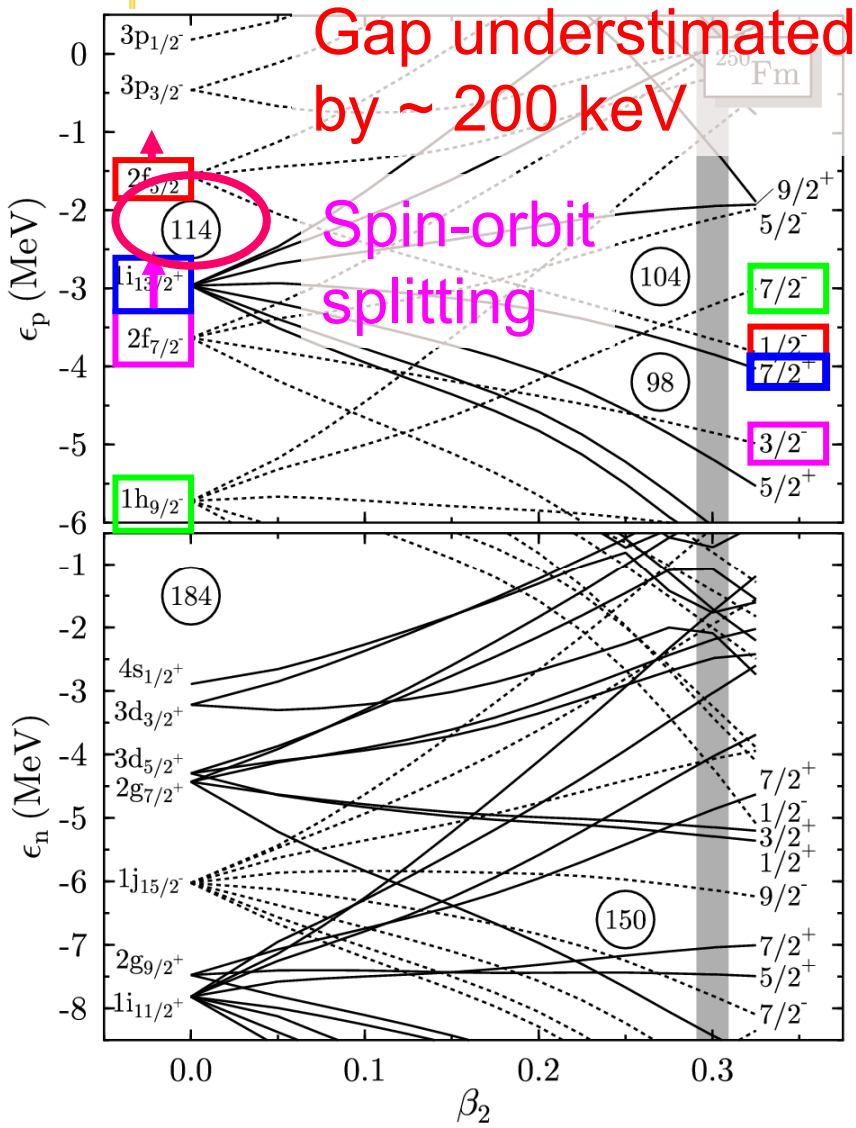

A. Chatillon et al., EPJA 30 (2006) 397

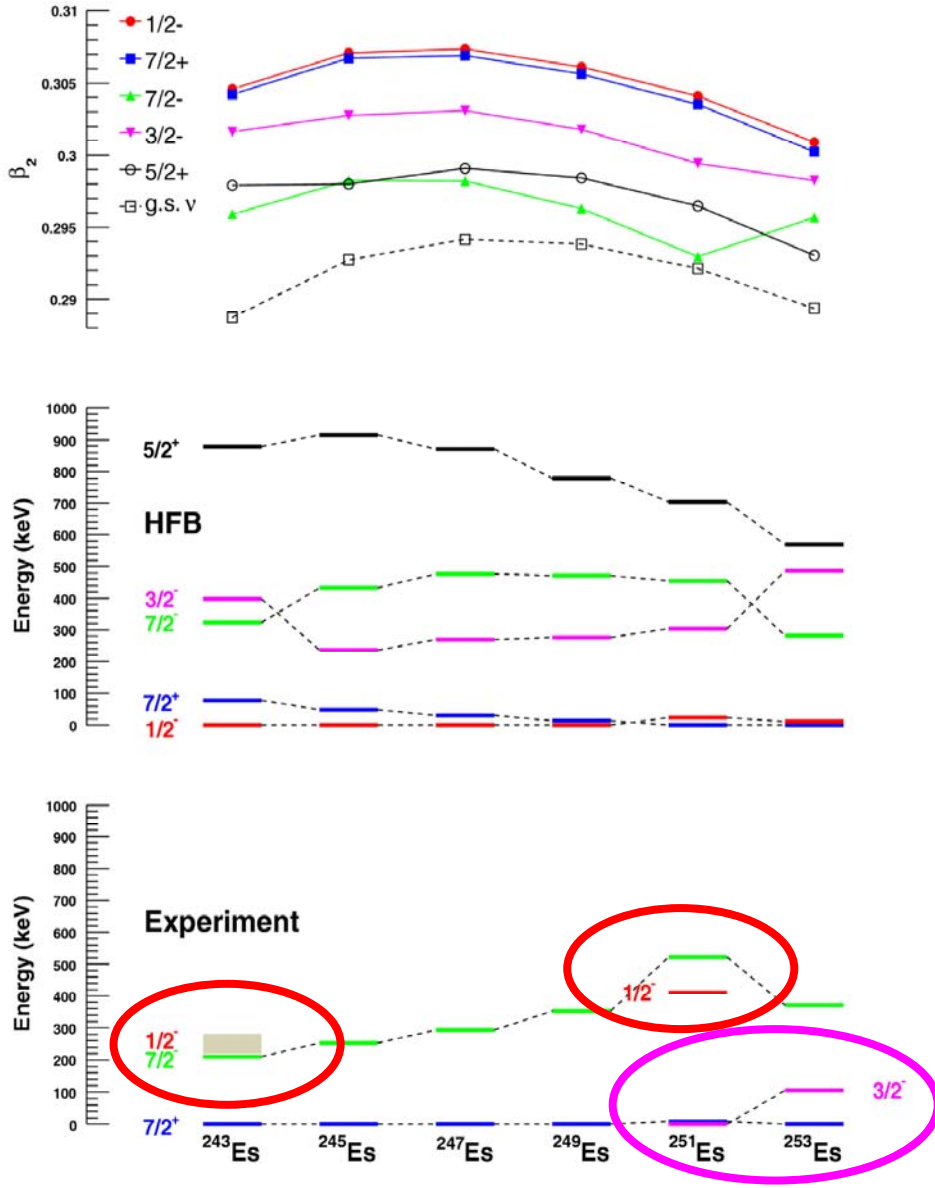
# Comparison with theory Es isotopes (II)



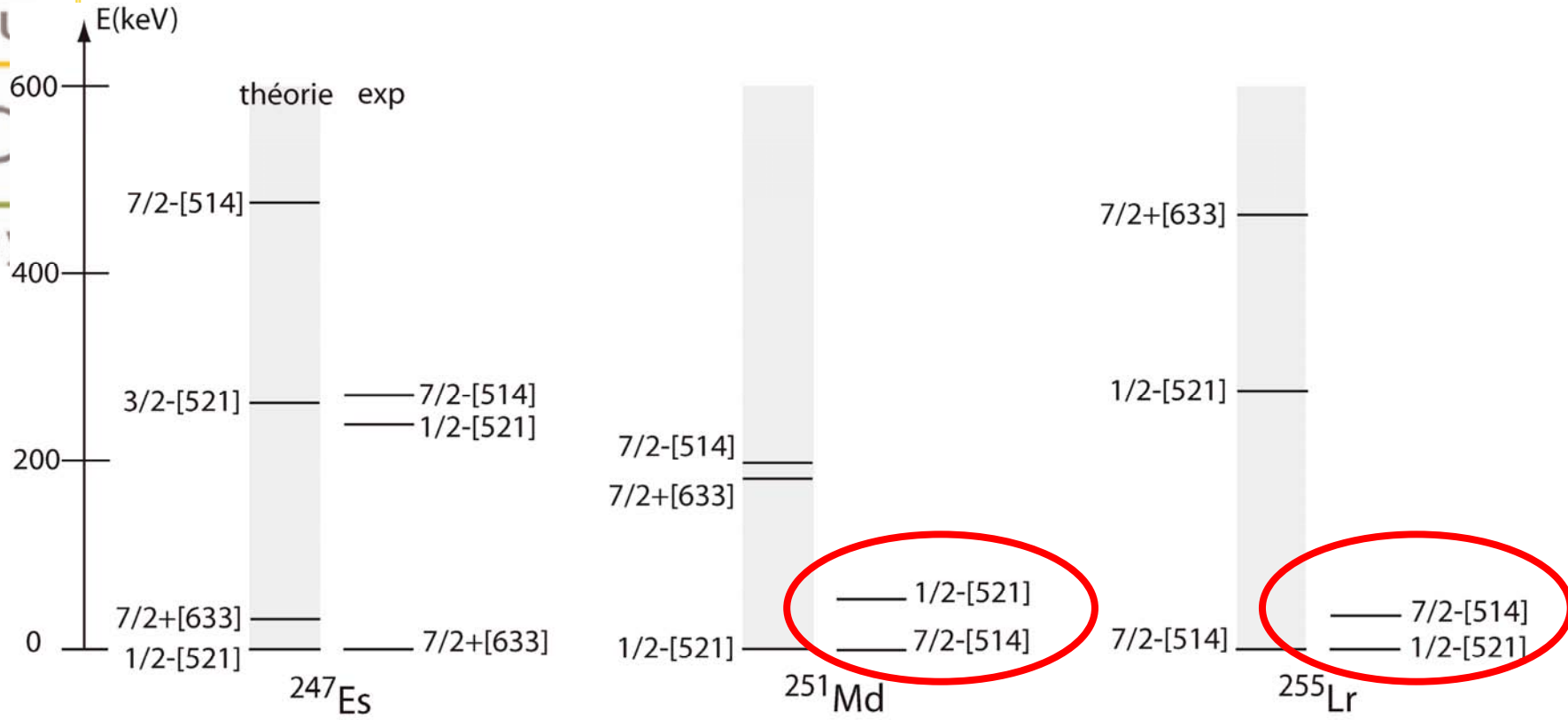
# Comparison with theory Es isotopes (III)



# Comparison with theory Es isotopes (IV)

- Same conclusions for $^{251}$Md and $^{255}$Lr




- N=152 not well reproduced
- Spin-orbit splitting overestimated
- Z=114 gap slightly underestimated, but too small to establish a major shell closure

# Separators, Spectrometers, Focal plane devices

- SHIP : GSI
- TASCA : GSI
- VASSILISSA + GABRIELLA : DUBNA
- DGFRS Dubna Gas Filled Recoil Separator : DUBNA
- LISE (FULIS) + BEST : GANIL
- RITU + GREAT : JYVASKYLA
- FMA : ARGONNE
- BGS : BERKELEY
- GARIS Gas Filled Recoil Ion Separator: RIKEN
- Gas Jet : JAERI

Beam rejection factor =

beam intensity / beam reaching the focal plane

# Gas / Vacuum separator

## Velocity filter

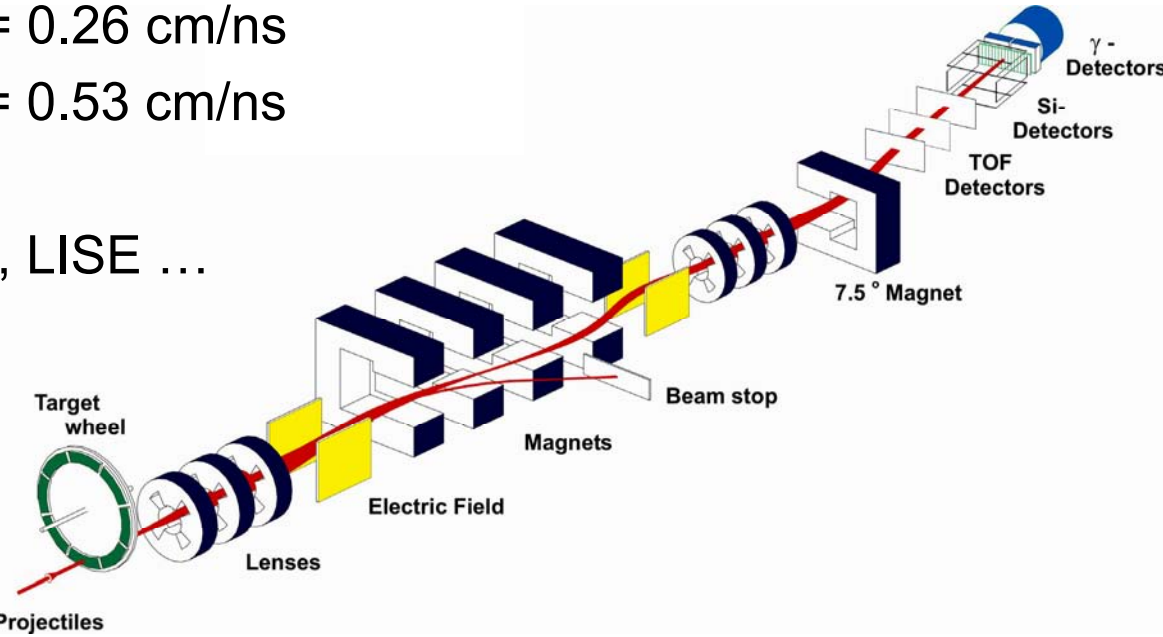
- Combination of electric and magnetic field

  $F_B = F_E$ => v=E/B

Example $^{22}Ne + ^{238}U$:

- $^{22}Ne$(112 MeV) v = 3.1 cm/ns,
- $^{260}No$ (9 MeV) v = 0.26 cm/ns
- $^{238}U$ (34 MeV) v = 0.53 cm/ns

- Examples ; SHIP, LISE …



# Gas / Vacuum separator

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Gas separator = magnetic rigidity filter

$F_B = qvB = mv^2/\rho$

gas : $\langle q \rangle = v/v_0\, Z^{1/3} \Rightarrow B\rho \propto m/Z^{1/3}$

Example $^{22}Ne+^{238}U$:

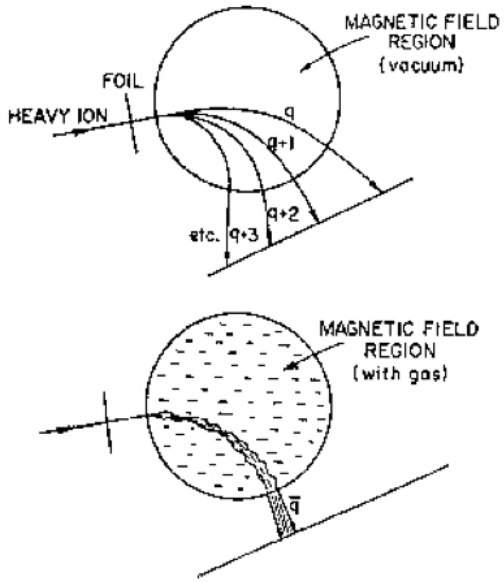
$^{22}Ne$ - $B\rho$ = 0.76 T.m

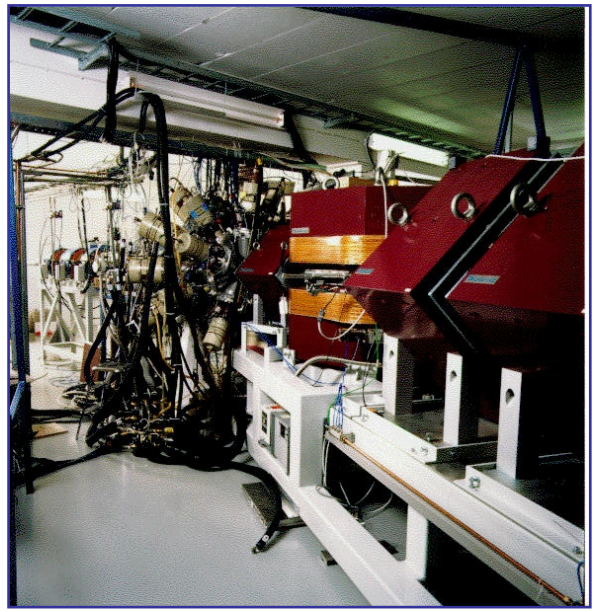
$^{260}No$ - $B\rho$ = 1.82 T.m

$^{238}U$ - $B\rho$ = 1.89 T.m

- High transmission
- Target cooling
- No mass selection
- Ion slowing down

- Examples : RITU, BGS Berkeley, DGFRS Dubna, Tasca (GSI), GARIS (RIKEN)



# Gas / Vacuum separator

Irfu cea saclay

## Electric rigidity filter

$F_E = qE$

$T = 1/2mv^2$

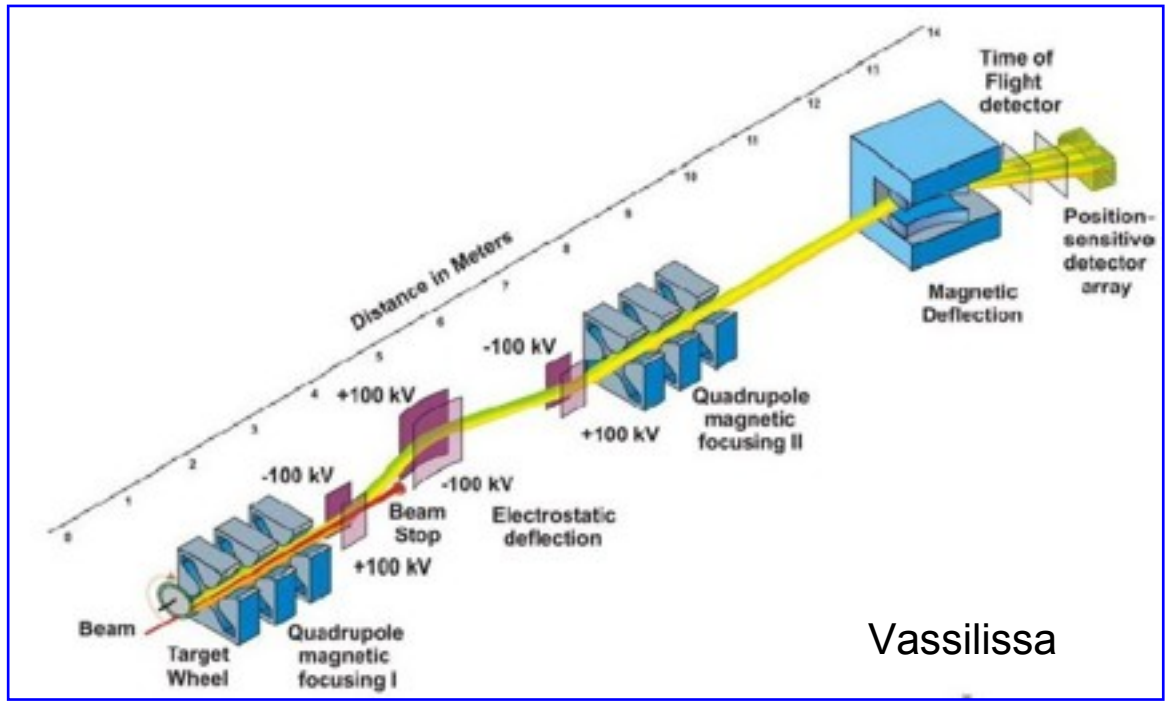
$E\rho = T/q$

Example $^{22}Ne + ^{238}U$:

$^{22}Ne$ - $E\rho$ = 11.7 MV

$^{260}No$ - $E\rho$ = 0.99 MV

$^{238}U$ - $E\rho$ = 1.93 MV

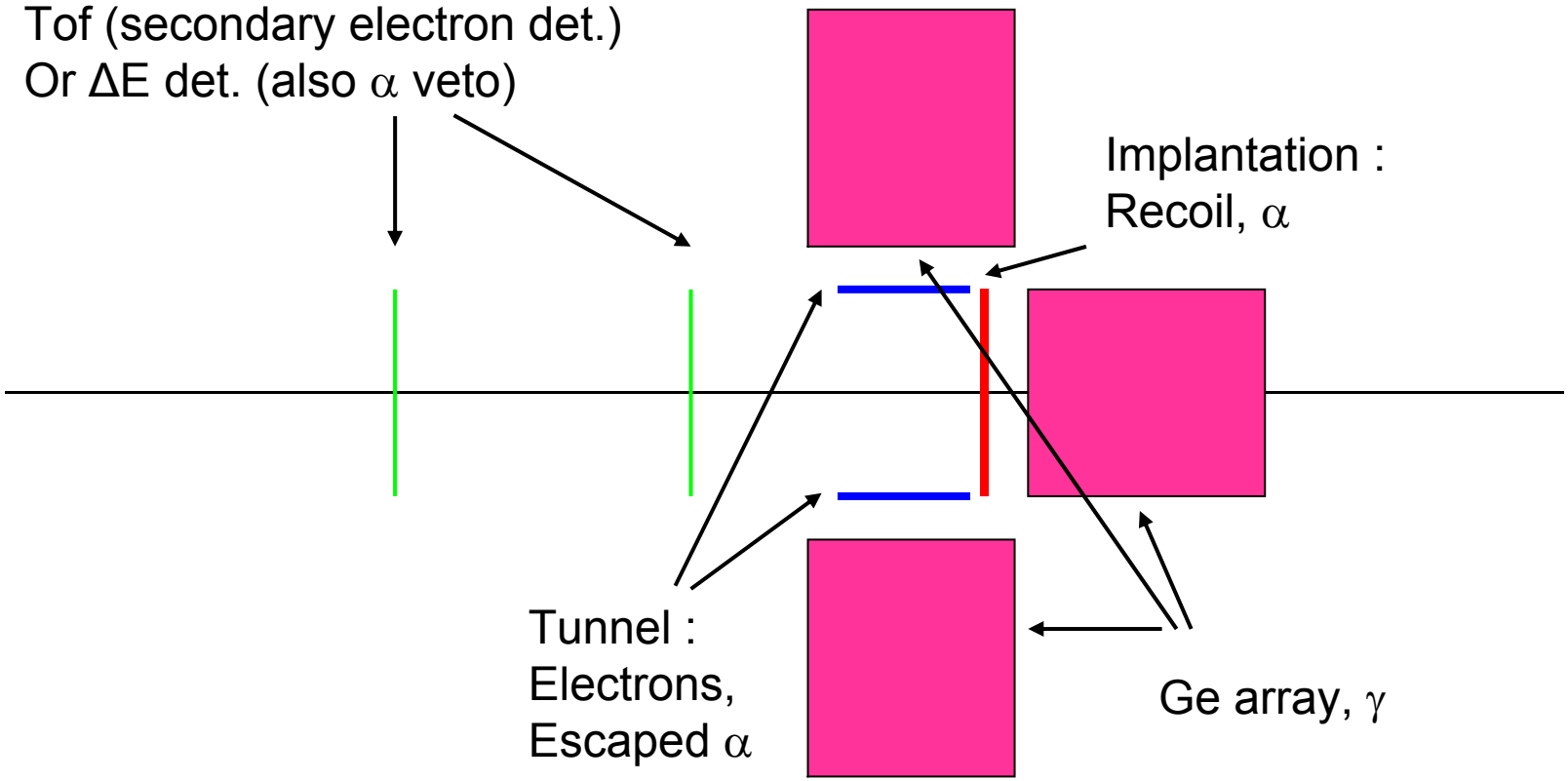


# Focal plane devices

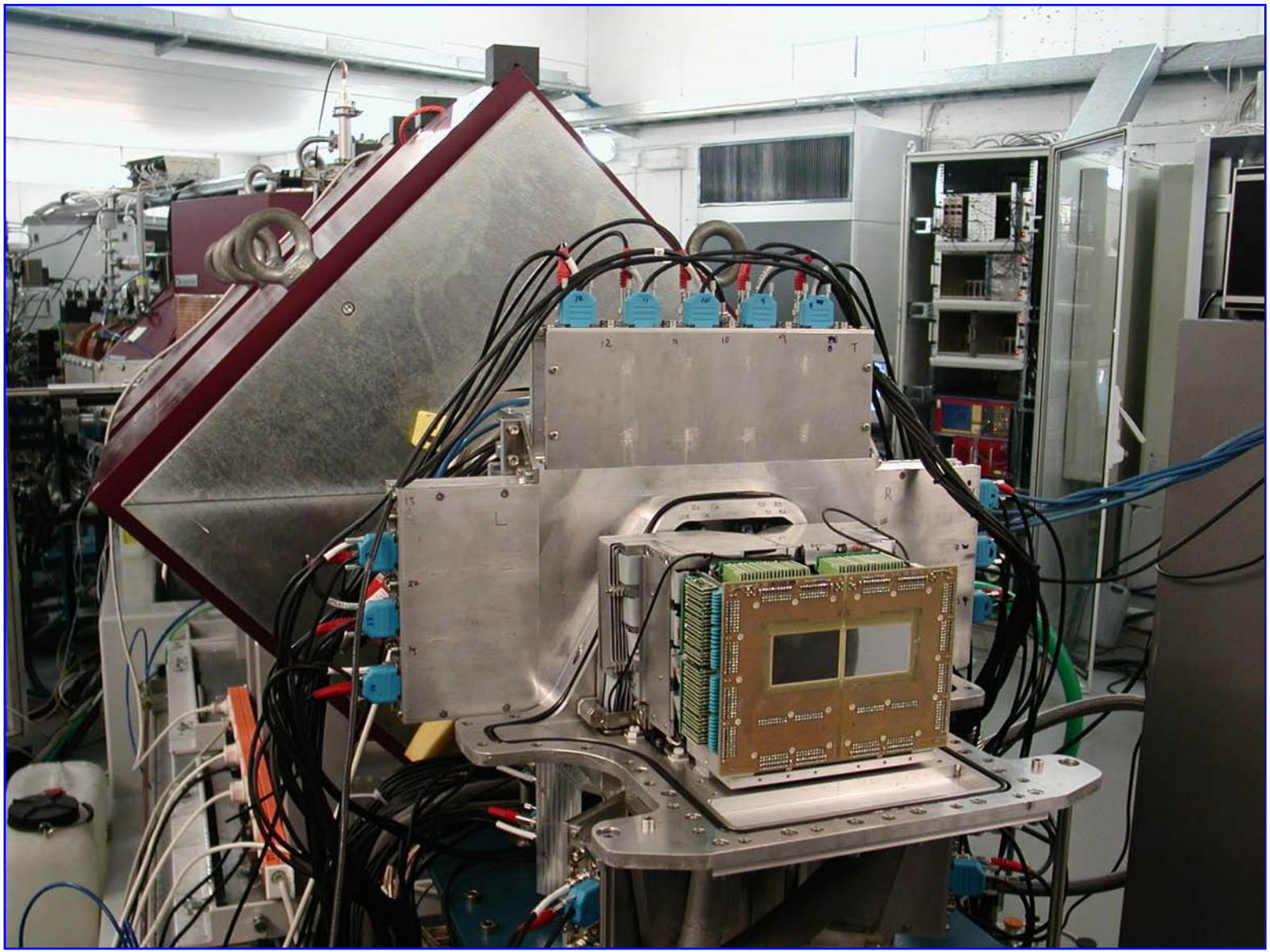
Need to combine

- Recoil energy and position
- Time of Flight or Energy loss for Recoils
- Alpha decay energy and position with best energy resolution
- Gamma detection with best efficiency and resolution
- Electron detection with best efficiency and resolution

# Basics of focal plane detection



# Great @ RITU

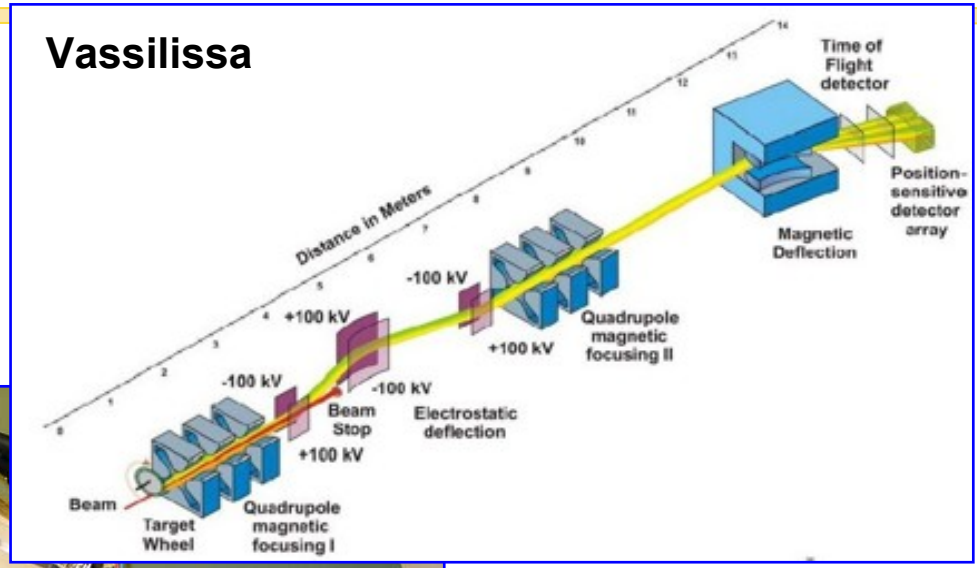


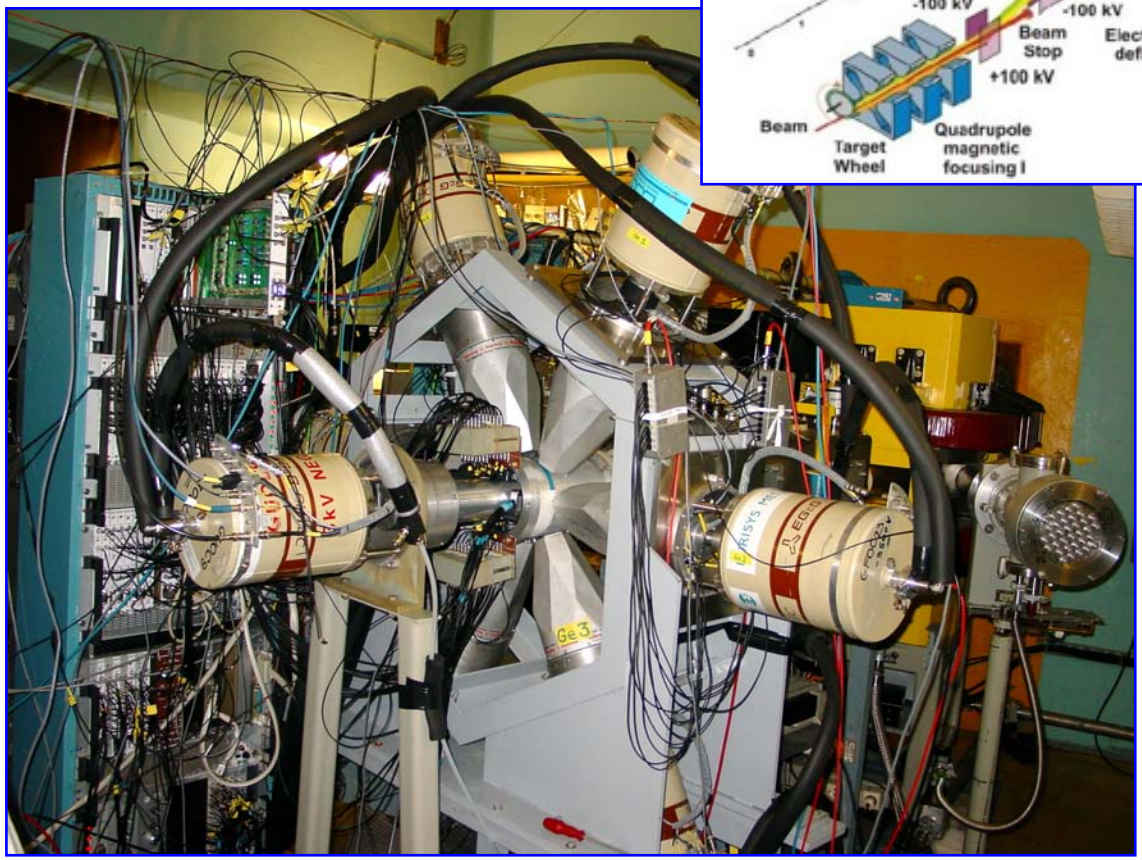
# Gabriela at VASSILISSA (Dubna)

Irfu

cea

saclay



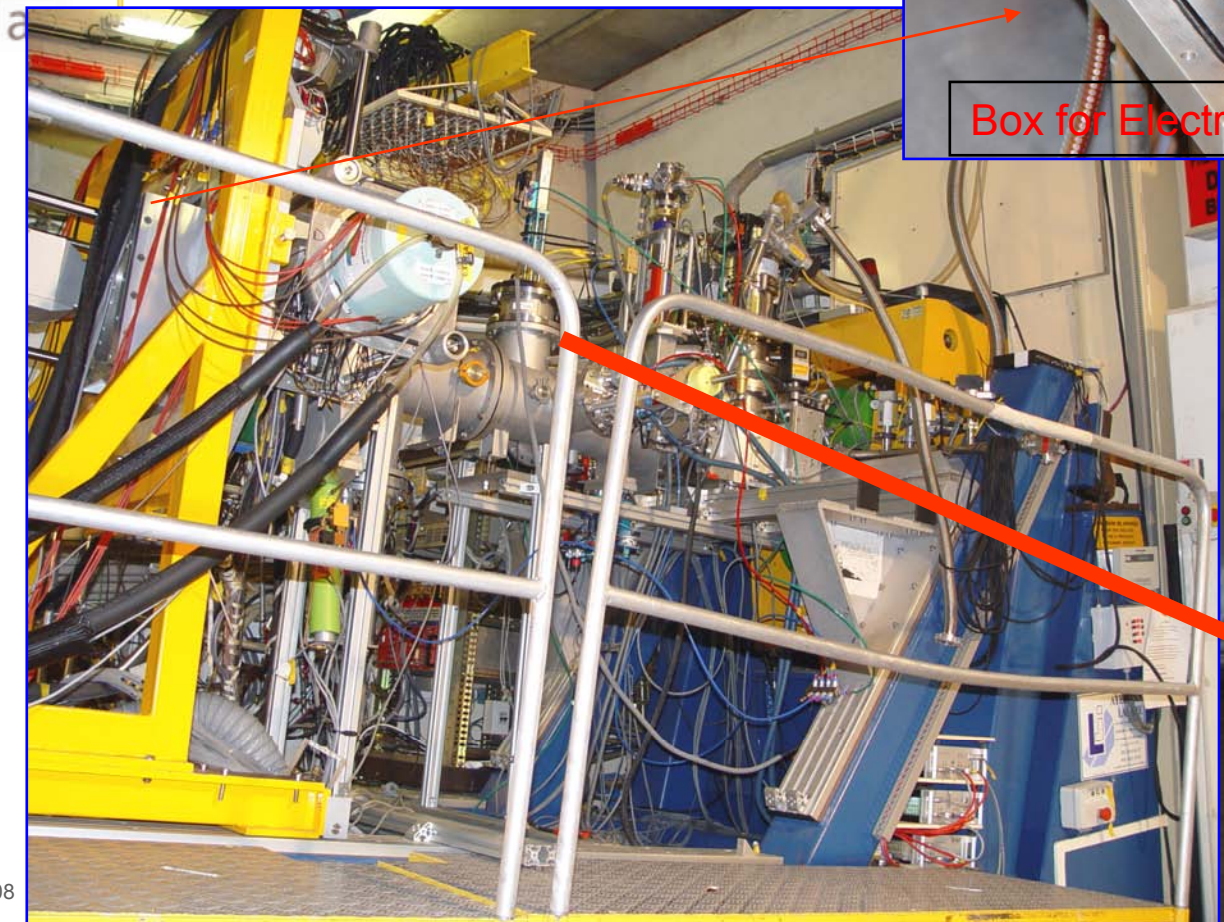



# BEST at LISE (Ganil)

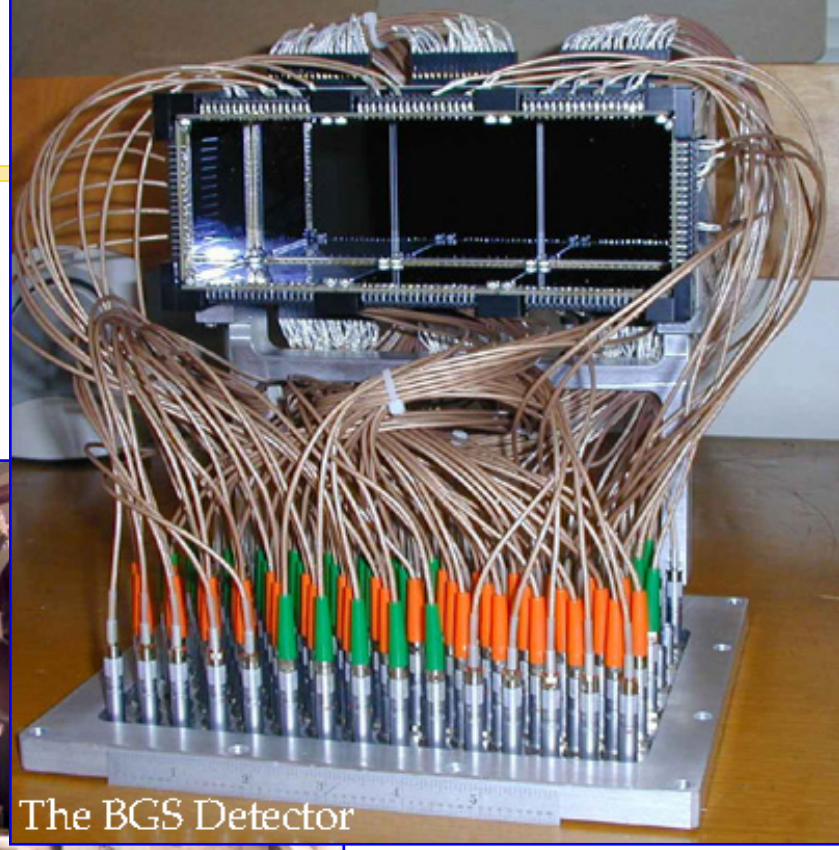
Irfu

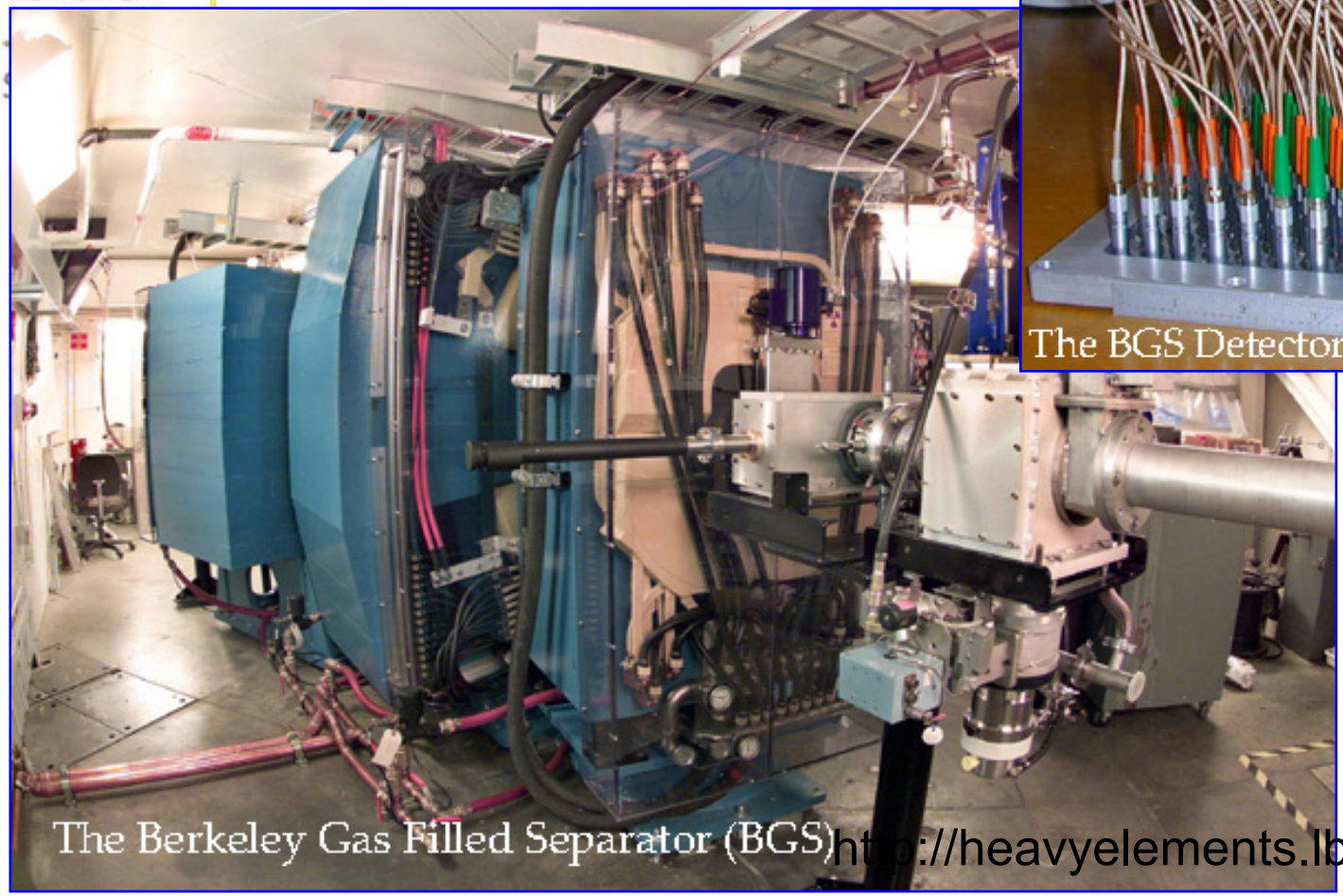
cea

sacla



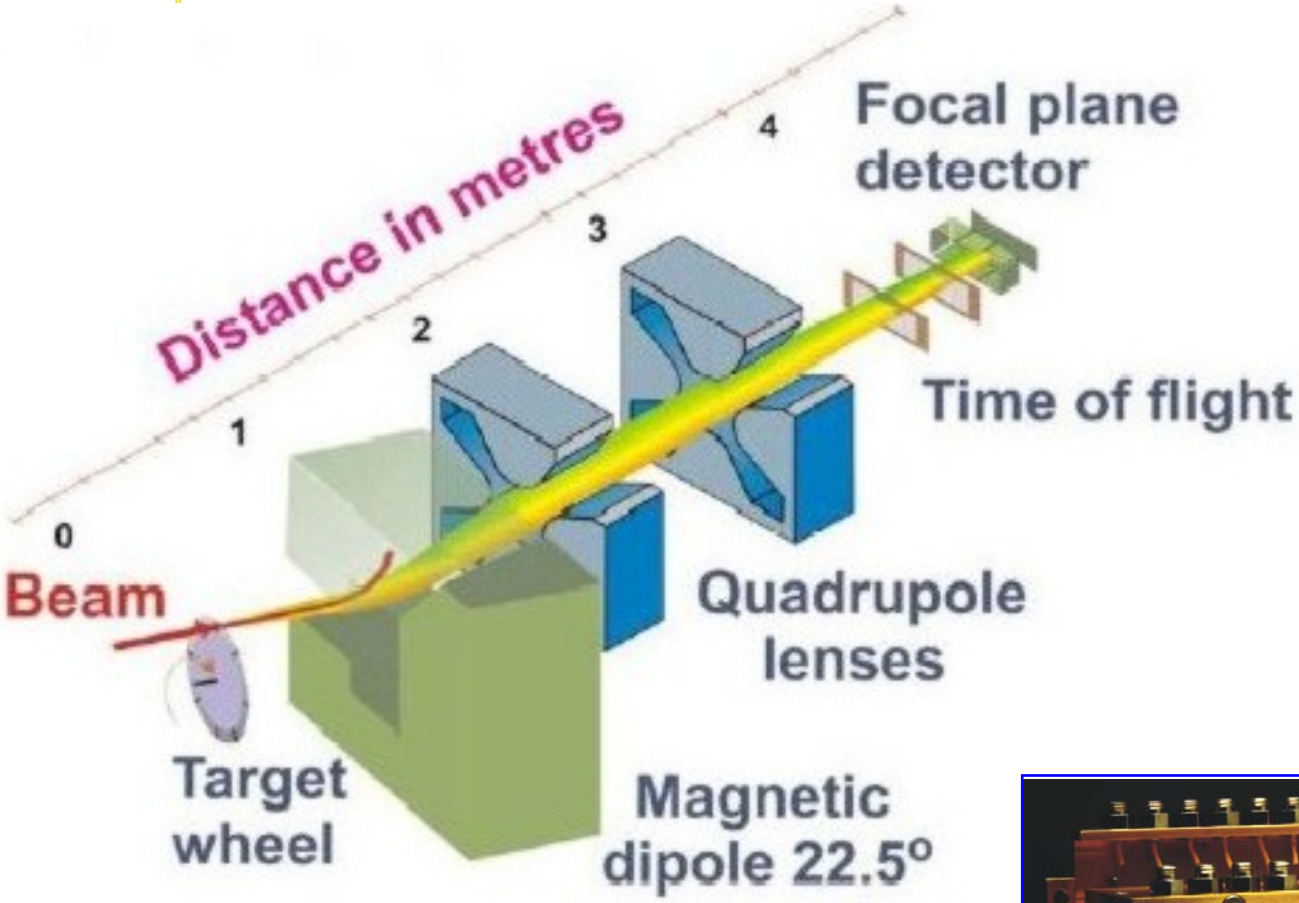
# BGS Berkeley

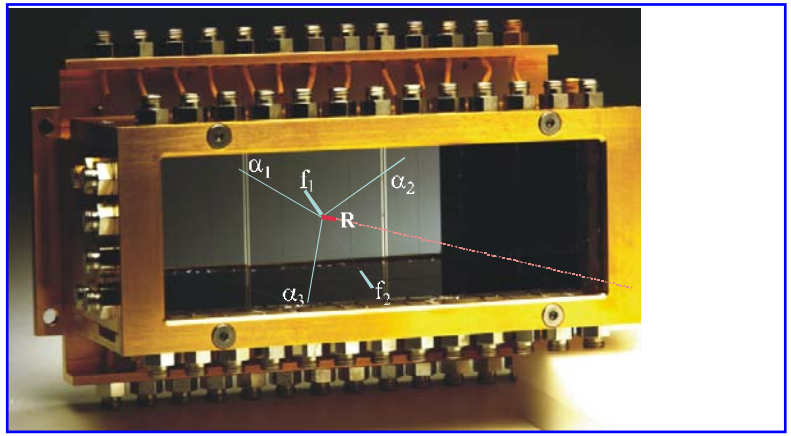

The BGS Detector


The Berkeley Gas Filled Separator (BGS)

http://heavyelements.lbl.gov/

# DGFRS


Distance in metres
0
1
2
3
4
Focal plane detector
Time of flight
Beam
Quadrupole lenses
Target wheel
Magnetic dipole 22.5°


α1
f1
α2
R
α3
f2

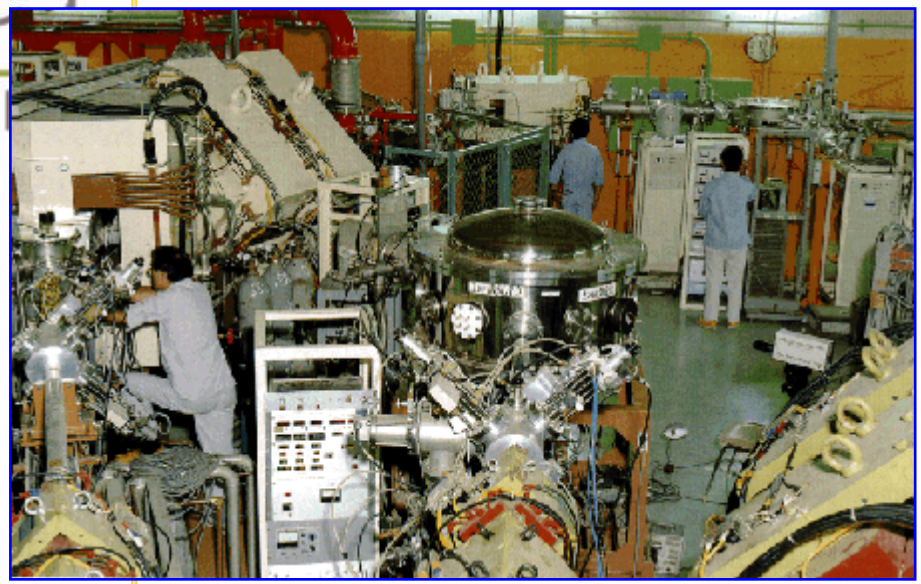
# FMA Argonne

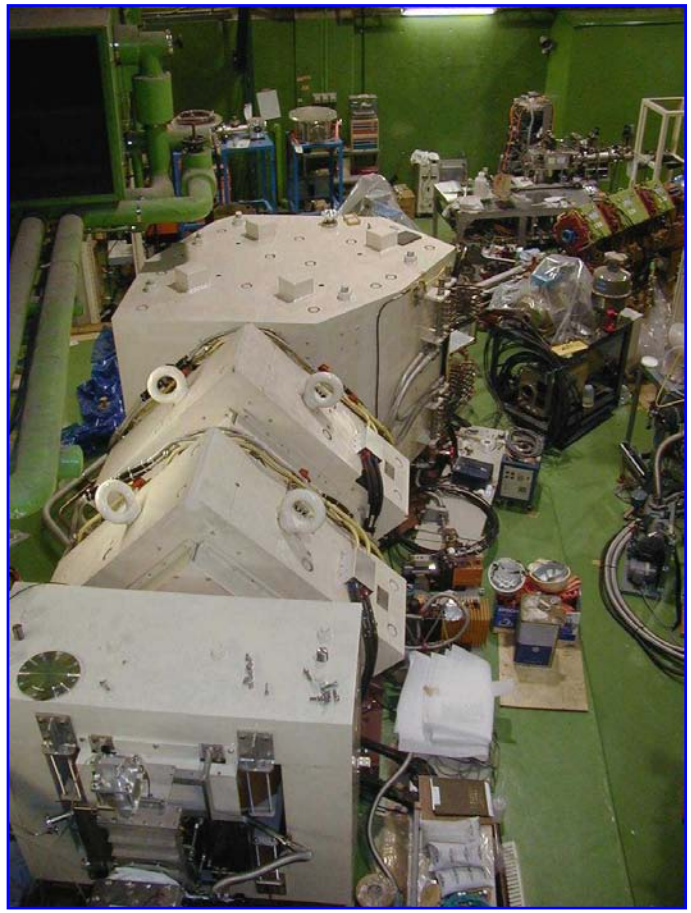
Irfu cea saclay

http://www.phy.anl.gov/fma/

# GARIS - RIKEN

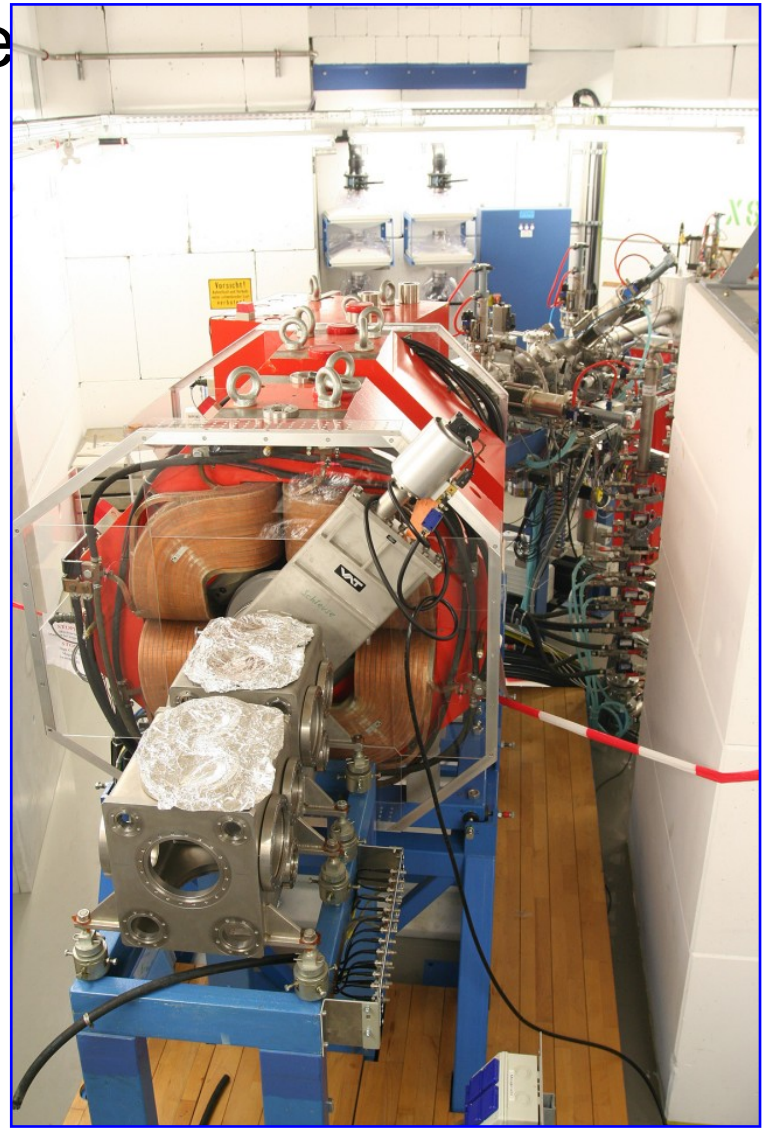
http://www.rarf.riken.go.jp/facility/garis/garis.html



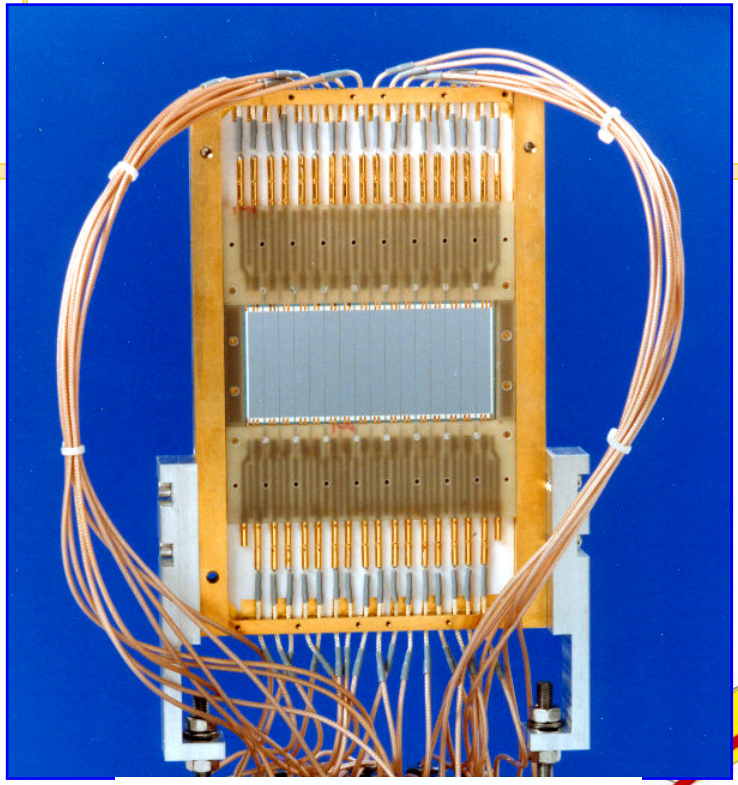


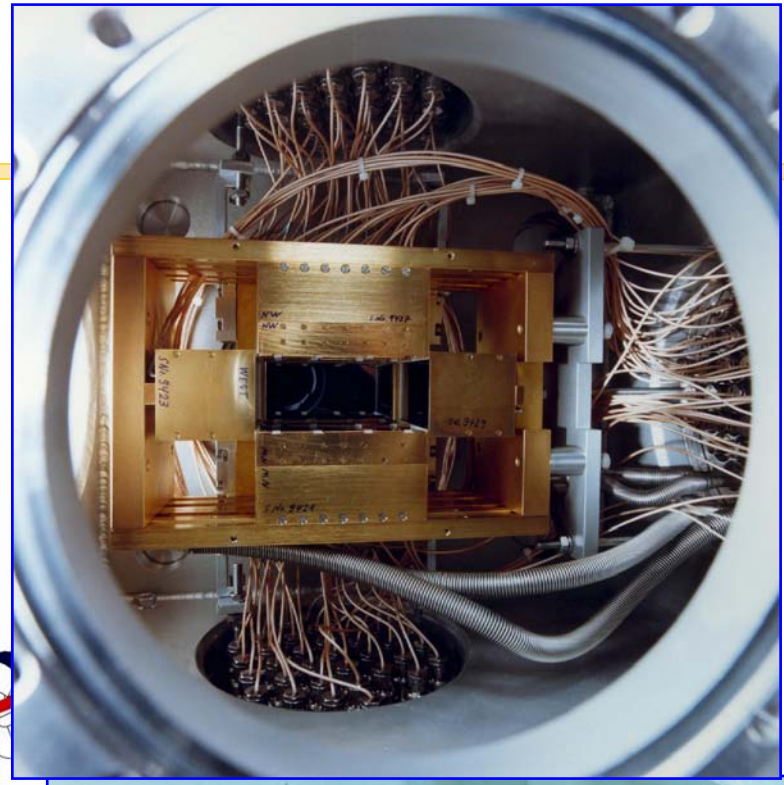
# TASCA - GSI

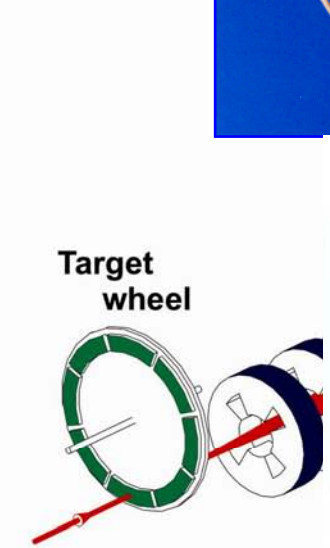
http://www-win.gsi.de

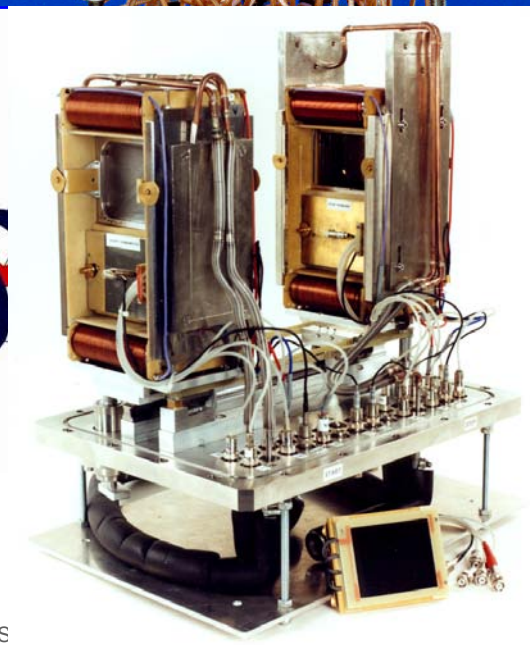


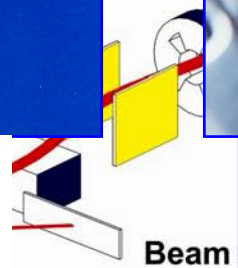
Irfu



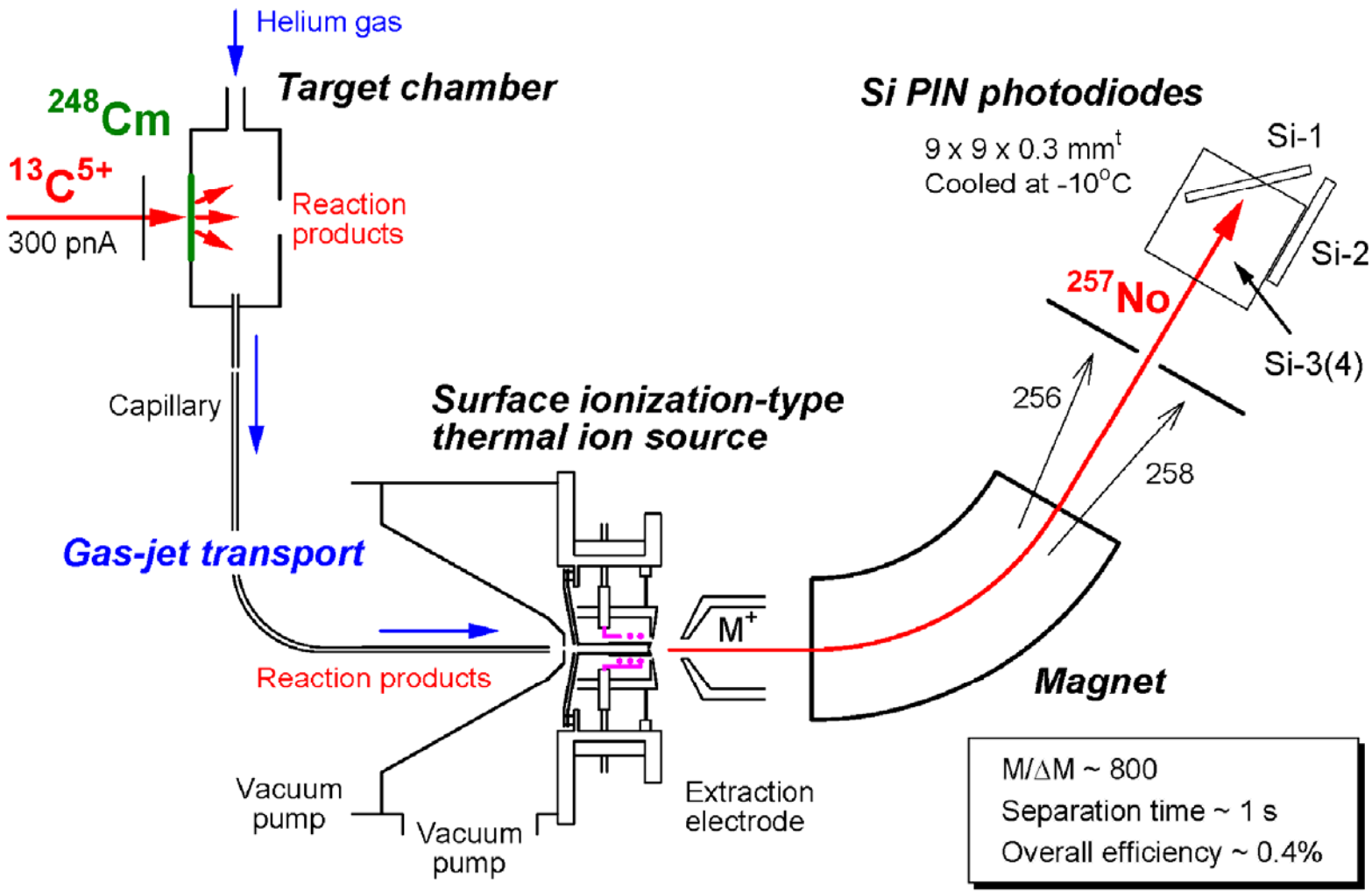






# JAEA, gas-jet


Helium gas
Target chamber
248Cm
13C5+
300 pnA
Reaction products
Capillary
Gas-jet transport
Surface ionization-type thermal ion source
Reaction products
M+
Vacuum pump
Vacuum pump
Extraction electrode
Si PIN photodiodes
9 x 9 x 0.3 mmt
Cooled at -10°C
Si-1
Si-2
Si-3(4)
257No
256
258
Magnet
M/ΔM ~ 800
Separation time ~ 1 s
Overall efficiency ~ 0.4%

# Targets

Irfu cea saclay

Decay spectroscopy

No detector around the target + high beam rejection

→ Use as much beam intensity as possible

→ Gas helps to cool the targets

→ Rotating targets

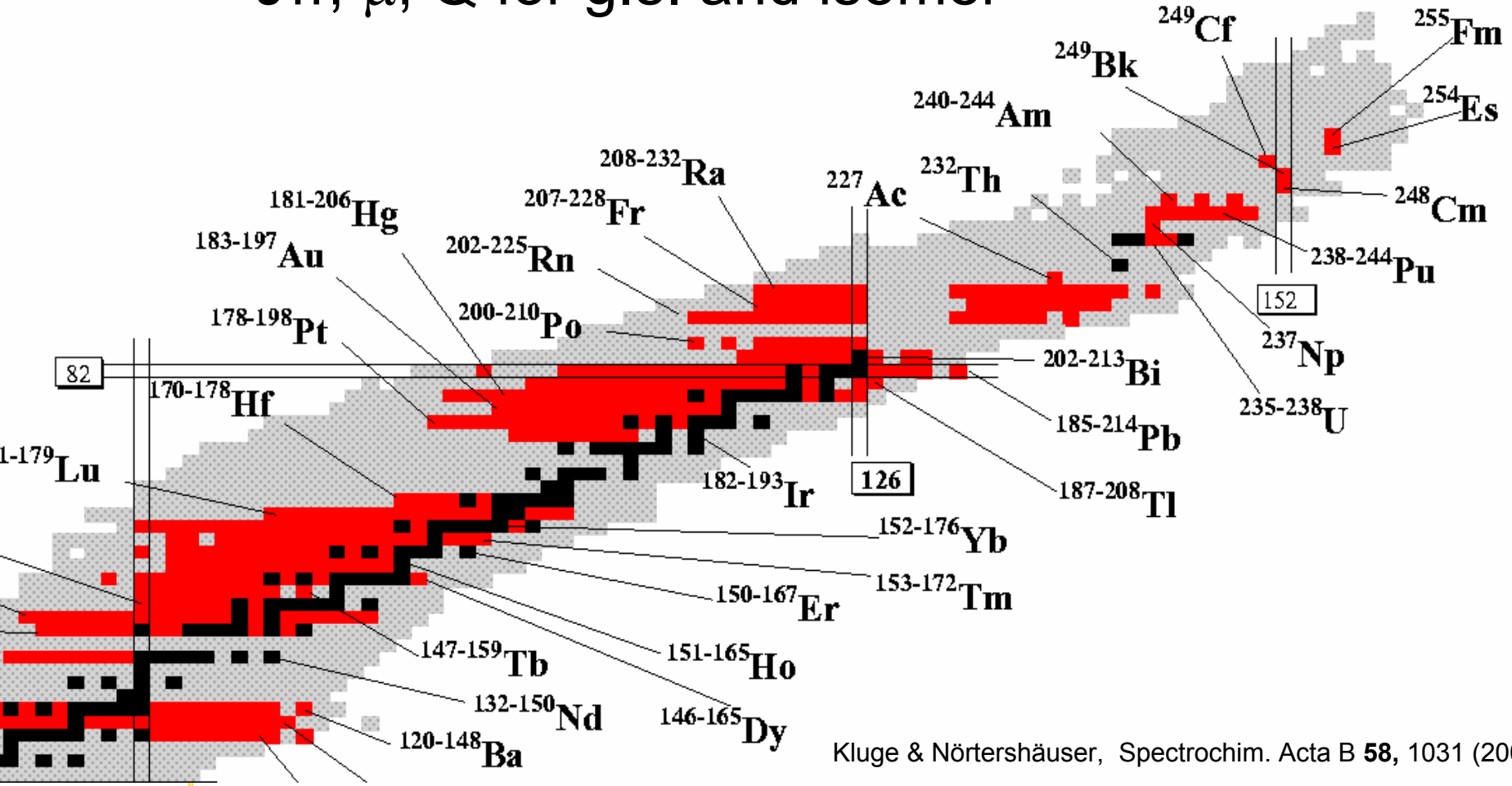
GSI

GANIL

# Laser spectroscopy

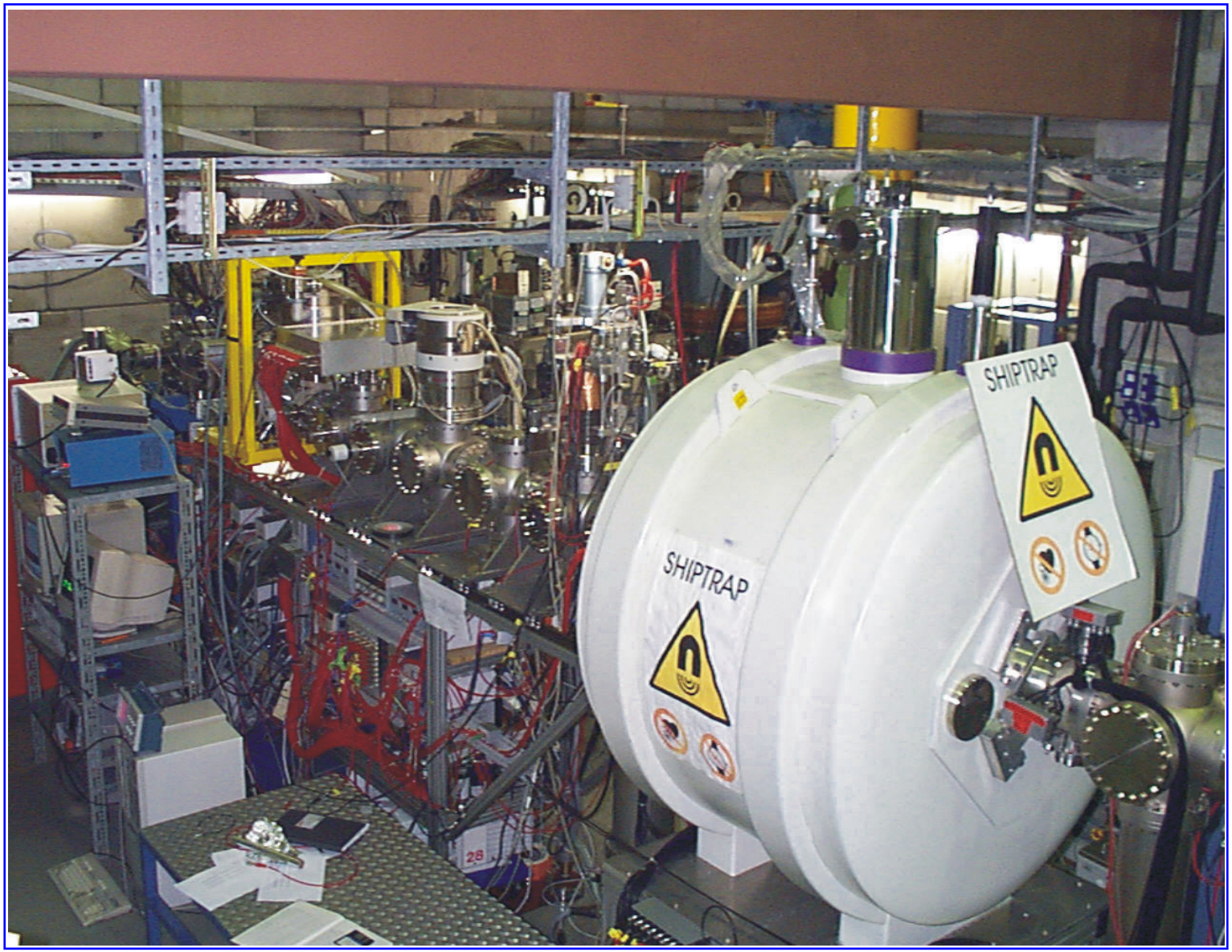
Irfu

Measure of
Jπ, μ, Q for g.s. and isomer

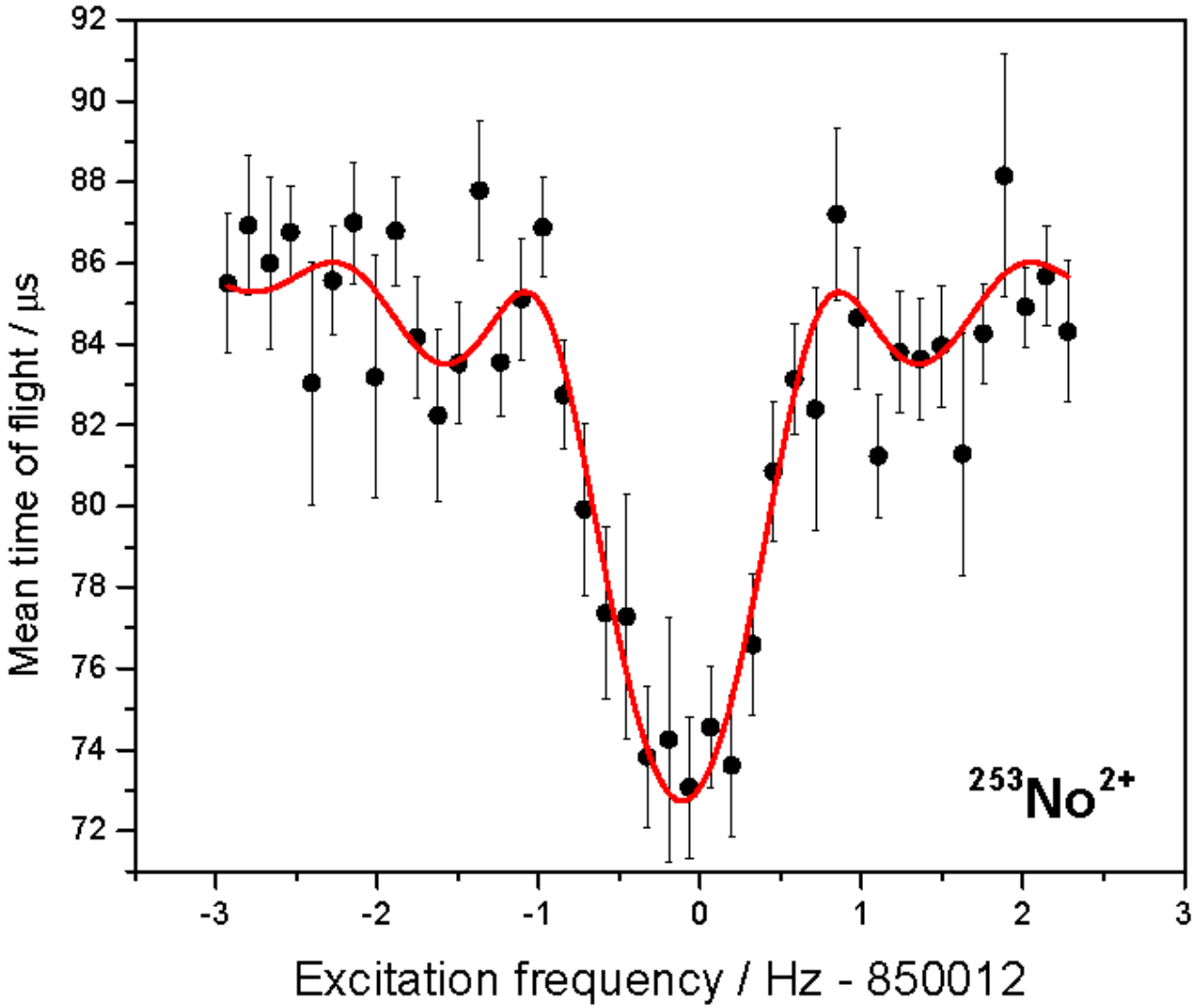



Kluge & Nörtershäuser, Spectrochim. Acta B **58,** 1031 (2003)

# Mass measurement : SHIPTRAP

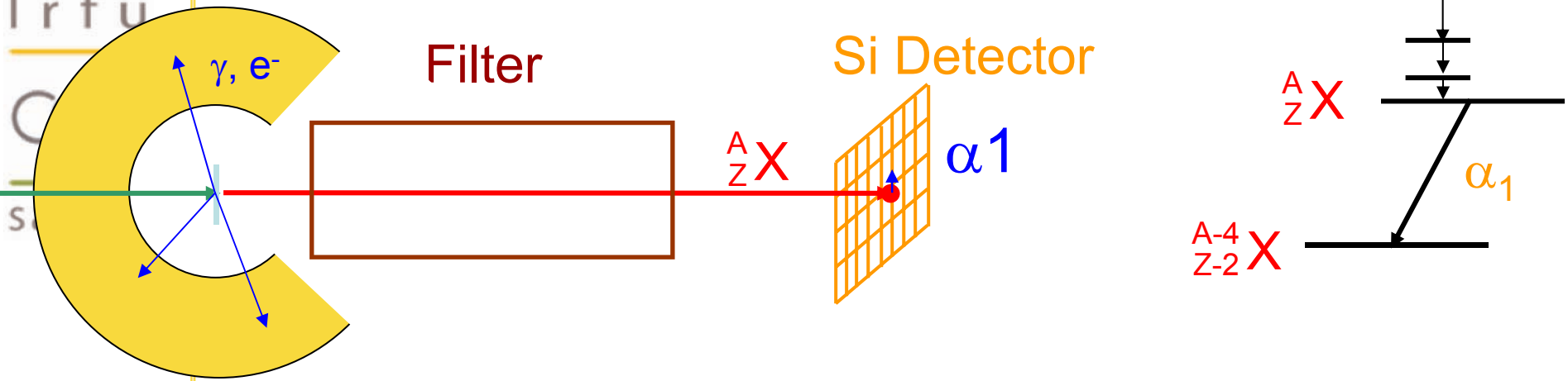


# Mass measurement : SHIPTRAP




M. Block et al., August 2008, unpublished

# Recoil tagging and Recoil Decay Tagging



Fusion-evaporation
+ electromagnetic
transitions

Implantation

$^{A}_{Z}X$

$E(^{A}_{Z}X),x_1,y_1$

α decay

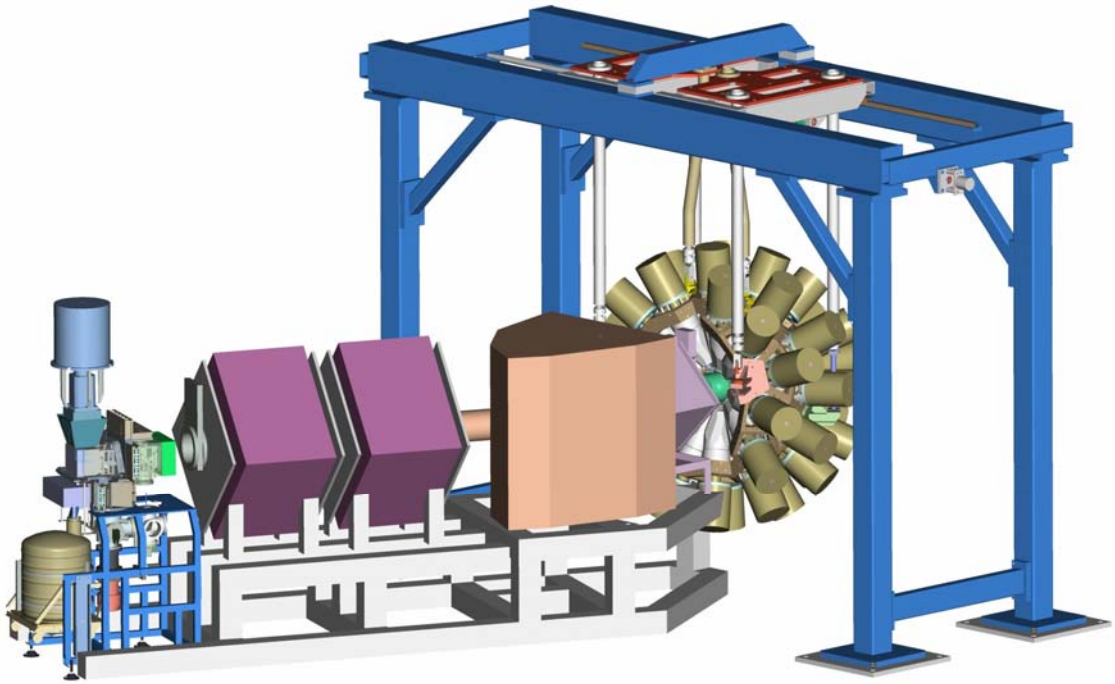
$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X$

$E(\alpha_1),x_2,y_2$

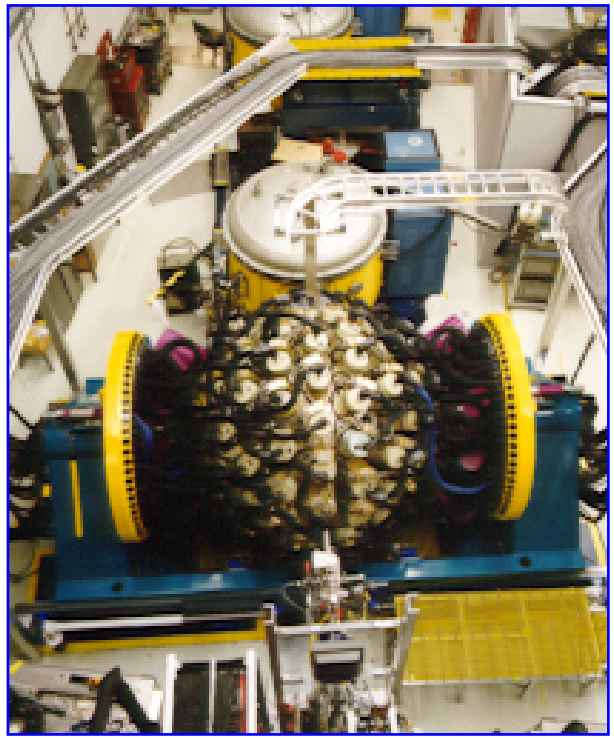
Recoil Tagging

Recoil Decay Tagging

# Prompt detectors



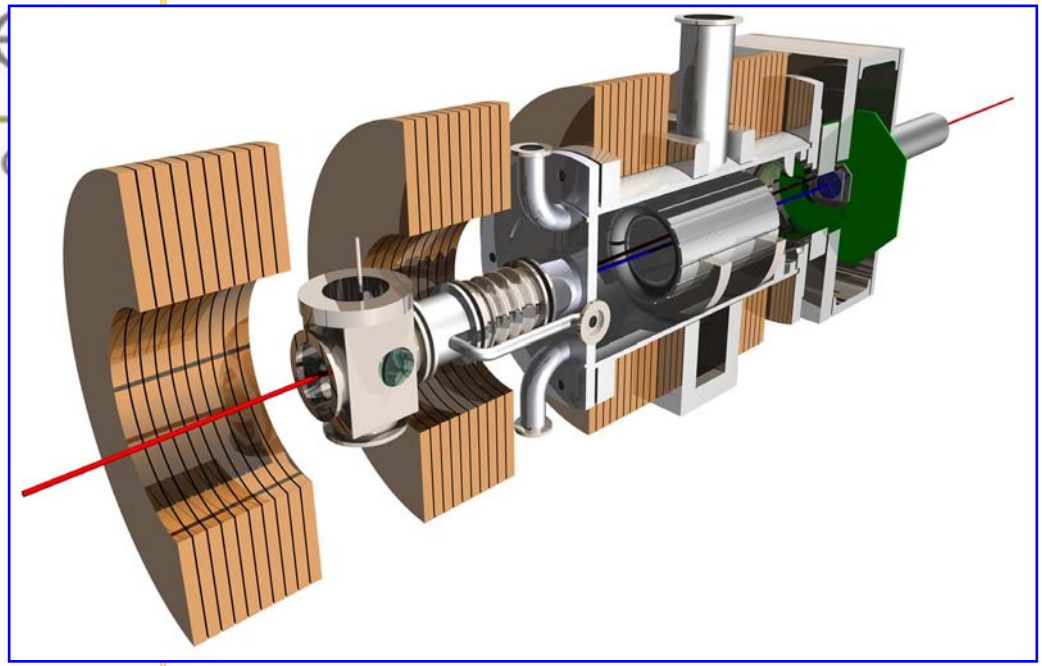
Jurogam + RITU

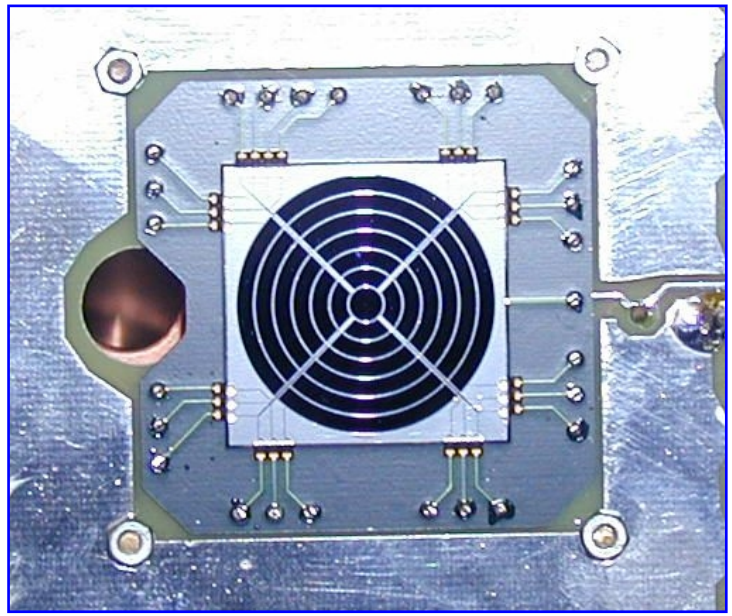


GammaSphere + FMA

# Prompt detectors

Conversion is high !





Sacred + RITU

# Prompt spectroscopy

Irfu cea saclay

Decay spectroscopy : low spin, low multiplicity cascades, mostly single particle states

Prompt spectroscopy : high spin because of fusion-evaporation reaction, high multiplicity, mostly collective states

Detection rate : dominated by fission; few 100 mb

beam intensity ~ 10 pnA

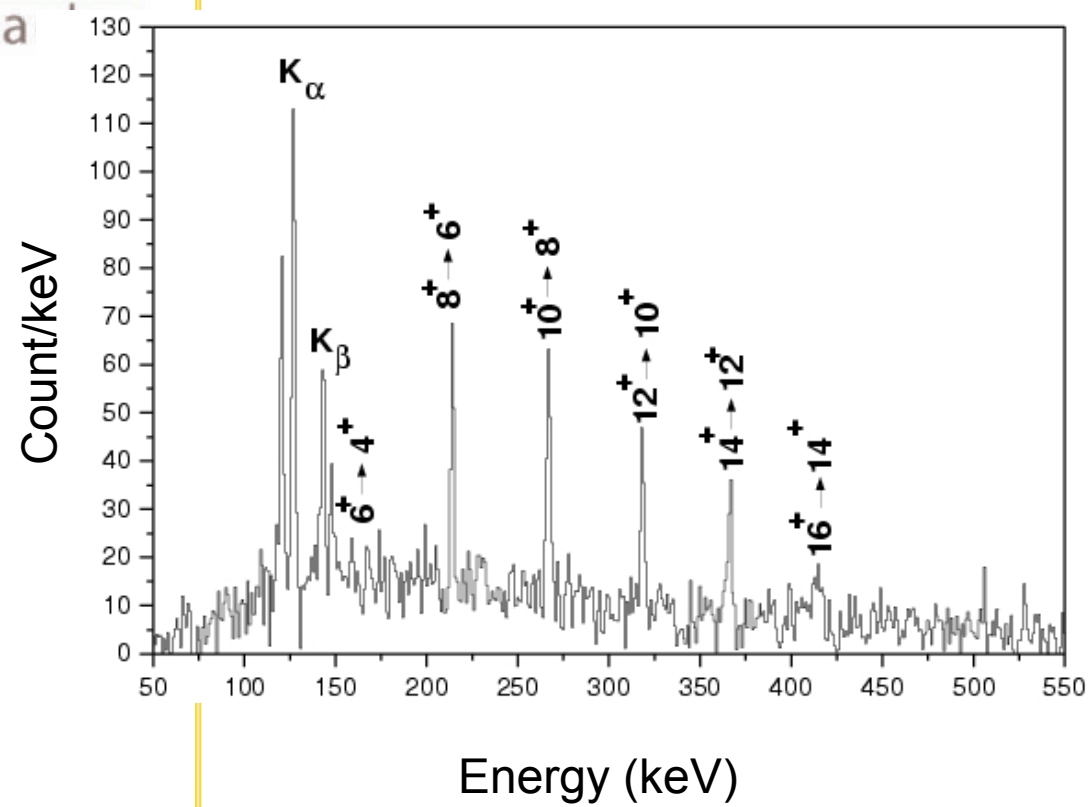
event of interest ~ few / hour

$\rightarrow$ very high sensitivity needed

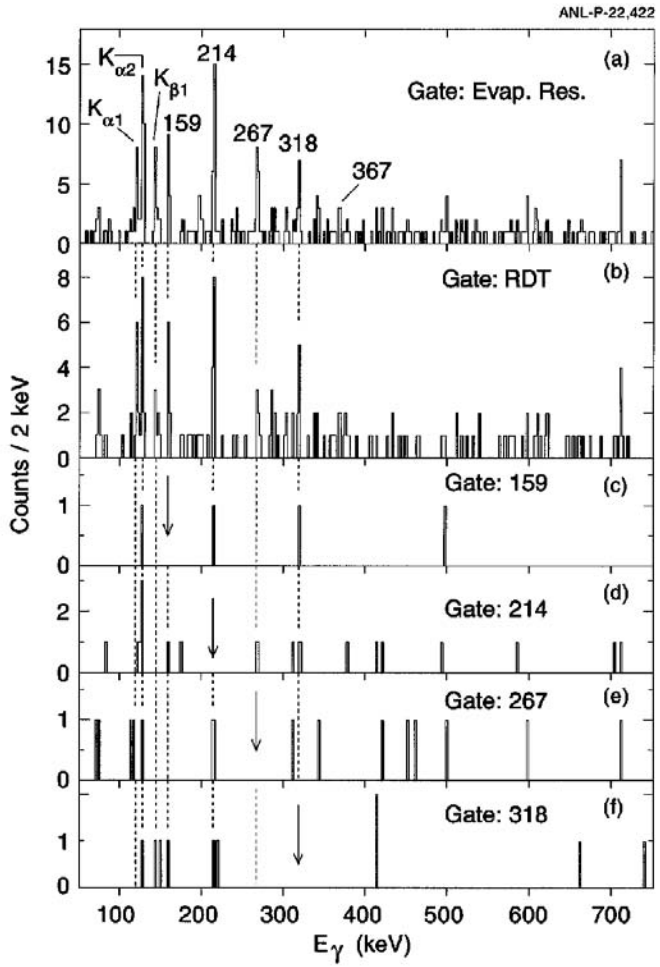
# A textbook example : $^{254}$No

$^{208}$Pb($^{48}$Ca,2n)$^{254}$No σ ~ 2 μb

Pioneer work performed (almost) at the same time at Argonne and Jyvaskyla




M. Leino *et al.* Eur. J. Phys A6 (1999) 63




P. Reiter *et al.* Phys. Rev. Lett 82 (1999) 509

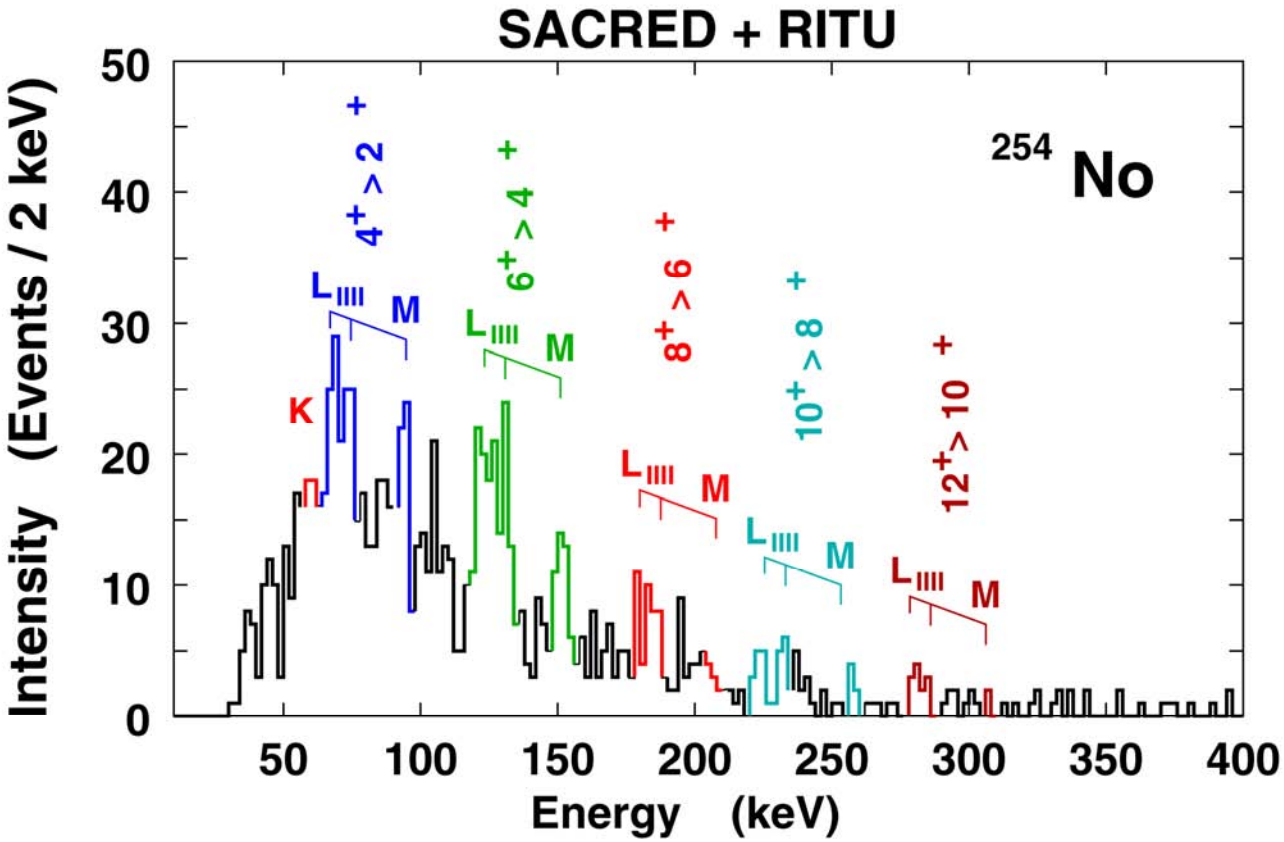
# $^{254}$No

Finding a needle in a haystack :

- $I_{beam}$ = 10 pnA
- Ge counting rate $\simeq$ 100 kHz
- Good events $\simeq$ 10/hour

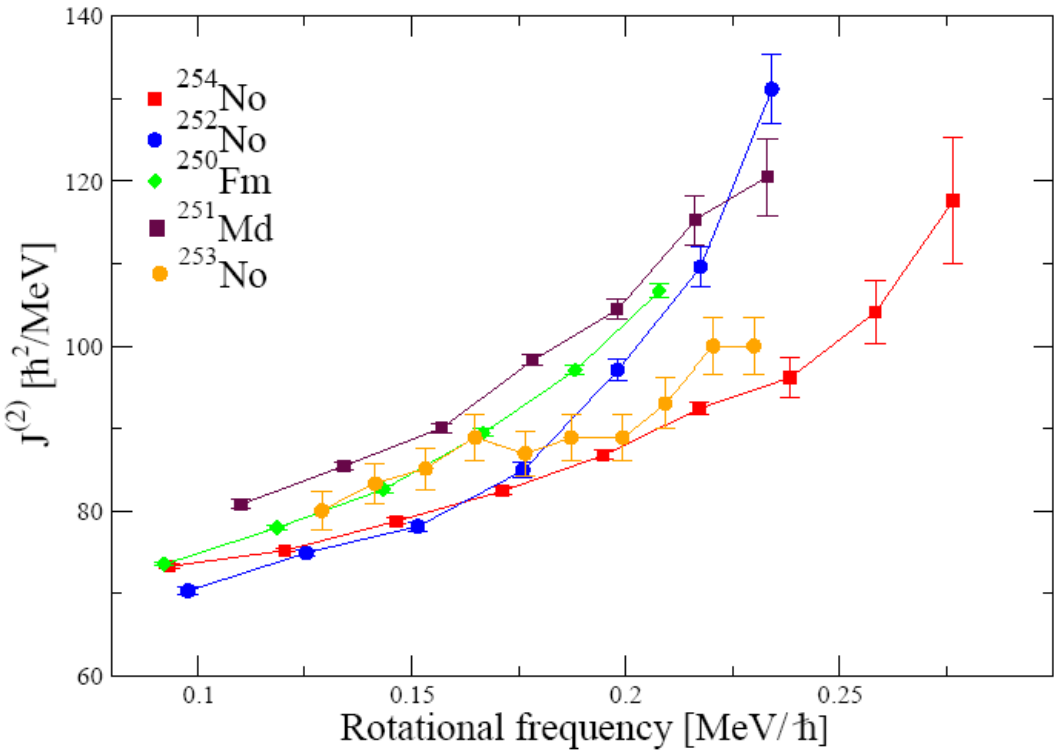
- Sensitivity ~ $10^{-8}$

# $^{254}$No Electron spectroscopy




P.A. Butler et al. Phys. Rev. Lett. 89 (2002) 202501

# What to do with rotational bands ?




$$E(I) = E_0 + \frac{\hbar^2}{2\Im} I(I+1)$$

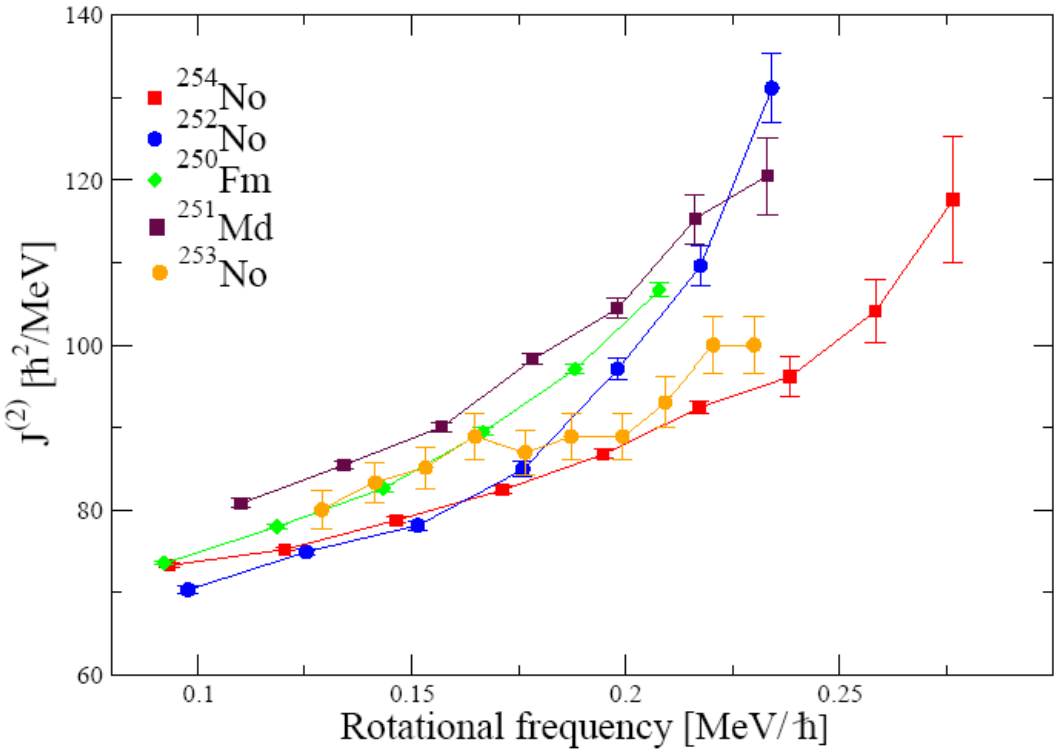
$$E_\gamma(I) = E(I+2) - E(I)$$

$$\Delta E_\gamma(I) = E_\gamma(I+2) - E_\gamma(I)$$

$$\hbar\omega = \frac{dE}{dI} \approx \frac{E_\gamma}{2}$$

$$\Im^{(2)} = \left(\frac{\partial^2 E}{\hbar^2 \partial I^2}\right)^{-1} = \hbar \frac{\partial I}{\partial \omega} \approx \frac{\Delta I^2}{\Delta E_\gamma}$$

# What to do with rotational bands ?




Trends :

- Increase : pair alignment

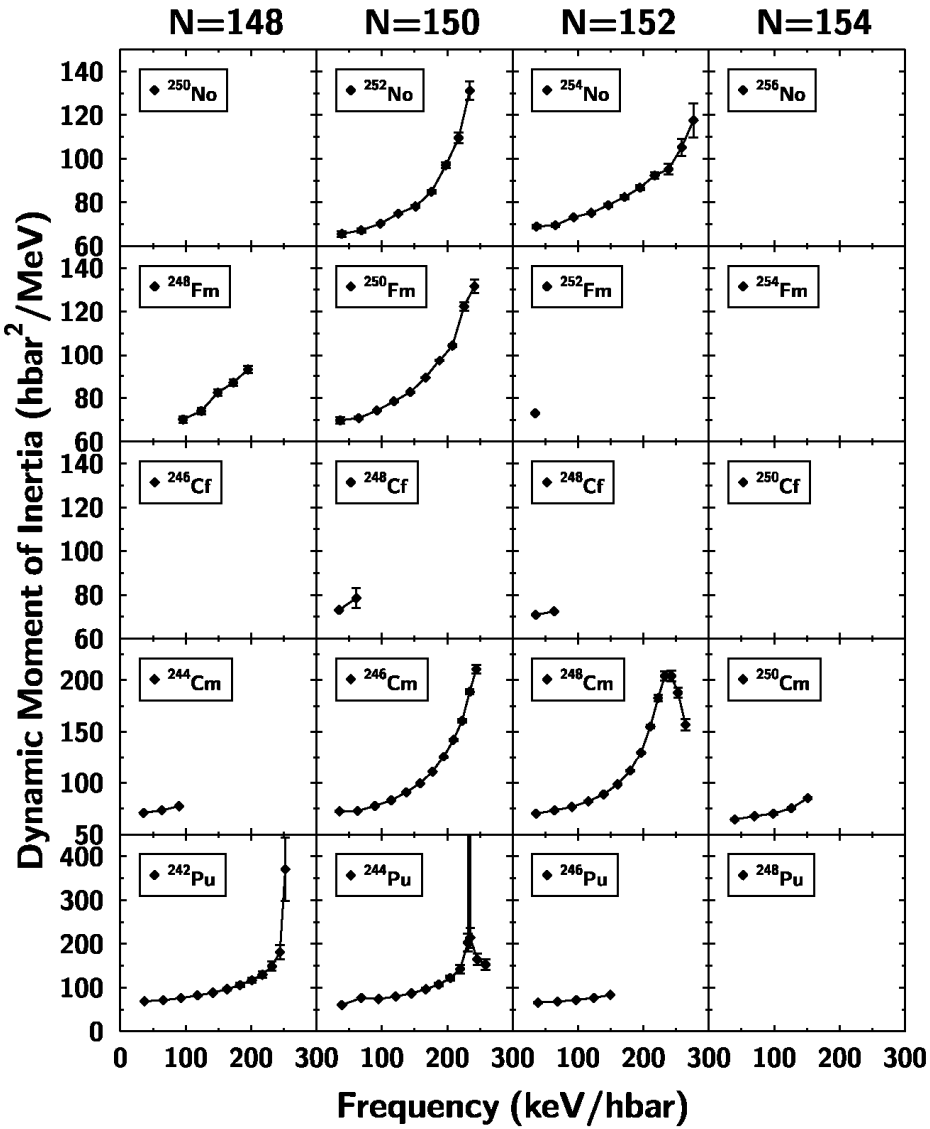
- Alignment faster for N=150

As compared to N=152

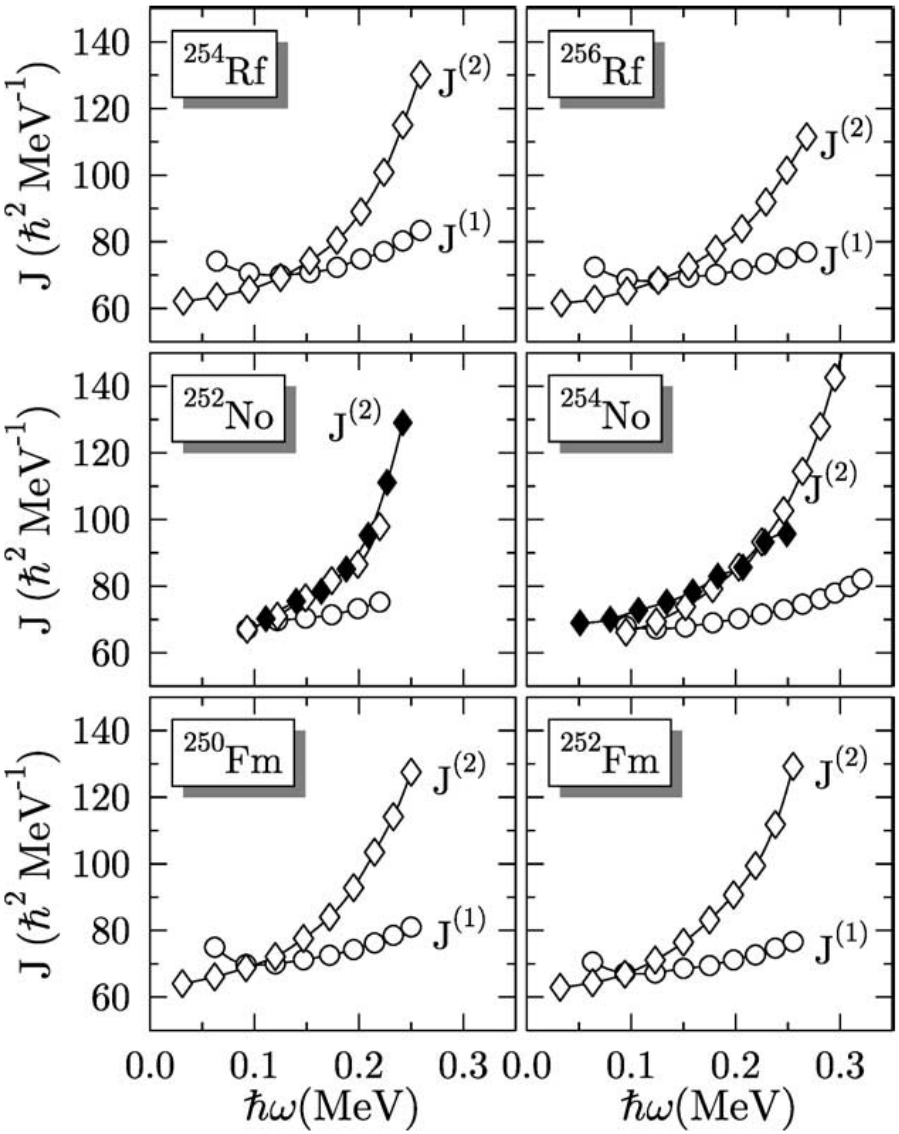
- Odd-even effect difference : blocking

Duguet et al., NPA 679, 427 (2001)
Bender et al., NPA 723, 354 (2003)
Afanasjev et al., PRC 67, 024309 (2003)
Egido and Robledo, PRL 85 1198 (2000)

# Moment of Inertia



# Comparison with theory




M.Bender et al.,
NPA 723 (2003) 354

# Deformation

Irfu cea saclay

## From Grodzin systematics : $E^{2+} \leftrightarrow$ deformation

L. Grodzins, Phys. Lett. 2 (1962) 88

$$Q_0 = \frac{\sqrt{3}}{2} \frac{6Zea_0^2 A^{2/3}}{\sqrt{15\pi}} \beta_2 (1 + 0.360\beta_2)$$

$B(E2; 2+ \rightarrow 0+) = 5/16\pi \; Q_0^2 \langle 2020|00\rangle^2$

$T(E2) = 1.22 \; 10^9 \; B(E2) E^5$

Grodzin systematic on heavy nuclei :

Lifetime = $f(A, E^{2+})$ : see R.-D. Herzberg et al. Phys. Rev.C65 (2001) 014303

If $E^{2+}$ no known experimentally (high conversion)

$\rightarrow$ Harris fit $\hbar(I + 1/2) = A\,\omega + B\,\omega^3$

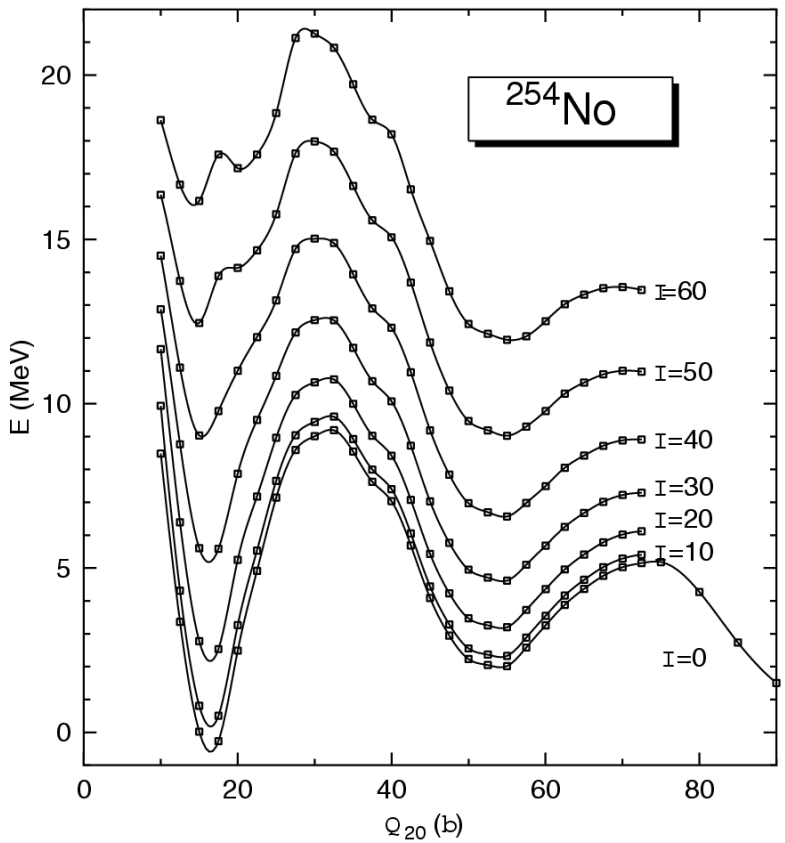
# Deformation

| | $E^{2+}$(keV) | $\tau^{2+}$(ps) | $Q_0$ (e.fm2) | $Q_{proton;theo}$ (e.fm2) | $\beta_2$ |
|---|---|---|---|---|---|
| $^{250}$Fm | 44.2 | 1.39 $10^5$ | 1325 | 1320 | 0.278 |
| $^{252}$No | 46.4 | 1.05 $10^5$ | 1347 | 1351 | 0.276 |
| $^{254}$No | 44.0 | 1.25 $10^5$ | 1412 | 1351 | 0.287 |

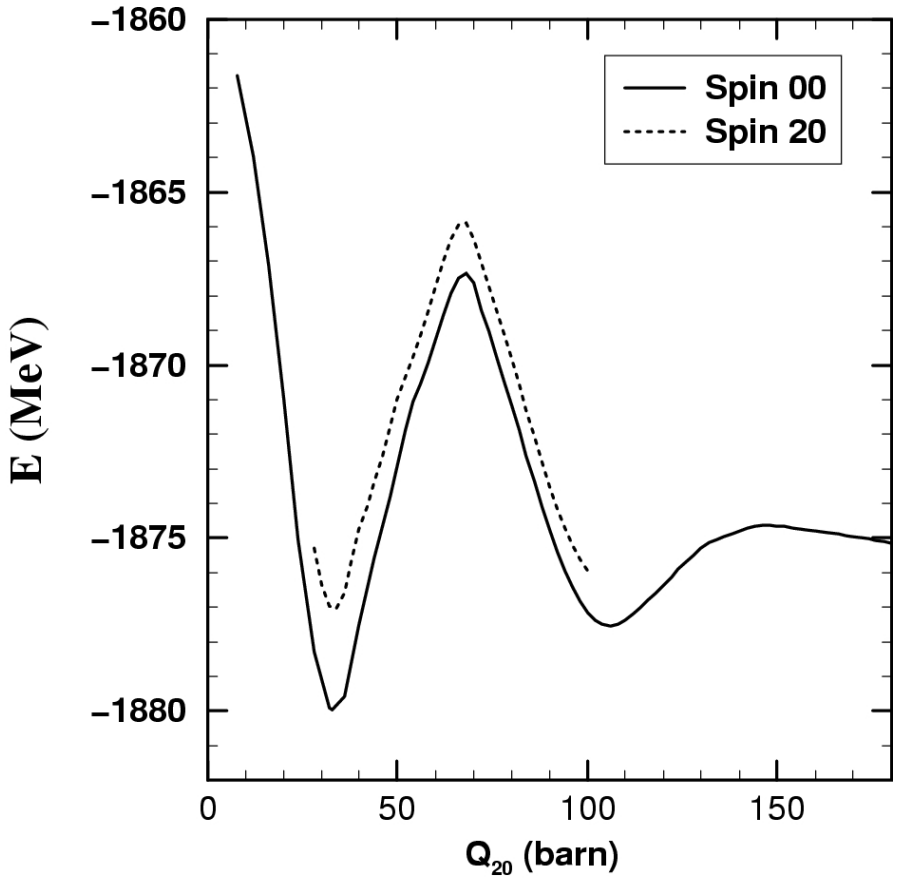
$Q_0$ theo from T. Duguet et al NPA 679 (2001) 427

- Notes :
  - Assumes pure axial symmetry and pure collective excitation
  - Be careful with Harris fit !
  - Direct $Q_0$ of B(E2) measurement would be great !

# Fission and angular momentum

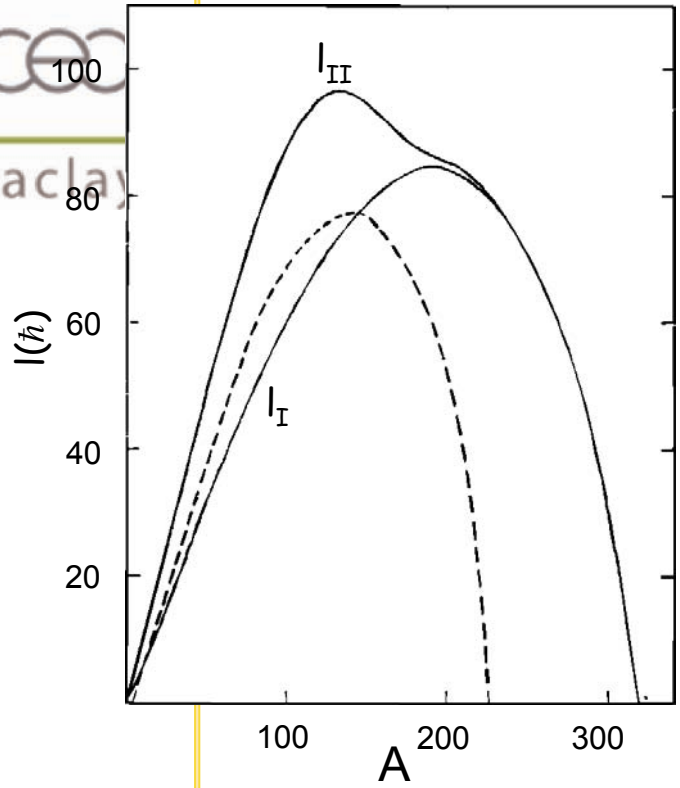



J.L. Egido, L.M. Robledo. P.R.L. 85 (2000) 1198

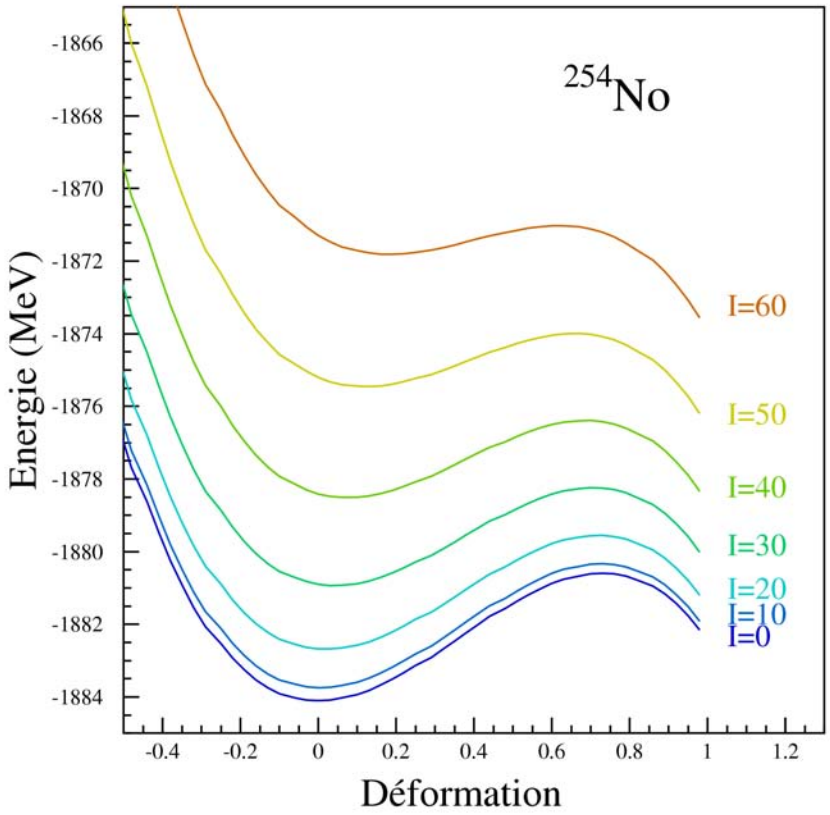



Th. Duguet *et al.* Nucl. Phys. A697 (2001) 427

# Fission and angular momentum




Cohen, Plasil, Swiatecki. Ann. Phys. 82 (1974) 557

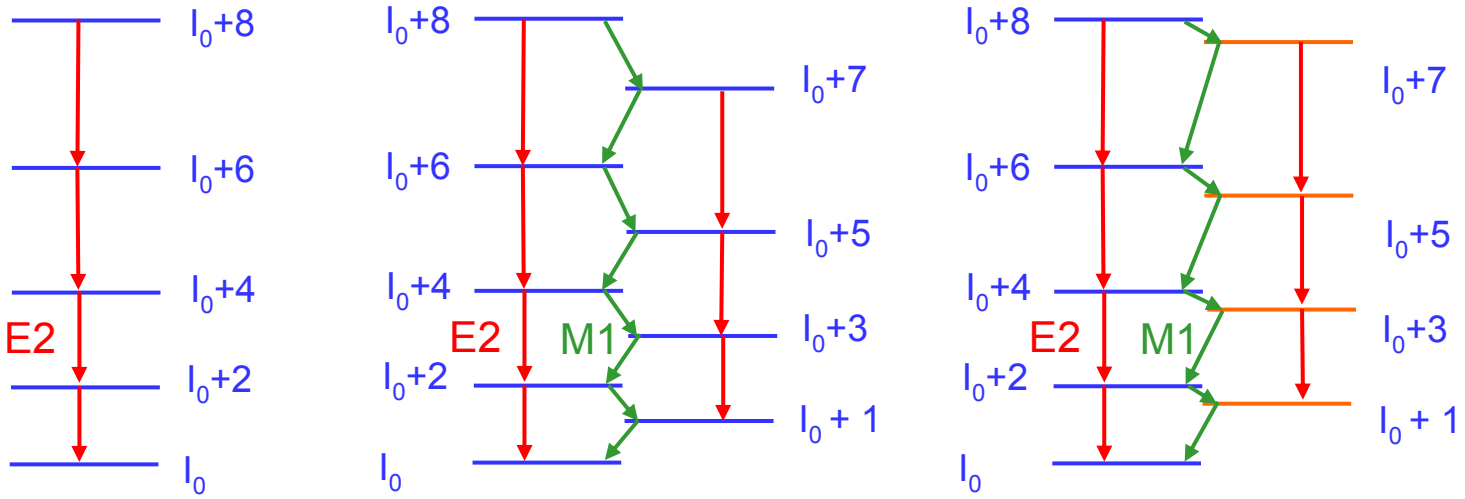



$$E_{L.D.}(Z,N,def,I) = E(Z,N,def) + \frac{\hbar^2 I^2}{2J(Z,N,def)}$$

# Fission and angular momentum

- Transfermium nuclei should survive up to high spin ~ 60 $\hbar$
- Experimentally, rotation observed up to ~ 20 $\hbar$
- This is because experimentally, nuclei are produced using fusion-evaporation reaction with excitation energy (in addition to collective excitation). Fission probability is hence very large, which limits angular momentum (entry point).

# Odd nuclei




$$E = \frac{\hbar^2}{2J}\{I(I+1) - K^2 + a\delta_{K,1/2}(-1)^{(I+1/2)}(I+1/2)\}$$

M1/E2 ratio
→magnetic moment
→ configuration

# B(M1)/B(E2) ratio

$$B(E2) = \frac{5}{16\pi} \langle I\ K\ 2\ 0 \mid I\text{-}2\ K\rangle^2\ Q_0^2\ (e^2\ fm^4)$$

$$B(M1) = \frac{3}{4\pi} K^2 (g_K - g_R)^2 \langle I\ K\ 1\ 0 \mid I\text{-}1\ K\rangle^2\ (\mu_n^2)$$

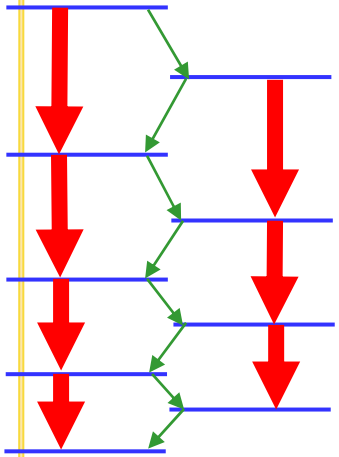
$$B(M1;\ I \rightarrow I\text{-}1) = \frac{1}{2} \left| \langle + | iO(M1,y) + O(M1,z) | - \rangle \right|^2$$

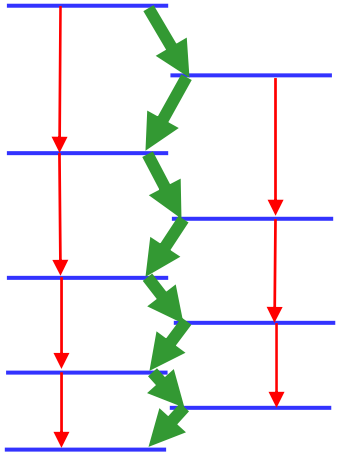
(x: rotational axis)

with : ✓ $O(M1) = \sqrt{\frac{3}{4\pi}}\ [(g_l^{eff}\text{-}g_R)l + (g_s^{eff}\text{-}g_R)s]$

✓ magnetic moment : $\mu_{y/z} = \langle + | O(M1,y/z) | - \rangle$

# Example : $^{253}$No





[624]7/2$^+$

$g_K$ = 0.28

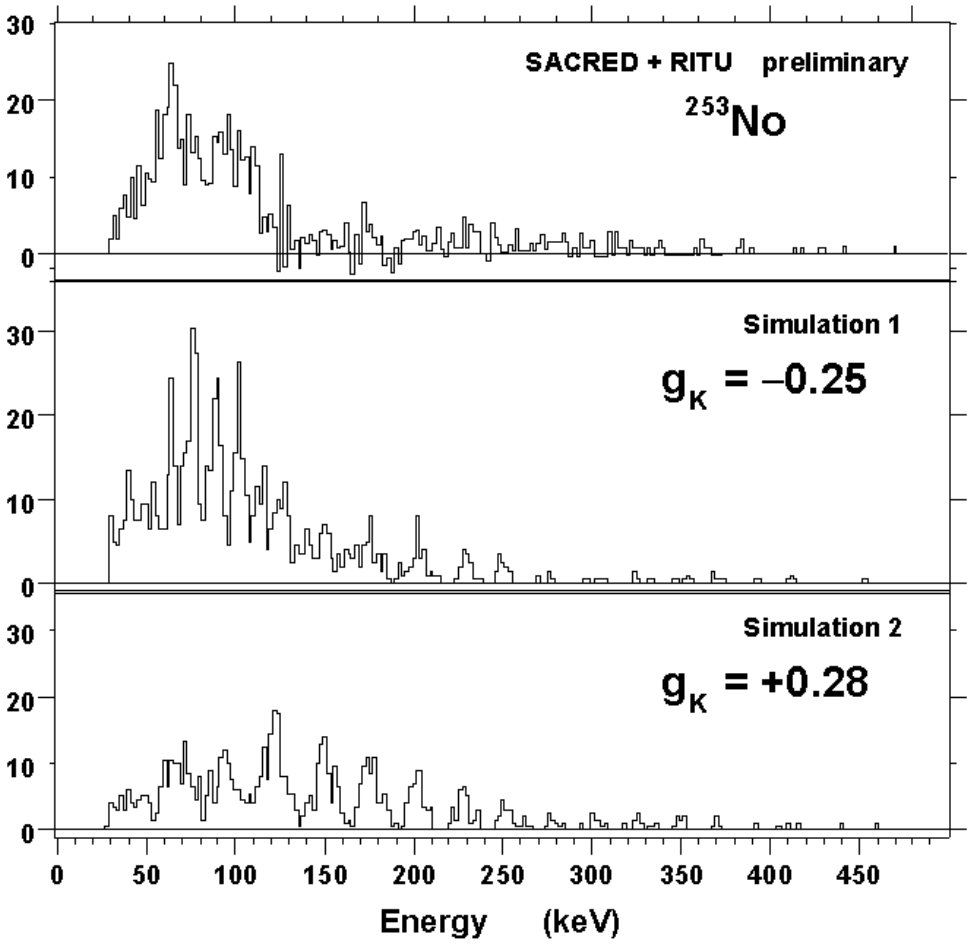
[734]9/2$^-$

$g_K$ = -0.25

$B(M1)/B(E2) \sim$

$K^2(g_K-g_R)^2/Q_0^2$

# From electron spectroscopy

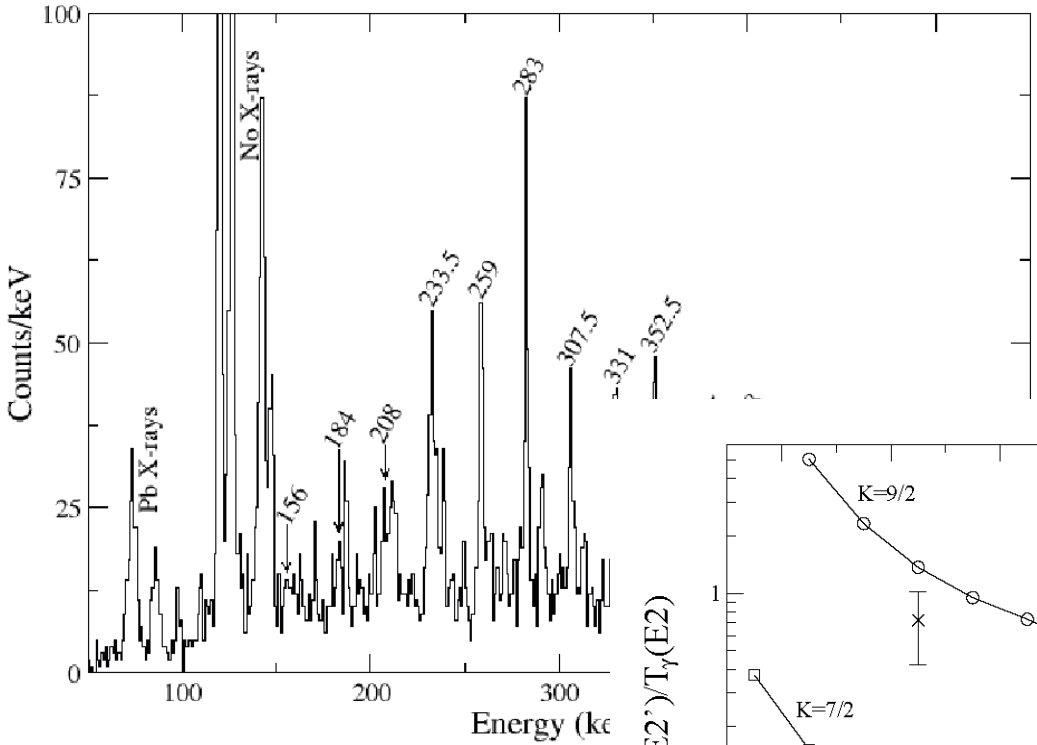


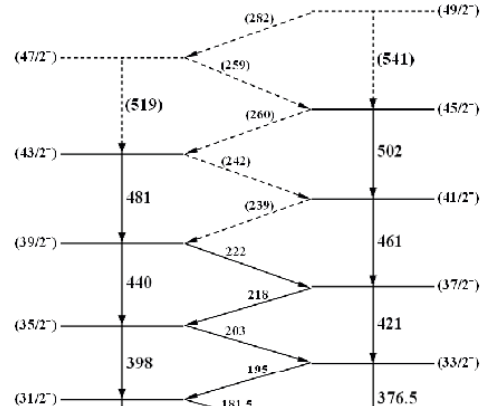

$9/2^-[734]$ (gs)

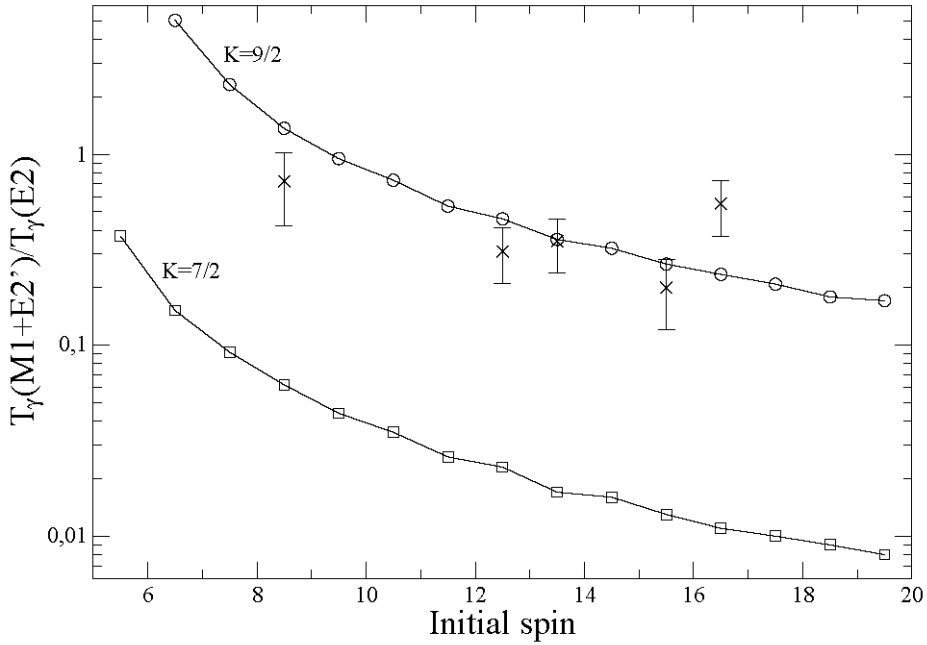
$7/2^+[624]$

R.-D. Herzberg et al EPJA 15 (2002) 205.

# From gamma spectroscopy

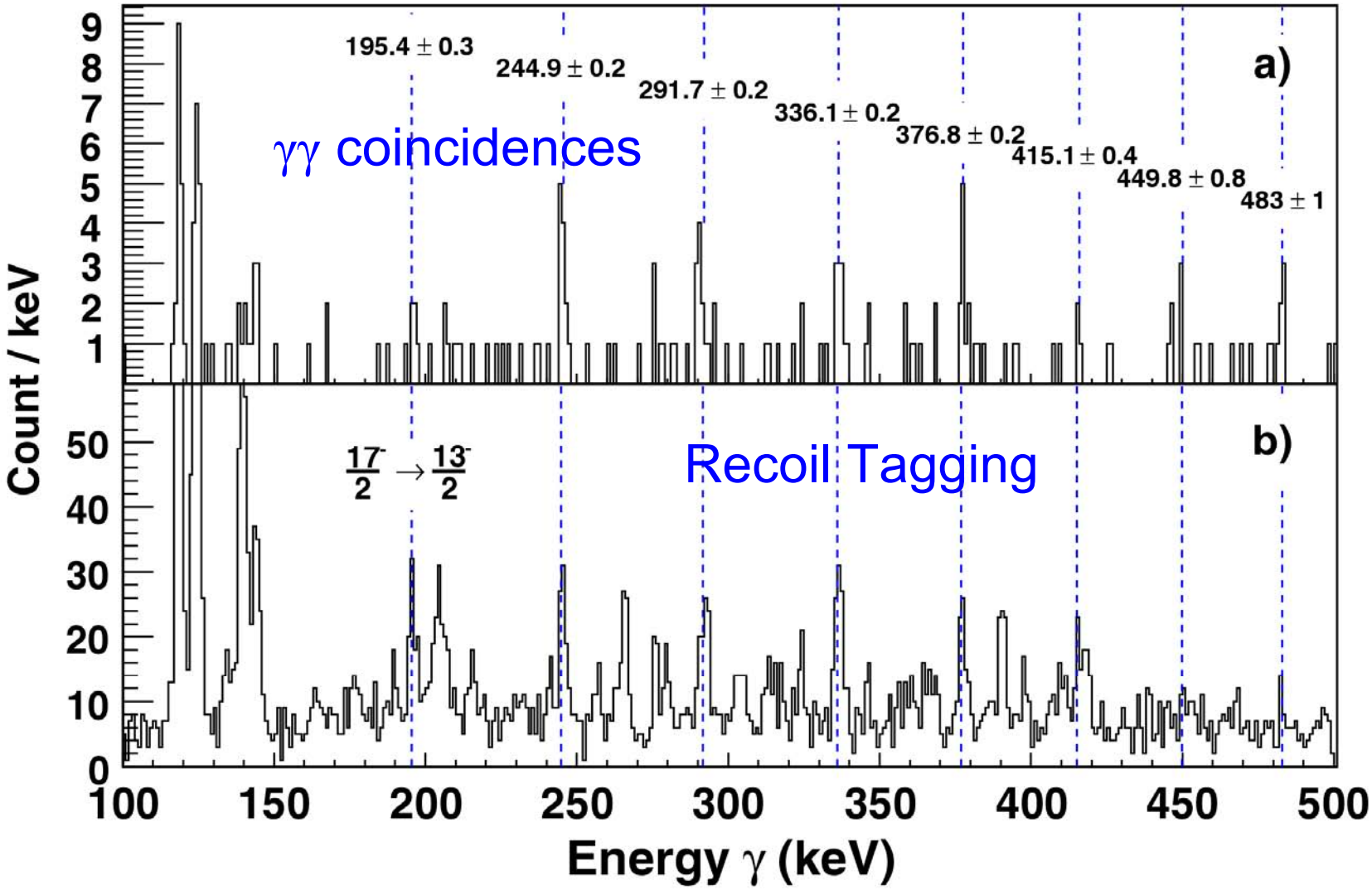


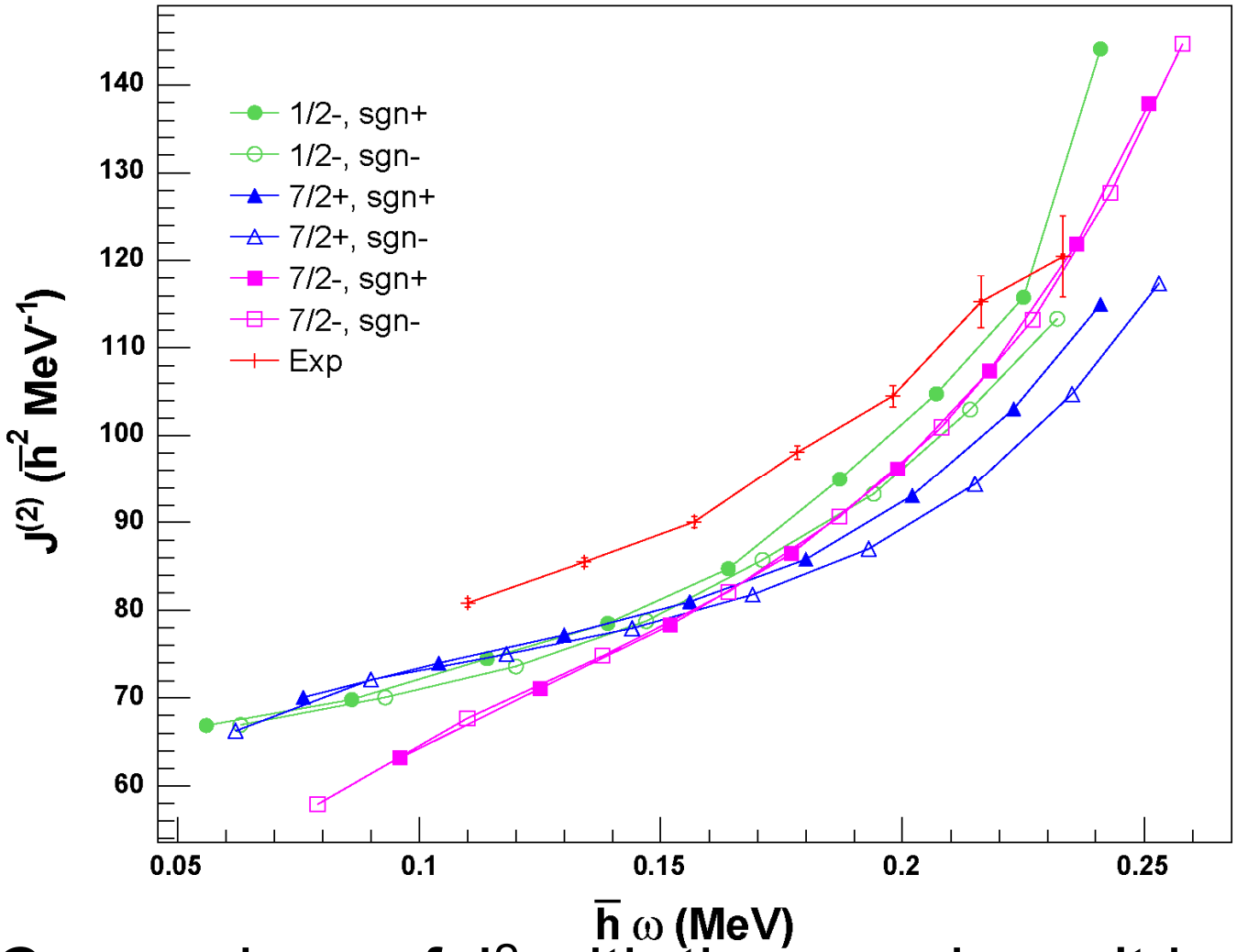

S. Eeckhaudt, PhD Thesis

# $^{251}$Md

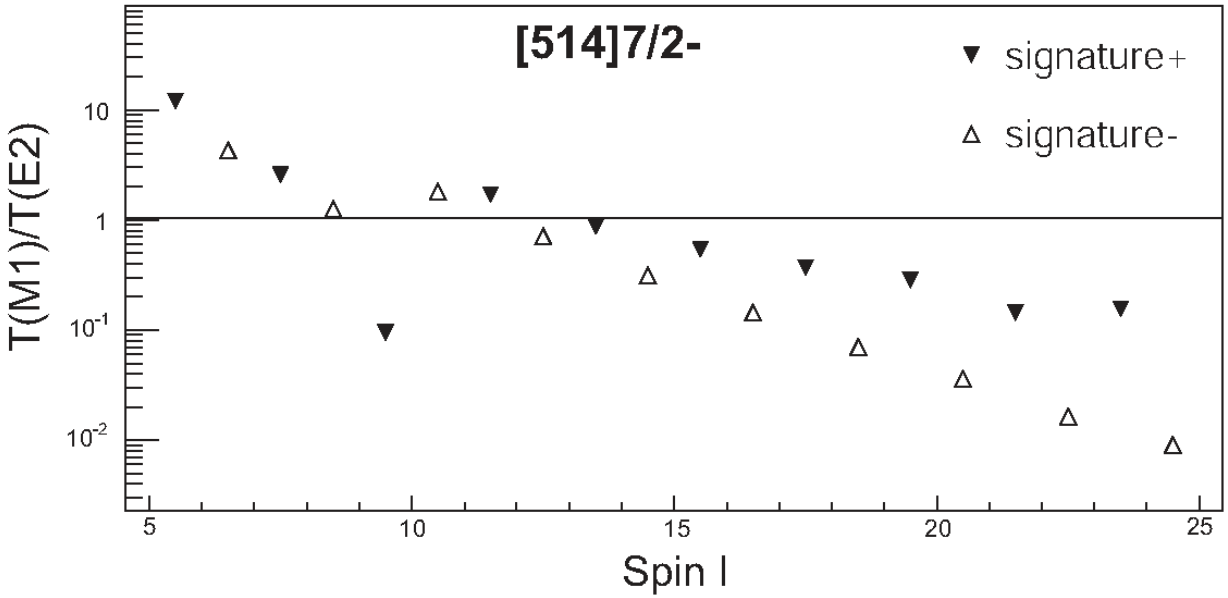


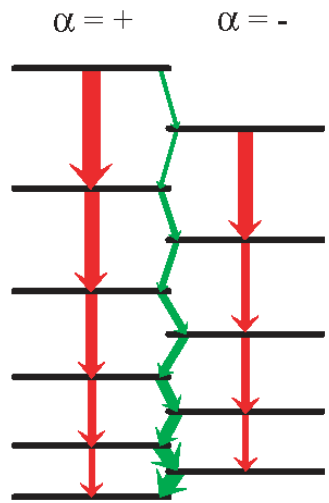

A. Chatillon et al. PRL 98 (2007) 132503

# $^{251}$Md prompt spectroscopy




Comparison of $J^2$ with theory : doesn't help to assign configuration


[514]7/2-
signature+
signature-
T(M1)/T(E2)
Spin I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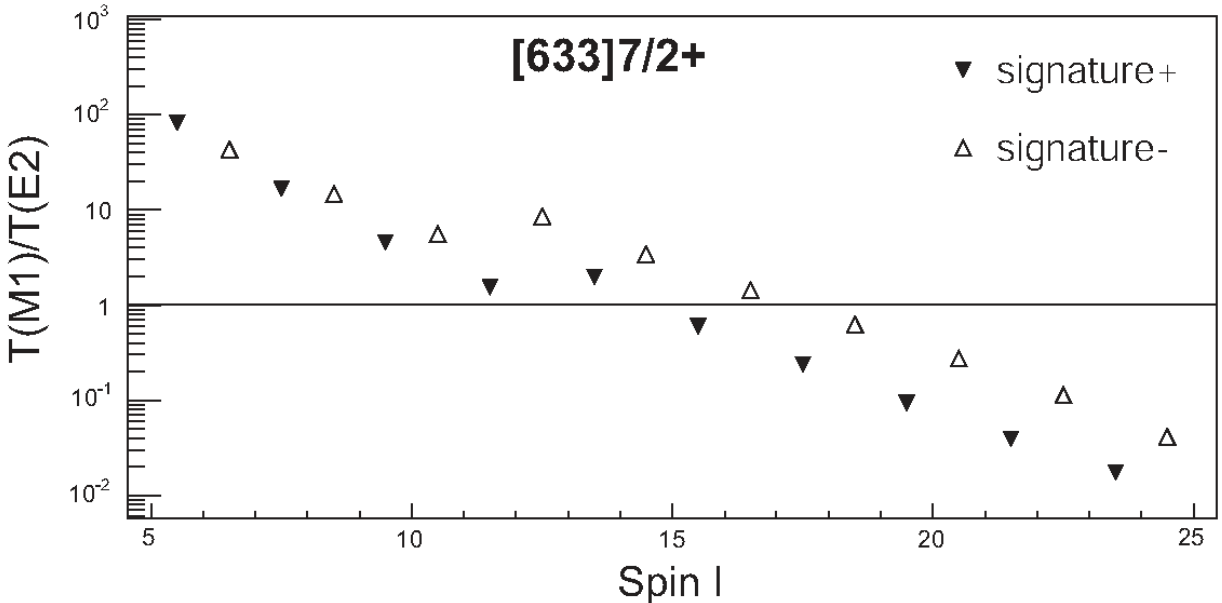
α = -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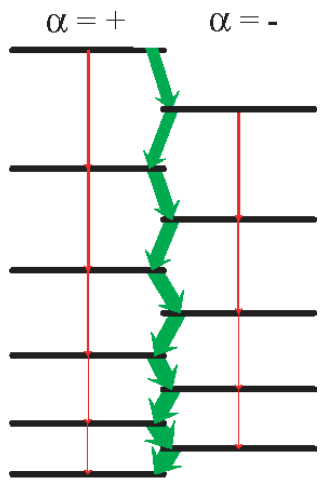
signature-
T(M1)/T(E2)
Spin I


α = +
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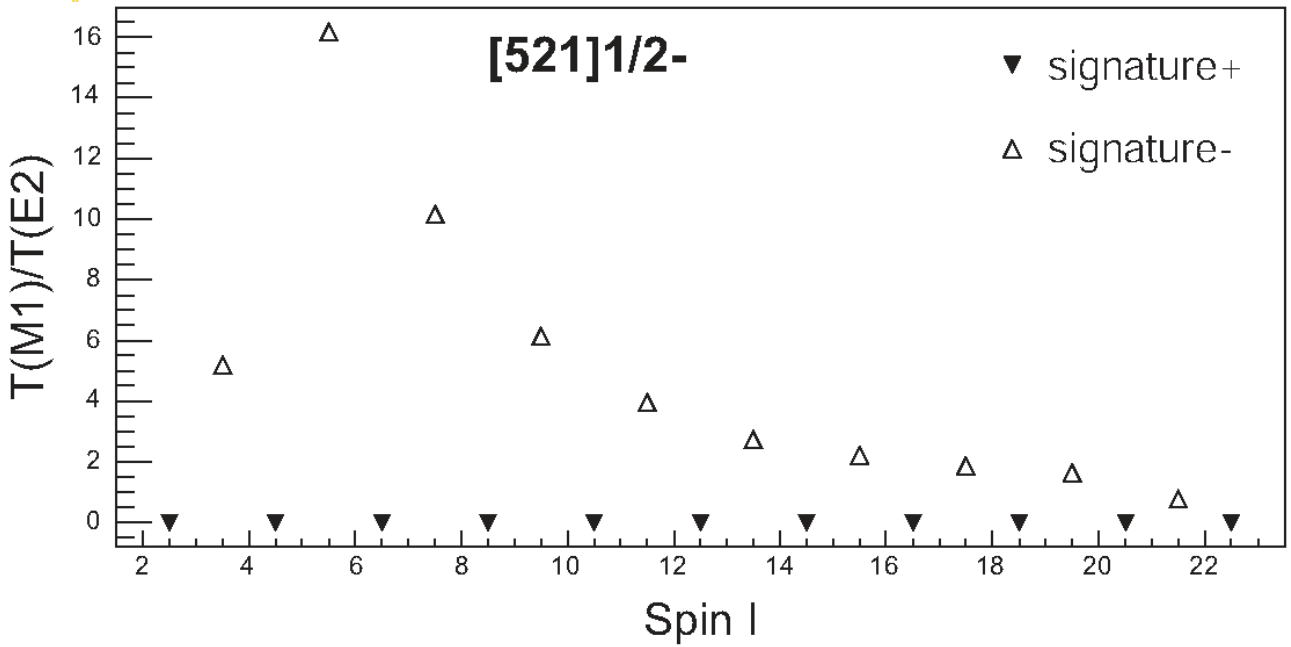
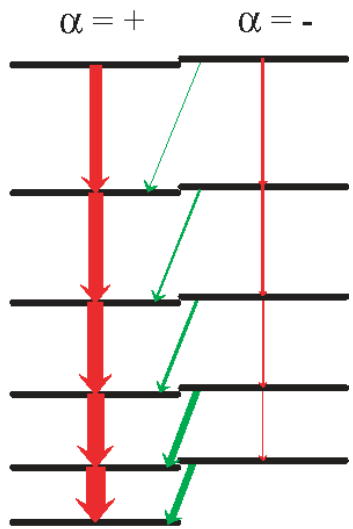


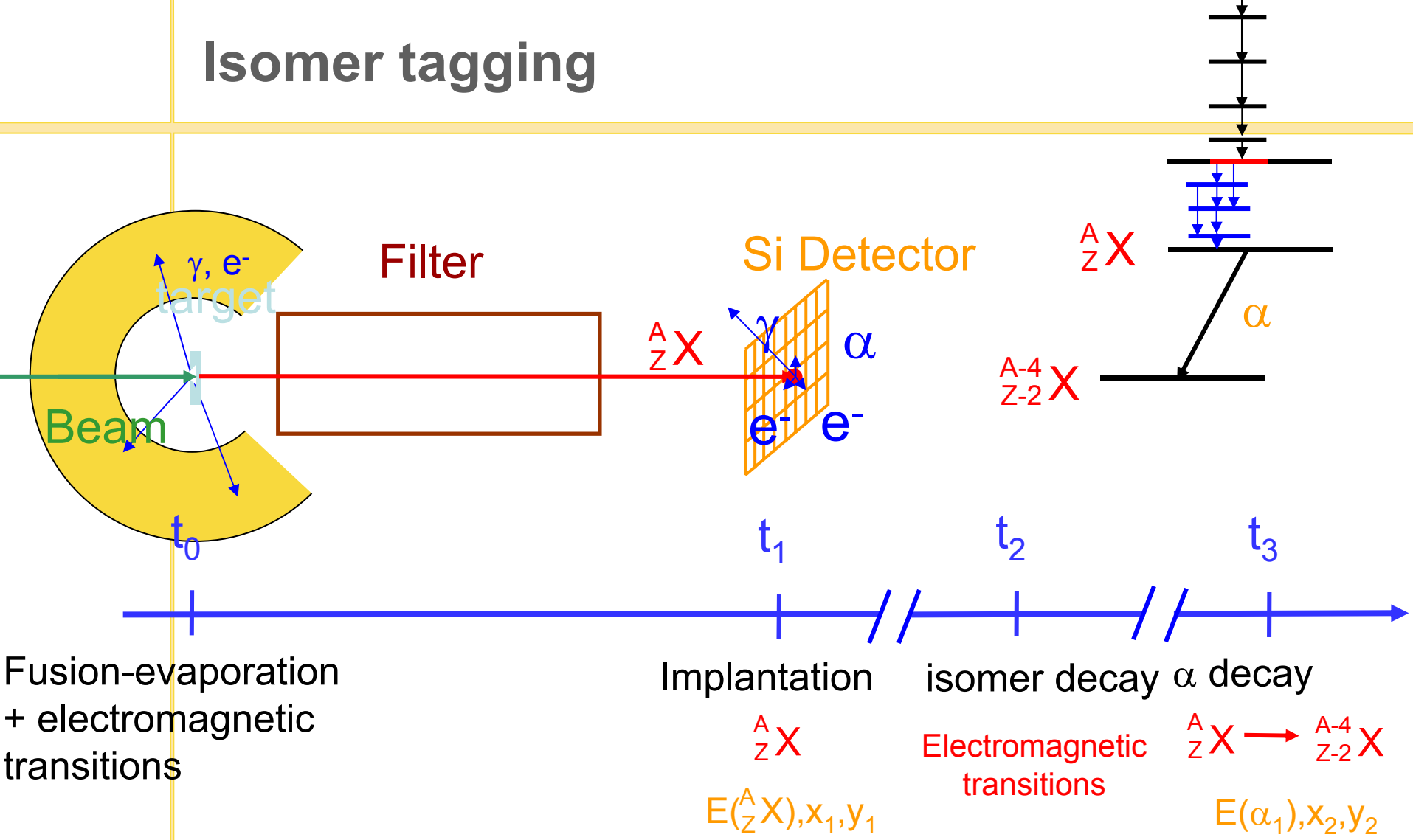




Decoupling parameter a ~ 1

Only configuration compatible with experimental data

# Rotational bands and K-isomers

# Isomer tagging




Fusion-evaporation + electromagnetic transitions

Implantation

$^{A}_{Z}X$

$E(^{A}_{Z}X), x_1, y_1$

isomer decay

Electromagnetic transitions

$\alpha$ decay

$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X$

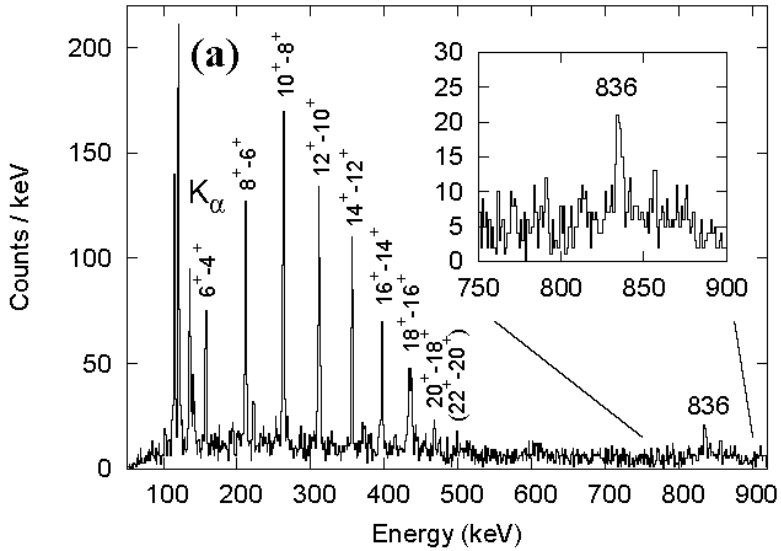
$E(\alpha_1), x_2, y_2$

Calorimeter technique :
isomer tagging using the implantation detector
G.D. Jones, Nucl. Instr. And Meth. A 488 (2002) 471

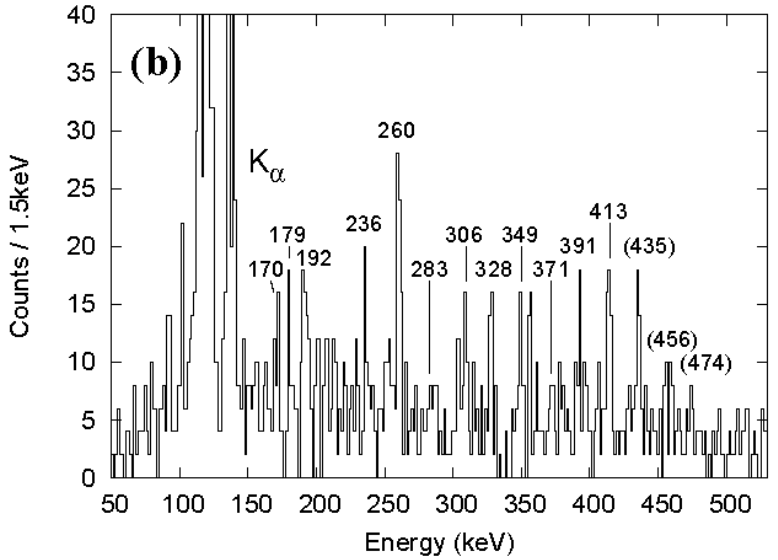
$\Delta t = t_2 - t_1$

$\Rightarrow t_{1/2}(\text{isomer})$

# $^{250}$Fm



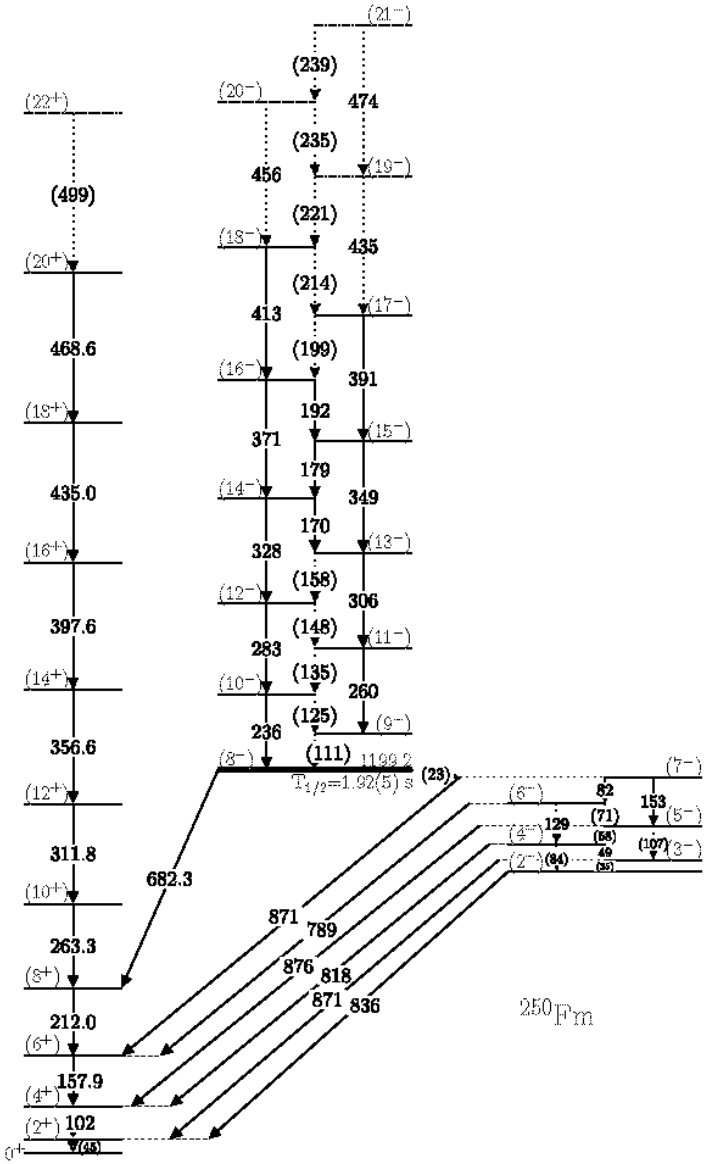

Recoil tagging




Isomer tagging

P. Greenlees *et al*., PRC in pres

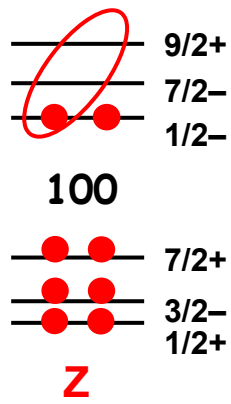
# $^{250}$Fm


(21⁻)
(239)
(20⁻)
474
(235)
456
(19⁻)
(221)
(18⁻)
435
(214)
413
(17⁻)
(199)
(16⁻)
391
192
371
(15⁻)
179
(14⁻)
349
170
328
(13⁻)
(158)
(12⁻)
306
(148)
283
(11⁻)
(135)
(10⁻)
260
(125)
236
(9⁻)
(111)
(8⁻)
1199.2
T1/2=1.92(5) s
(23)
(7⁻)
82
153
(6⁻)
(71)
(5⁻)
129
(58)
(4⁻)
(107)
(3⁻)
49
(84)
(2⁻)
(35)
(22⁺)
(499)
(20⁺)
468.6
(18⁺)
435.0
(16⁺)
397.6
(14⁺)
356.6
(12⁺)
311.8
(10⁺)
682.3
263.3
(8⁺)
871
789
876
818
871
836
212.0
(6⁺)
157.9
(4⁺)
(2⁺)
102
0⁺
(45)
250Fm

# Single particle states for $^{250}$Fm

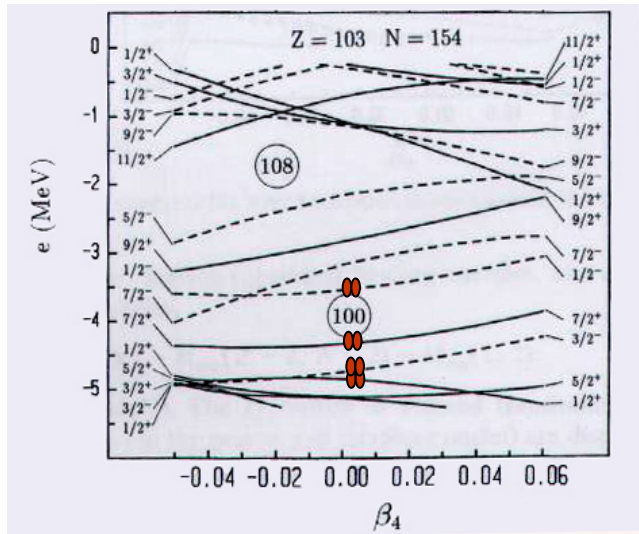
Calculated proton configuration:
$K_\pi = 8^-$ $E_{exc}$ = 1.44 MeV **

$$\pi\frac{7}{2}^-[514]\otimes\pi\frac{9}{2}^+[624]$$




$g_k$ ππ(th.)= 1.001

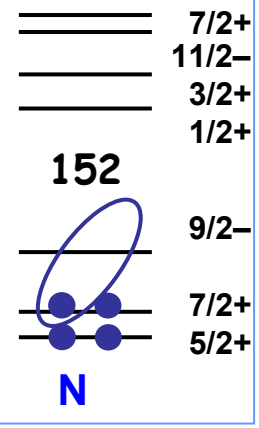
$g_k$ (exp.)= 0.09



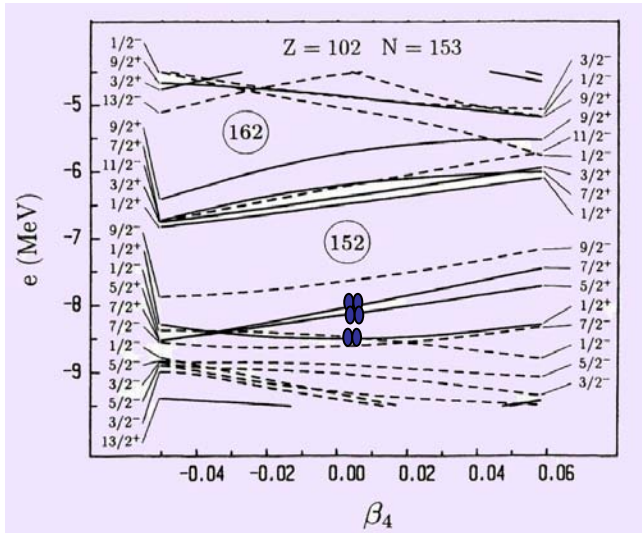

Neutron single particle levels around Z=153 in the wood-Saxon potential as funcions of $\beta_4$

Calculated neutron configuration:
$K_\pi = 8^-$ $E_{exc}$ = 0.97 MeV *

$$\nu\frac{7}{2}^+[624]\otimes\nu\frac{9}{2}^-[734]$$




$g_k$ νν(th.)= - 0.025




*Xu et al.PRL vol 92(2004) 25

**Soloviev et al.Sov.J.Nucl.Phys. 54, 748 (1991)



S.Cwiock et al.Nuclear Physics A573(1994) 356-394

# K isomers : an old story

PHYSICAL REVIEW C VOLUME 7, NUMBER 5 MAY 1973

## Isomeric States in $^{250}$Fm and $^{254}$No†

Albert Ghiorso, Kari Eskola,* Pirkko Eskola,* and Matti Nurmia
*Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720*
(Received 30 November 1972)

A preliminary report on the discovery of isomeric states in $^{250}$Fm and $^{254}$No was included in a recent article on $\alpha$-emitting isotopes of element 104. The existence and assignments of the 1.8± 0.1-sec isomer to $^{250}$Fm and the 0.28± 0.04-sec isomer to $^{254}$No have now been confirmed by cross-bombardment techniques. Isomeric ratios based on measurements of collection efficiency of recoil atoms from the decay of isomeric states are given. An interpretation of the even-even isomers as high-spin two-quasiparticle states is discussed.

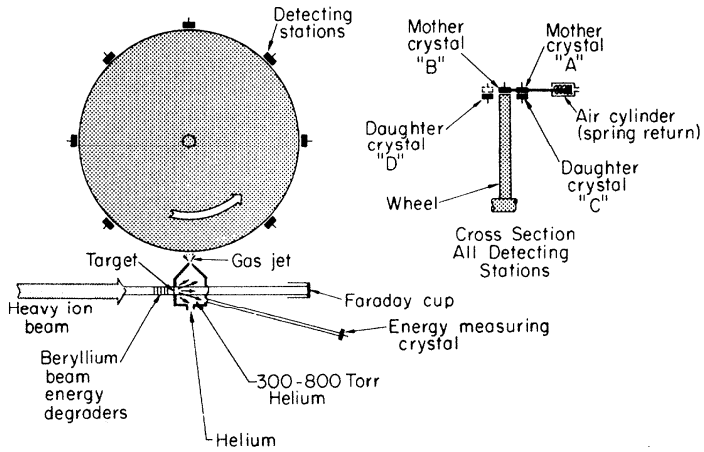
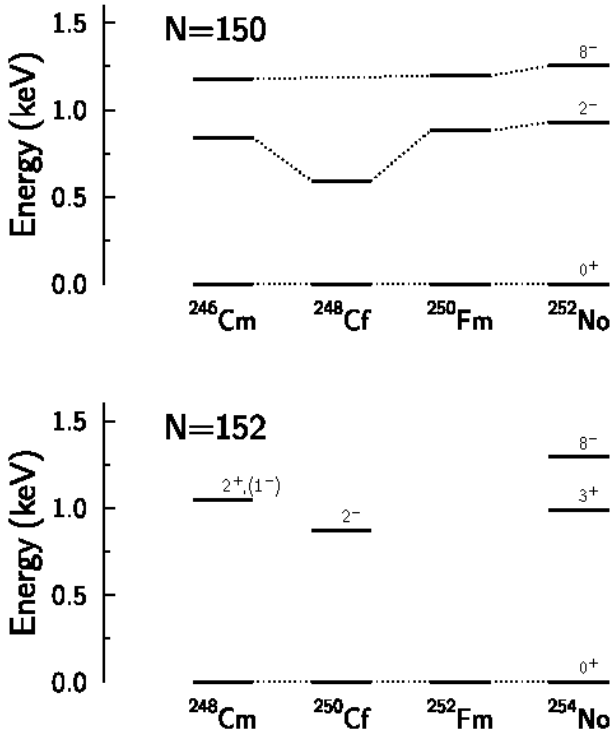
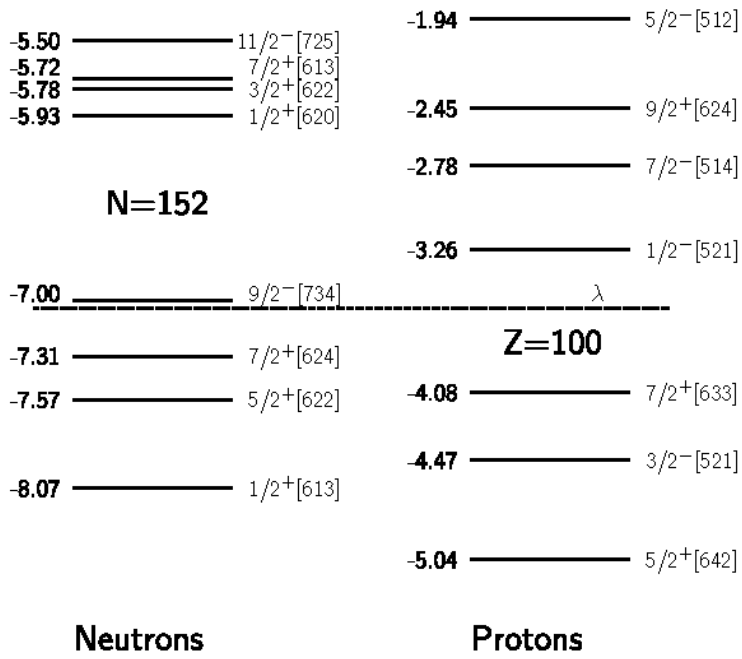


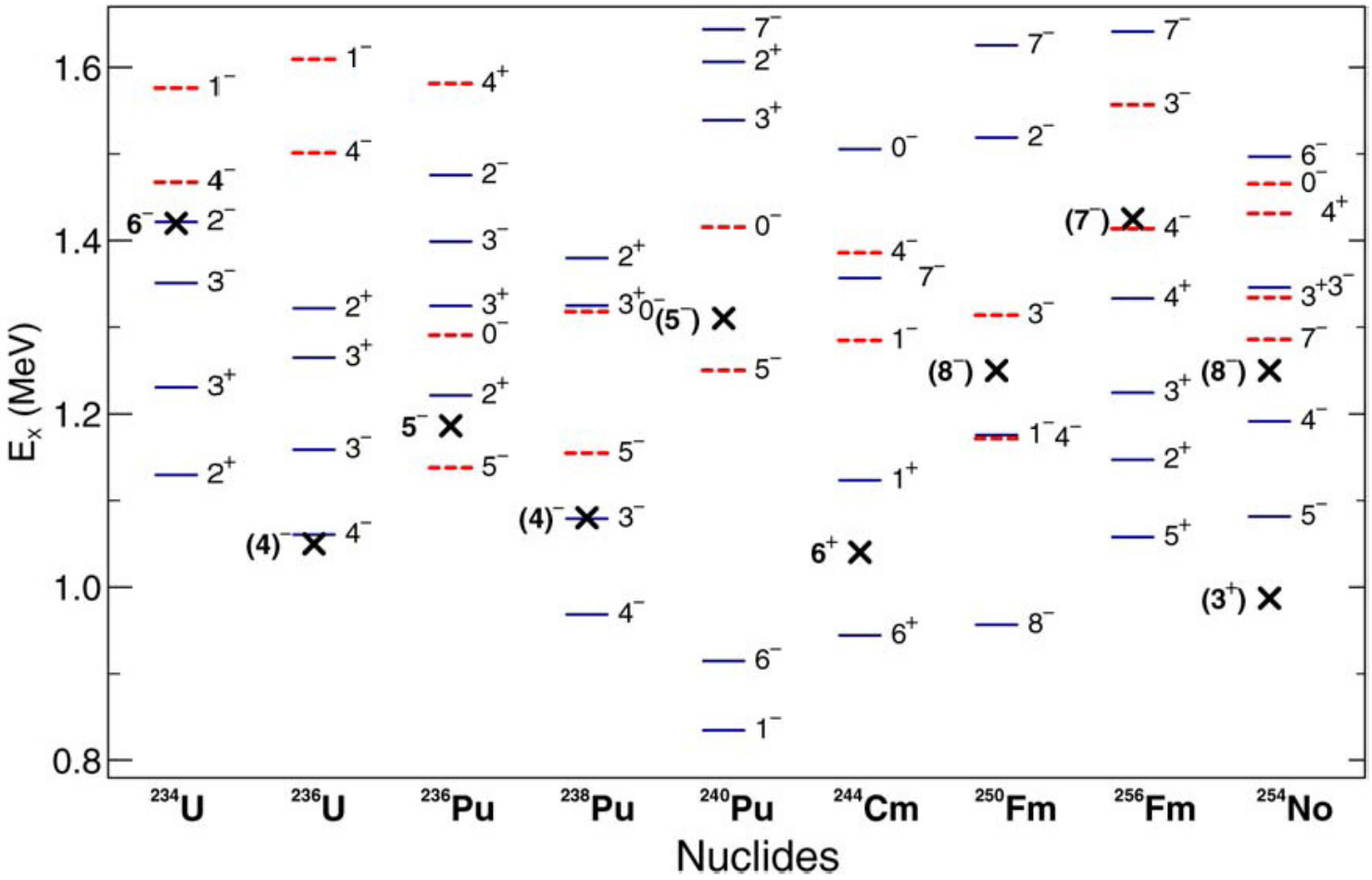

FIG. 1. A schematic diagram of the seven-detector-station system. The cross section at right shows the arrangement of the two movable mother detectors and the two stationary daughter detectors.

# Systematics of K-isomers

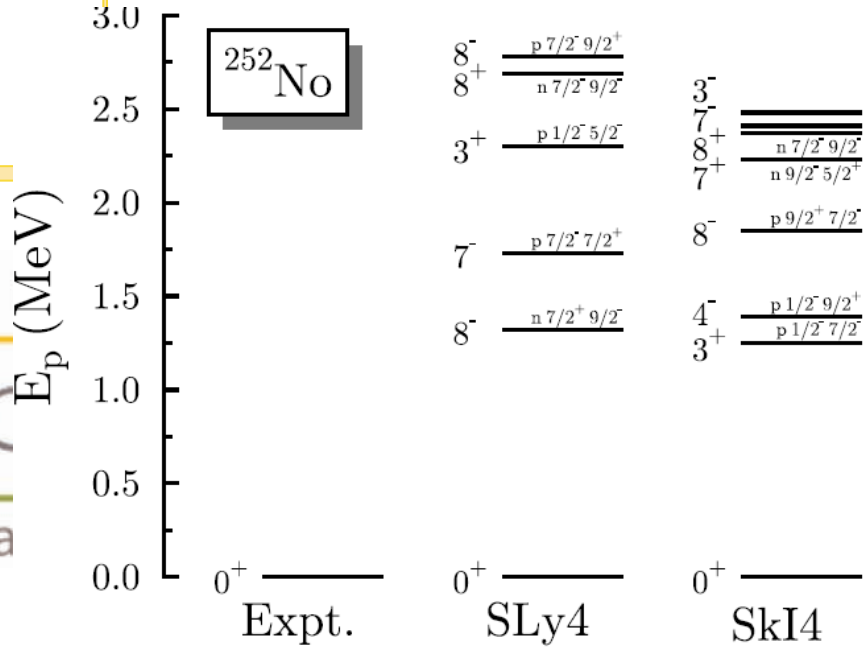


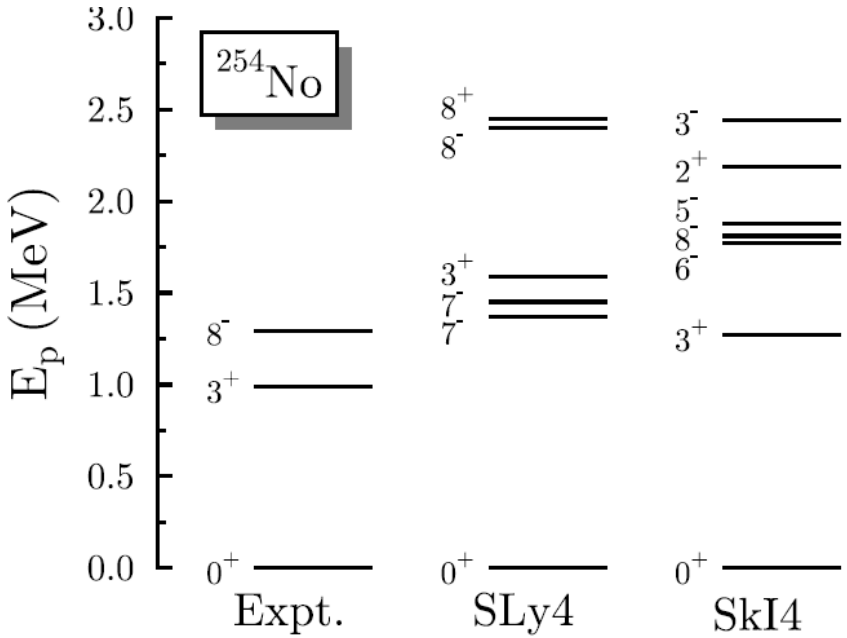



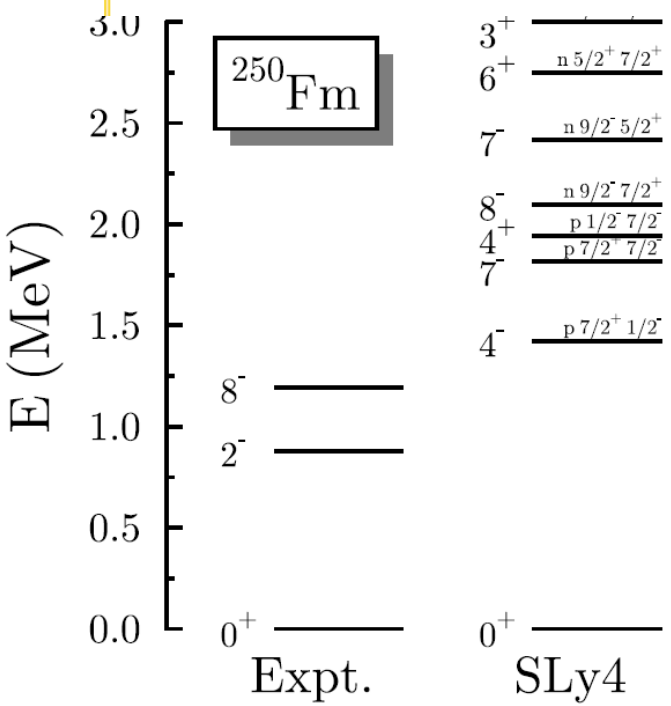
# K-isomers




J.-P. Delaroche *et al.* NPA 771 (2006) 103

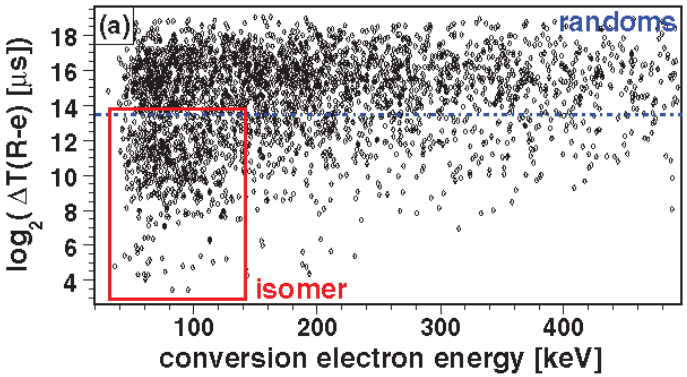


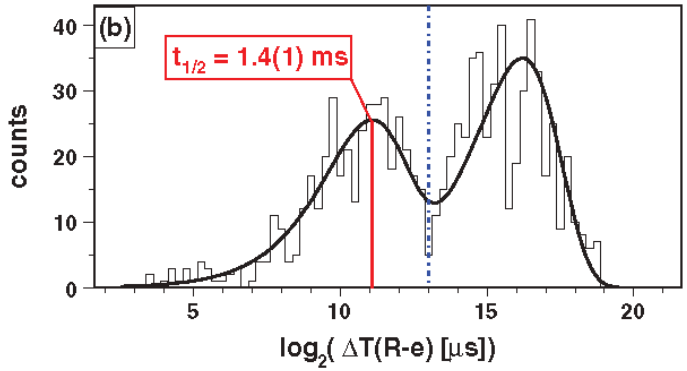



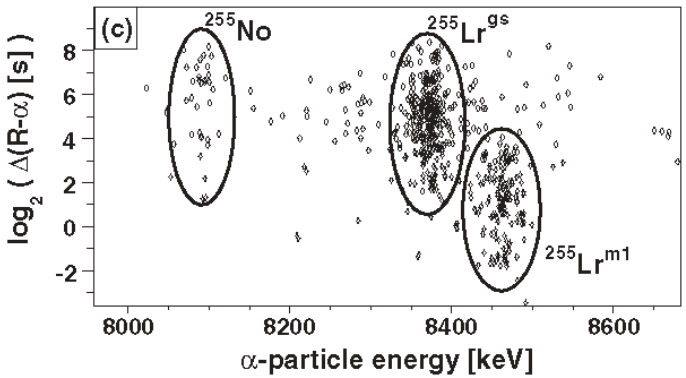



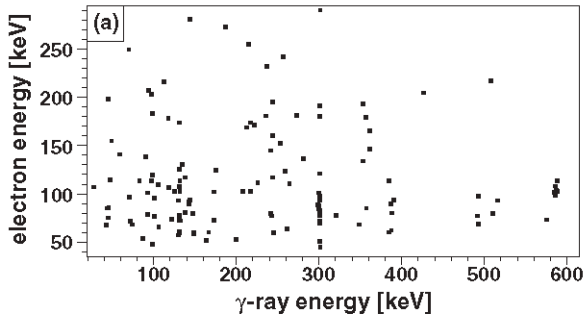

PHH, unpublished

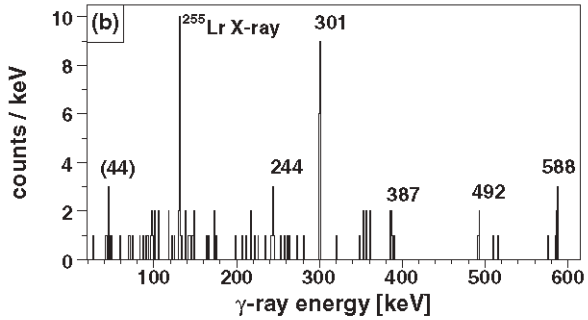
# 3qp isomer in $^{255}$Lr

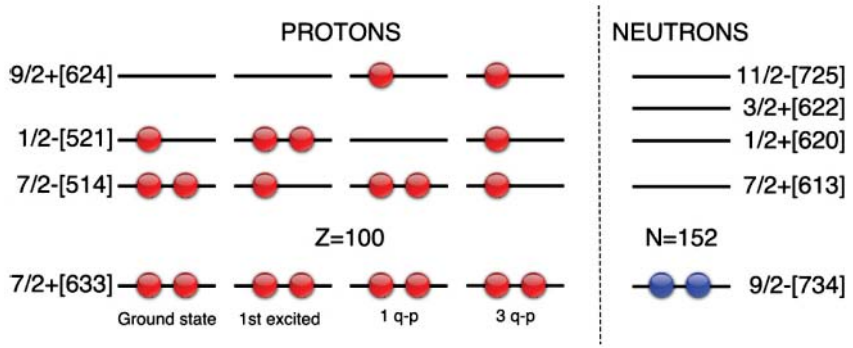



K. Hauschild et al, PRC in press

# Pushing the limits : prompt spectroscopy

- Trends :
  - Combination of gamma and electron spectroscopy : SAGE
  - Improving counting rate capabilities using digital electronics
    - JUROGAM II (Jyväskylä)
    - EXOGAM II (GANIL)
    - …
  - Gamma-ray tracking
    - AGATA (Europe)
    - GRETA (USA)

# Pushing the limits : decay spectroscopy

- Use highest beam intensity
  - LINAG

  Need high rejection spectrometer like S3

- Sophisticated focal plane devices

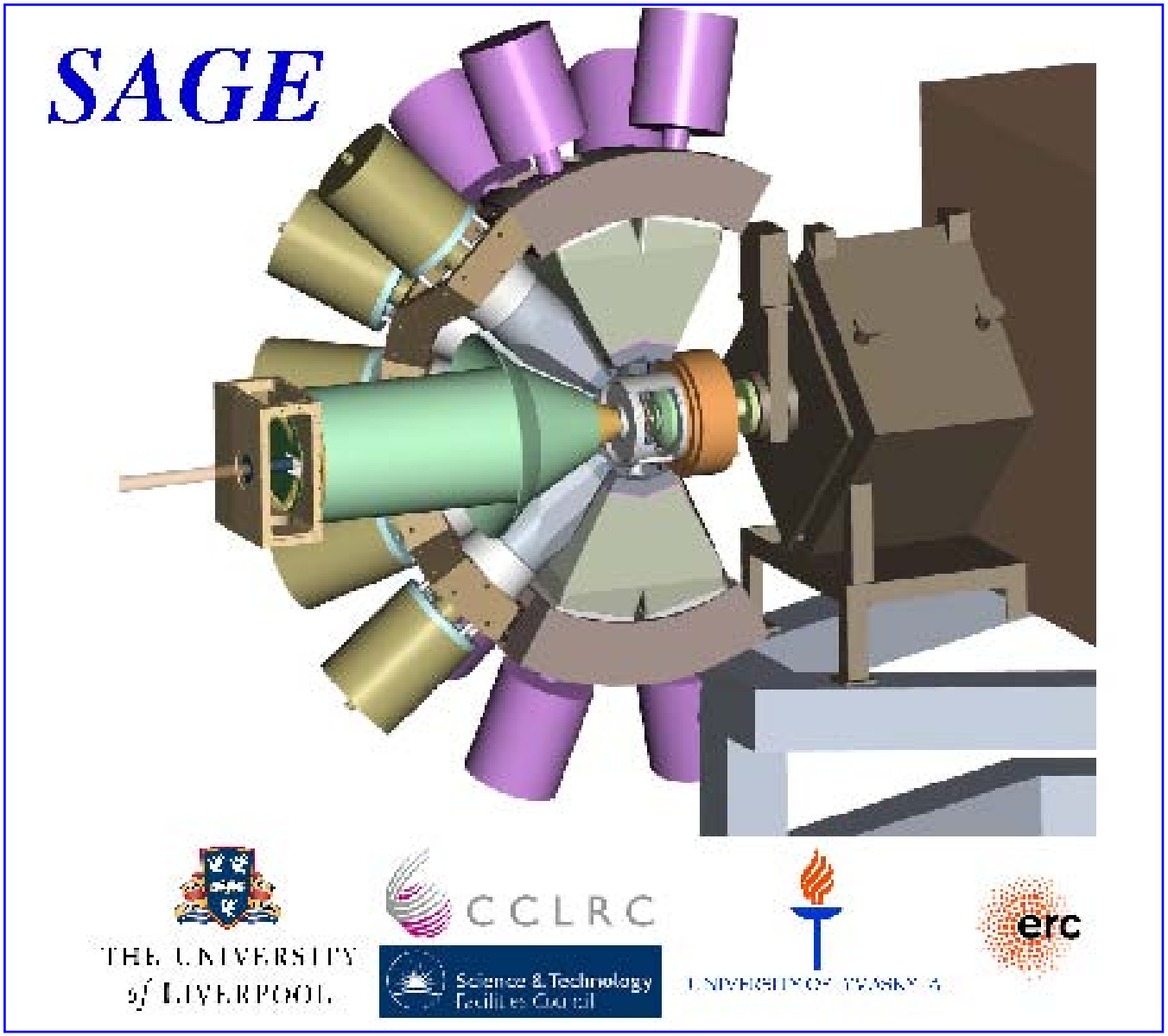
# Pushing the limits : ground state properties

- Mass measurement
  - Shiptrap
- Optics spectroscopy
- Chemistry

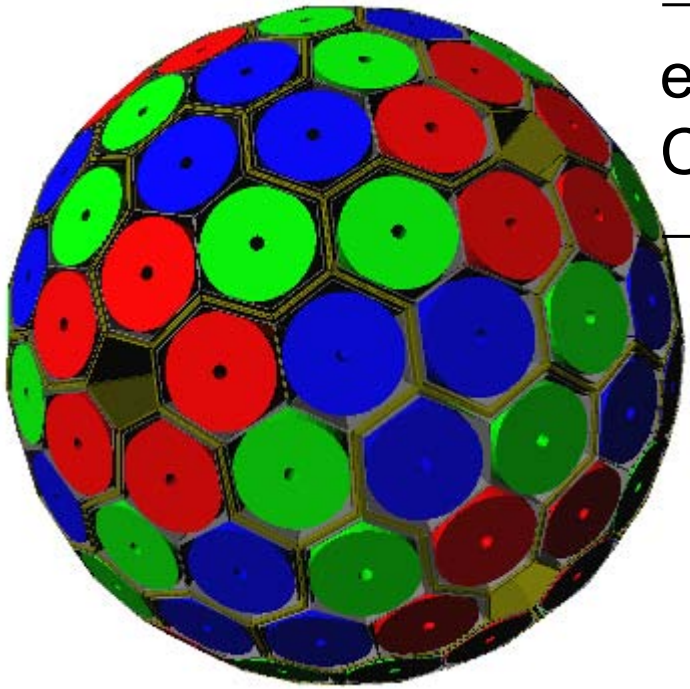
# Pushing the limits : radioactive beams

- High intensity radioactive beams
  - Spiral II
  - Reaction mechanism to be studied eg symmetric reaction

# SAGE


SAGE
THE UNIVERSITY of LIVERPOOL
CCLRC
Science & Technology Facilities Council
erc

# AGATA

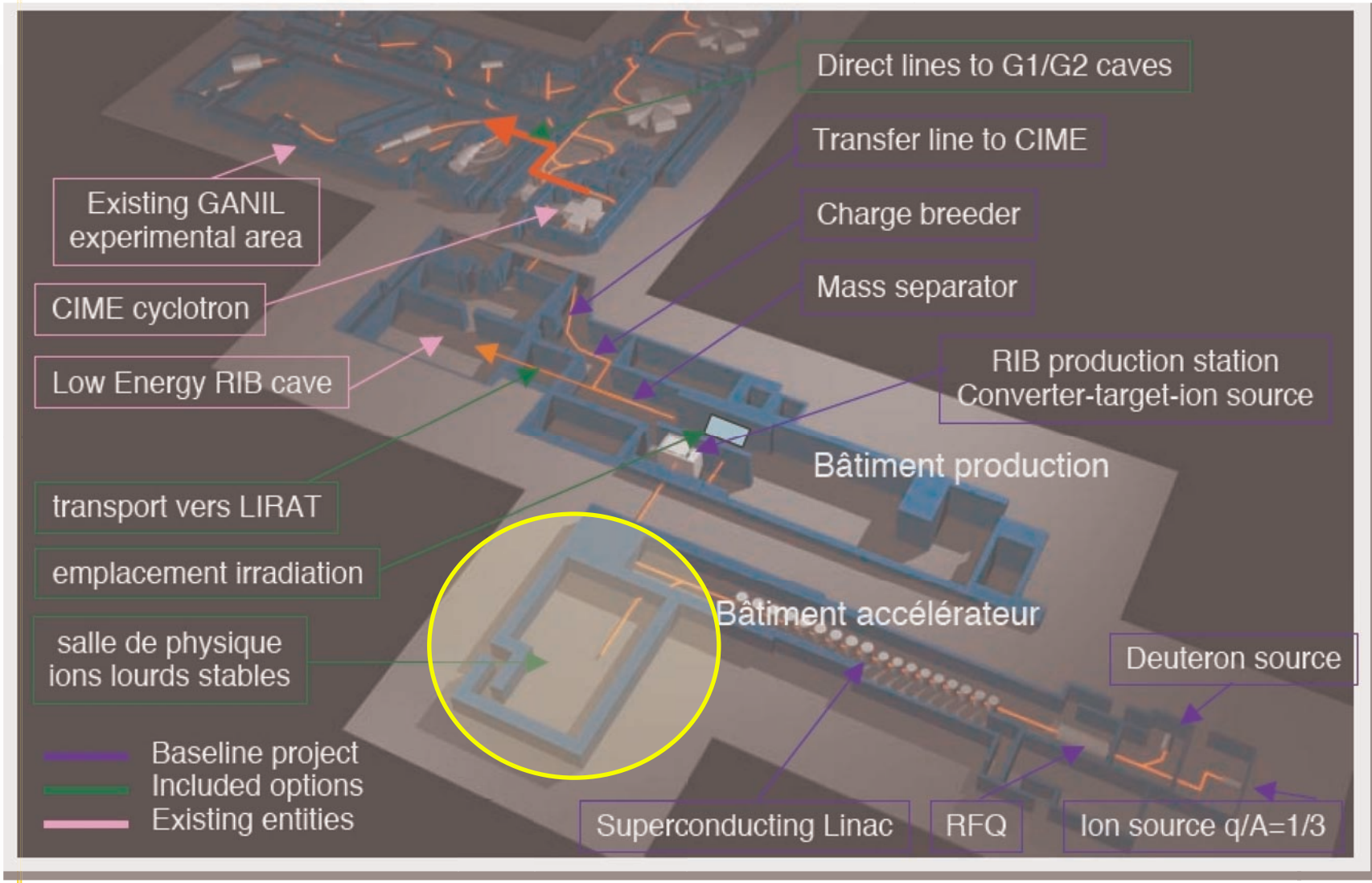


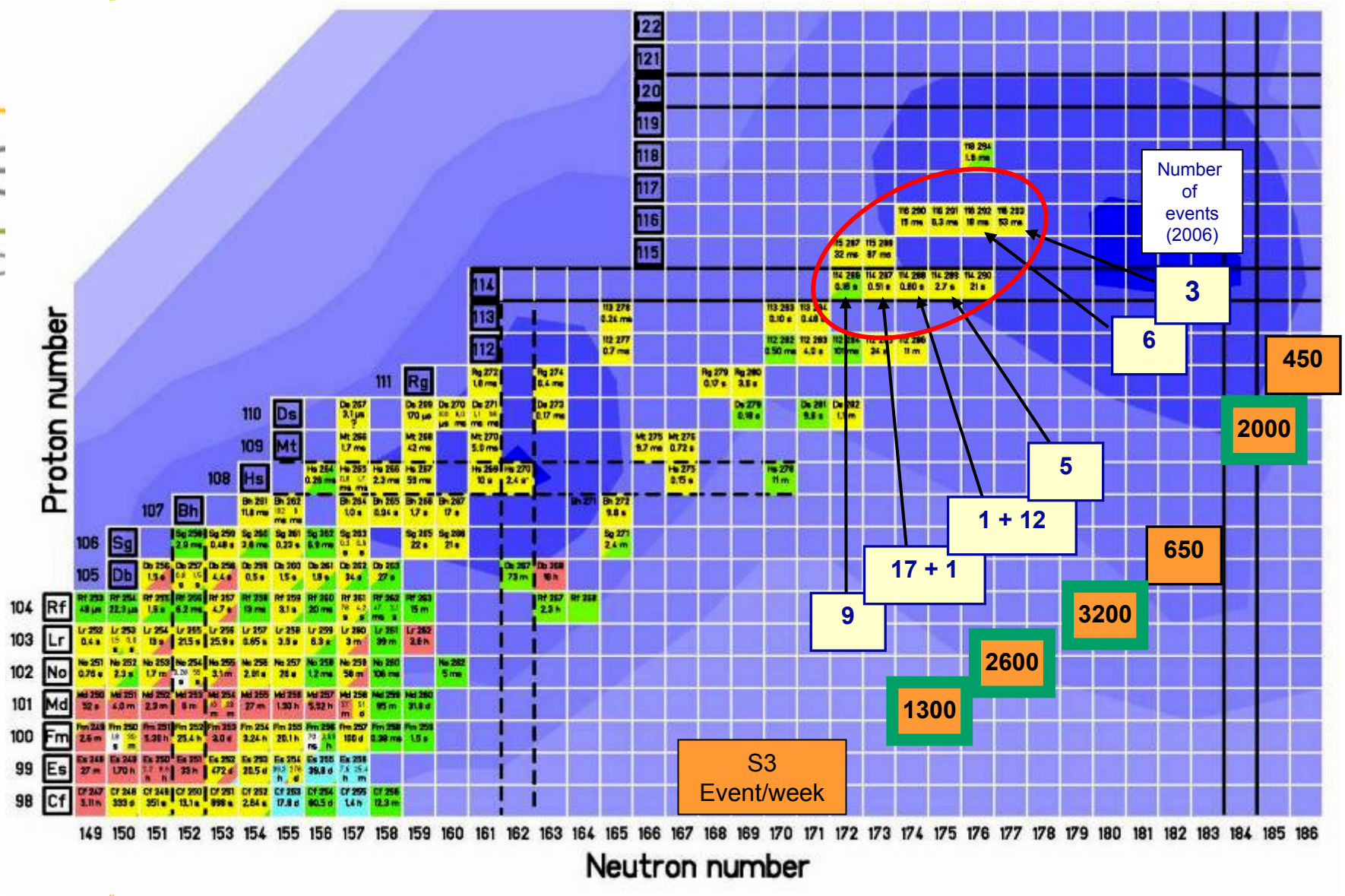
Efficiency ~ 40 %
→Huge gain in γγ, γγγ, …
efficiency
Cristal rate up to 50 kHz
→ Larger beam intensity

- **180 large volume 36-fold segmented Ge crystals in 60 triple-clusters**
- **Digital electronics and sophisticated signal processing algorithms (PSA)**
- **Operation of Ge detectors in position sensitive mode → γ-ray tracking**

http://www-w2k.gsi.de/agata/

# S3


Direct lines to G1/G2 caves
Transfer line to CIME
Existing GANIL experimental area
Charge breeder
CIME cyclotron
Mass separator
Low Energy RIB cave
RIB production station Converter-target-ion source
Bâtiment production
transport vers LIRAT
emplacement irradiation
Bâtiment accélérateur
salle de physique ions lourds stables
Deuteron source
Baseline project
Included options
Existing entities
Superconducting Linac
RFQ
Ion source q/A=1/3


Proton number
Neutron number
Number of events (2006)
3
6
5
1 + 12
17 + 1
9
450
2000
650
3200
2600
1300
S3 Event/week

# References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- http://www.transfermium.net/
- Wikipedia : “transuranium element”, “island of stability”

Thank you