

# Perspectives for laser spectroscopy and electron scattering at Orsay

David Verney, IPN Orsay

distant past  
↓  
(far ?) future

- The laser spectroscopy tradition in Orsay (a short entertaining historical introduction)
  - ISOCELE
  - the COMPLIS adventure at ISOLDE
  - laser-spectroscopy perspectives for ALTO as viewed from 2004 (!) and... now
- laser spectroscopy based observables : physics case for neutron-rich medium mass nuclei (ALTO is an ISOL photo-fission machine)
  - the  $N=50$  and  $N=82$  kinks
  - pseudo-spin symmetry
- (possible) future opportunities for e-scattering off RIBs at Orsay
  - the DESTIN project at the Orsay-hosted PERLE demonstrator



## Laser spectroscopy experiments on fission products

### Introduction : hyperfine interaction

**Principle** : use the electronic cloud to probe the nuclear electromagnetic properties

**Measured quantities** : spin  $I$ , magnetic moment  $\mu_I$ , spectroscopic quadrupole moment  $Q_S$ , evolution of the mean square charge radius  $\delta\langle r^2 \rangle_c$

### Physics case (part of)

Physics of medium mass nuclei produced by fission

### Laser spectroscopy systems

Resonant Ionisation spectroscopy (RIS) : COMPLIS

Collinear Spectroscopy after beam cooling : future laser system at ALTO

a long road ...

green light from French nuclear safety authorities



BEDO commissioning

first laser ionized RIB

building of the low energy beam lines + laser ion source

Commissioning : tests and radiation safety measurements

TIS vault

UCx target on line with e-beam – production yields measurements

First e-beam extracted

RF system

construction of the LINAC bunker

arrival of the LINAC cavity from decommissioned LEP injector

exploratory photofission experiment at CERN

ISOL available at TANDEM PARRNe mass-separator on line

2013

2012

2011

2010

2009

2008

2007

2006

2005

2004

2003

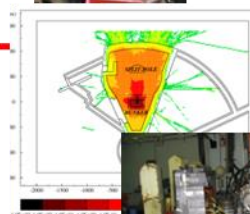
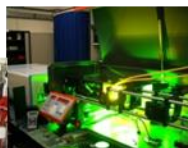
2002

2001

2000

1999

1998

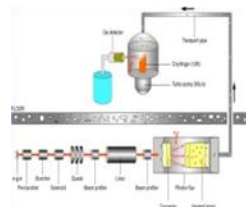


$84\text{Ga} \rightarrow 84\text{Ge} \beta\text{-decay}$



$81\text{Zn} \rightarrow 81\text{Ga} \beta\text{-decay}$

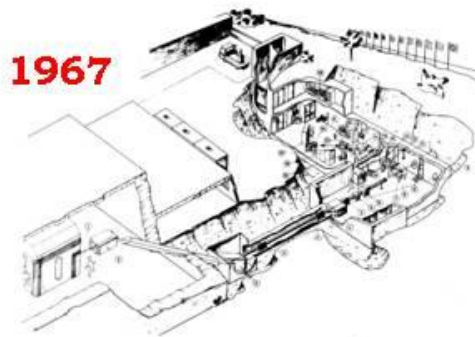
$83\text{Ga} \rightarrow 83\text{Ge} \beta\text{-decay}$



initial idea of a R&D test bench for the SPIRAL2 project at the Orsay Tandem



# At the dawn of the “industrial” ISOL production of RIBs



+ LISOL @  
Louvain-la-  
Neuve

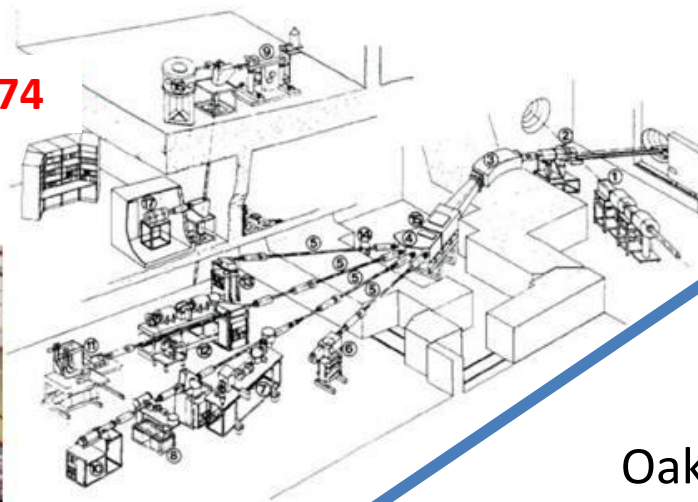
ISOLDE I  
@ CERN SC

SC upgrade  
 $I \times 100$



ISOLDE II  
@ CERN SC

1974



UNISOR  
Oak Ridge, Tennessee



towards the glorious  
ISOLDE@BOOSTER (as we  
know it)

towards the glorious  
HRIBF  
(unfortunately  
decommissioned)



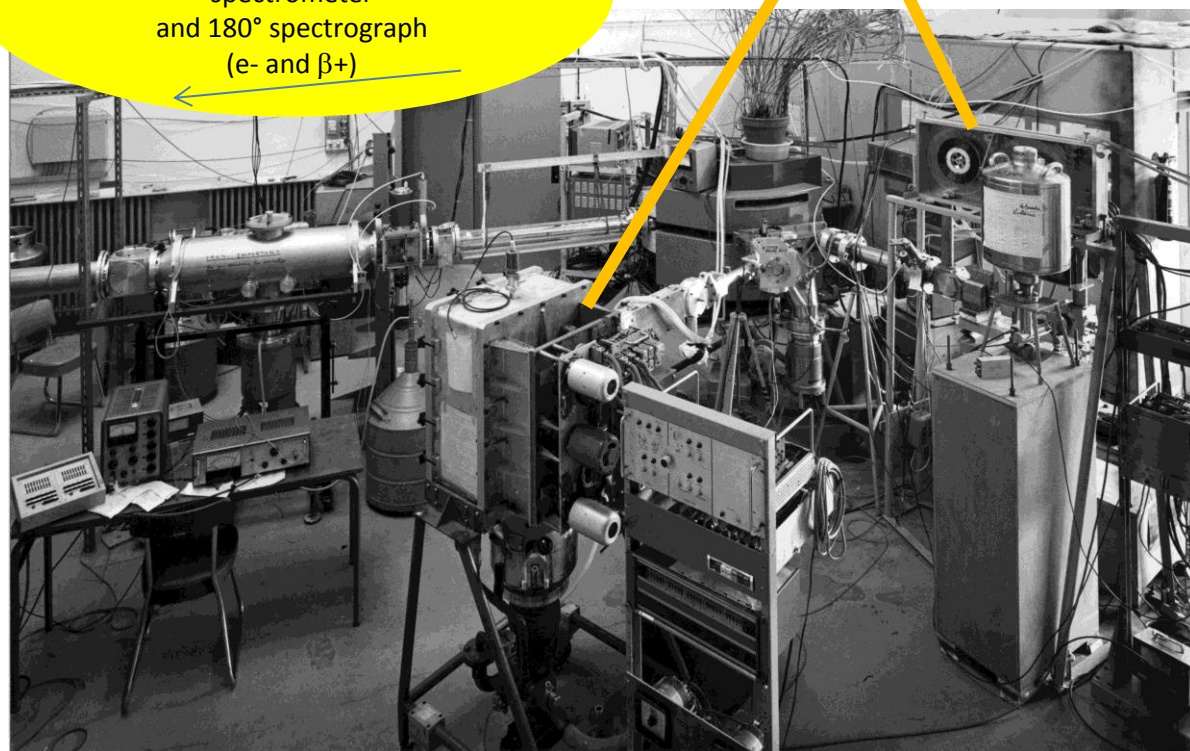
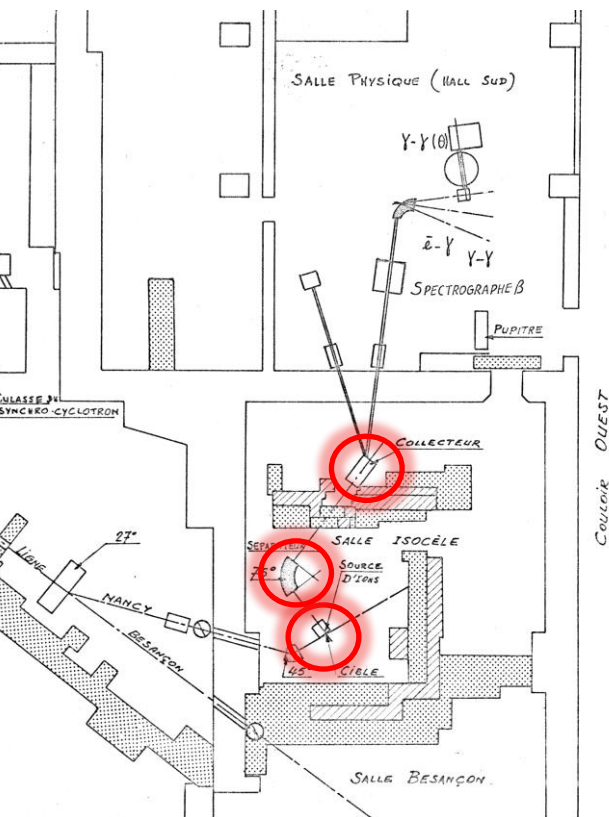


## meanwhile at Orsay... ISOCELE

An ISOL device on line with the Orsay's SC just came into operation  
~40 people (researchers, engineers, technicians)

First RIB experiment in march 1974

at the "Nancy" SC beam line



towards  
Gerholm double  
spectrometer  
and 180° spectrograph  
(e- and  $\beta^+$ )

Movable tape  
collectors



## ISOCELE II

On may 75, the Orsay SC is stopped for major upgrades:

p : 155 → 200 MeV

$^3\text{He}$  : 206 → 280 MeV

→  $I \times 20$

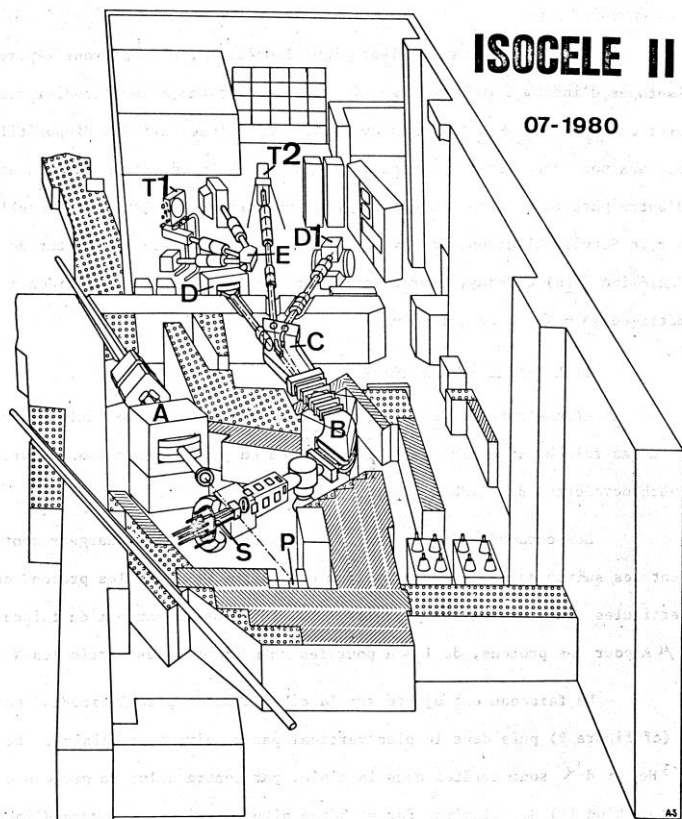


Figure 2 : Vue éclatée d'Isocèle.

A, B, D : aimants; C : collecteur; D1 : distributeur de pastilles; E : aiguillage; P : piège pour le faisceau de protons ; S : source d'ions; T1,T2 : transporteurs à bande.





## Post-ISOCLE Laser Isobar Separation : PILIS

after SC shutdown from September 85 till July 86 (serious SC coil shortcut)  
the physics program started again with a new device:

The PILIS laser system

J. Lee (McGill University) and J. Pinard (Laboratoire Aimé Cotton Orsay)

Prof. J. Lee

B. Roussière

F. Le Blanc

J. Sauvage



## ISOCELE-2 twilight

10% government budget cut

Pierre Lehman  
Director IN2P3

Jean-Claude Lehman  
(dir. dpt CNRS)



Sylvain Liberman  
(dir. Lab. Aimé Cotton)

Henri Sergolle  
(dir. IPN)

1989  
ending







# ISOCELE-2 twilight

PHYSICAL REVIEW C

VOLUME 38, NUMBER 6

RAPID COMMUNICATIONS

DECEMBER 1988

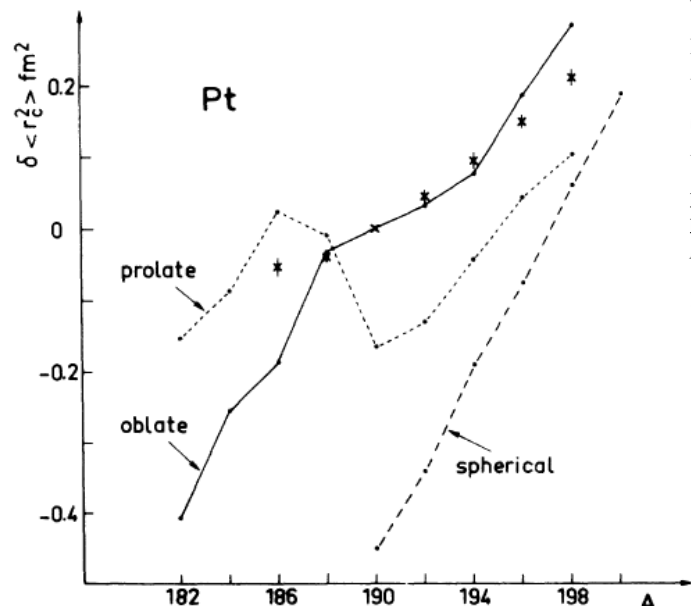
## Charge-radius changes in even- $A$ platinum nuclei

J. K. P. Lee, G. Savard,\* J. E. Crawford, and G. Thekkadath  
Foster Radiation Laboratory, McGill University, Montréal, Canada

H. T. Duong, J. Pinard, and S. Liberman  
Laboratoire Aimé Cotton, Centre National de la Recherche Scientifique II, Orsay, France

F. Le Blanc, P. Kilcher, J. Obert, J. Oms, J. C. Putaux,  
B. Roussière, and J. Sauvage  
Institut de Physique Nucléaire, Orsay, France  
(Received 13 July 1988)

Isotope shift measurements on even- $A$  Pt isotopes have been obtained from  $A=186$  to  $A=198$ . Charge radius differences have been extracted, and are compared to constrained Hartree-Fock plus BCS calculations. A possible shape transition between  $^{186}\text{Pt}$  and  $^{188}\text{Pt}$  is discussed.



Volume 217, number 4

PHYSICS LETTERS B

2 February 1989

## SHAPE TRANSITION IN NEUTRON DEFICIENT Pt ISOTOPES

H.T. DUONG, J. PINARD, S. LIBERMAN

Laboratoire Aimé Cotton, CNRS II, F-91405 Orsay, France

G. SAVARD, J.K.P. LEE, J.E. CRAWFORD, G. THEKKADATH

Foster Radiation Laboratory, McGill University, Montréal, Québec, Canada H3A 2B2

F. LE BLANC, P. KILCHER, J. OBERT, J. OMS, J.C. PUTAUX, B. ROUSSIÈRE, J. SAUVAGE and the ISOCELE Collaboration

Institute de Physique Nucléaire, F-91405 Orsay, France

Received 27 September 1988



Sylvain Liberman  
(dir. Lab. Aimé Cotton)

Henri Sergolle  
(dir. IPN)

1989  
ending

07-11 Oct. 2019



ESNT Laser Spectroscopy – Saclay

Verney – IPN Orsay



# The first collinear laser spectroscopy experiment in Orsay (off line !)

VOLUME 72, NUMBER 17

PHYSICAL REVIEW LETTERS

25 APRIL 1994

## Nuclear Properties of the Exotic High-Spin Isomer $^{178}\text{Hf}^{m2}$ from Collinear Laser Spectroscopy

N. Boos,<sup>1</sup> F. Le Blanc,<sup>2</sup> M. Krieg,<sup>1</sup> J. Pinard,<sup>3</sup> G. Huber,<sup>1</sup> M. D. Lunney,<sup>2</sup> D. Le Du,<sup>4</sup> R. Meunier,<sup>4</sup> M. Hussonnois,<sup>2</sup> O. Constantinescu,<sup>2</sup> J. B. Kim,<sup>2</sup> Ch. Briangon,<sup>4</sup> J. E. Crawford,<sup>6</sup> H. T. Duong,<sup>3</sup> Y. P. Gangrski,<sup>7</sup> T. Kühl,<sup>5</sup> B. N. Markov,<sup>7</sup> Yu. Ts. Oganessian,<sup>7</sup> P. Quentin,<sup>4</sup> B. Roussière,<sup>2</sup> and J. Sauvage<sup>2</sup>

<sup>1</sup>Institut für Physik der Universität Mainz 55099 Mainz, Germany

<sup>2</sup>Institut de Physique Nucléaire, Institut National de Physique Nucléaire et de Physique des Particules—Centre National de la Recherche Scientifique, 91406 Orsay, France

<sup>3</sup>Laboratoire Aimé Cotton, 91405 Orsay, France

<sup>4</sup>Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse—Orsay, Institut National de Physique Nucléaire et de Physique des Particules—Centre National de la Recherche Scientifique, 91405 Orsay, France

<sup>5</sup>Gesellschaft für Schwerionenforschung Darmstadt m.b.H., 64291 Darmstadt, Germany

<sup>6</sup>Foster Radiation Laboratory, McGill University, Montréal, Canada

<sup>7</sup>Joint Institute for Nuclear Research, Dubna, POB 79, 101000 Moscow Region, Russia  
(Received 27 September 1993)

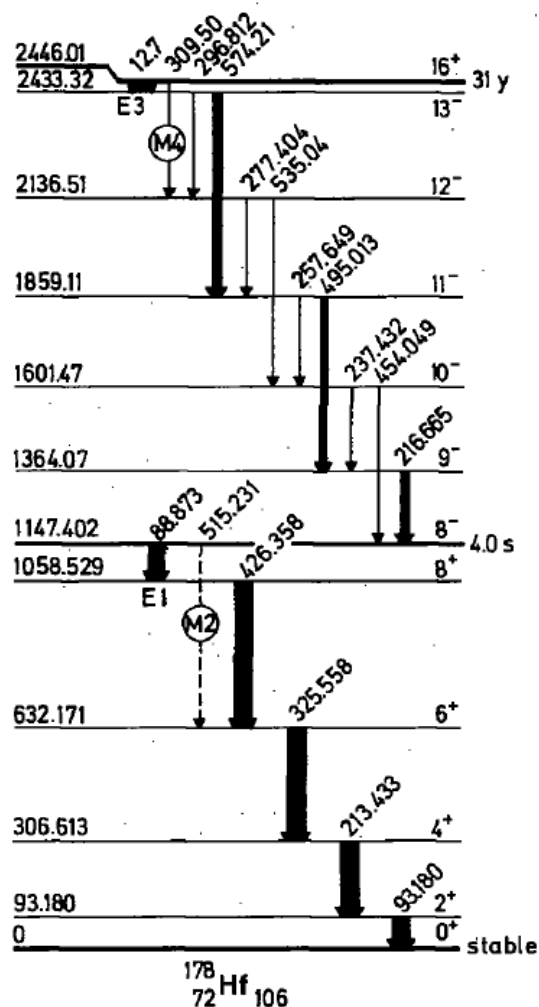


Fig. 1. Decay scheme.

$^{176}\text{Yb}(\alpha, 2n)^{178}\text{Hf}$  @ 36 MeV at Dubna  
96% enriched Yb target  
chemical separation at Orsay,  
a sample of 6 ng of  $^{178m2}\text{Hf}$  was prepared !

$$\delta\langle r^2 \rangle^{178, 178m2} = -0.059(9) \text{ fm}^2$$

$$\mu_I^{178m2} = +8.16(4) \mu_N$$

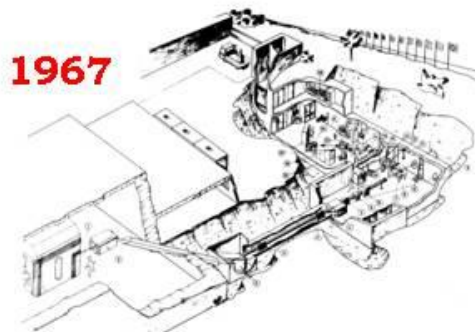
$$Q_s^{178m2} = +6.00(7) \text{ b}$$



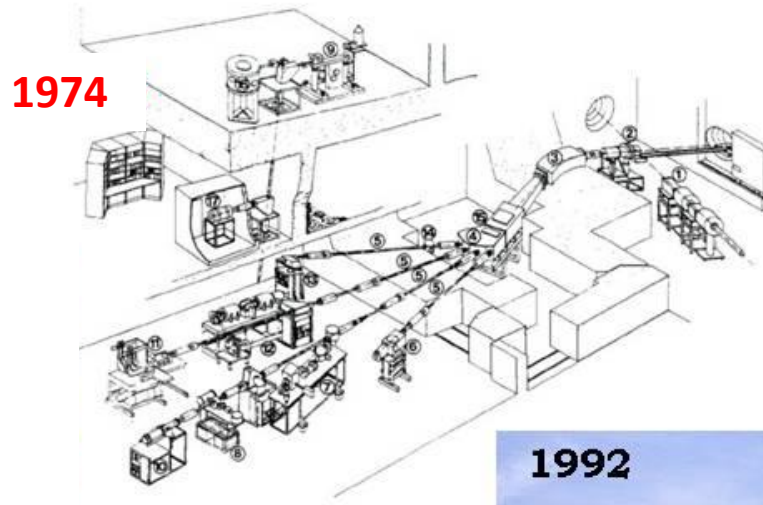
# ~~Post-ISOCELE Laser Isobar Separation: PILIS~~ → COMPLIS

ISOLDE I  
@ CERN SC

SC upgrade  
 $I \times 100$



ISOLDE II  
@ CERN SC



ISOLDE @ CERN  
BOOSTER

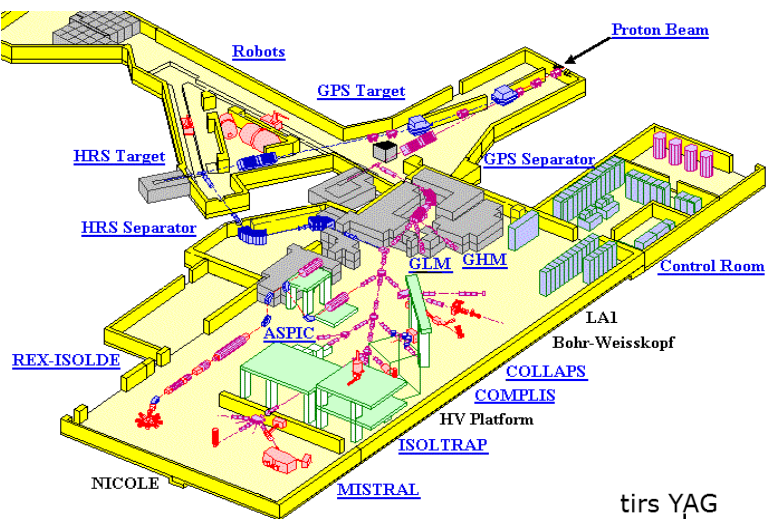




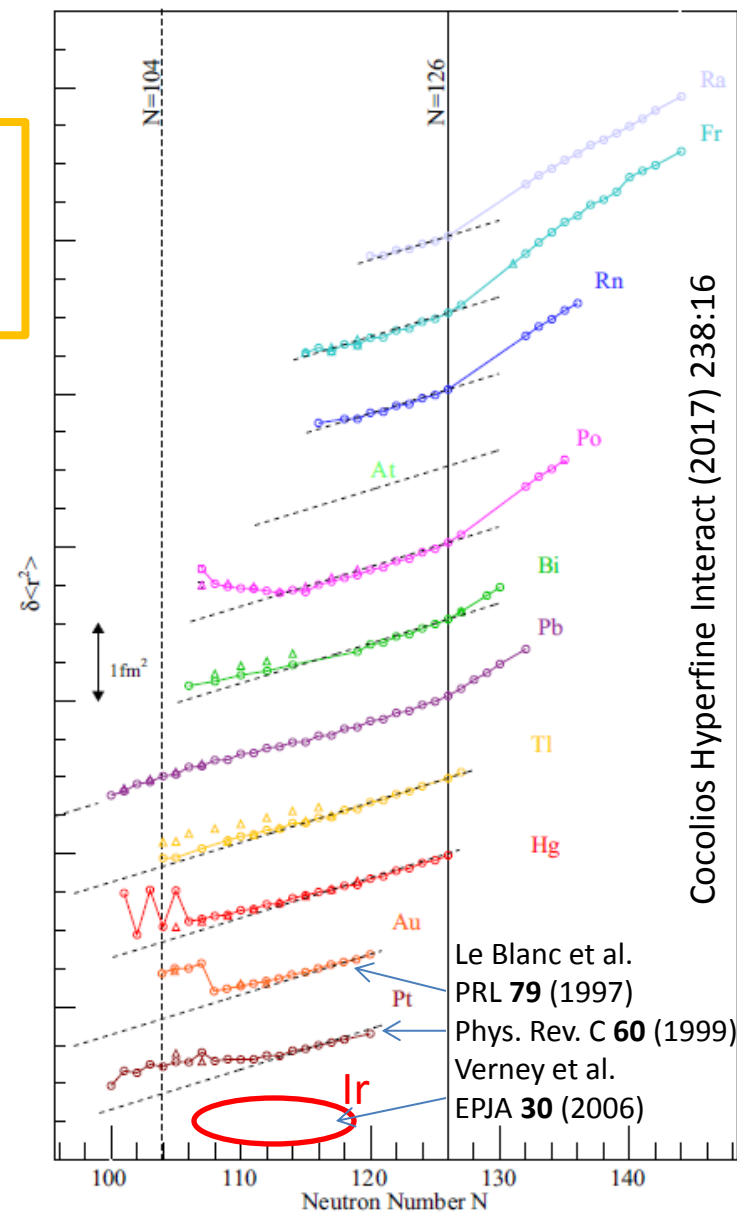
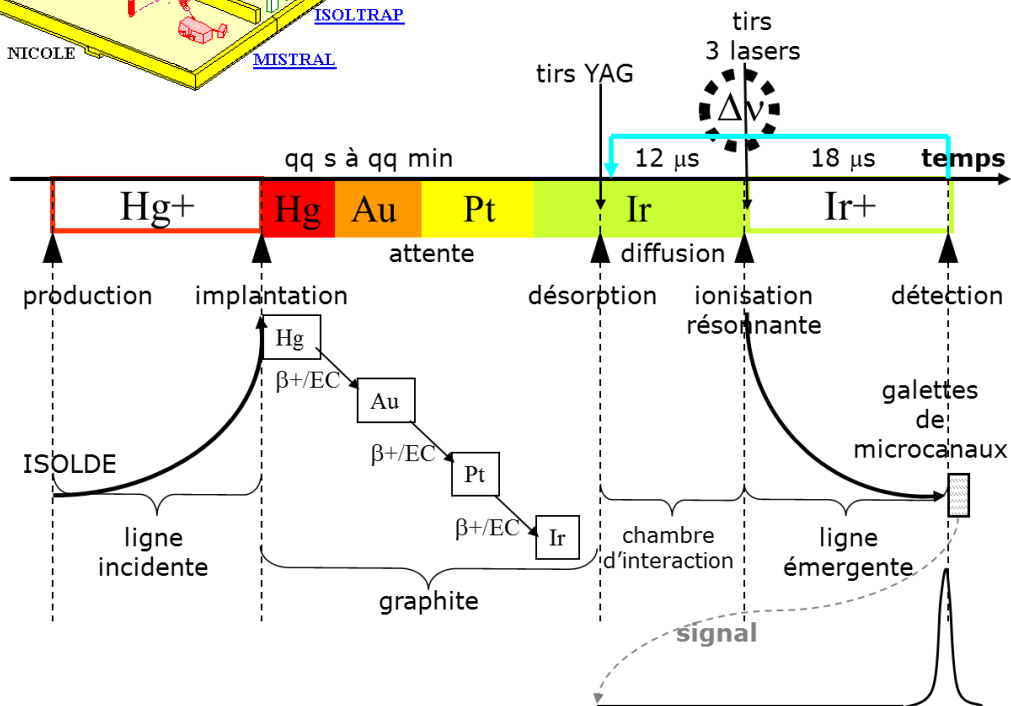
# COMPLIS glory : refractory elements of the Pt region

## COllaboration for spectroscopic MMeasurements using a P Pulsed Laser Ion SSource

early coined “COmplicated” by our beloved Anglo-Saxon colleagues

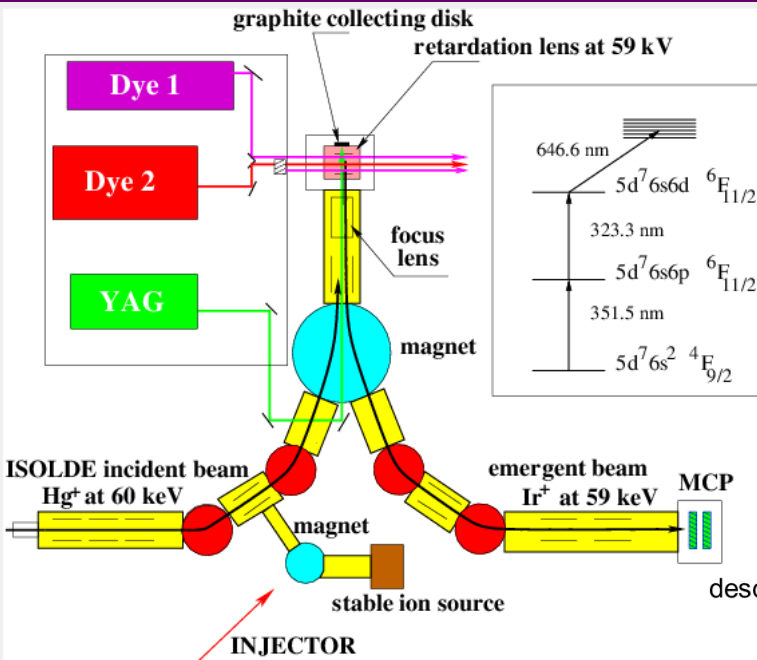


molten Pb target introduced at ISOLDE on the occasion (original design from Orsay)

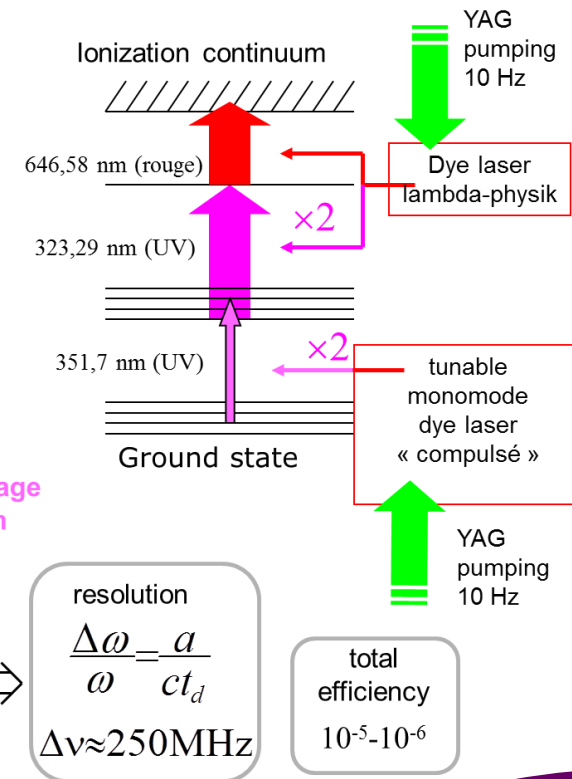
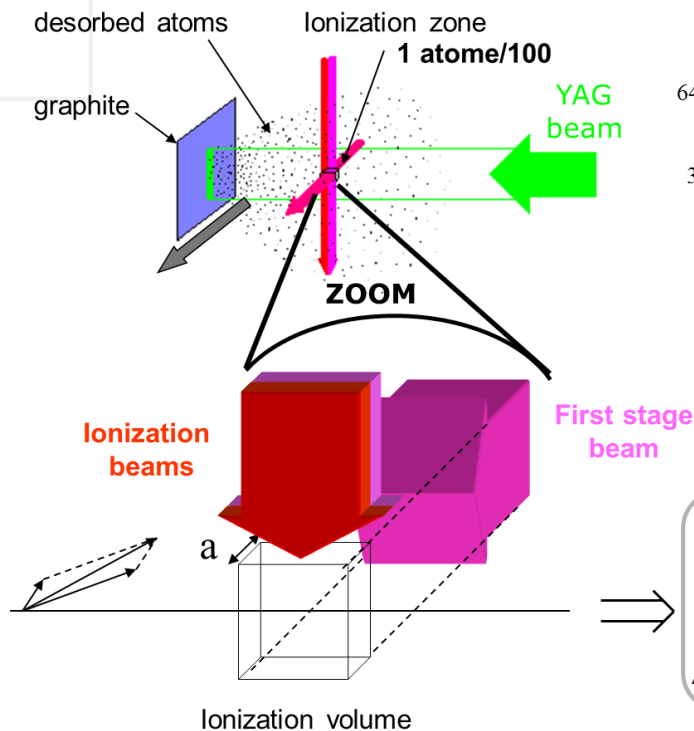


Cocolios Hyperfine Interact (2017) 238:16

# COMPLIS principle



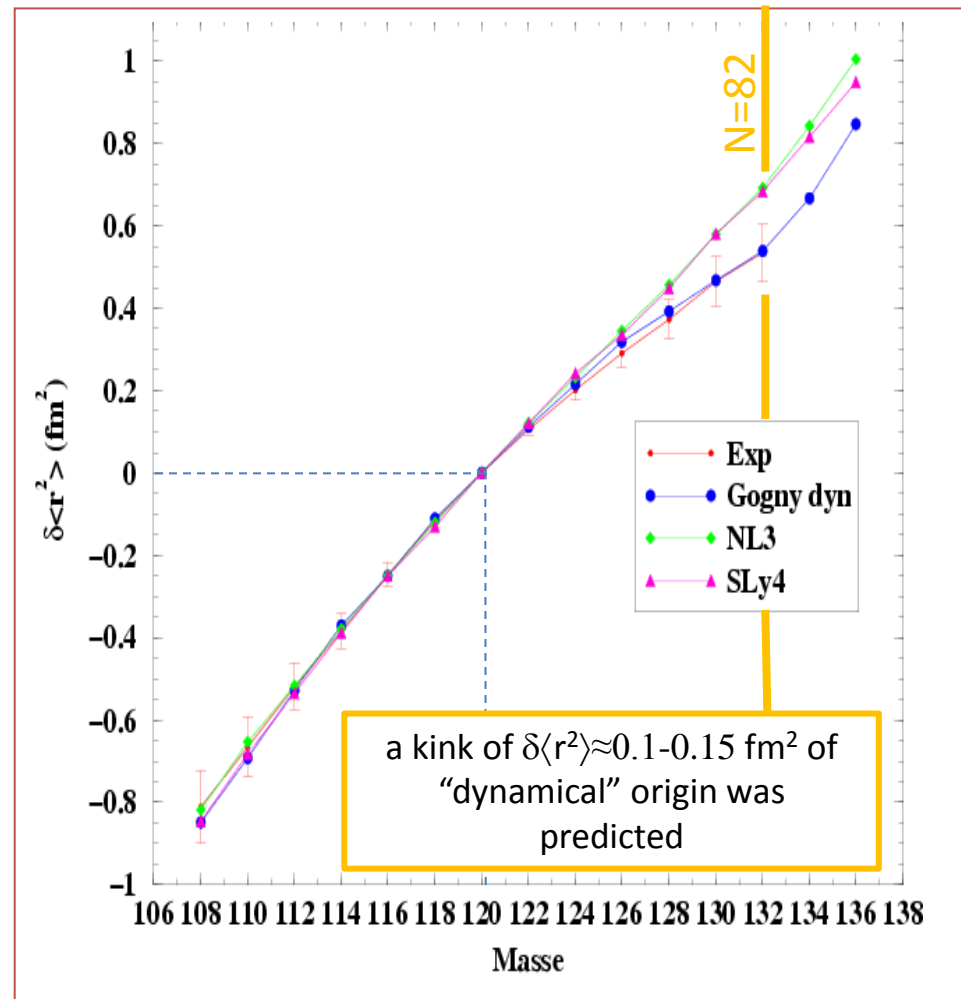
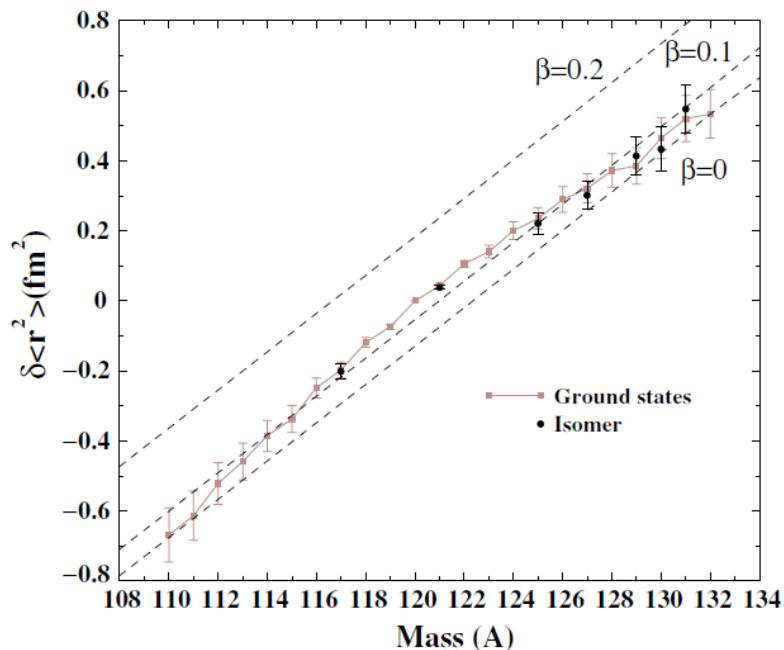
A principle very close to what is now called laser ablation resonance ionization mass spectrometry (LA-RIMS)



Le Blanc et al. PRC **72**, 034305 (2005)

TABLE III. Isotope shift,  $\delta\langle r_c^2 \rangle$  relative to  $^{120}\text{Sn}$  and absolute charge radii.

A	$IS[\text{GHz}]$	$\delta\langle r_c^2 \rangle^{120,A}[\text{fm}^2]$	$r_c[\text{fm}]$
$125^g$	0.503(11)	0.236(31)	4.677(3)
$125^m$	0.455(8)	0.221(30)	4.676(3)
126	0.63(1)	0.290(37)	4.683(4)
$127^g$	0.685(10)	0.322(42)	4.687(4)
$127^m$	0.622(10)	0.302(41)	4.685(4)
128	0.801(12)	0.373(48)	4.692(4)
$129^g$	0.794(11)	0.384(52)	4.693(5)
$129^m$	0.881(9)	0.411(53)	4.696(6)
$130^g$	1.006(10)	0.465(59)	4.702(6)
$130^m$	0.906(8)	0.434(63)	4.699(6)
$131^g$	1.141(12)	0.521(66)	4.708(7)
$131^m$	1.226(10)	0.548(67)	4.711(7)
132	1.140(6)	0.534(69)	4.709(7)



NL3 : G.A Lalazissis et al., At. Data and Nucl. Data Tables 71 (1999)1.

Gogny : M. Girod and S. Péru, Private comm. (2001)

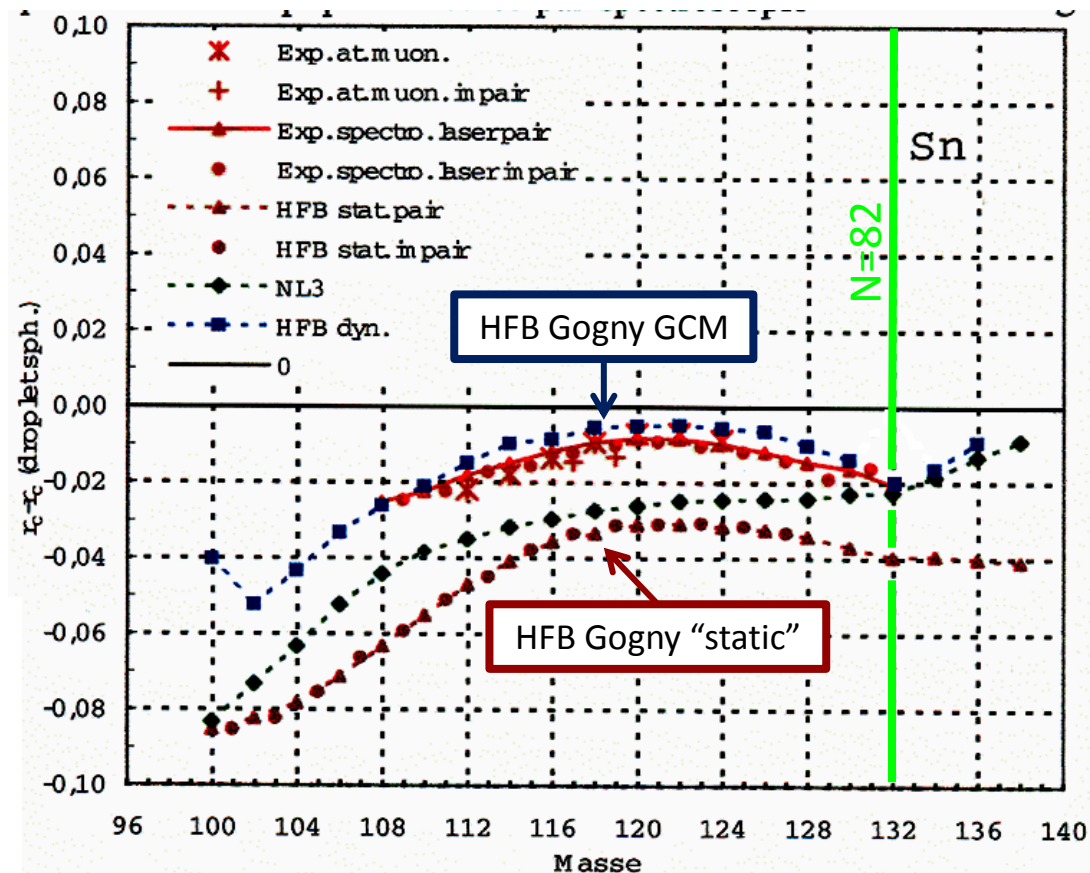
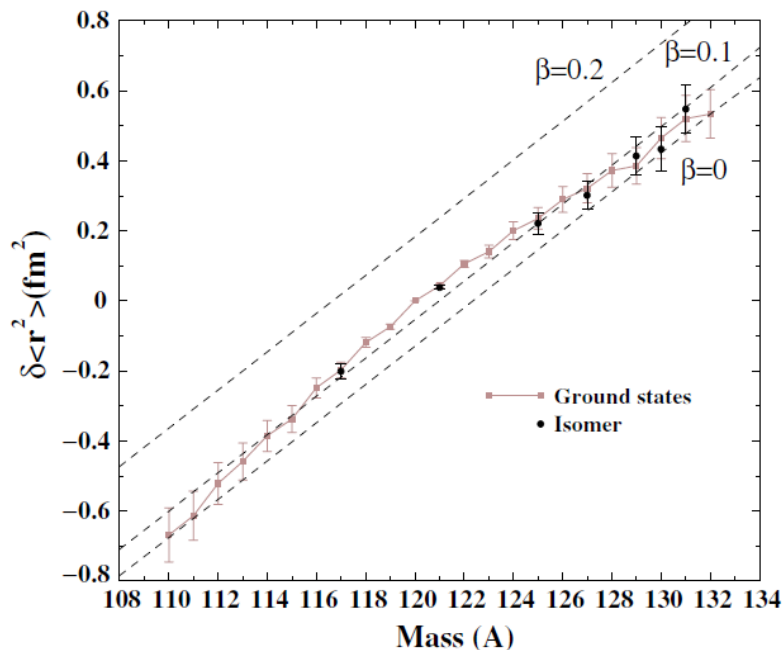
SLy4 and SLy7 : P. Bonche and J. Meyer, Private comm. (2002).



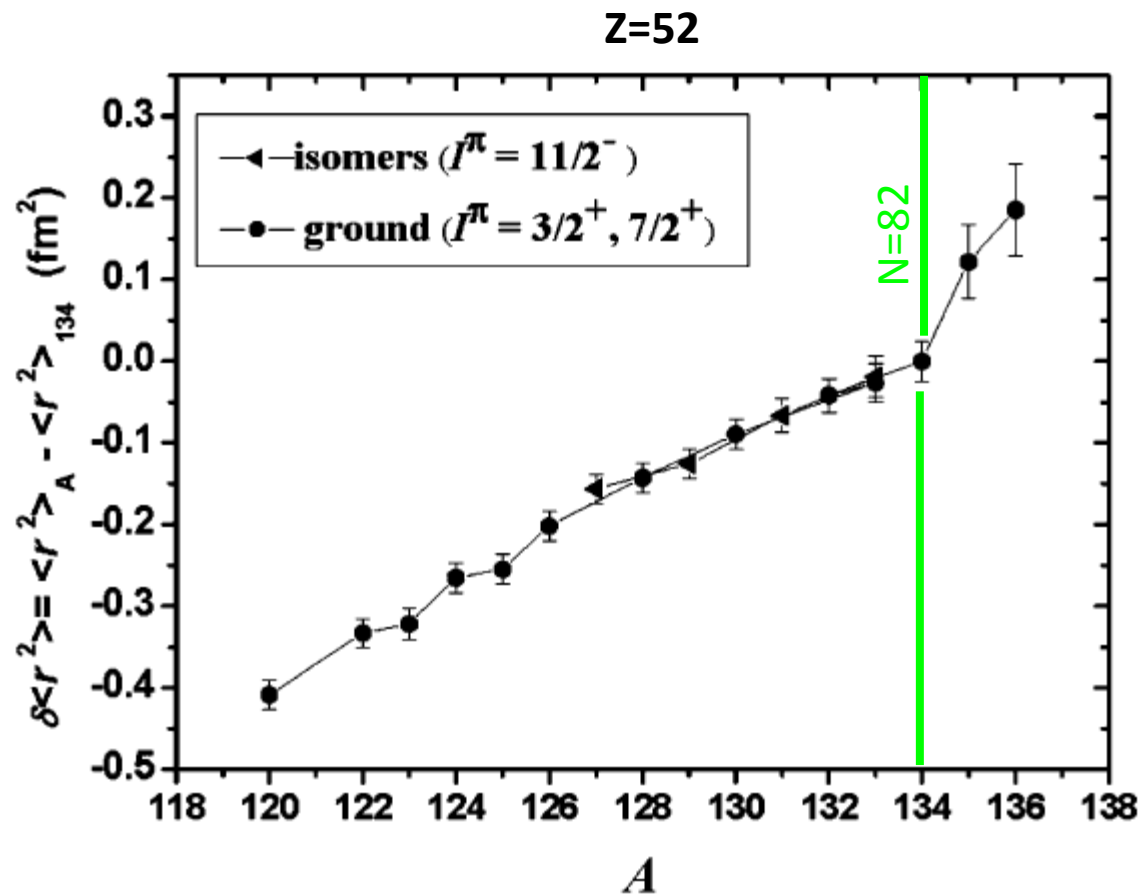
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conclusion : the bell-shaped  $\delta\langle r^2 \rangle$ -curve has a dynamical origin (so has the possible kink)



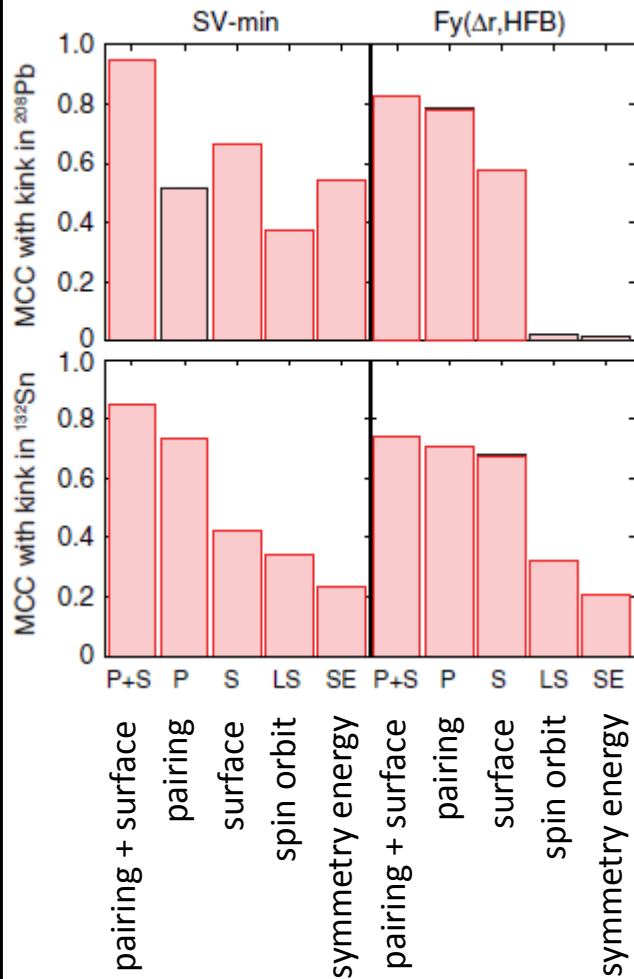
conclusion : the  $\delta\langle r^2 \rangle$ -kink at N=82 is gorgeous

# Almost two decades later : COLLAPS has taken over for n-rich Sn's

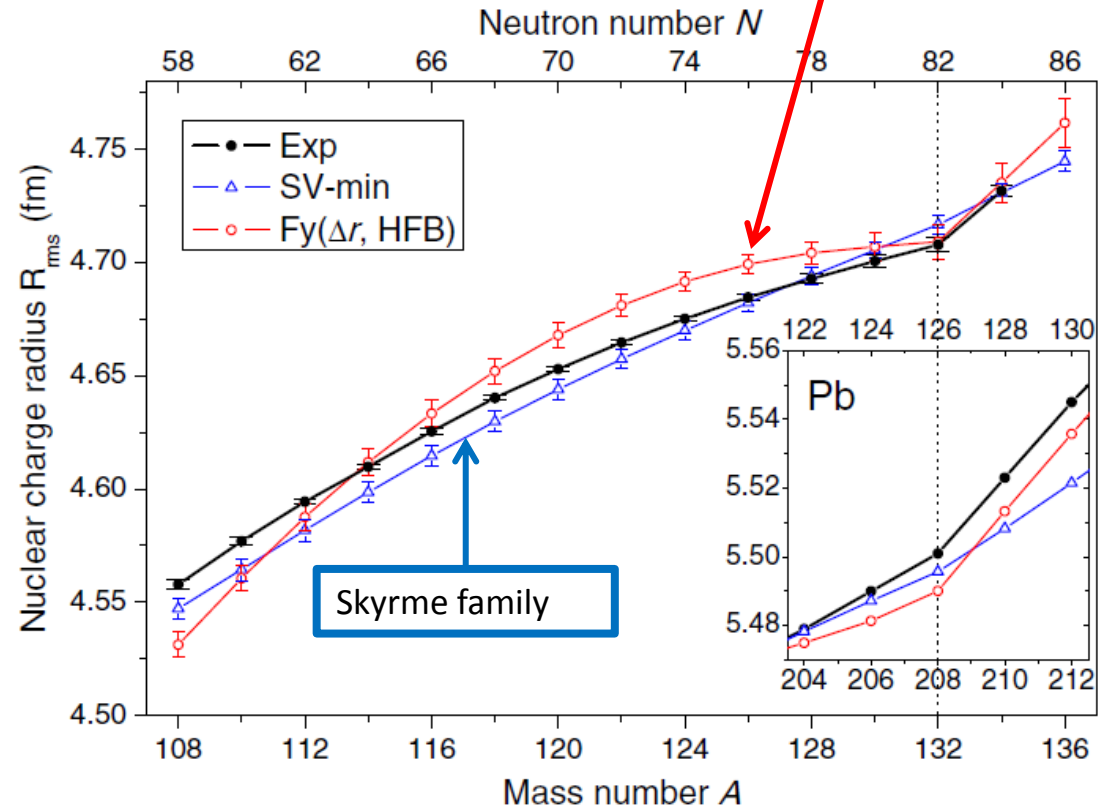
C. Georges et al. PRL **122**, 192502 (2019)  
presented by D.T. Yordanov this morning

a significant N=82 kink is discovered

correlation coefficients of a kink with  
groups of model parameters



Fayans functional involving gradient  
terms in surface and pairing energies

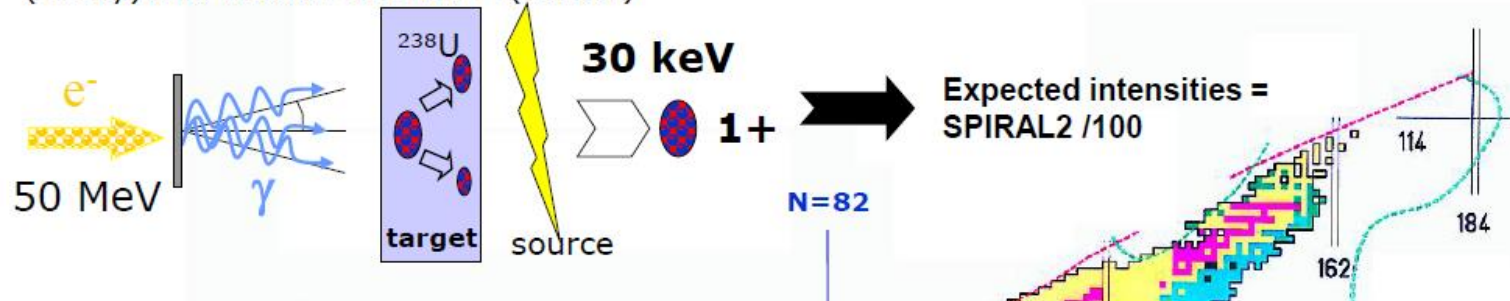


“It becomes clear that the kinks in charge radii in magic nuclei are statistically correlated with odd-even staggering of radii and odd-even staggering of binding energies, both significantly impacted by nucleonic pairing.”

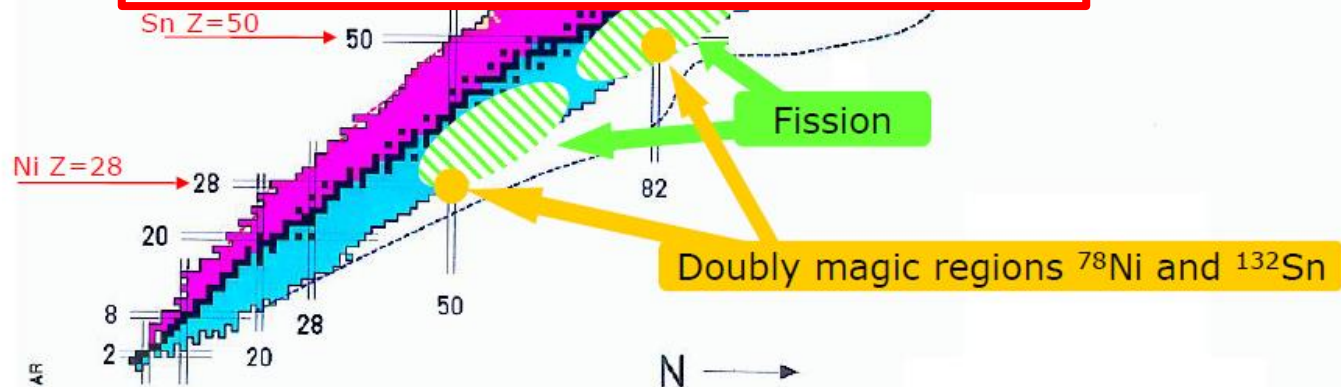


## Nuclear regions explored at ALTO

neutron rich nuclei produced by fission at **ALTO** (Orsay) and then at **SPIRAL2** (GANIL)



15 years later :  
the laser-spectroscopy program at ALTO is just about to start  
while SPIRAL2 (phase 2) is postponed *sine die*  
and ISOLDE and IGISOL are moving fast...



## Expected yields at ALTO

Extrapolations from measured yields at PARRNe

Represented yields  $\geq 10^4$ pps

minimum yield for the laser set-up we envisage

$Z=50$  - Sn

In  
Cd

$N=50$

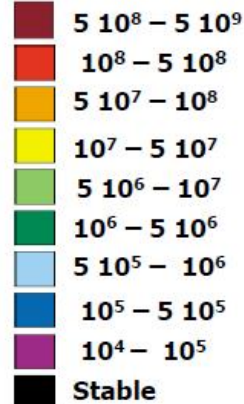
$N=82$

62 64 66 68 70 72 74 76

Sr  
Rb  
Kr

$Z=28$

Yields pps (10  $\mu$ A)  
FEBIAD



## First measurements at ALTO

• Ag (Z=47) : from A=111 to A=123 (or further from the stability line depending on the effective productions)  $\Rightarrow$  complete the measurements on this isotopic chain on the right side of the valley of stability

• Transition : Z.Phys. A274 (1975)79.

Ag111	Ag112	Ag113	Ag114	Ag115	Ag116	Ag117	Ag118	Ag119	Ag120	Ag121	Ag122	Ag123	Ag124	Ag125	Ag126	Ag127
73.6 d	3.330 h	5.35 h	4.6 s	26.9 m	238 m	72.1 s	2.6 s	21 s	123 s	68 s	64 s	630 s	637 s	160 ms	107 s	
1/2-	2-	1/2-	1+	1/2-	(2-)	(1/2-)	(1)-	(7/2+)	(3+)	(7/2-)	(3+)	(7/2-)	(7/2-)			
Pd110	Pd111	Pd112	Pd113	Pd114	Pd115	Pd116	Pd117	Pd118	Pd119	Pd120	Pd121	Pd122	Pd123			
0+	35.4 m	21.03 h	93 s	242 m	25 s	11.4 s	4.3 s	1.9 s	0.92 s	0.5 s		0+				
11.72																

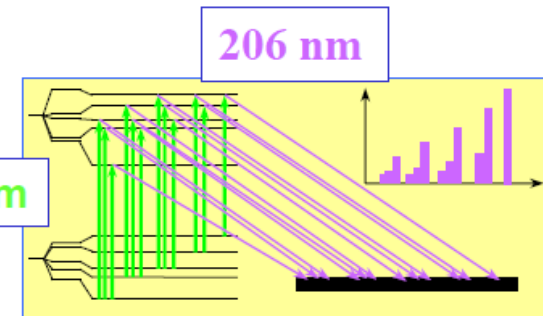
78

• Ge (Z=32) : from A=77 to A=83  $\Rightarrow$  N=50 crossing

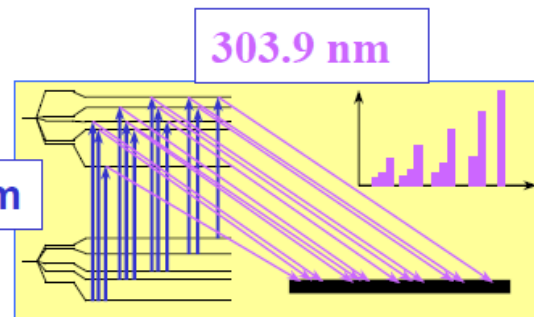
Ge75	Ge76	Ge77	Ge78	Ge79	Ge80	Ge81	Ge82	Ge83	Ge84	G
82.78 m	0+	11.30 h	88.0 m	18.98 s	29.5 s	7.6 s	4.60 s	1.85 s	966 ms	5-
1/2-		7/2+	0+	(1/2-)	0+	(9/2+)	0+	(5/2+)	0+	
Ga74	Ga75	Ga76	Ga77	Ga78	Ga79	Ga80	Ga81	Ga82	Ga83	G
8.12 m	126 s	32.6 s	13.2 s	5.09 s	2.847 s	1.697 s	1.217 s	0.599 s	0.31 s	8-
(3-)	3/2-	(2+,3+)	(3/2-)	(3+)	(3/2-)	(3)	(5/2-)	(1,2,3)		

N=50

• then, les Br, As and Ga towards Ni, Sb, I, ...



547.7 nm



422.7 nm



# ISOL back to Orsay – separation online with the MP Tandem

PARRNe « Production d'Atomes Radioactifs Riches en Neutrons »

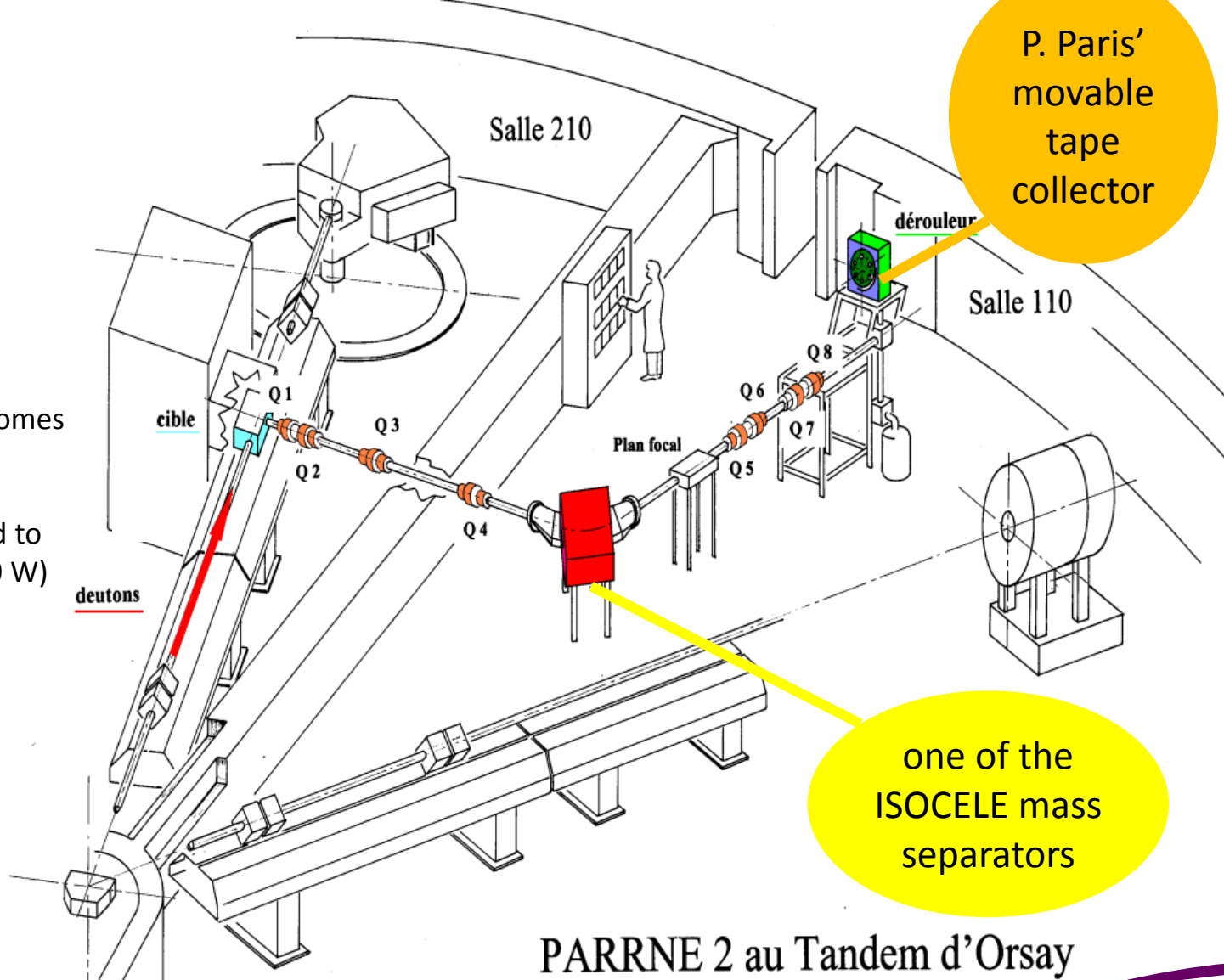
Jacques Obert  
and his team at work

within the framework of the  
SPIRAL2 project

under the high guidance  
of Director S. Galès

In year 2006 : the driver becomes  
a 50 MeV electron LINAC

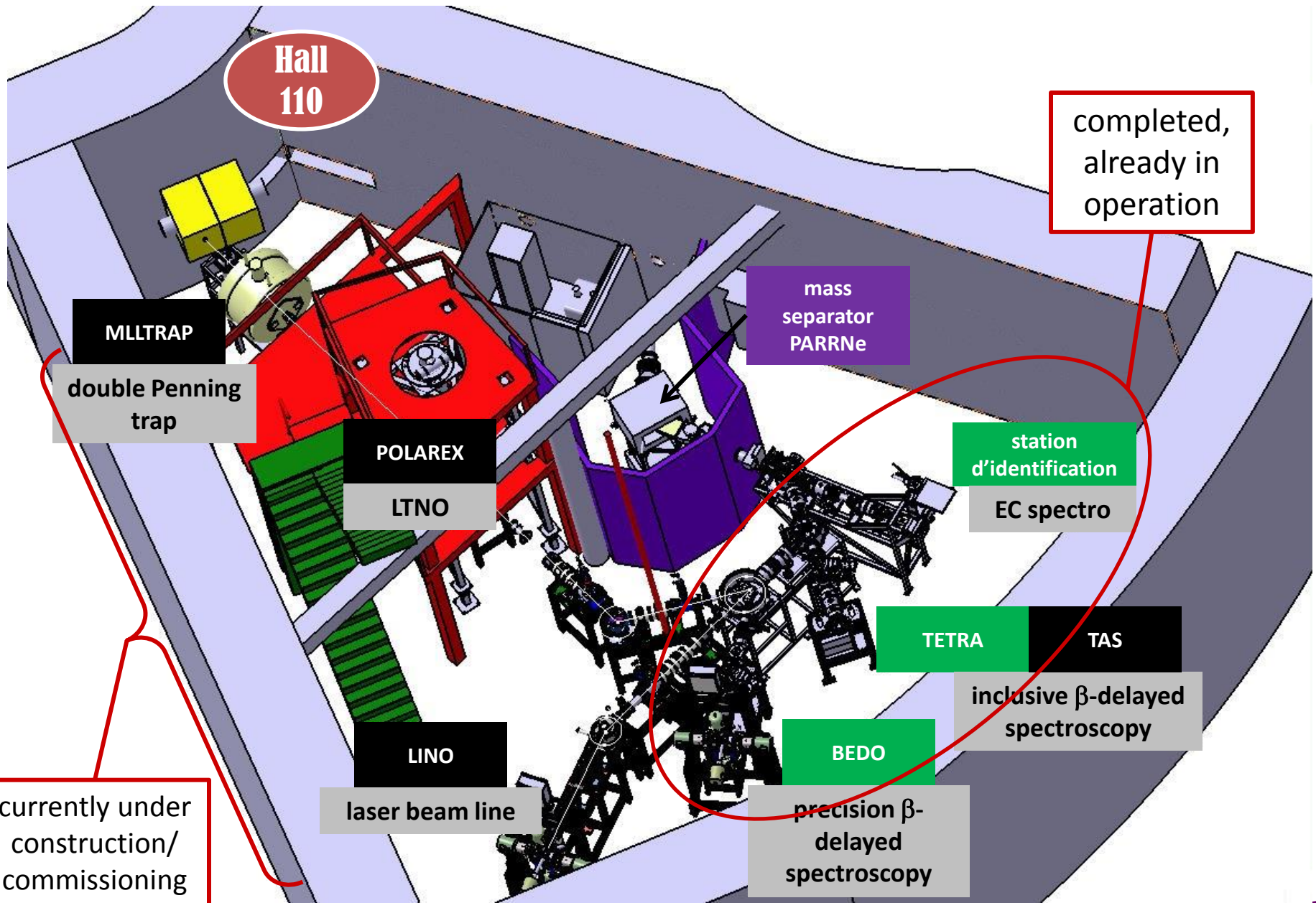
In 2012 : we were authorized to  
use it at nominal power (500 W)  
 $I_e = 10 \mu\text{A}$



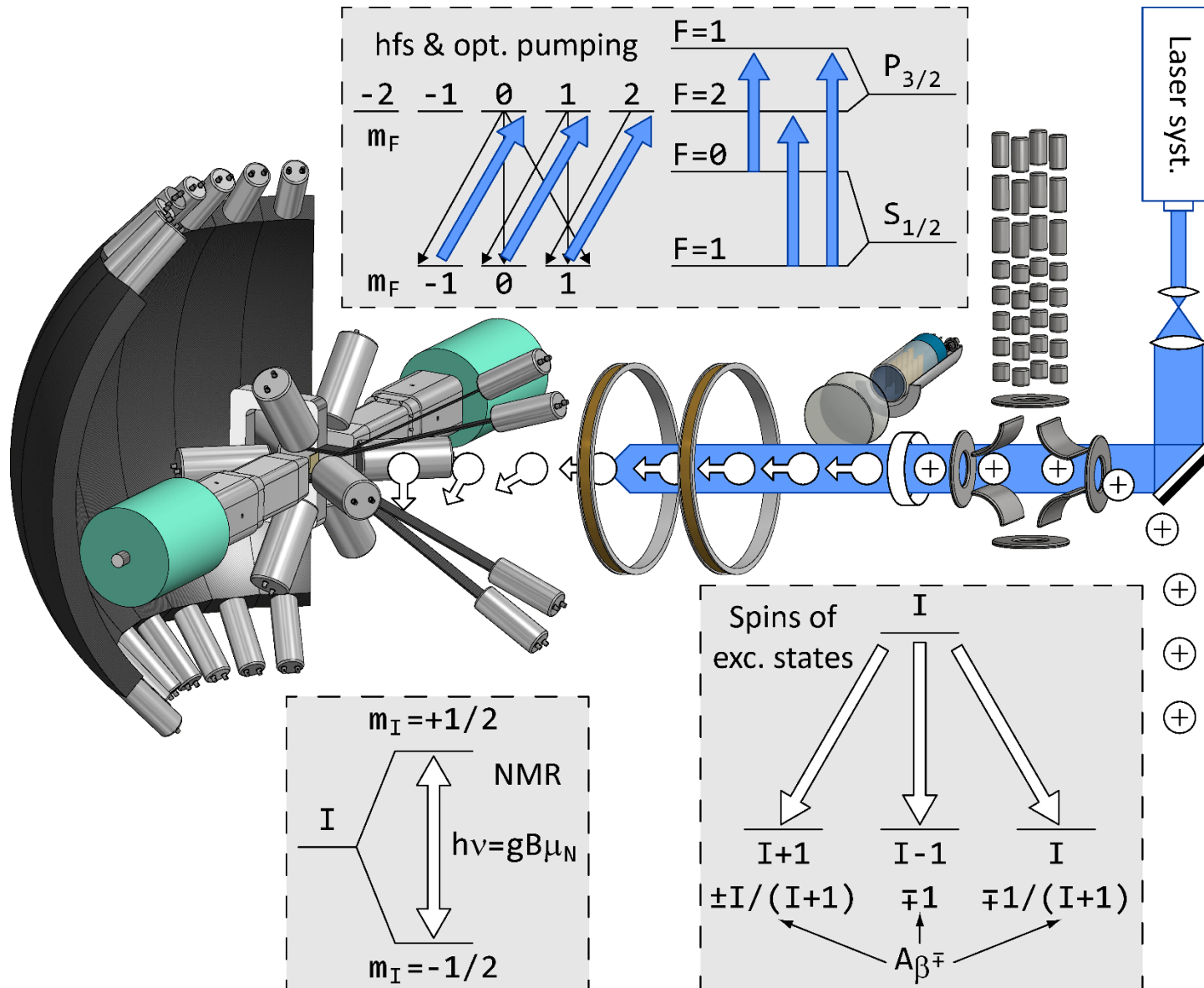
PARRNE 2 au Tandem d'Orsay



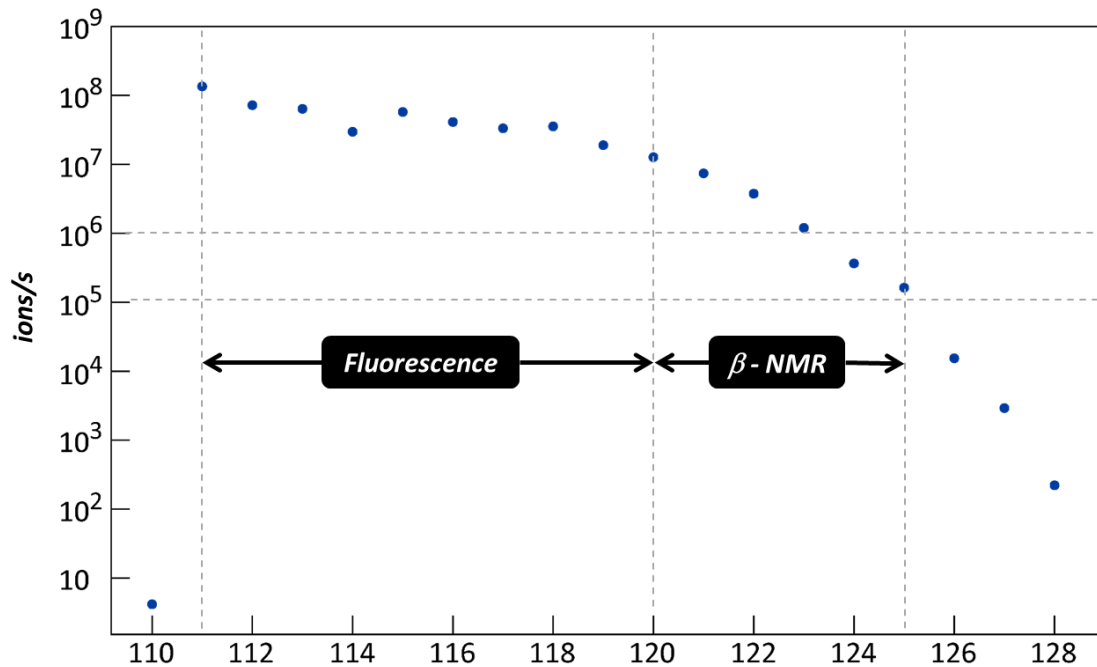
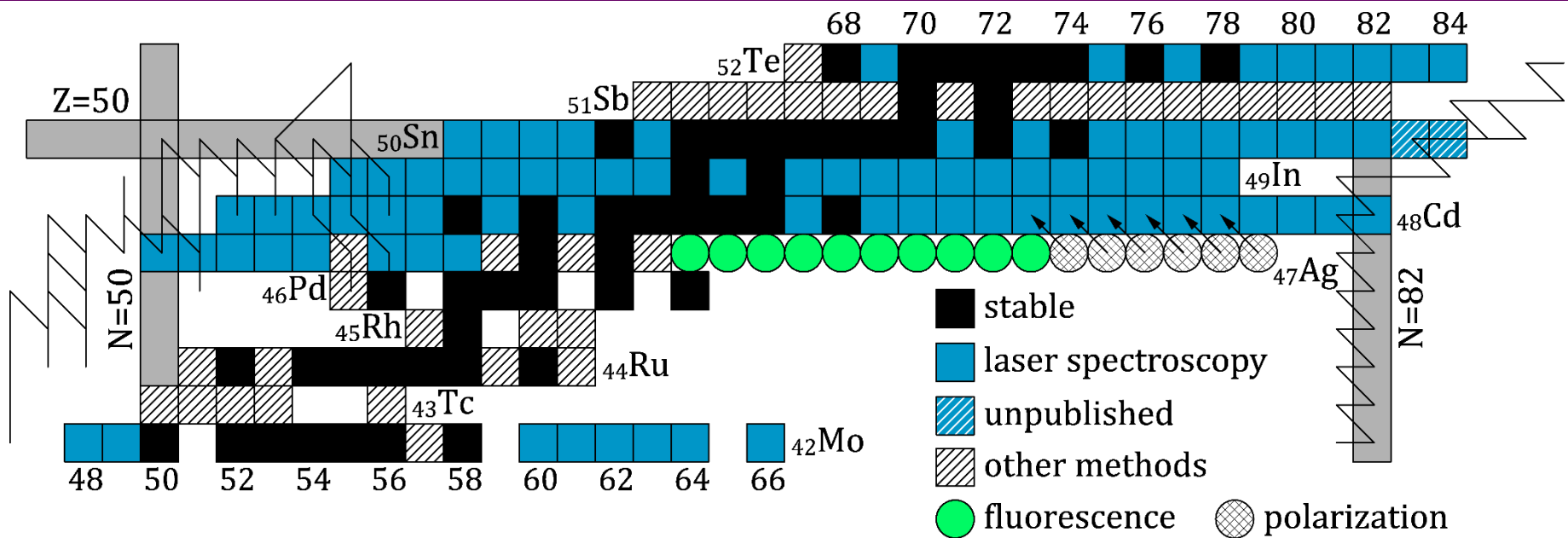
# ALTO's instrumentation : still upgrading



## Laser Induced Nuclear Orientation – PI: D. Yordanov



# LINO's day one (and two) experiments



quite unexpectedly,  
15 years later,  
we stick to the original  
plan !

## First measurements at ALTO

• Ag (Z=47) : from A=111 to A=123 (or further from the stability line depending on the effective productions)  $\Rightarrow$  complete the measurements on this isotopic chain on the right side of the valley of stability

• Transition : Z.Phys. A274 (1975)79.

Ag111	Ag112	Ag113	Ag114	Ag115	Ag116	Ag117	Ag118	Ag119	Ag120	Ag121	Ag122	Ag123	Ag124	Ag125	Ag126	Ag127
73.6 d	3.330 h	5.35 h	4.6 s	26.9 m	238 m	72.1 s	2.6 s	21 s	123 s	68 s	64 s	630 s	637 s	160 ms	107 s	
1/2-	2-	1/2-	1+	1/2-	(2-)	(1/2-)	(1)-	(7/2+)	(3+)	(7/2-)	(3+)	(7/2-)	(7/2-)			
Pd110	Pd111	Pd112	Pd113	Pd114	Pd115	Pd116	Pd117	Pd118	Pd119	Pd120	Pd121	Pd122	Pd123			
0+	35.4 m	21.03 h	93 s	242 m	25 s	11.4 s	4.3 s	1.9 s	0.92 s	0.5 s		0+				
11.72																

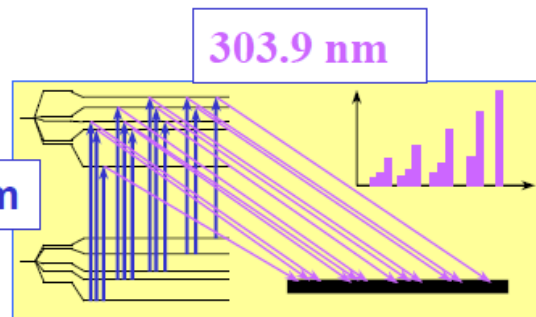
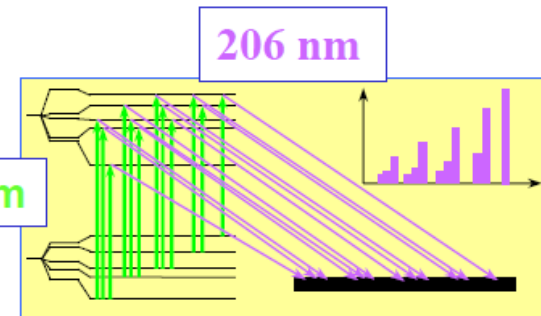
78

• Ge (Z=32) : from A=77 to A=83  $\Rightarrow$  N=50 crossing

Ge75	Ge76	Ge77	Ge78	Ge79	Ge80	Ge81	Ge82	Ge83	Ge84	G
82.78 m	0+	11.30 h	88.0 m	18.98 s	29.5 s	7.6 s	4.60 s	1.85 s	966 ms	5
1/2-		7/2+	0+	(1/2-)	0+	(9/2+)	0+	(5/2+)	0+	
Ga74	Ga75	Ga76	Ga77	Ga78	Ga79	Ga80	Ga81	Ga82	Ga83	G
8.12 m	126 s	32.6 s	13.2 s	5.09 s	2.847 s	1.697 s	1.217 s	0.599 s	0.31 s	8
(3-)	3/2-	(2+,3+)	(3/2-)	(3+)	(3/2-)	(3)	(5/2-)	(1,2,3)		

N=50

• then, les Br, As and Ga towards Ni, Sb, I, ...





# The question of the kink at N=50

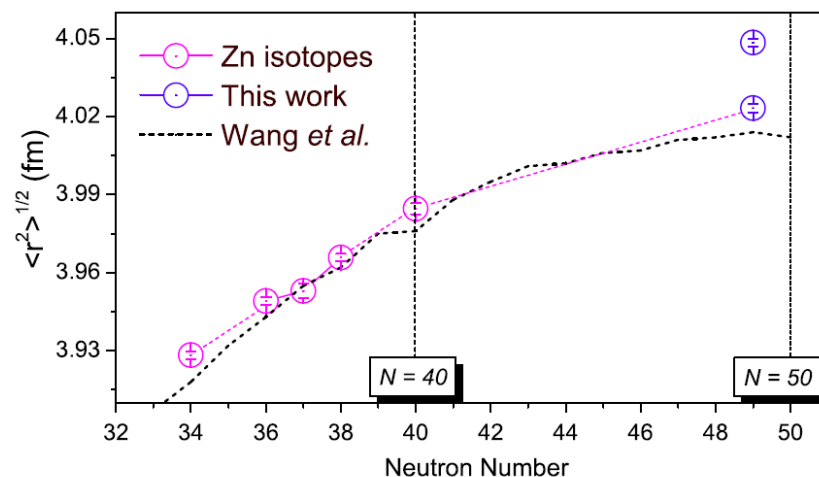
and shape coexistence in the N=50 region !

borrowed from Greg Farooq-Smith's PhD manuscript  
with his kind authorization  
PhD defense on Friday !

COLLAPS result

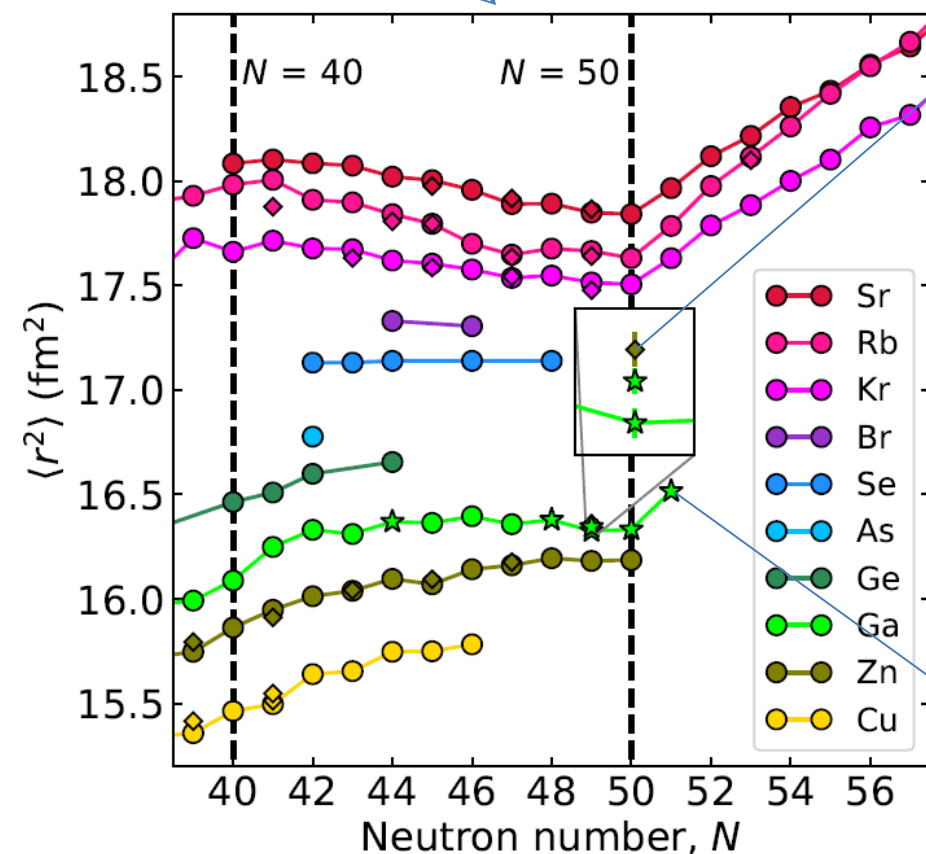
X. Yang et al. PRL 116 182502 (2016)

$$\langle r_c^2 \rangle(^{79m}\text{Zn}) - \langle r_c^2 \rangle(^{79g}\text{Zn}) = 0.204(6)[36] \text{ fm}^2$$



CRIS results (stars)

G.J. Farooq-Smith PRC 96, 044324 (2017)

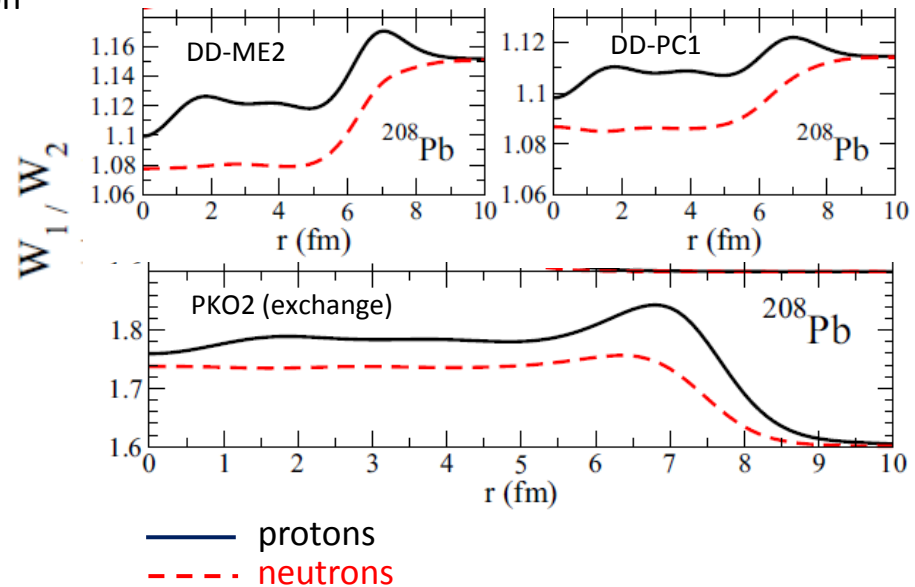
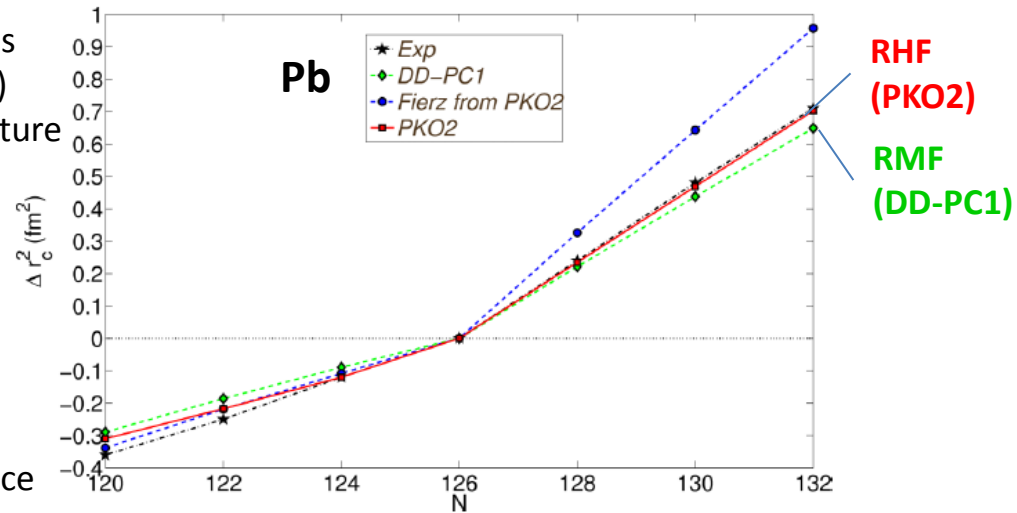


# Kinkology and the isospin dependence of the SO potential

Skyrme and Gogny forces do not reproduce kinks unless the density dependence of the two-body spin-orbit (SO) potential is modified to get a relativistic spin-orbit structure  
 Reinhard & Flocard NPA 584 467 (1995)  
 Ebran et al. PRC 94 024304 (2016) (and Refs therein)

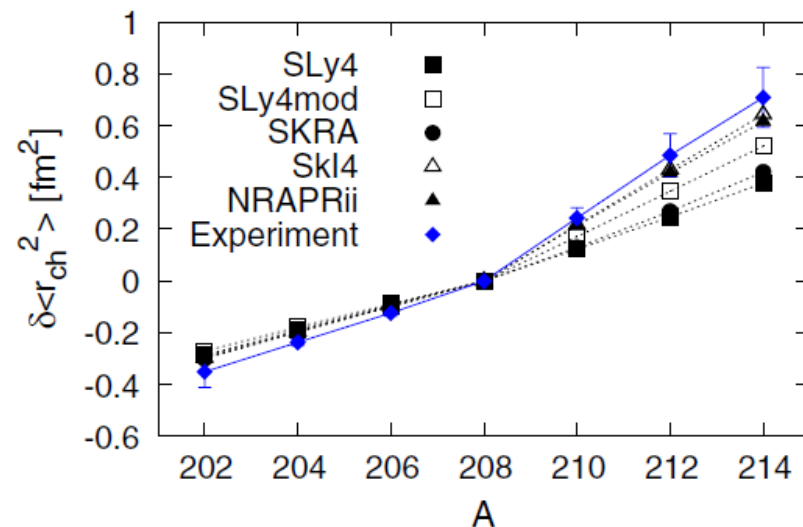
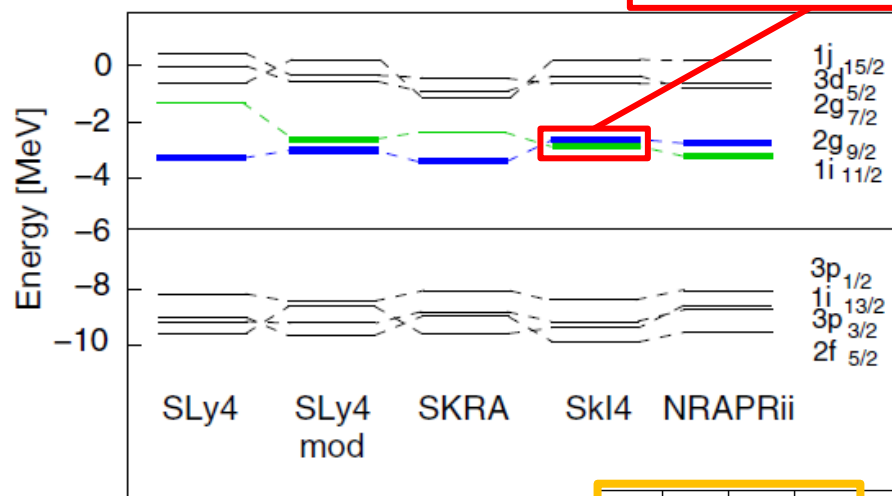
$$V_{\text{so}}^{(q)} = \left[ W_1 \frac{d\rho_B^{(q)}}{dr} + W_2 \frac{d\rho_B^{(q' \neq q)}}{dr} \right] \vec{l} \cdot \vec{s} \quad q=p,n$$

$\frac{W_1}{W_2} (\alpha_\sigma, \alpha_\omega, \alpha_\rho)$  determines the isospin dependence of the SO potential  
 =2 in Skyrme parameterization



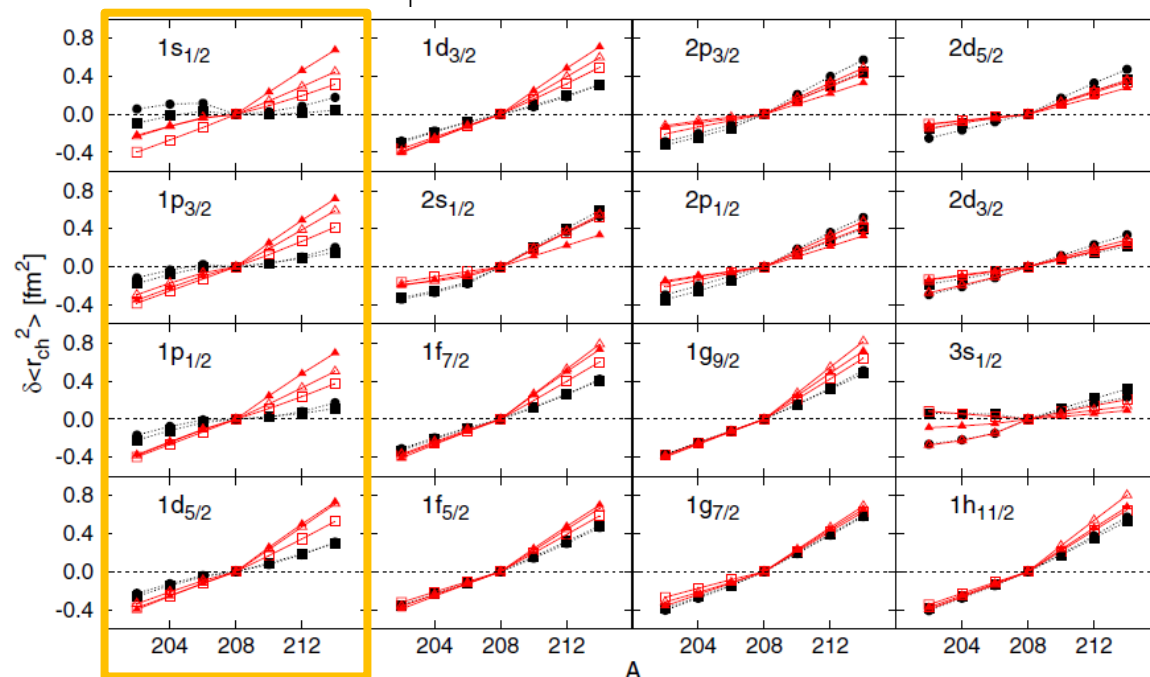
# Kinkology and the isospin dependence of the SO potential

Goddard et al. PRL **110**, 032503 (2013)



strong effect of the  $1h_{11/2}$  occupation on charge radii

orbits with the same nodal structure ( $n=1$ ) contribute in an essential way



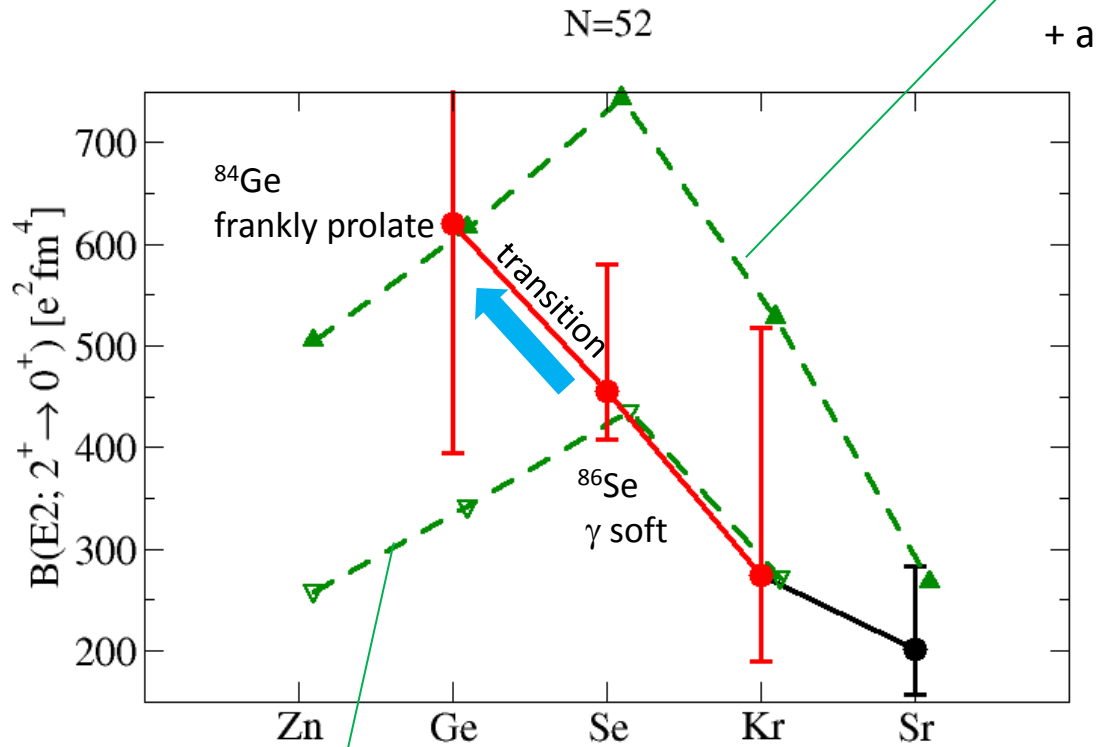
# Pseudo-spin symmetry : the hidden architect of shape coexistence in the N=50 region ?

$^{84}\text{Ge}$   $2^+$  lifetime measurement :

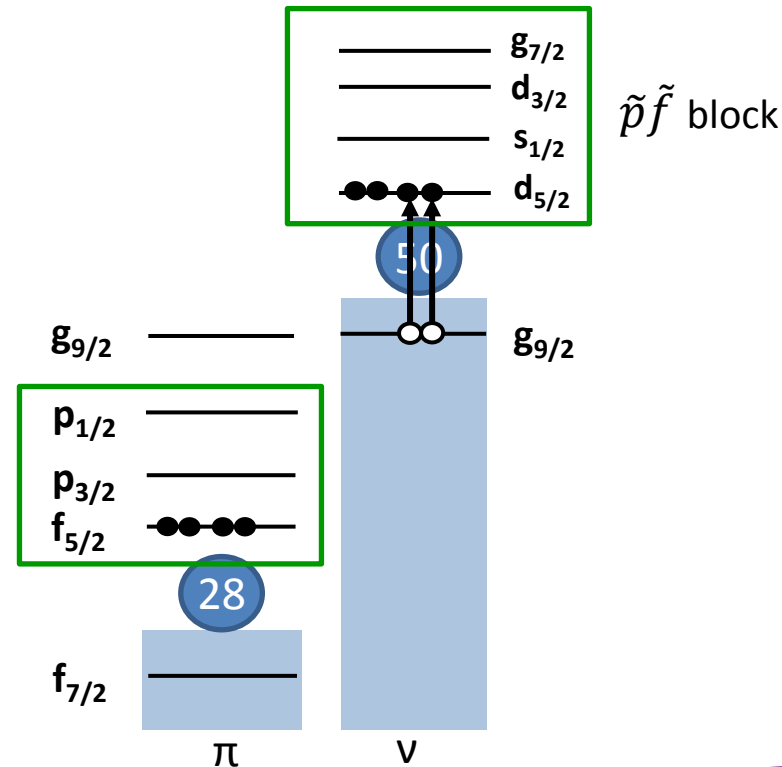
plunger AGATA + VAMOS – Exp. E669 GANIL

C. Delafosse et al. PRL 121, 192502 (2018)

quadrupole collectivity originates from  
the proton  $\tilde{s}\tilde{d}$   
+ a neutron-pair promotion towards  $\tilde{p}\tilde{f}$

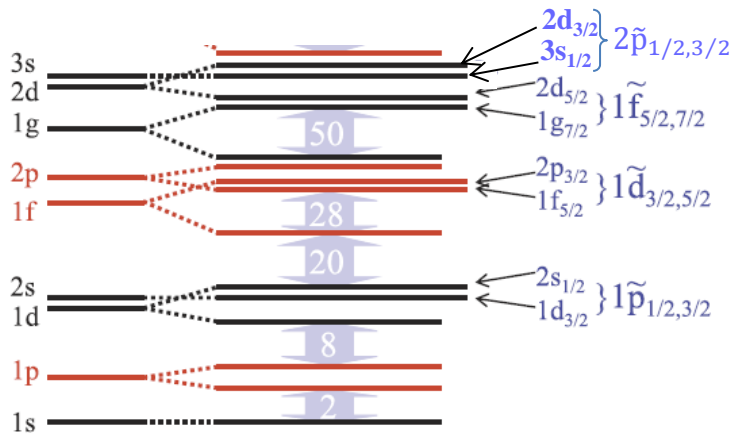


all quadrupole collectivity originates  
from the proton  $\tilde{s}\tilde{d}$  uniquely





# Pseudo-spin symmetry : the hidden architect of shape coexistence in the N=50 region ?



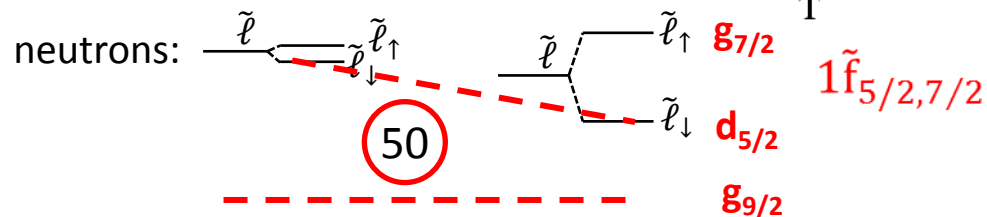
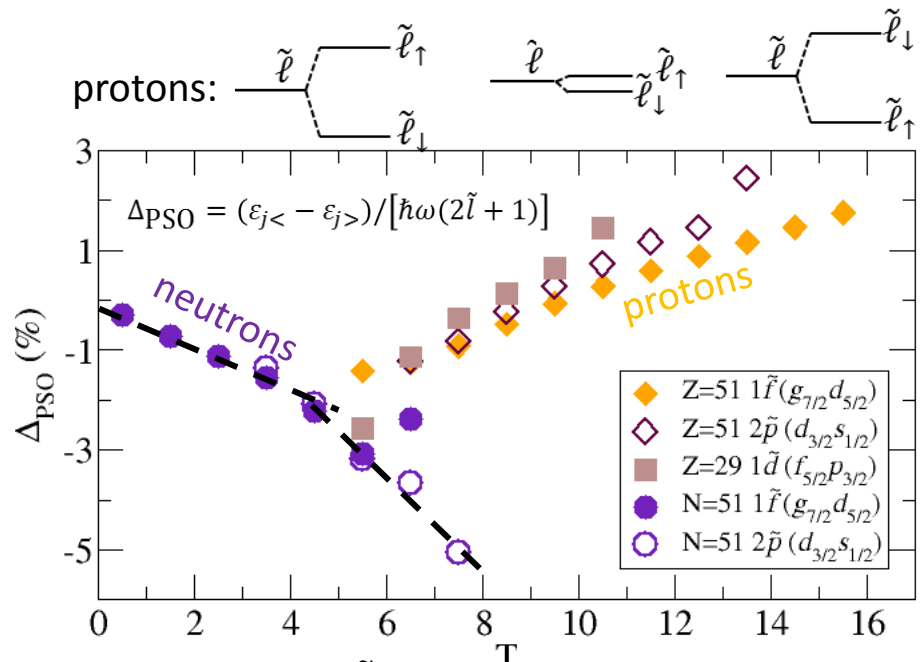
**isospin dependence of the pseudospin symmetry**

**$\rho$  meson interaction, in neutron rich nuclei :**

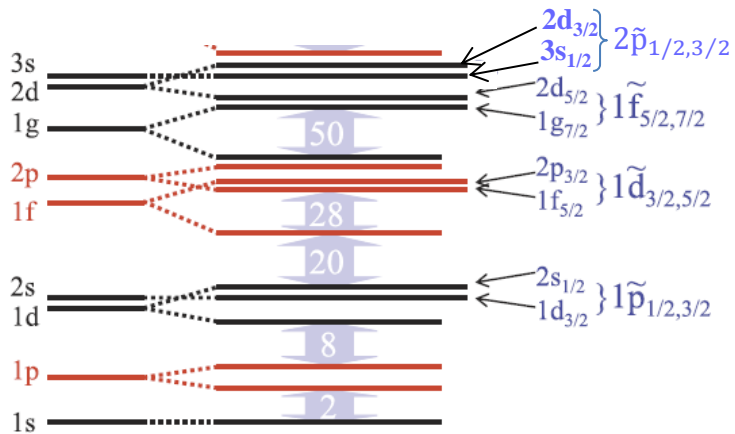
- repulsive for the neutrons
- attractive for the protons

$$V = V_\omega + V_\rho = V_\omega \pm \frac{g_\rho}{2} \rho_0$$

neutron diffusivity



# Pseudo-spin symmetry : the hidden architect of shape coexistence in the N=50 region ?

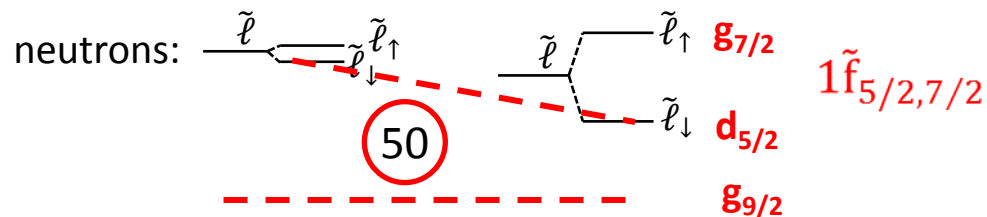
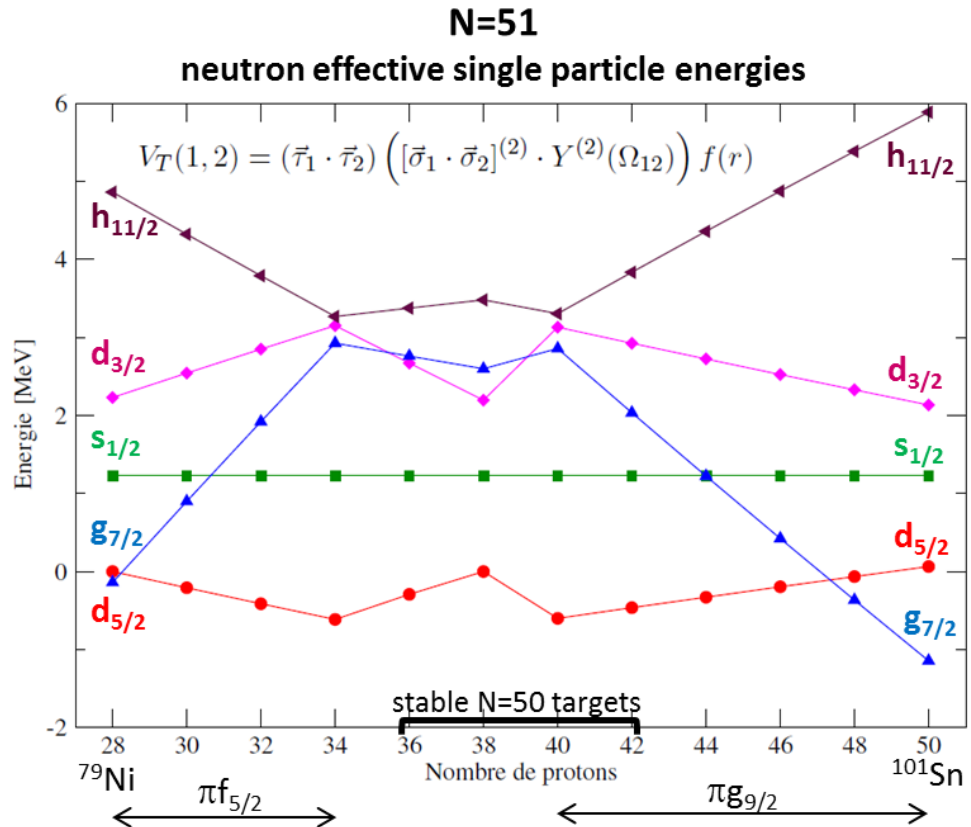


isospin dependence of the pseudospin symmetry

- $\rho$  meson interaction, in neutron rich nuclei :
- repulsive for the neutrons
  - attractive for the protons

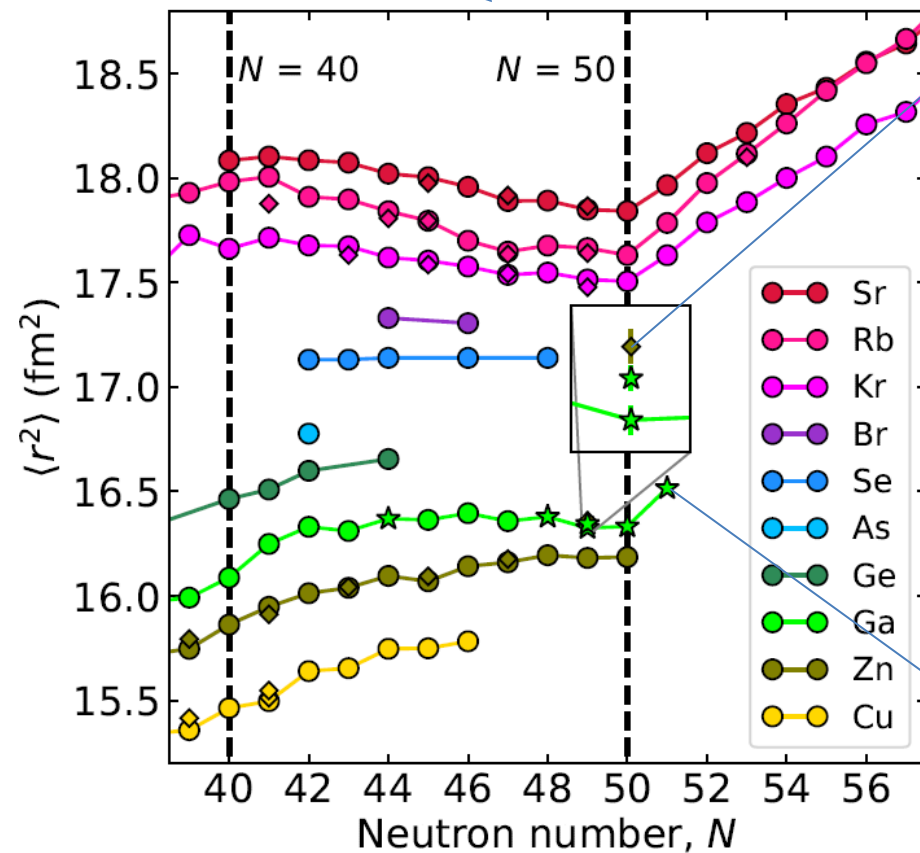
$$V = V_\omega + V_\rho = V_\omega \pm \frac{g_\rho}{2} \rho_0$$

neutron diffusivity



# kink and shape coexistence : related phenomena in the N=50 region ?

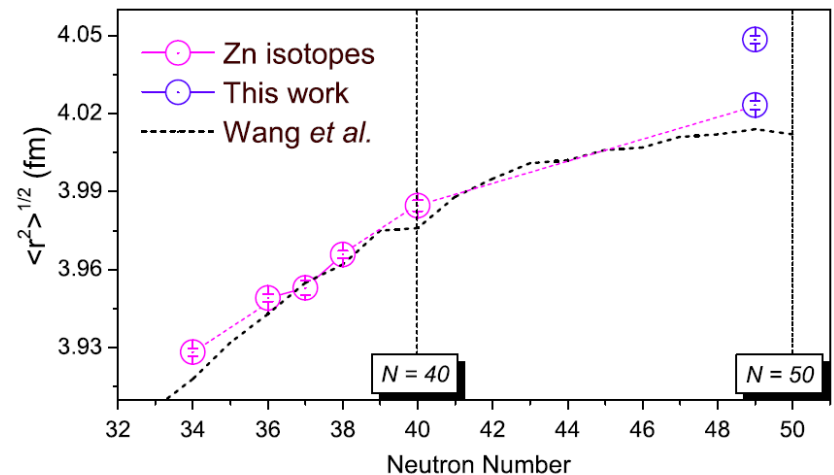
borrowed from Greg Farooq-Smith's PhD manuscript  
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PhD defense on Friday !



COLLAPS result

X. Yang et al. PRL 116 182502 (2016)

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CRIS results (stars)

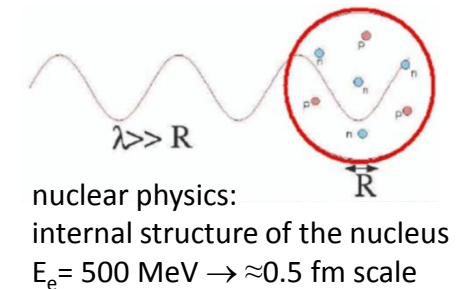
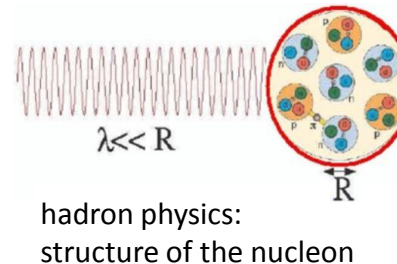
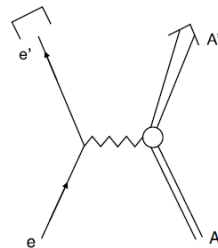
G.J. Farooq-Smith PRC 96, 044324 (2017)

further development of Ge beams at ALTO:  
sulfuration ( $\text{GeS}^{1+}$ ): 1<sup>st</sup> try at ALTO in November this year  
in collaboration with ISOLDE and SPES

# The electromagnetic probes

- ion manipulation with em fields: mass measurements
- interaction with the hyperfine field : laser spectroscopy, nuclear orientation  $\rightarrow I^{(\pi)}, \mu, Q_s, \delta \langle r_c^2 \rangle$
- $\gamma$ -spectroscopy : lifetimes,  $B(E\lambda), B(M\lambda)$
- e- scattering

e momentum transfer  $q \approx 1/\lambda$



contrary to hadron probe, the only unknown in the reaction is the nuclear part

A(e,e) elastic cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{eA \rightarrow eA} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{1 + \frac{2E}{M} \sin^2(\theta/2)} |F(\vec{q})|^2$$

point charge nucleus

$$F(\vec{q}) = \frac{1}{Ze} \int \rho(\vec{r}) e^{i\vec{q} \cdot \vec{r}} d^3r$$

form factor

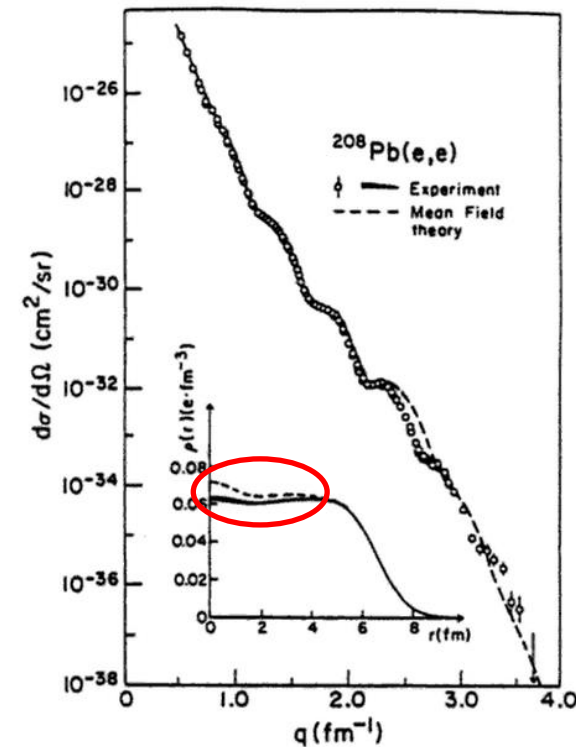
Fourier transform

$$\rho(\vec{r}) = \frac{Ze}{(2\pi)^3} \int F(\vec{q}) e^{-i\vec{q} \cdot \vec{r}} d^3q$$

charge distribution  
"model independent"



# The e-probe revolution



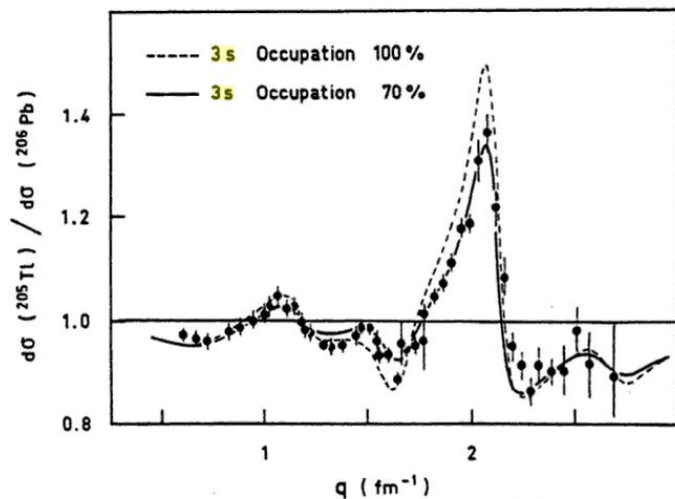
12 orders of magnitude !

B. Frois and Papanicolas  
Ann. Rev. Nucl. Part. Sci 37 (1987)

Dechargé and Gogny  
PRC 81 (1980)

Cavedon, Frois, Goutte et al.  
PRL 49 (1982)

etc...

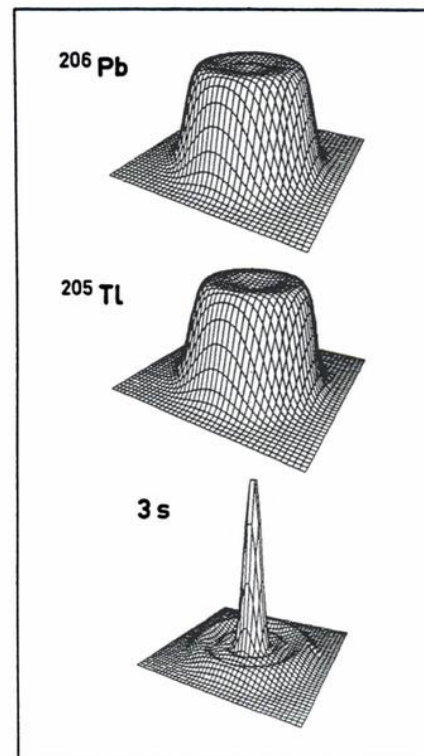


revealed in medium effects

(how far a "single particle" is from a free nucleon)

- part of the single-particle quenching has well understood origins: core (collective) couplings, many-body correlations

- short-range correlations, non-local part of the potential  
→  $\delta\langle r^2 \rangle_c$  kinks, neutron skin and giant haloes formation ?  
→ shell evolution ?



B. Frois et al  
in Modern Topics in  
Electron Scattering  
(World Scientific  
1991)

# e-scattering as a precision spectroscopy tool

$A(e,e')$  inelastic cross section

$$\frac{d\sigma}{d\Omega} = \sigma_p \eta \left[ \sum_{\lambda=0}^{\infty} \frac{q_{\mu}^4}{q^4} |F_{\lambda}^C(q)|^2 + \left( \frac{q_{\mu}^2}{2q^2} + \tan^2 \frac{\theta}{2} \right) \sum_{\lambda=1}^{\infty} \{ |F_{\lambda}^E(q)|^2 + |F_{\lambda}^M(q)|^2 \} \right]$$

point charge nucleus

longitudinal form factor

transverse form factor

recoil factor

$$\rho_{\lambda}(r) = \int \langle \psi_f | \rho_{op}(\mathbf{r}) Y_{\lambda}(\hat{\mathbf{r}}) | \psi_i \rangle d\hat{\mathbf{r}}$$

charge transition density

$$J_{\lambda\lambda'}(r) = \frac{i}{c} \int \langle \psi_f | \mathbf{J}_{op}(\mathbf{r}) \cdot \mathbf{Y}_{\lambda\lambda'}(\hat{\mathbf{r}}) | \psi_i \rangle d\hat{\mathbf{r}}$$

current transition density

$$B(E\lambda) = \frac{2J_f + 1}{2J_i + 1} \left[ \int_0^{\infty} \rho_{\lambda}(r) r^{\lambda+2} dr \right]^2$$

$$B(M\lambda) = \frac{\lambda}{\lambda + 1} \frac{2J_f + 1}{2J_i + 1} \left[ \int_0^{\infty} J_{\lambda\lambda}(r) r^{\lambda+2} dr \right]^2$$

$\mu \approx F_M$  for  $q \rightarrow 0$   
(elastic at  $180^\circ$ )

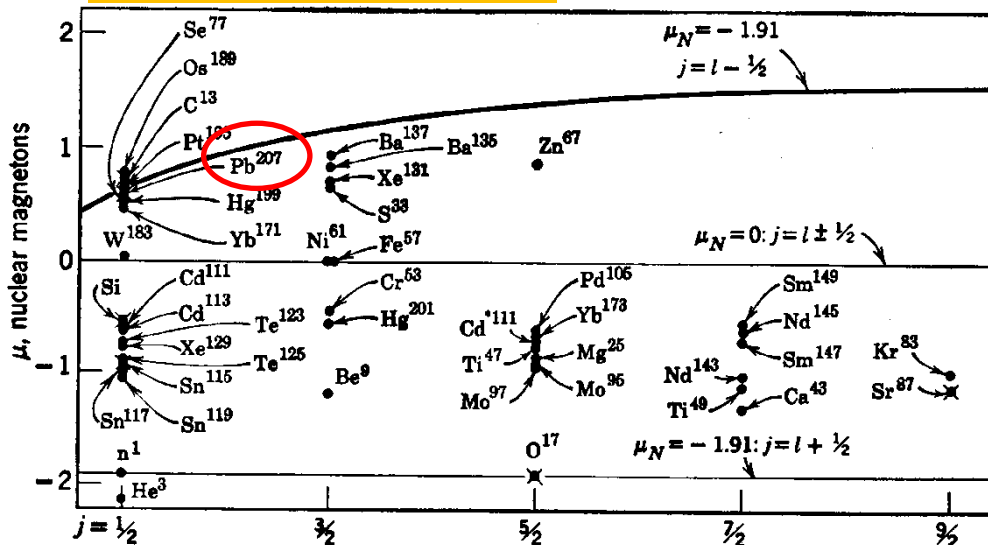
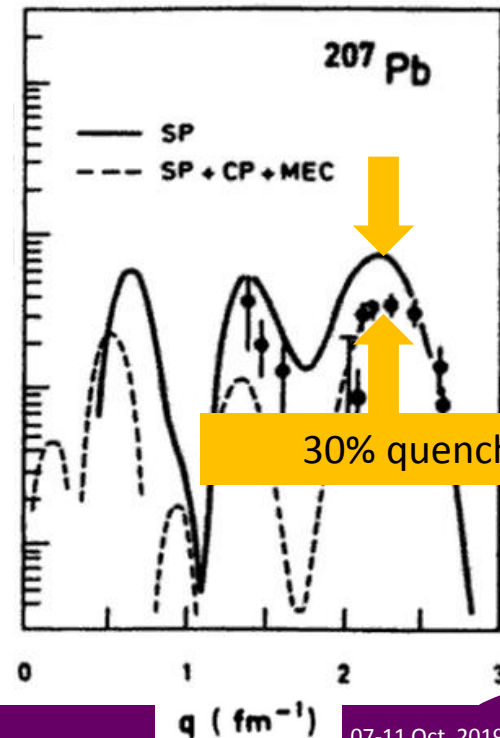
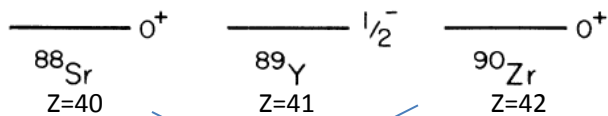
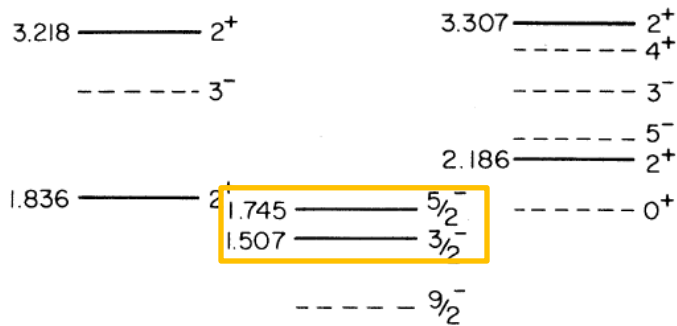


Fig. I.5. Magnetic moments of nuclei with odd  $N$  plotted against the spin.



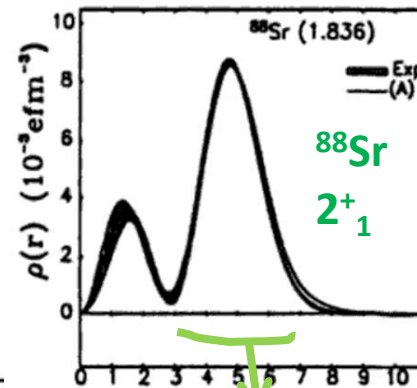
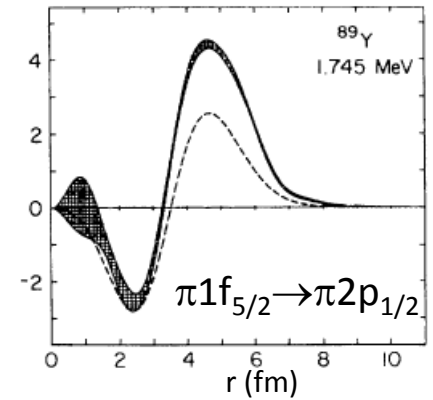
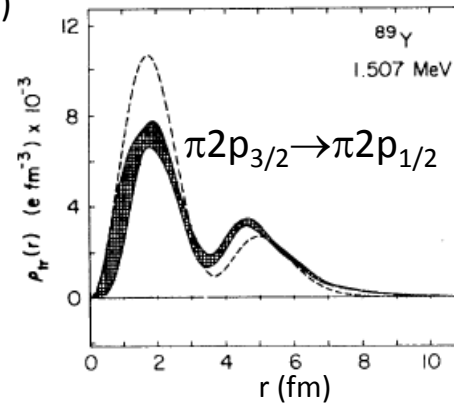
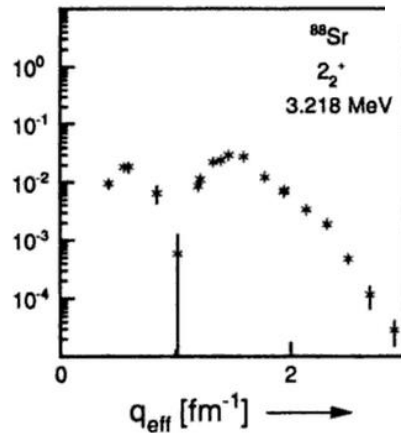
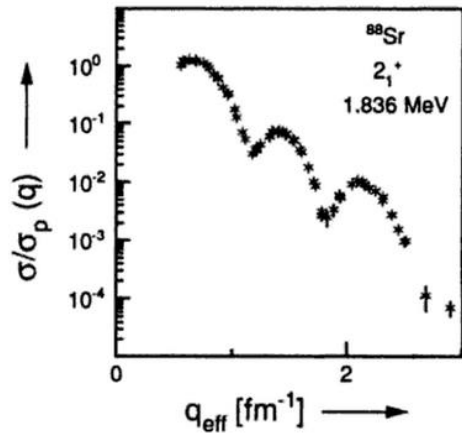
# e-scattering as a precision spectroscopy tool

One example: N=50 isotones Schwentker et al. PRL 50 (1983)

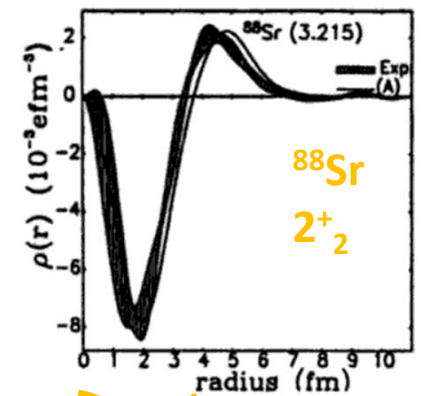


~~$[^{88}\text{Sr}; 2^+] \otimes \pi 2p_{1/2}$~~

curve "A": the two  $2^+$  are orthogonal linear combinations of  $[2p_{3/2}^{-1}2p_{1/2}]_{2^+}$  and  $[1f_{5/2}^{-1}2p_{1/2}]_{2^+}$



surface oscillation  
("standard" collective state)

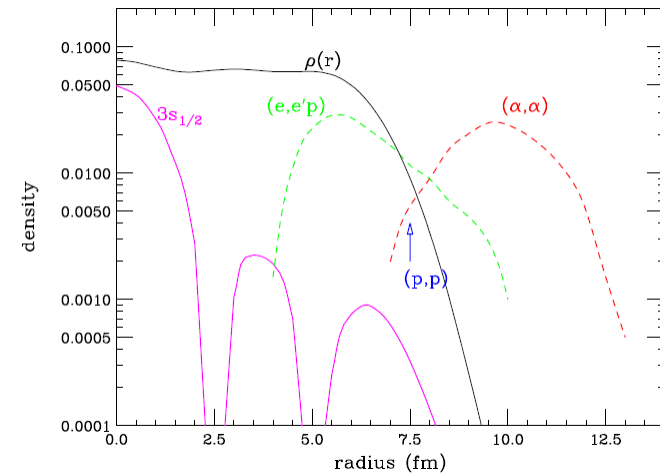
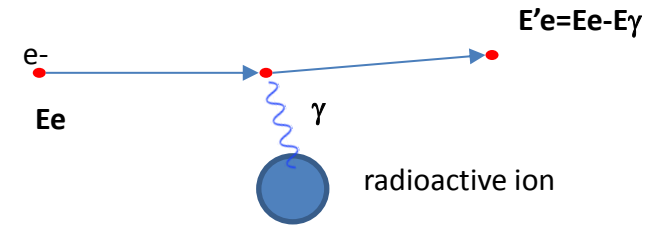


nuclear interior solicited

# (in)elastic electron scattering off RIB : a vast program

not to mention :

- radius, diffusivity
- perfect coulomb excitation : forward electron scattering (no multi-step process)
- “clean” excitation of 1p-1h configuration at high multipolarity
- Excitation of collective modes (PDR etc)
- fission studies (condition on electron energy would give precise information of the initial condition of the fissioning system)

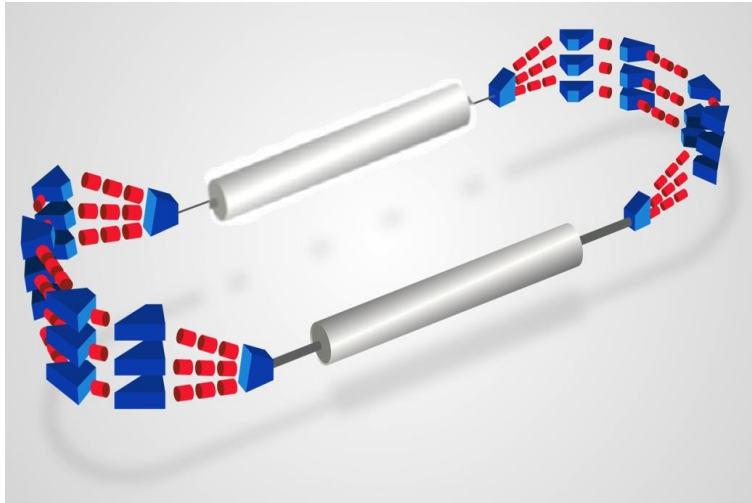


The possible physics program spans exactly the physics interests of the vast majority of the low-energy nuclear physics community in Orsay-Saclay and in France (and elsewhere) ... **with a much more powerful probe!**



# on possible nuclear-physics avenues offered by a Orsay-hosted 450-MeV PERLE version

David Verney, IPN Orsay



- Why seize the opportunity of the (possible) construction of an ERL prototype in Orsay to perform e-scattering off RIBs ?
  - The big picture
  - more detailed (realistic, sustainable) physics case :  
fission fragments ISOL-beams at Orsay (ALTO)
- tentative sketch of the project based on:
  - extrapolation from already available RIB from ALTO (FF: medium mass n-rich nuclei)
  - The aimed ERL machine

PERLE is a high current, multi-turn Energy Recovery LINAC(ERL) facility (900 MeV), designed to study and validate main principles of the Large Hadron Electron Collider (LHeC: 60 GeV) LHeC would use a 3-pass energy recovery, recirculating linac with 20 GeV per pass and a current of about 10 mA; the RF frequency would be 802 MHz

The Orsay realization of PERLE (called **PERLE@Orsay**) is a smaller version (500 MeV) with the same design challenges and the same beam parameters:

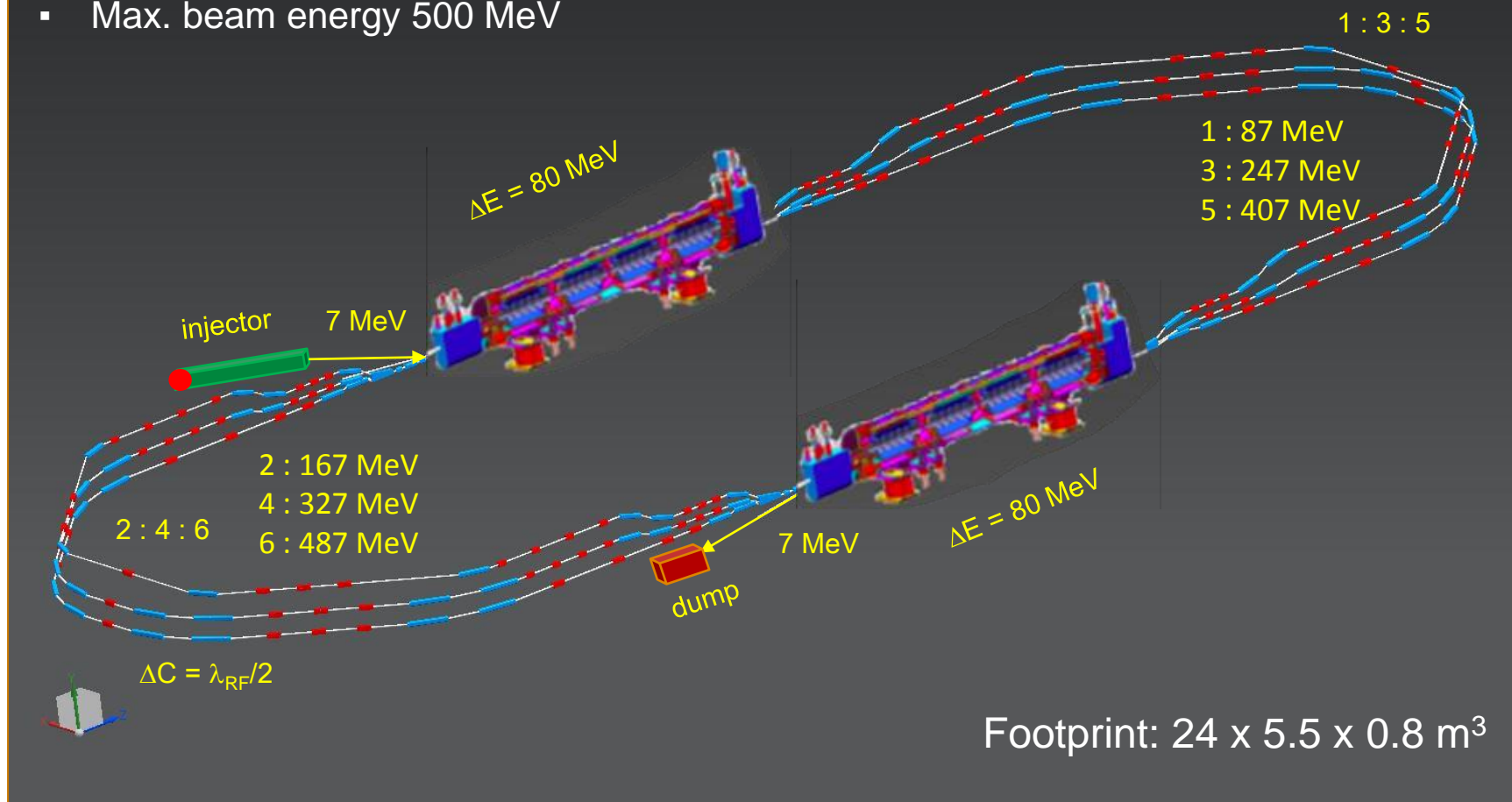


Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\epsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

Courtesy W. Kaabi (LAL Orsay)  
(LHeC/FCC-eh and PERLE Workshop, 27-29 June 2018, Orsay, France)

## The PERLE@Orsay configuration

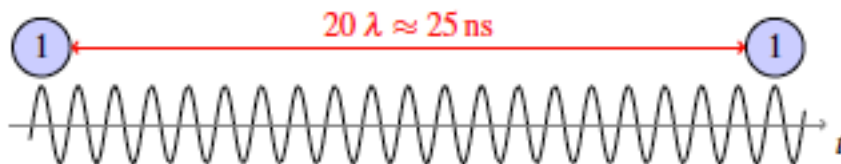
- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV



Courtesy W. Kaabi (LAL Orsay)  
(LHeC/FCC-eh and PERLE Workshop, 27-29 June 2018, Orsay, France)

## The PERLE@Orsay configuration

- Basic RF structure, without recirculation: Bunches are injected every 25 ns



801.58 MHz RF, 5-cell cavity:

$$\lambda = 37.40 \text{ cm}$$

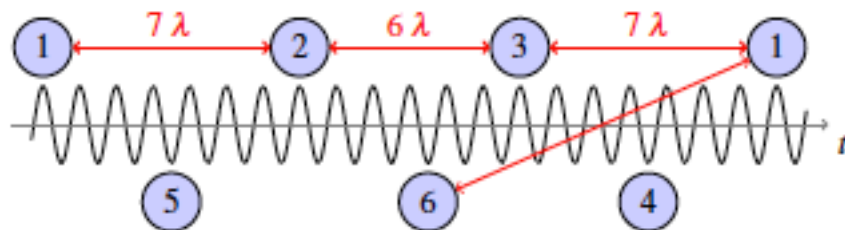
$$L_c = 5\lambda/2 = 93.50 \text{ cm}$$

$$\text{Grad} = 21.4 \text{ MeV/m (20 MeV per cavity)}$$

$$\Delta E = 80 \text{ MeV per Cryo-module}$$

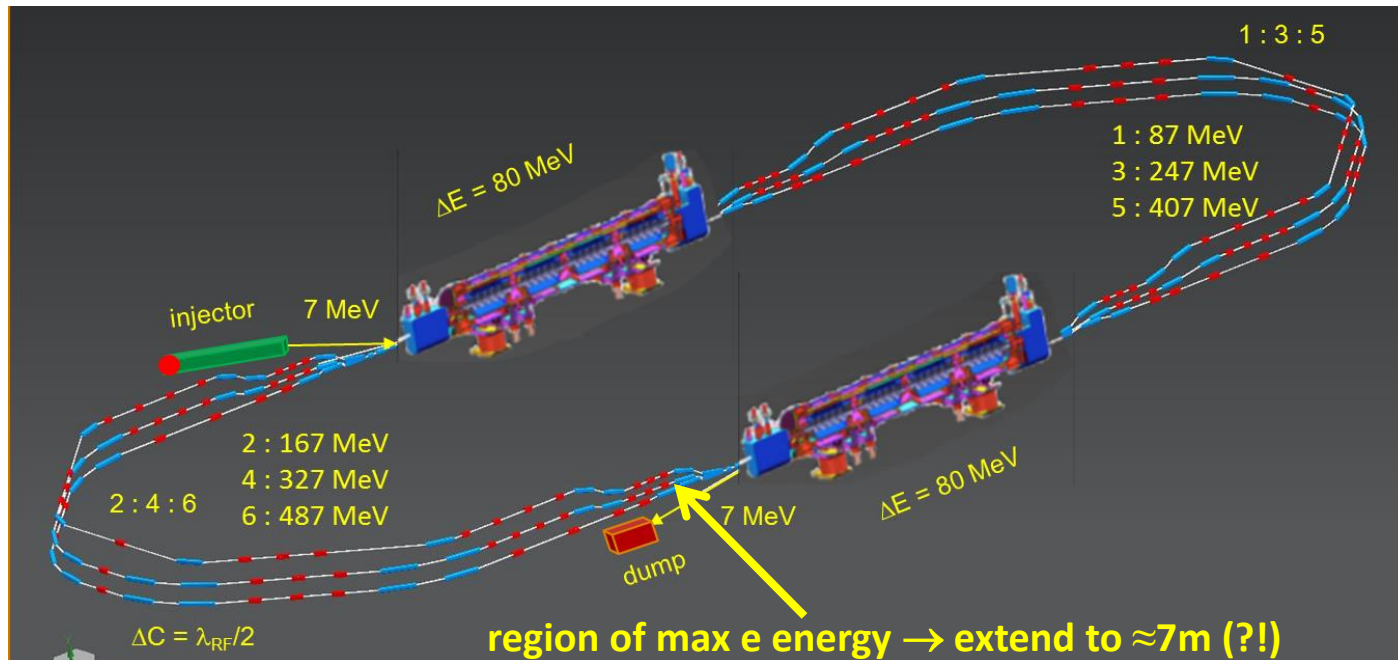
- When recirculation occurs: bunches at different turns in the linacs:
  - Ovoid bunches in the same bucket
  - Recombination pattern adjusted by tuning returned arcs length of the required integer of  $\lambda$ .

Turn number	Total pathlength
1	$n \times 20\lambda + 7\lambda$
2	$n \times 20\lambda + 6\lambda$
3	$n \times 20\lambda + 3.5\lambda$

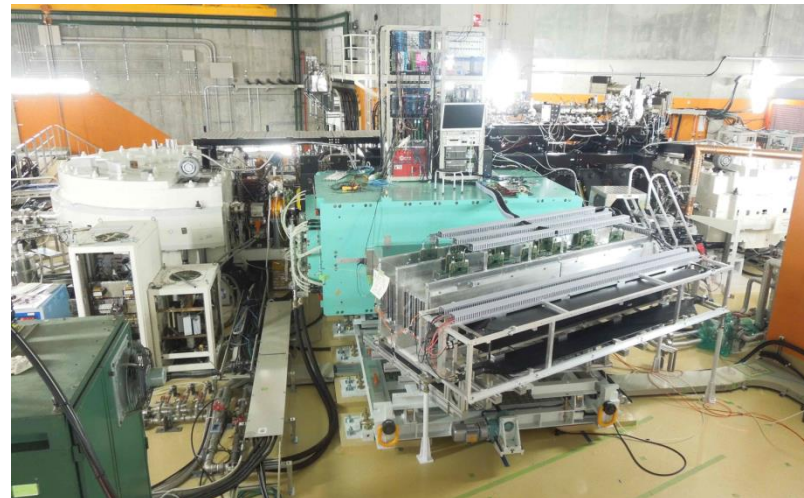
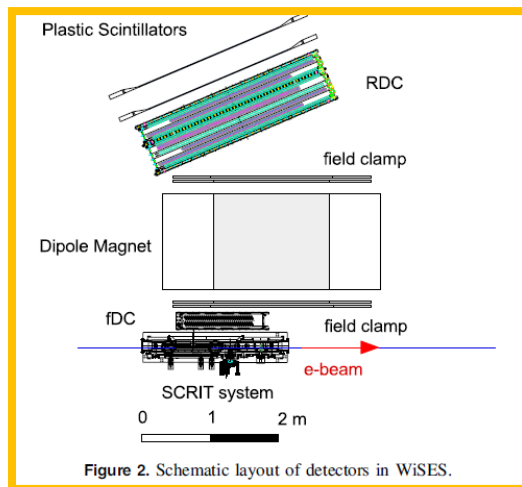


- Maximize the distance between the lowest energy bunches (1 & 6): ovoid reducing the BBU threshold current due to the influence of HOMs kicks.
- Achieve a nearly constant bunch spacing: minimize collective effects

injection of ALTO-like RIBS into the ERL



Largely inspired  
by the  
pioneering  
SCRIT example



T Ohnishi et al Phys. Scr. T166 (2015) 014071



# electron/RIB beams requirements

- all interesting phenomena occur at  $q \gtrsim 2\text{fm}^{-1}$  ; the higher the  $q$  transferred the lower the cross section;  
consider previous achievements in this domain  $\Rightarrow$  compromise  $E_e \simeq 500\text{ MeV}$

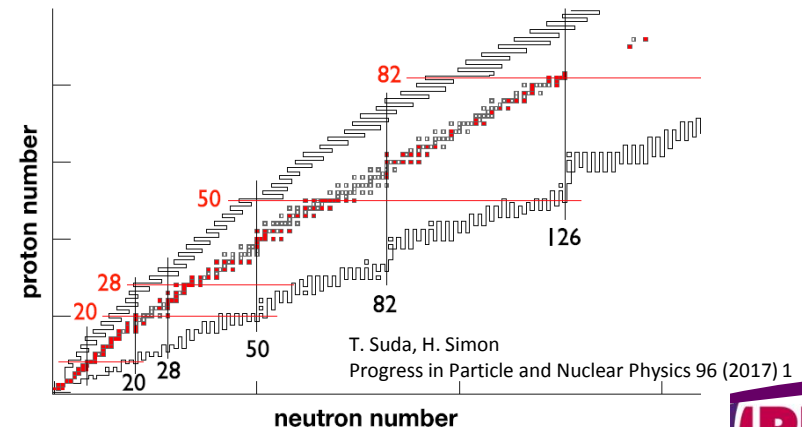
- Luminosity : 
$$L = F_e n_e \frac{N_e N_A}{4\pi\sigma_x\sigma_y} = \frac{I_e N_A}{4\pi\sigma_x\sigma_y q_e}$$

$\Rightarrow$  the aimed luminosity should be  $10^{29}\text{ cm}^{-2}\text{s}^{-1}$

but much can be already done at  $\mathcal{L} \simeq 10^{28}$  (with unstable nuclei EVERYTHING is new !)

Reaction	Deduced quantity	Type	Luminosity [ $\text{cm}^{-2}\text{s}^{-1}$ ]
<i>Elastic scattering at small <math>q</math></i>	r.m.s. charge radii	Light	$10^{24}$
<i>First minimum in elastic form factor</i>	Density distribution with 2 parameters	Light	$10^{28}$
		Medium	$10^{26}$
		Heavy	$10^{24}$
<i>Second minimum in elastic form factor</i>	Density distribution with 3 parameters	Medium	$10^{29}$
		Heavy	$10^{26}$
<i>Pygmy/Giant resonances</i>	Position, width, strength, decays	Medium	$10^{28}$
		Heavy	$10^{28}$
<i>Quasi-elastic scattering</i>	SF, spectral strength	Light	$10^{29}$

- strategy: fixed target  $\rightarrow$  trapped RI population  $10^6\text{-}10^8$

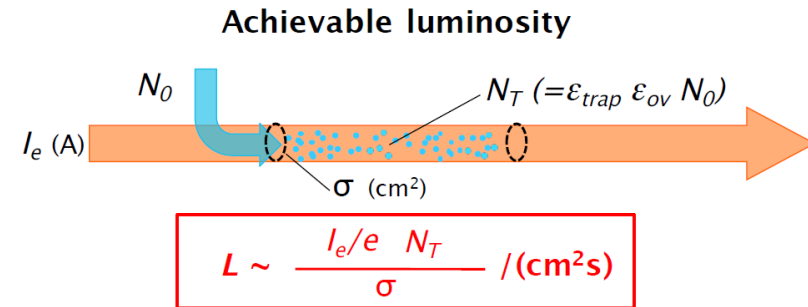


# The DESTIN project

Chancé et al (CEA Saclay) **ETIC** project within GANIL-2025 (2015)  
calculations within ERL hypothesis :

**$I_e=200$  mA  $N_A=10^6$  trapped ions:  $\mathcal{L} \simeq 10^{29}$  should be achieved**  
based on

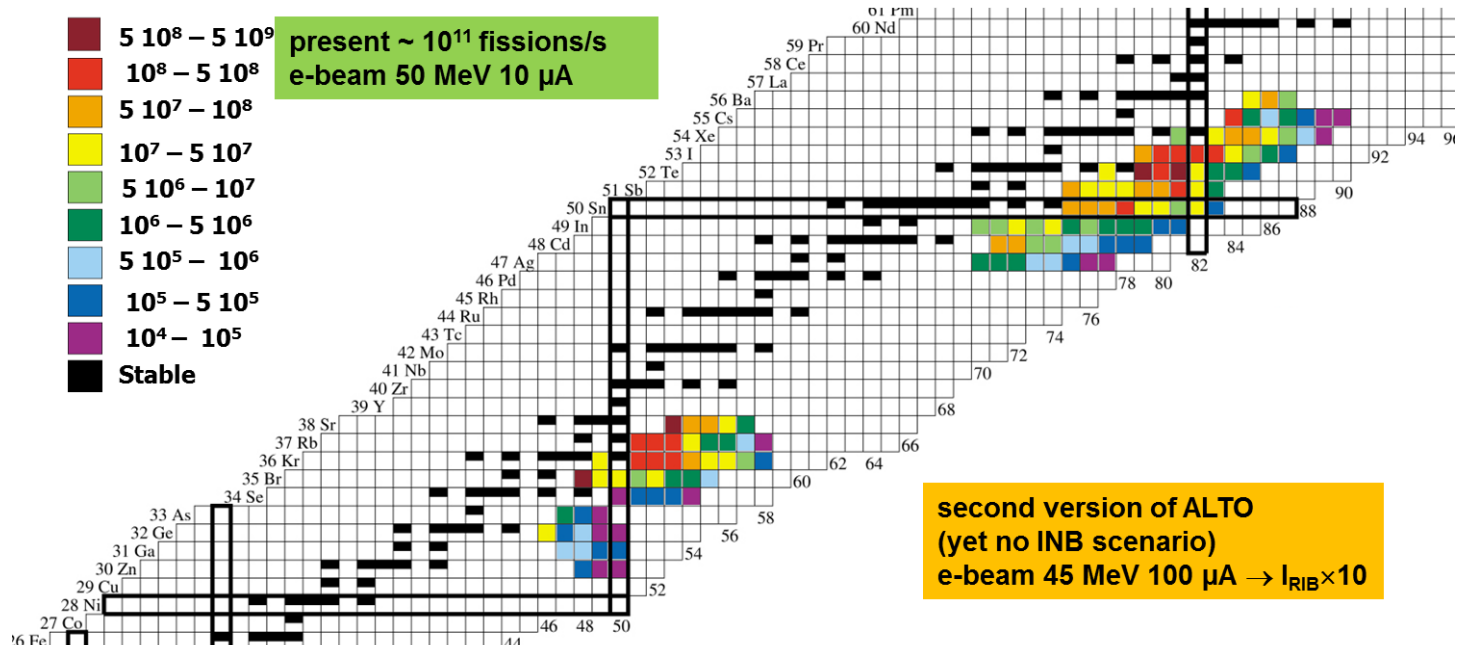
[A.N. Antonov et al., Nucl. Instr. and Meth. A **637** 60 (2011)] ELISE project GSI



PERLE@Orsay : 20 mA  $\rightarrow \mathcal{L} \simeq 10^{28}$  is *probably* achievable for a  **$10^6$**  trapped RI population **on the principle**

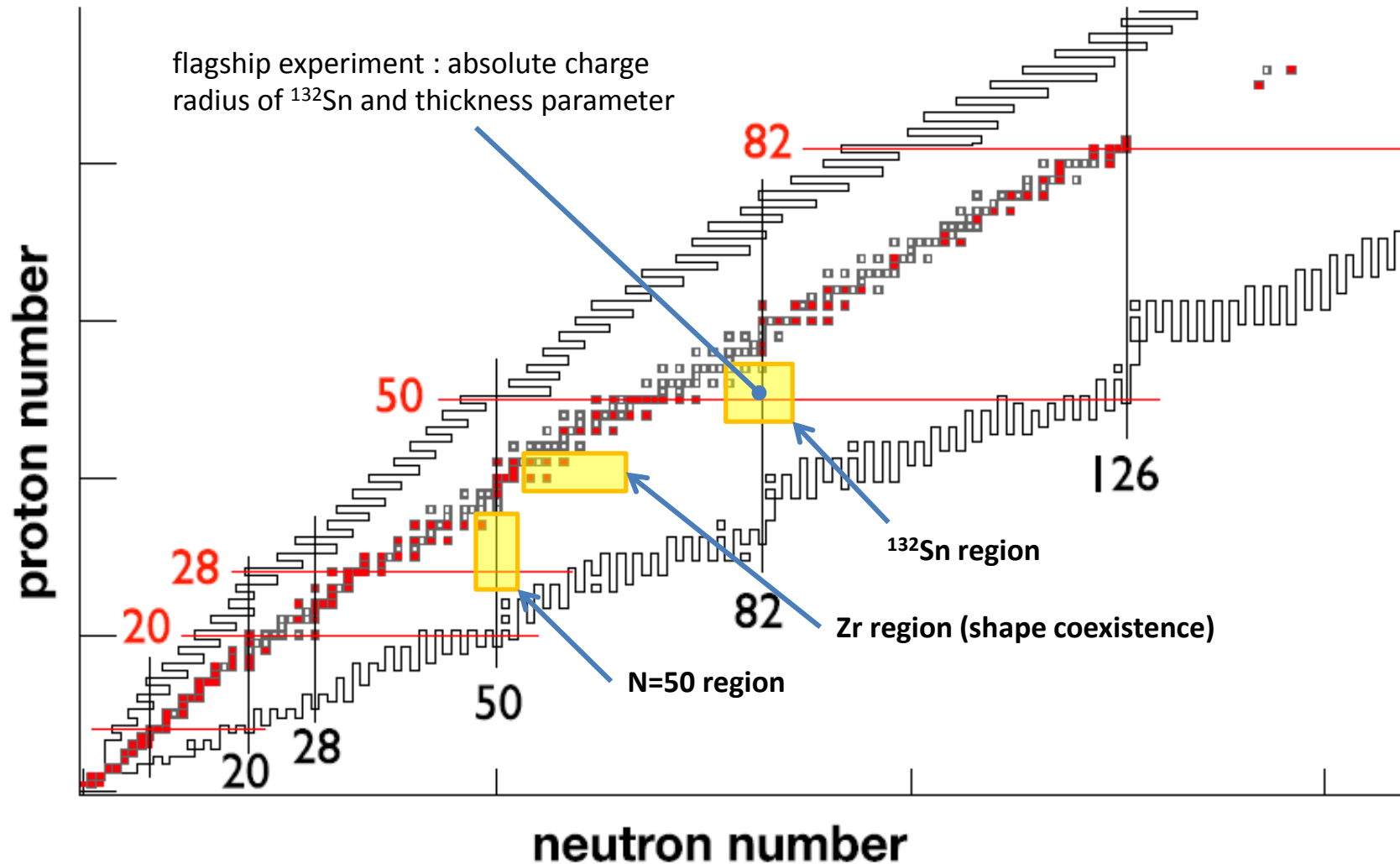
but the dynamical e-beam-RI coupling should be investigated : first time with a ERL time structure  
e-beam instabilities ? impact on ERL operation ?

## Production pps

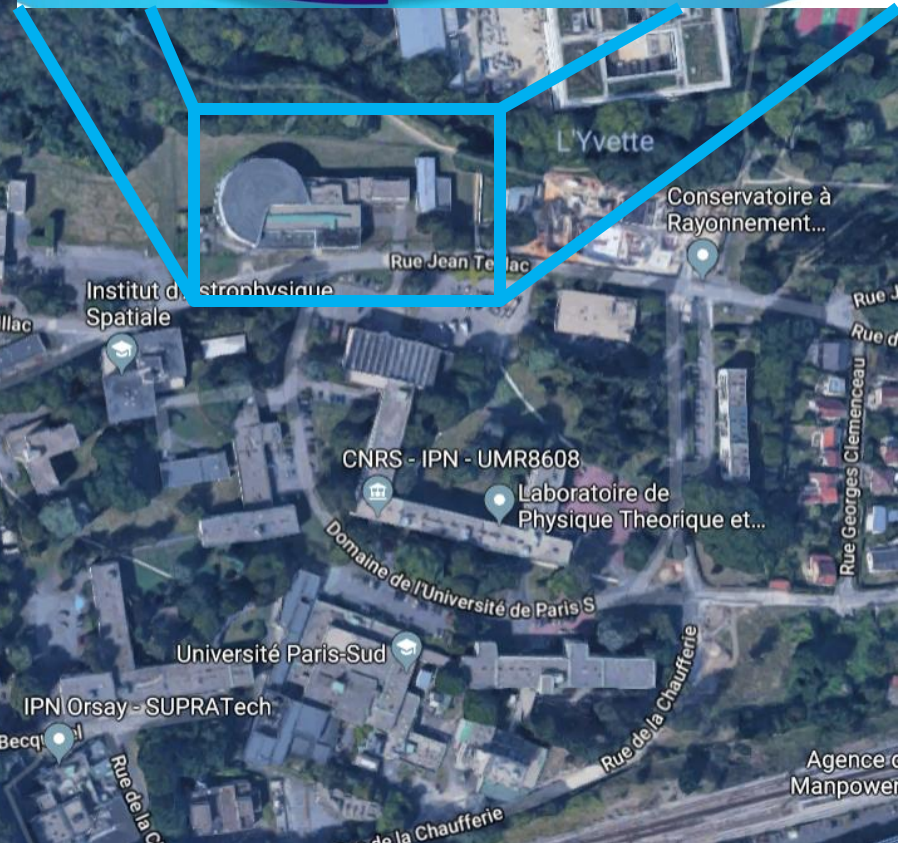
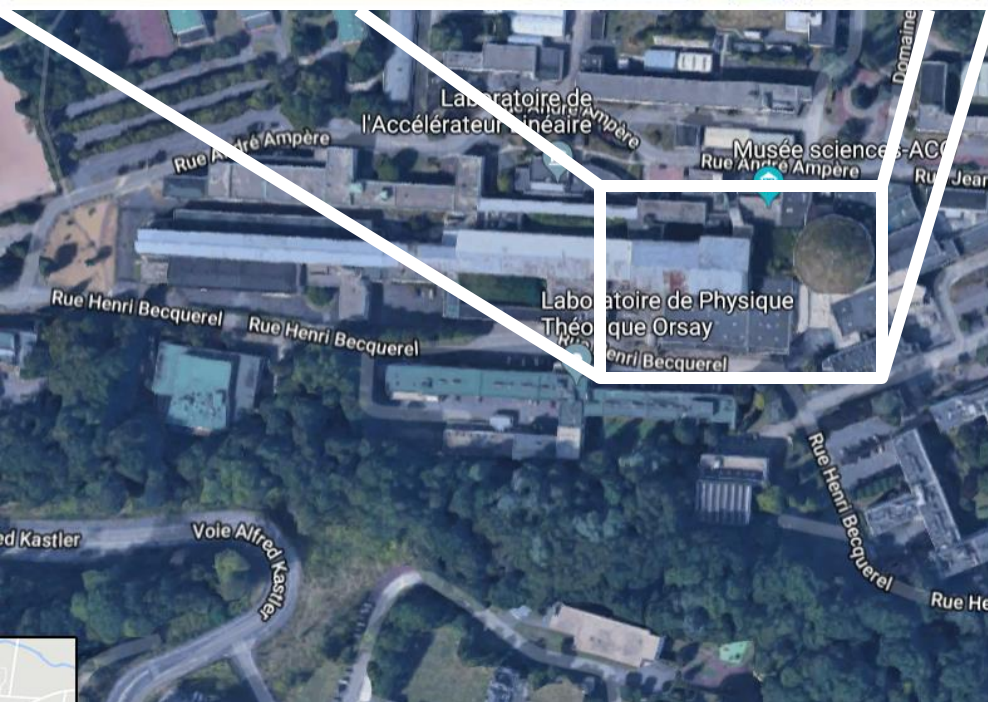


# The DESTIN project

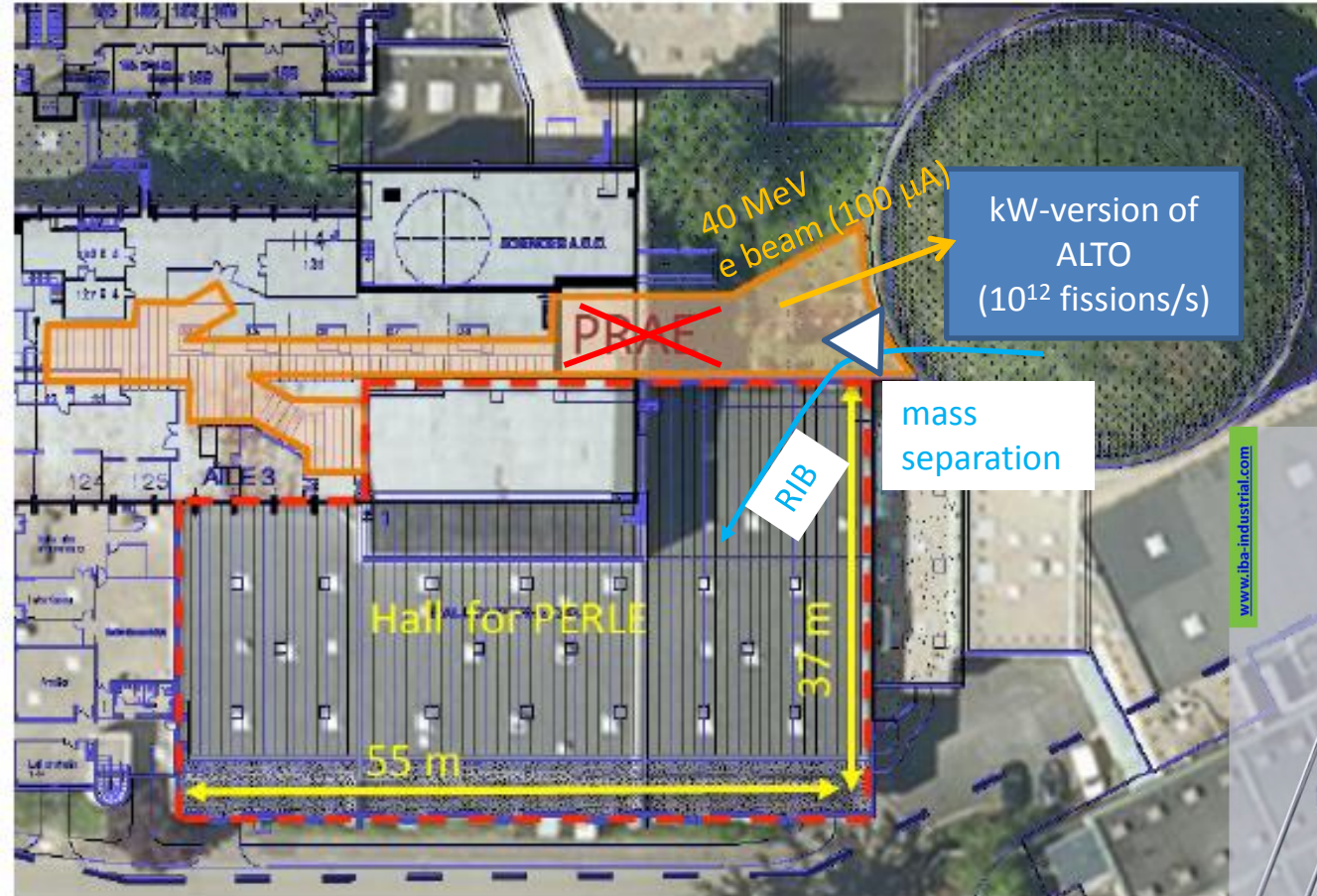
- stable targets already used T. Suda, H. Simon [Progress in Particle and Nuclear Physics 96 (2017) 1]
- radioactive targets envisioned with DESTIN (full glory)











40 MeV electrons  
125 kW  
(a priori exempt from INB regulation)



**Rhodotron® TT300-HE**  
High Energy Electron Generator



- We (ALTO people) hope we are back in laser business
- Anyway, if not directly, we can help indirectly (e.g. beam and instrumentation developments for DESIR, ISOLDE, SPES)
- We are ready to undertake the electron-scattering off-RIB adventure (possibly helping in a redefinition of the Phase 2 of SPIRAL2)