Electromagnetic probe in low-energy nuclear physics : from laser spectroscopy to electron scattering at IJCLab

Clément Delafosse (IJCLab)
on behalf of
David Verney (IJCLab)

distant past

- The laser spectroscopy tradition in Orsay

  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

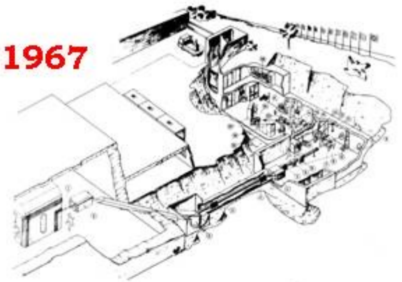
  the DESTIN project at the Orsay-hosted PERLE demonstrator

(far ?) future

At the dawn of the "industrial" ISOL production of RIBs (1974)

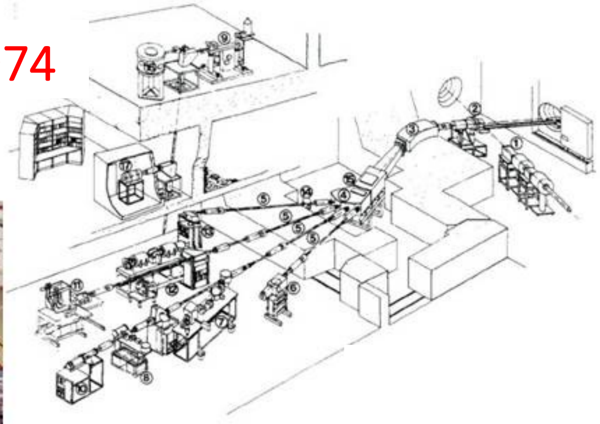
ISOLDE I
@ CERN SC

1967



SC upgrade
I×100

1974



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

ISOLDE II
@ CERN SC

EUROPE

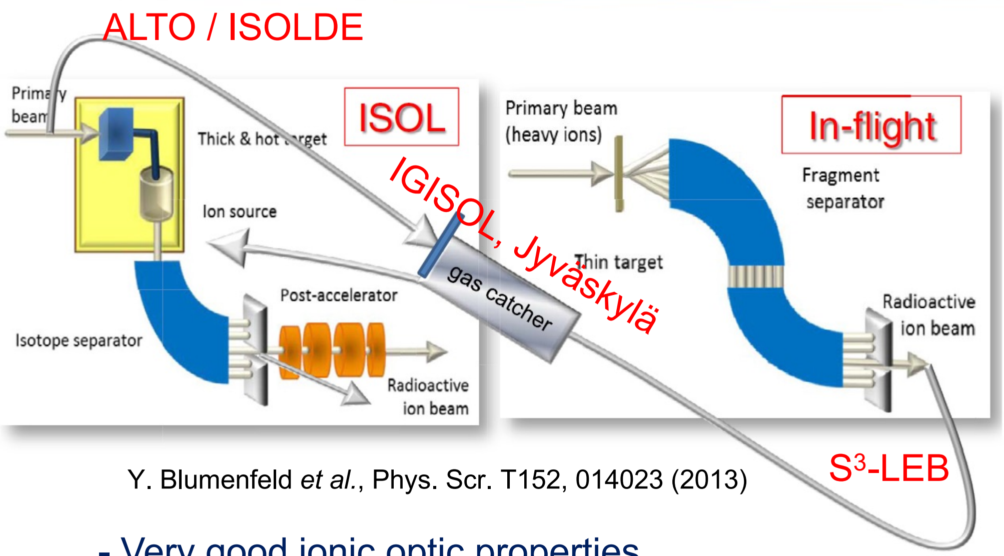
+ LISOL @
Louvain-la-
Neuve

US

UNISOR
Oak Ridge,
Tennessee

towards the glorious
HRIBF
(unfortunately
decommissioned)

A first parenthesis : the ISOL technique



Y. Blumenfeld *et al.*, Phys. Scr. T152, 014023 (2013)

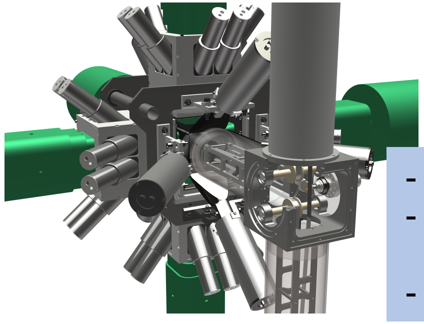
- Very good ionic optic properties
- Precision mesurement technics at low energy

Electromagnetic trapping

Penning trap

- **Binding energies (masses)**
- Excitation energies of β-isomers

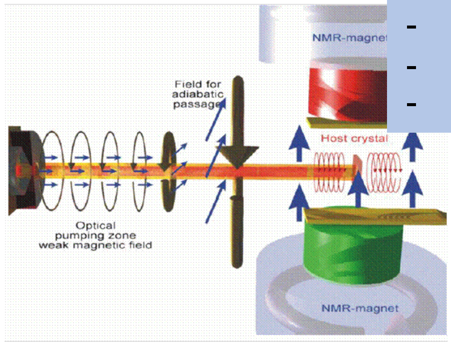
Decay spectroscopy



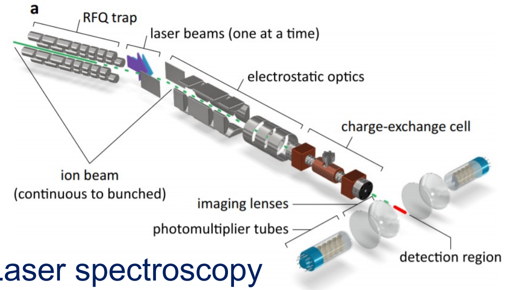
- **Level schemes**
- Lifetime (ground and excited states)
- Transition probabilities

Hyperfine interaction

- Spins
- Magnetic dipolar moment μ
- **Electric quadrupolar moment Q**
- **Charged mean square radius δ$<r^2>$**
- Mixing ratios δ



Nuclear orientation



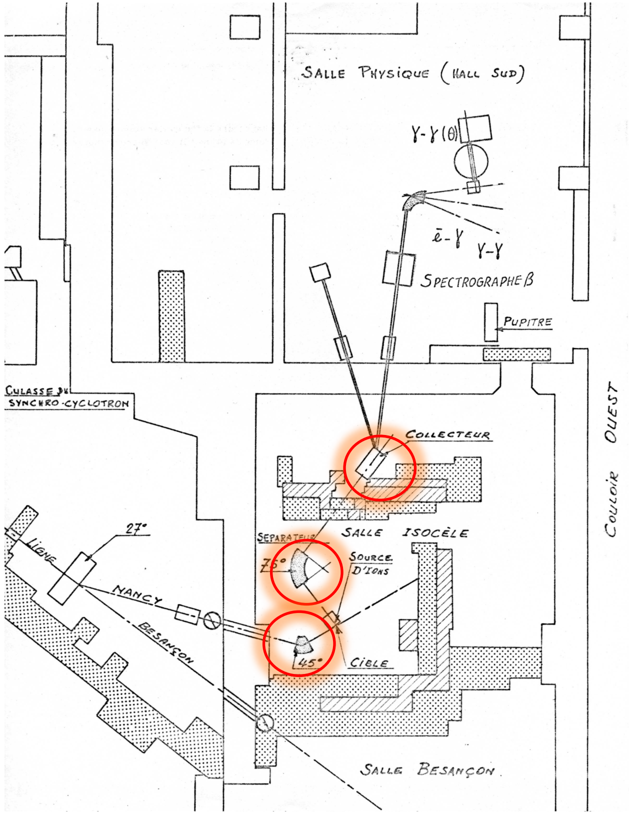
Laser spectroscopy

meanwhile at Orsay… ISOCELE (1974)

An ISOL device on line with the Orsay's SC just came into operation

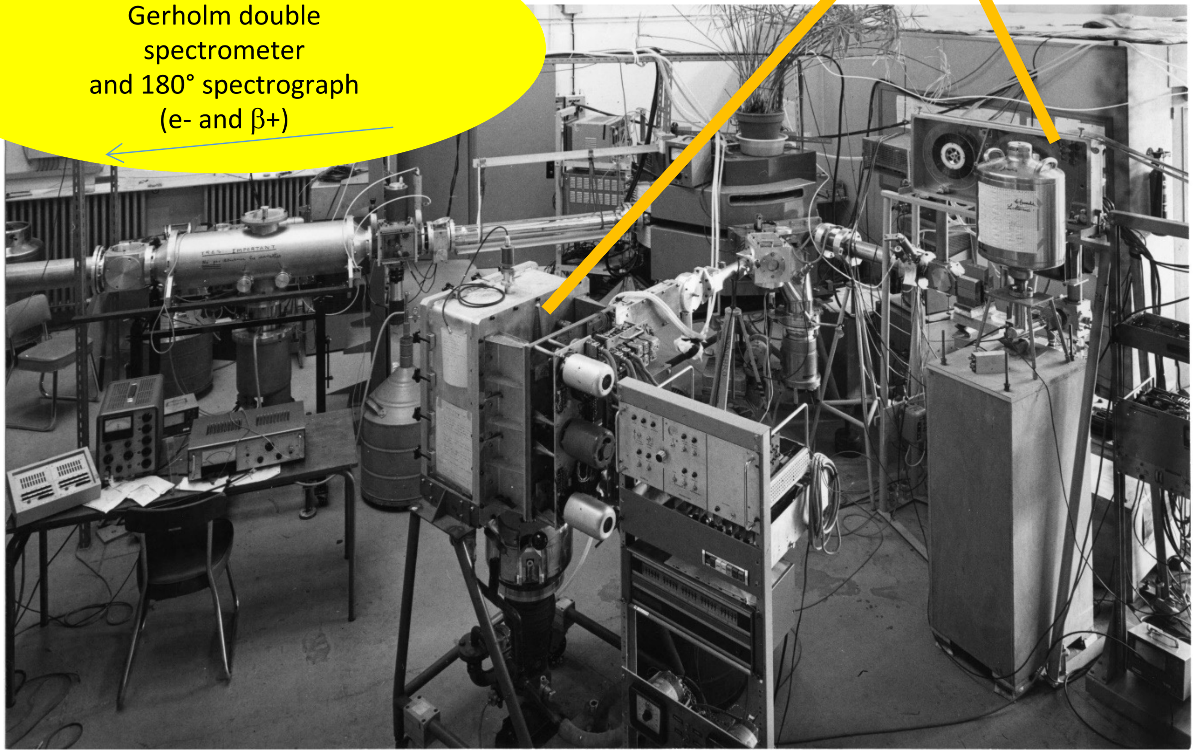
~40 people (researchers, engineers, technicians)

at the "Nancy" SC beam line



Movable tape collectors

towards
Gerholm double
spectrometer
and 180° spectrograph
(e- and β+)



ISOCELE II (1978)

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

p : 155 $\rightarrow$ 200 MeV

^{3}He : 206 $\rightarrow$ 280 MeV

$\rightarrow$ I $\times$ 20

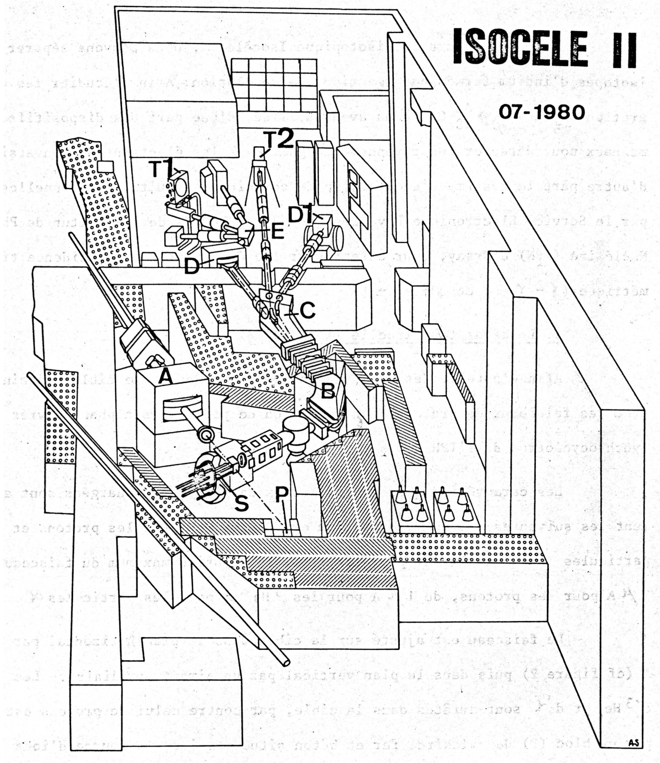
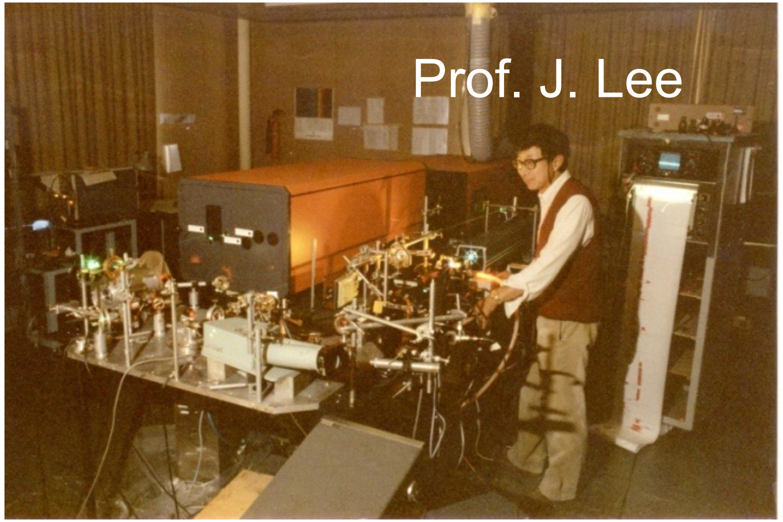


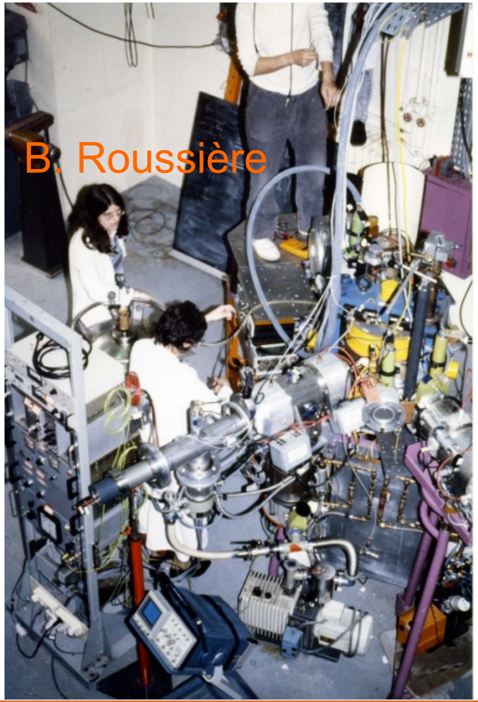
Figure 2 : Vue éclatée d'Isocèle.
A, B, D : aimants; C : collecteur; D1 : distributeur de pastilles; E : aiguillage; P : piège pour le faisceau de protons ; S : source d'ions; T1,T2 : transporteurs à bande.

Post-ISOCELE Laser Isobar Separation : PILIS

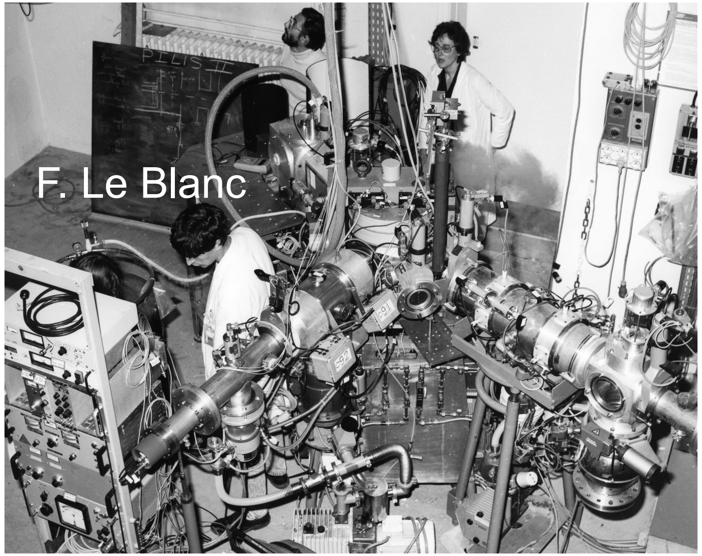
after SC shutdown from September 85 till July 86 (serious SC coil shortcut) the physics program started again with a new device:

The PILIS laser system J. Lee (McGill University) and J. Pinard (Laboratoire Aimé Cotton Orsay)

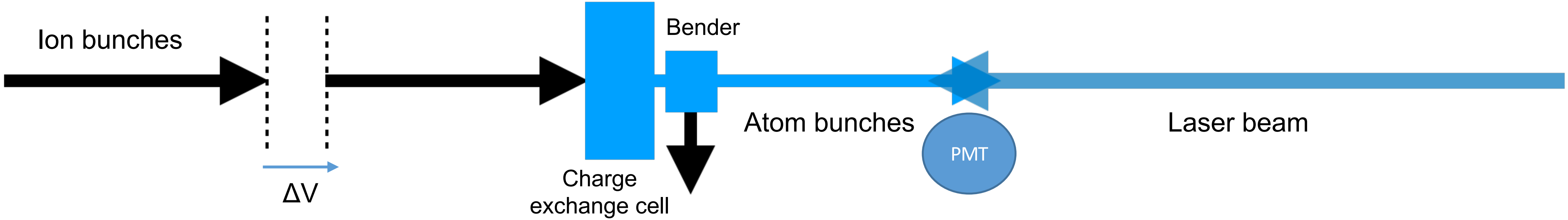




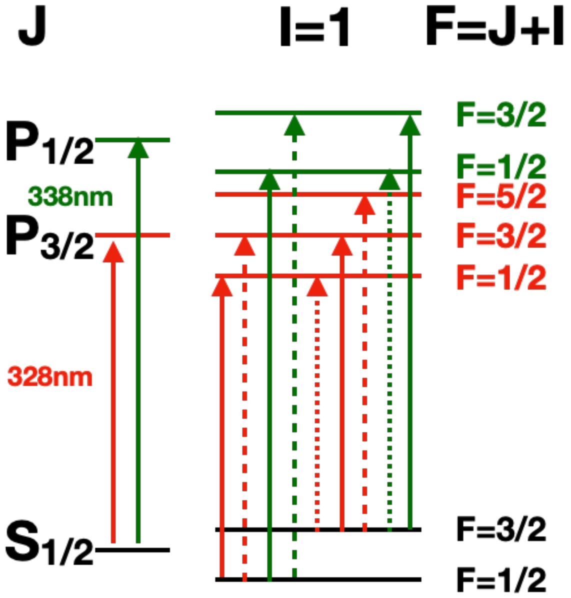
J. Sauvage

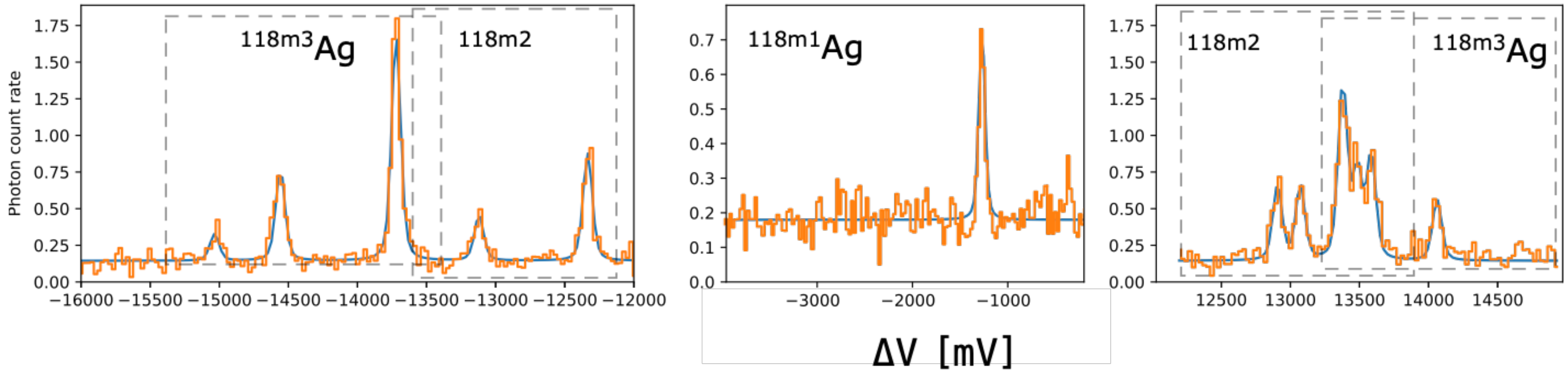


A second parenthesis : laser spectroscopy



Courtesy : R. de Groote (JYFL)

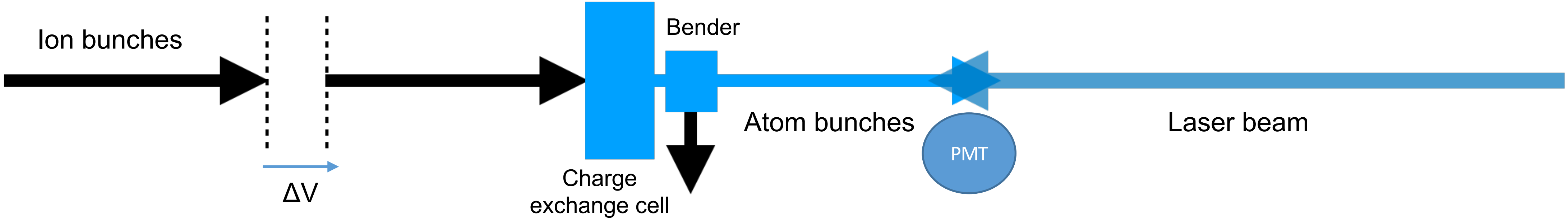




$$\Delta E_{JF} \approx \frac{1}{2} \cdot A \cdot K + B \frac{3\,(K(K+1) - 4I(I+1)J(J+1))}{8I(2I-1)J(2J-1)}$$

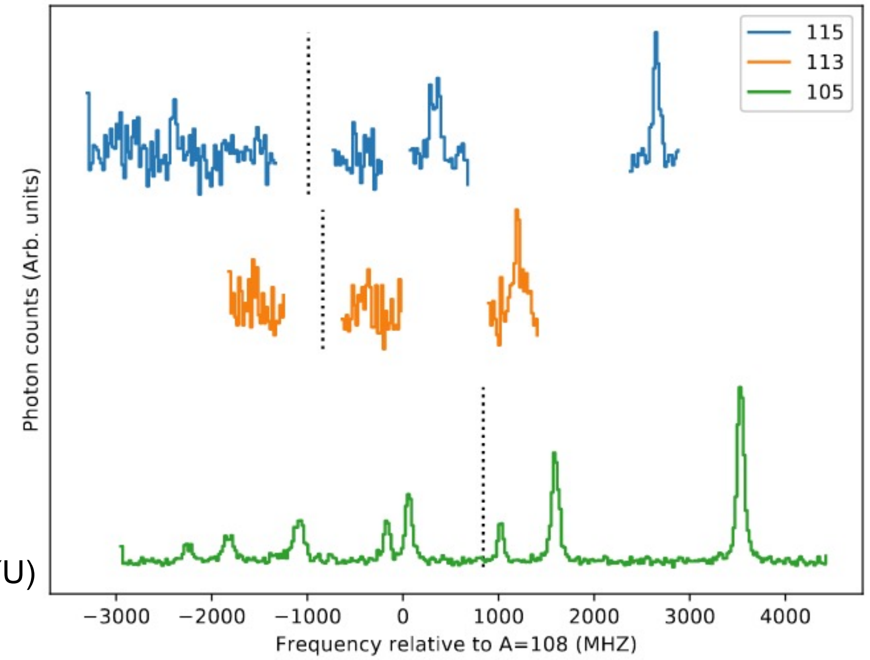
A α μ B α Q

A second parenthesis : laser spectroscopy



Laser spectroscopy of Pd isotopes

$\delta\langle r^2\rangle \propto \delta\langle \nu\rangle$



Sarina Geldhoff's PhD thesis (JYU)

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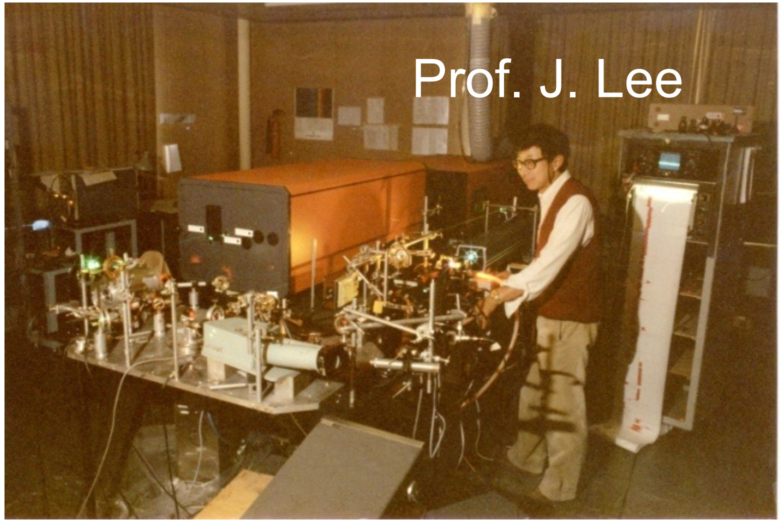
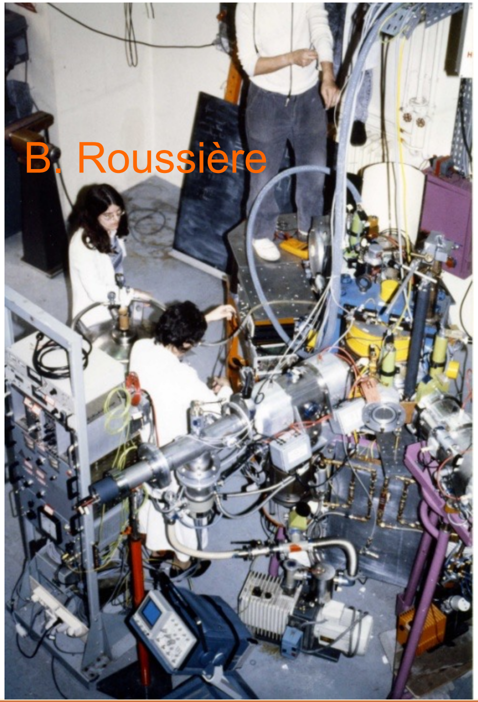
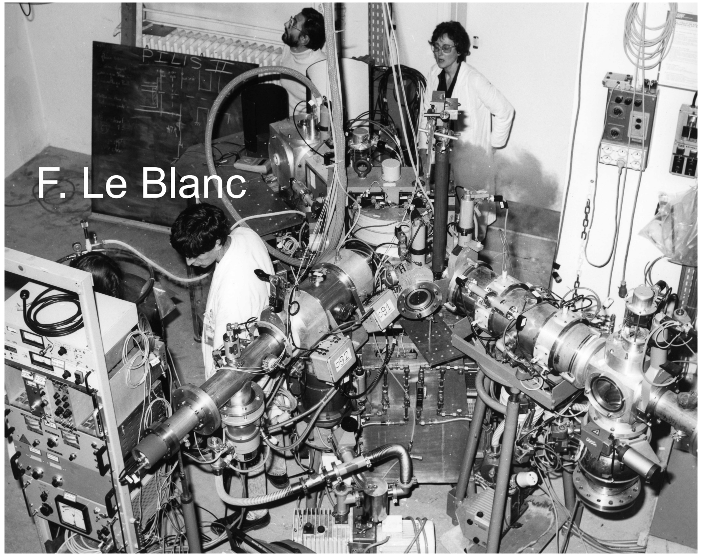




J. Sauvage



Shutdown in 1989 due to budget cut

Important results from laser spectroscopy at ISOCELE II

Experimental points are off the spherical estimation : deformation

Not pure prolate, neither pure oblate : shape transition

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 38, NUMBER 6 DECEMBER 1988

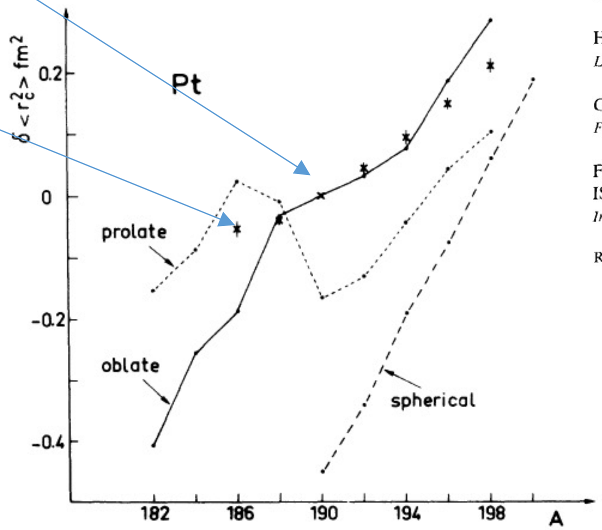
Charge-radius changes in even-A platinum nuclei

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}Pt and ^{188}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

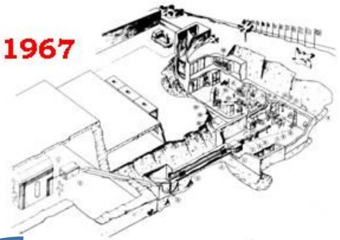
G. SAVARD, J.K.P. LEE, J.E. CRAWFORD, G. THEKKADATH
Foster Radiation Laboratory, McGill University, Montréal, Quebec, Canada H3A 2B2

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

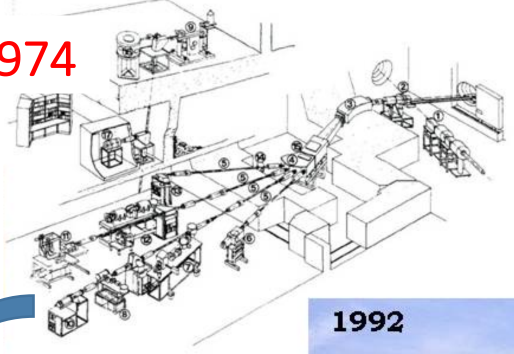
Received 27 September 1988

At the shutdown of ISOCELE II : Orsay laser spectroscopist went to ISOLDE

ISOLDE I
@ CERN SC

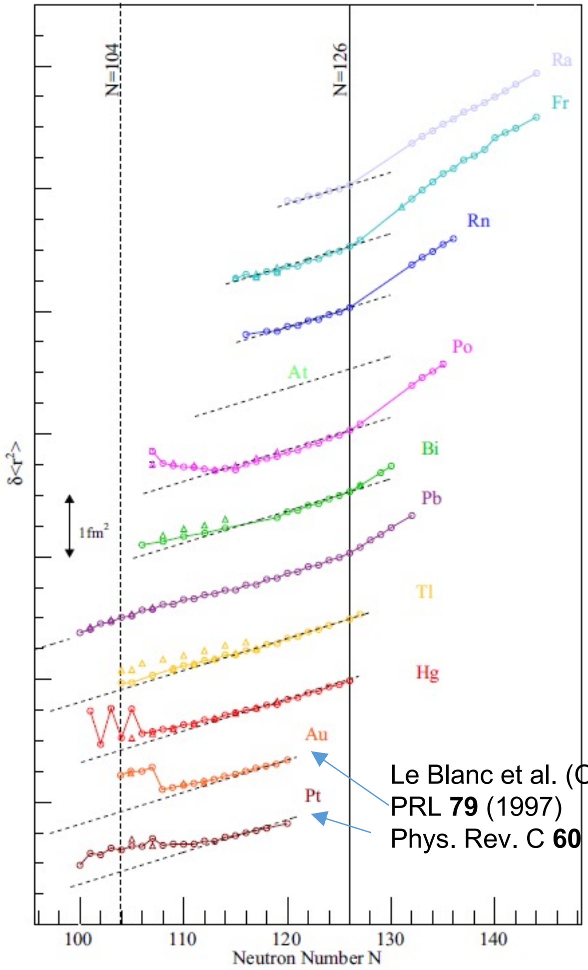


SC upgrade
I×100



ISOLDE @ CERN
BOOSTER

COllaboration for spectroscopic **M**easurements using a **P**ulsed **L**aser **I**on **S**ource

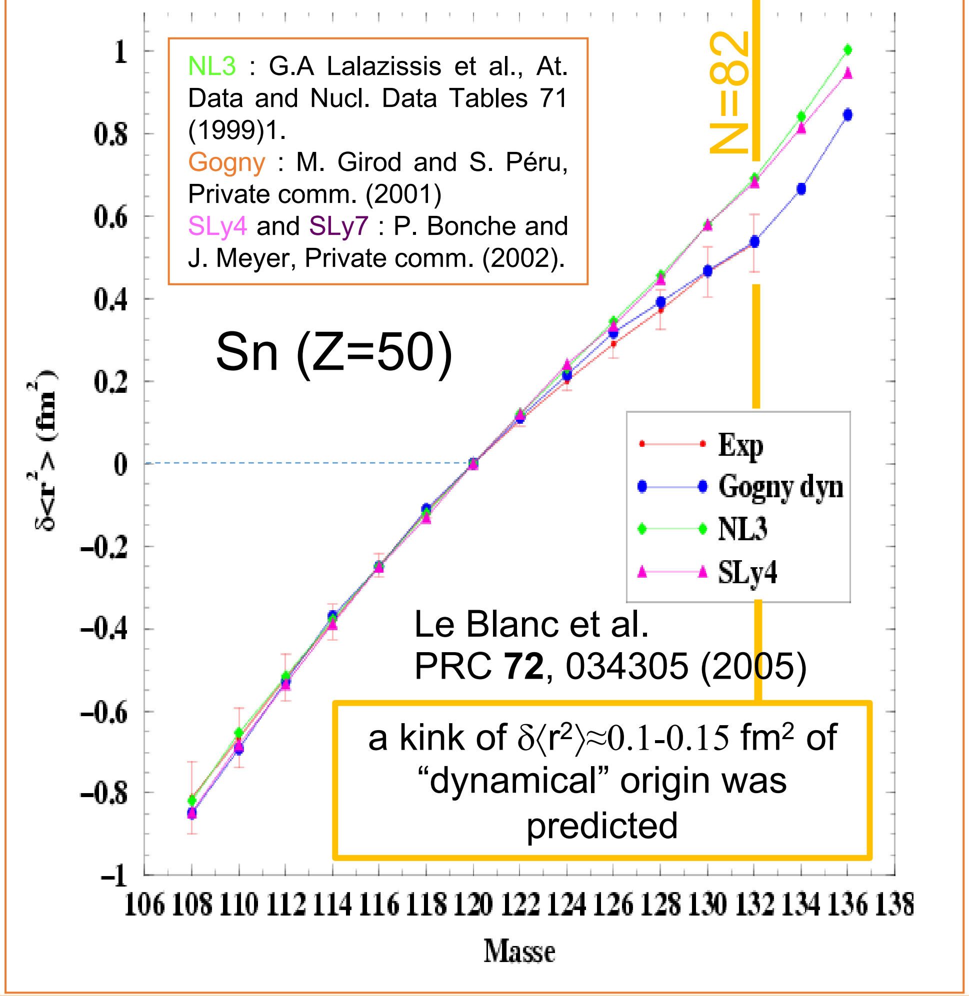


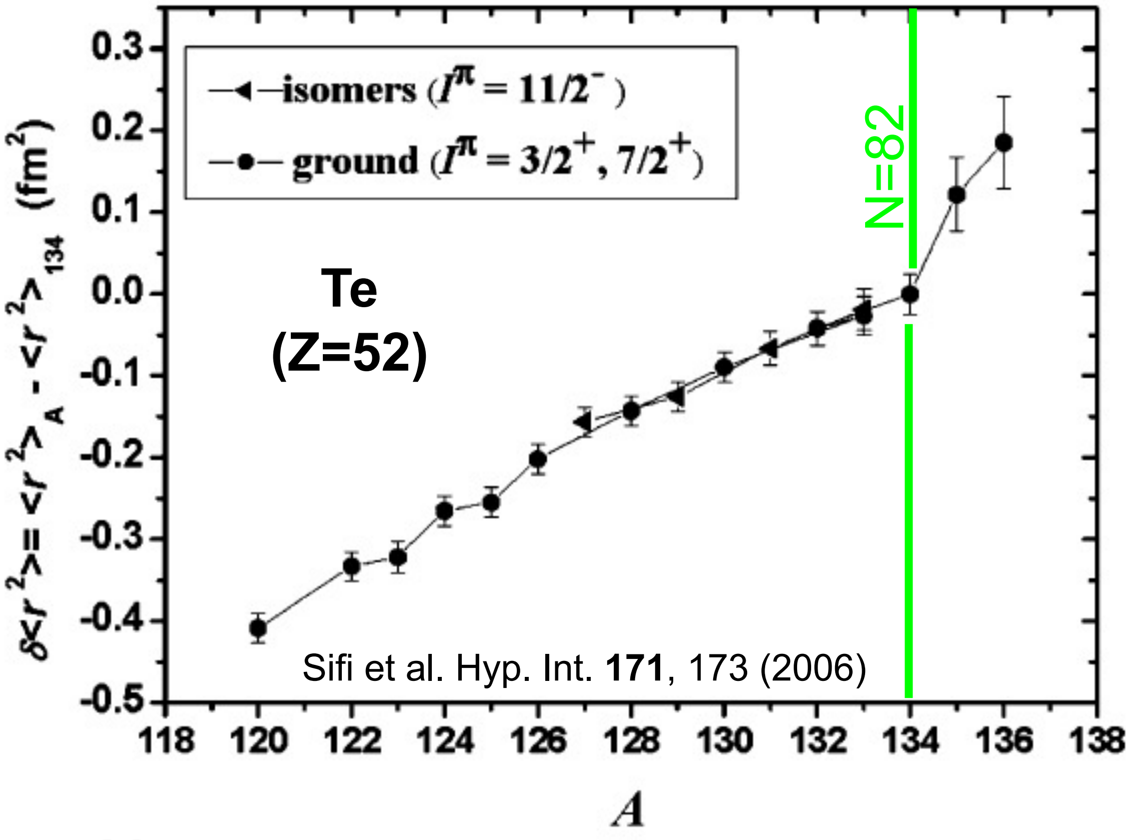
Cocolios Hyperfine Interact (2017) 238:16

Le Blanc et al. (Orsay)
PRL **79** (1997)
Phys. Rev. C **60** (1999)

Historical introduction

Another magic number inverstigated : N=82



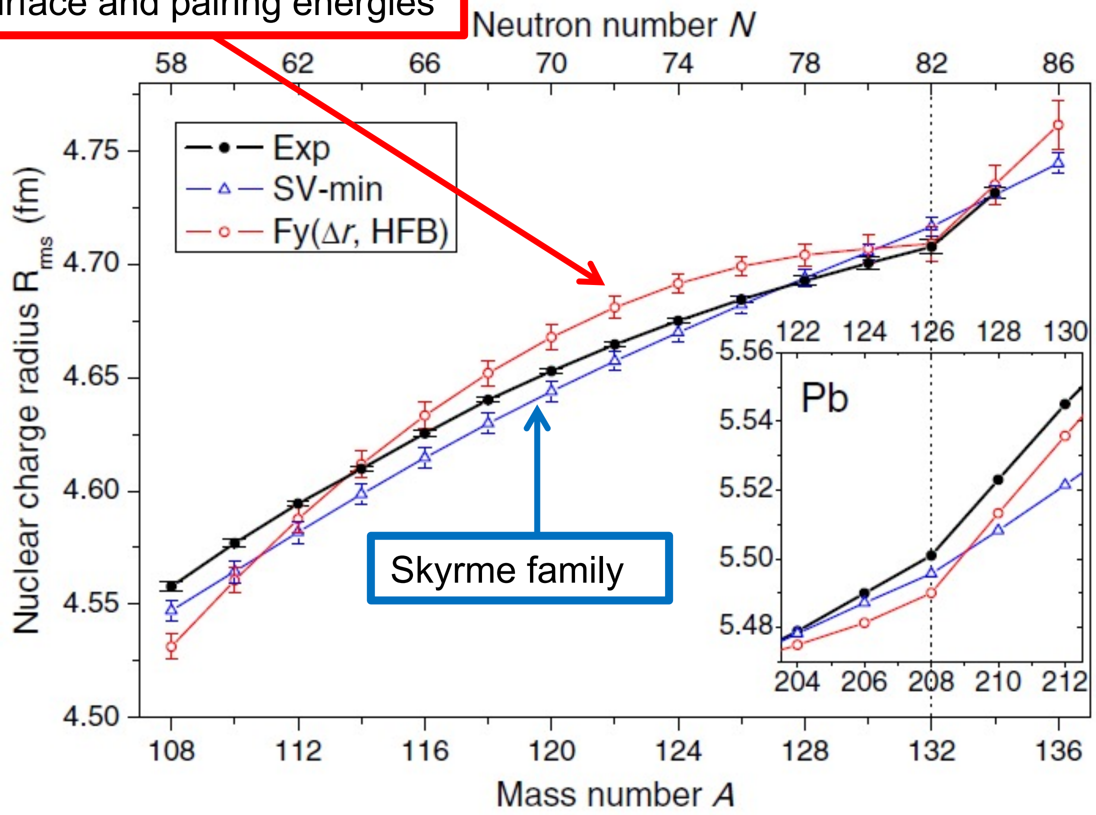


conclusion : the $\delta\langle r^2\rangle$-kink at N=82 is important

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

Fayans functional involving gradient terms in surface and pairing energies

C. Georges et al. PRL **122**, 192502 (2019)

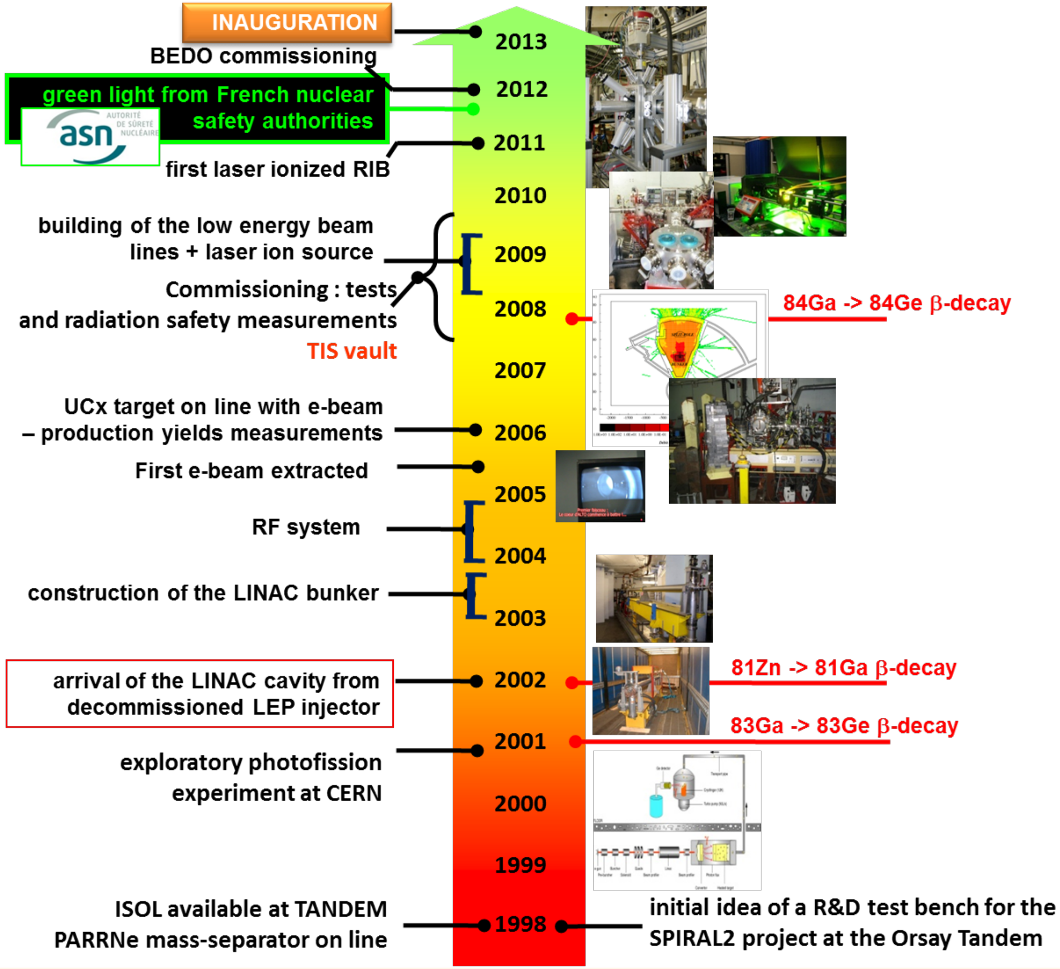


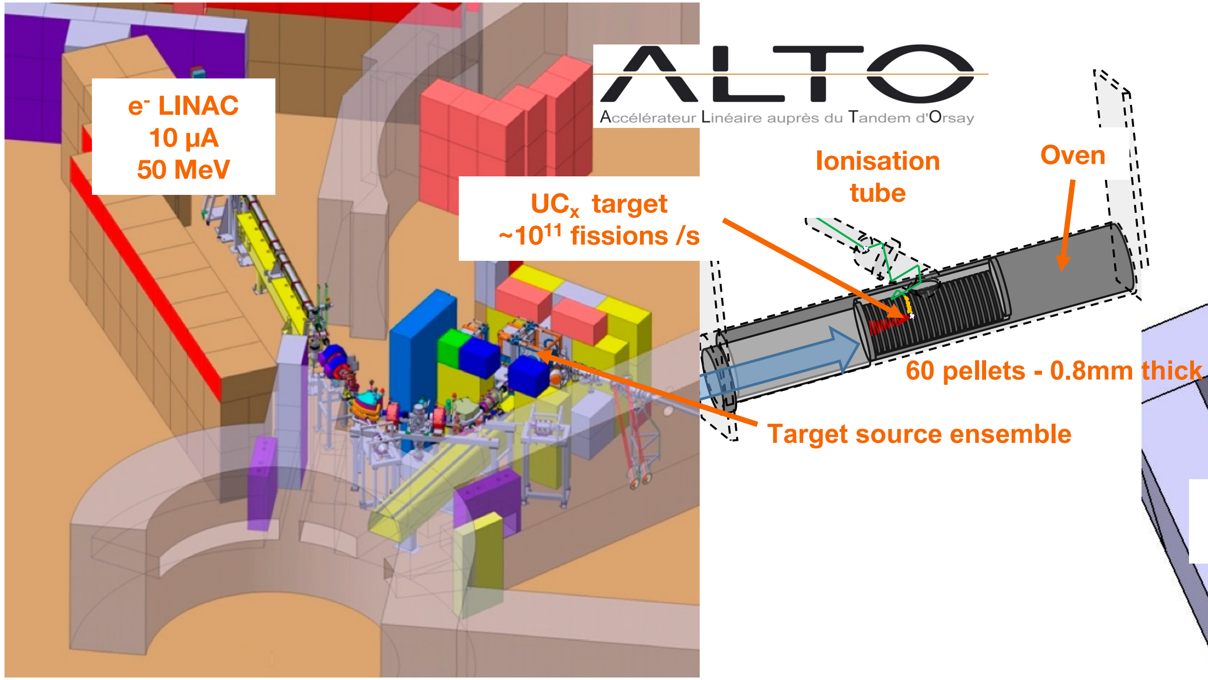
Skyrme family

a significant N=82 kink is discovered

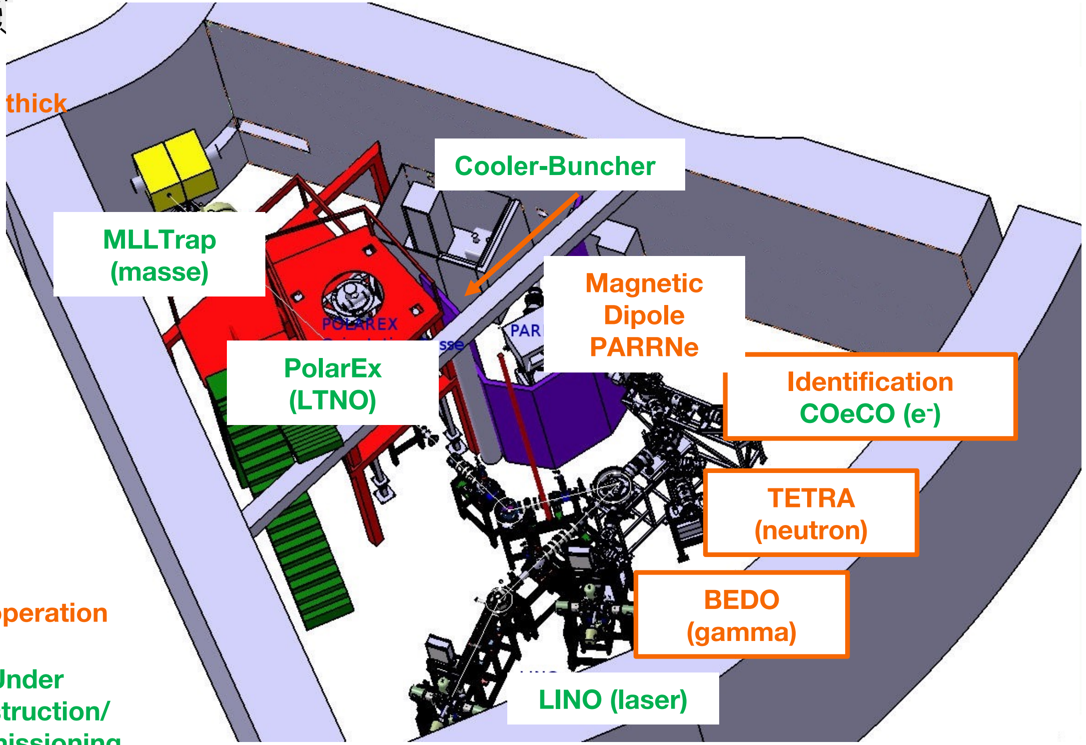
Historical introduction

ISOL technic and laser spectroscopy comeback in Orsay at ALTO





ALTO nowadays !



In operation

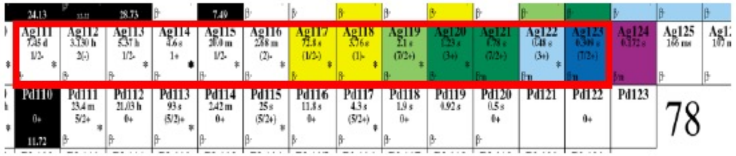
Under construction/ commissioning

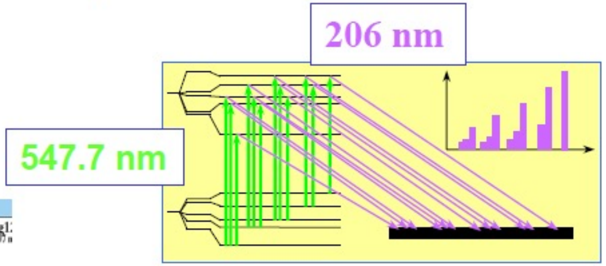
Historical introduction

First measurements at ALTO

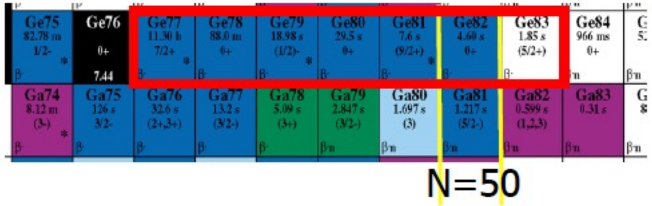
•Ag (Z=47) : from A=111 to A=123 (or further from the stability line depending on the effective productions)⇒ complete the measurements on this isotopic chain on the right side of the valley of stability

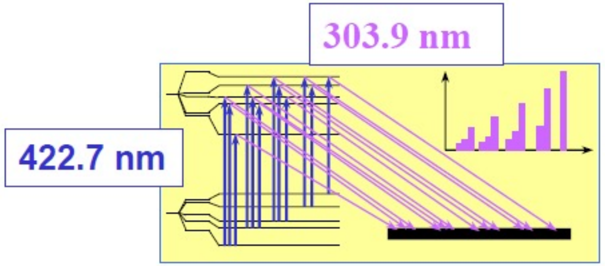
•Transition : Z.Phys. A274 (1975)79.





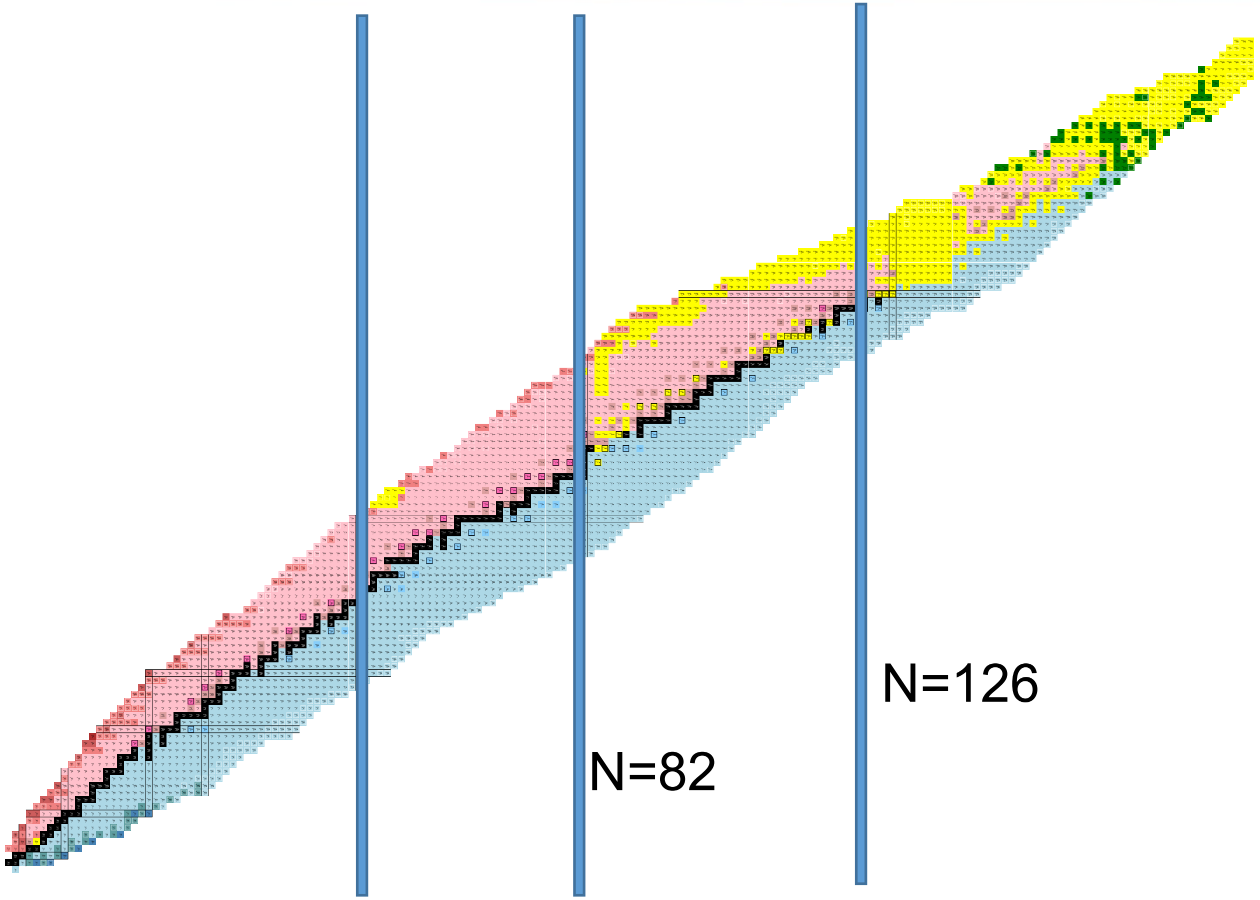
• Ge (Z=32) : from A=77 to A=83 ⇒ N=50 crossing





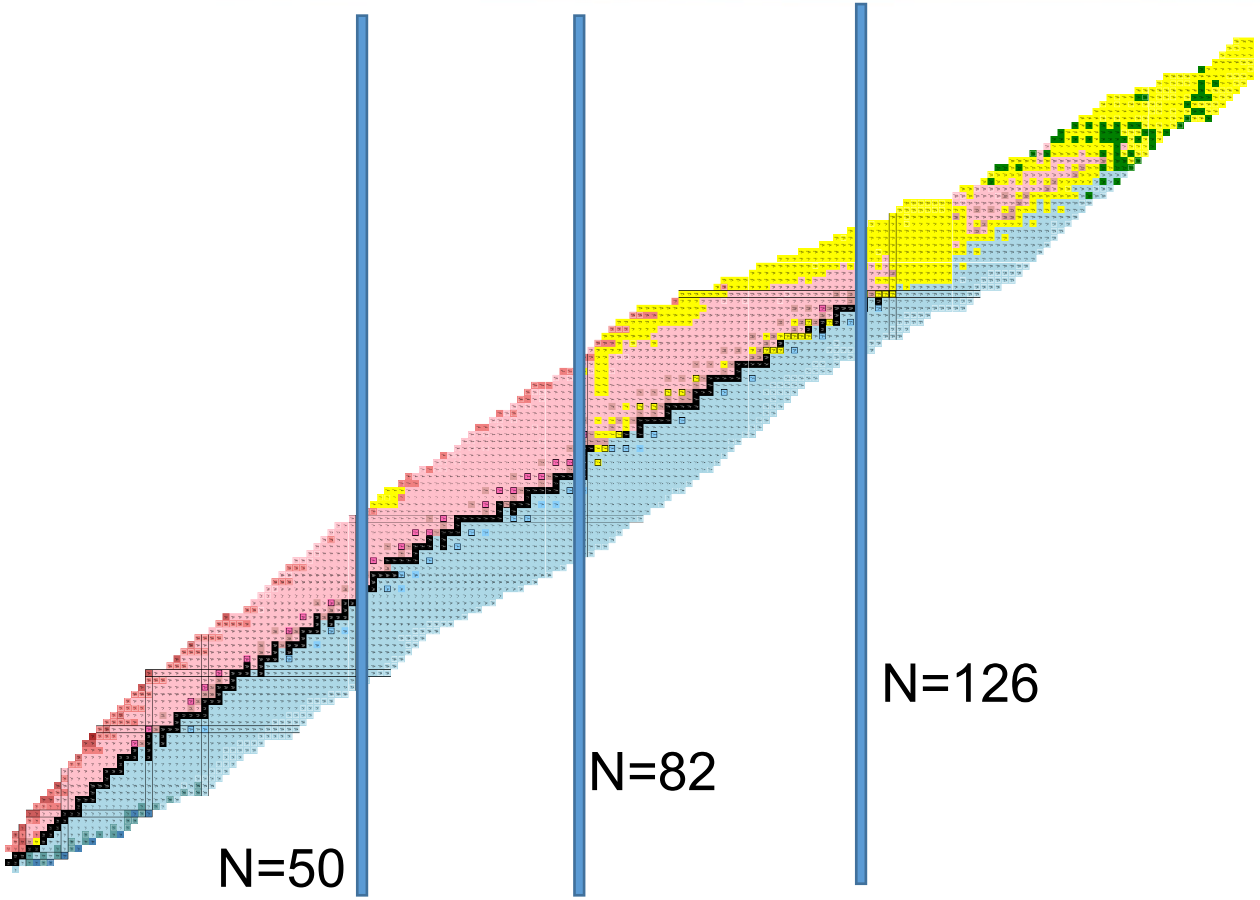
•then, les Br, As and Ga towards Ni, Sb, I, ...

A bit of « kinkology »



Kinks in charged mean square radius observed at N=82 and N=126.

A bit of « kinkology »



Kinks in charge mean square radius observed at N=82 and N=126.

What about N=50 ?

A bit of « kinkology »

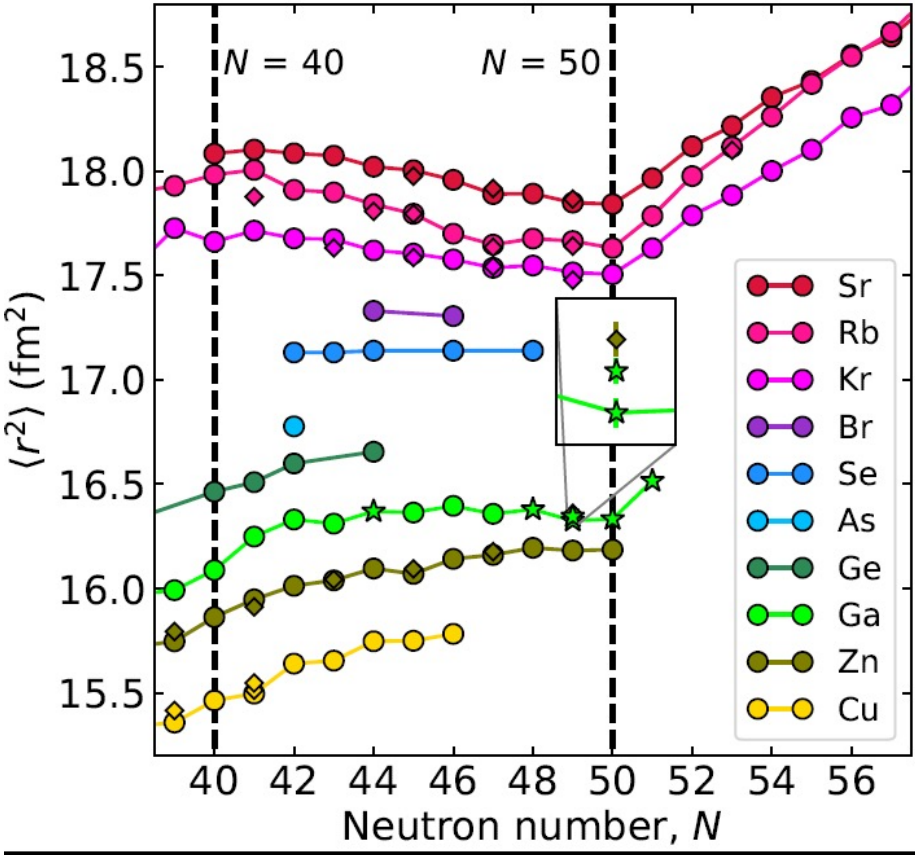
Much difficult to access region (tail of the 1st fission product peak)

A bit of « kinkology »

Much difficult-to-access region (tail of the 1st fission product peak)

Kink observed very recently (2017) in Ga isotopes

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



G. Farooq-Smith, PhD Thesis (KU Leuven)

A bit of « kinkology »

Much difficult-to-access region (tail of the 1st fission product peak)

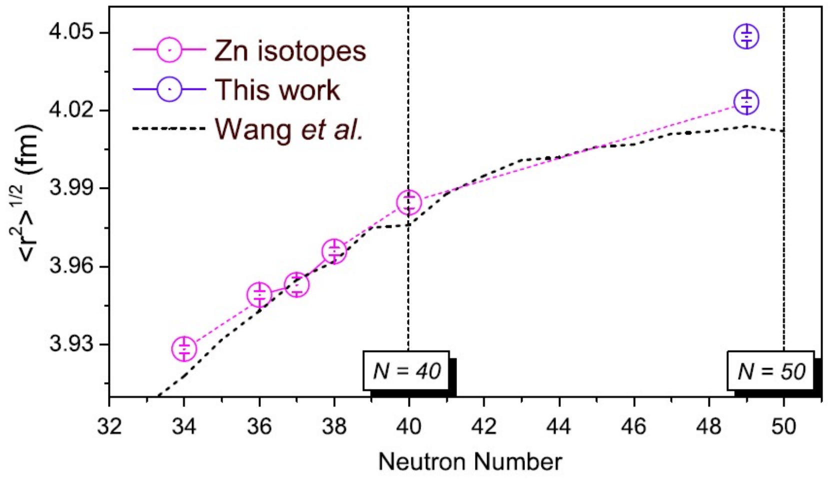
Kink observed very recently (2017) in Ga isotopes

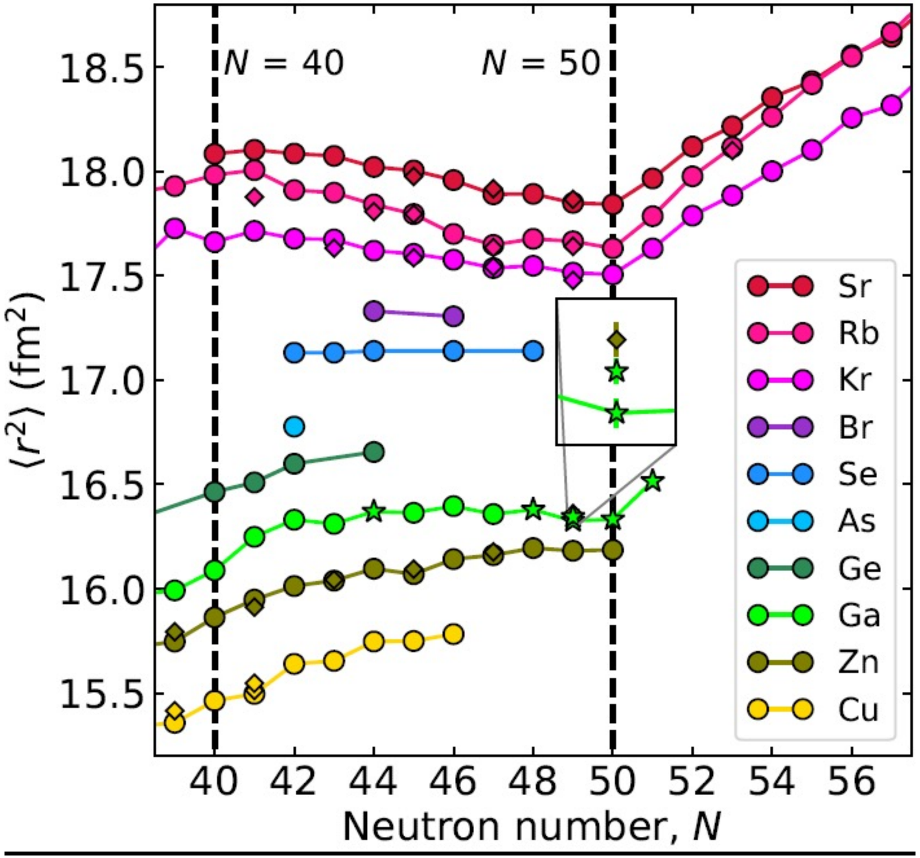
G.J. Farooq-Smith PRC 96, 044324 (2017)

Surprising very large ^{79m}Zn (larger than ^{80}Ga)

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

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





G. Farooq-Smith, PhD Thesis (KU Leuven)

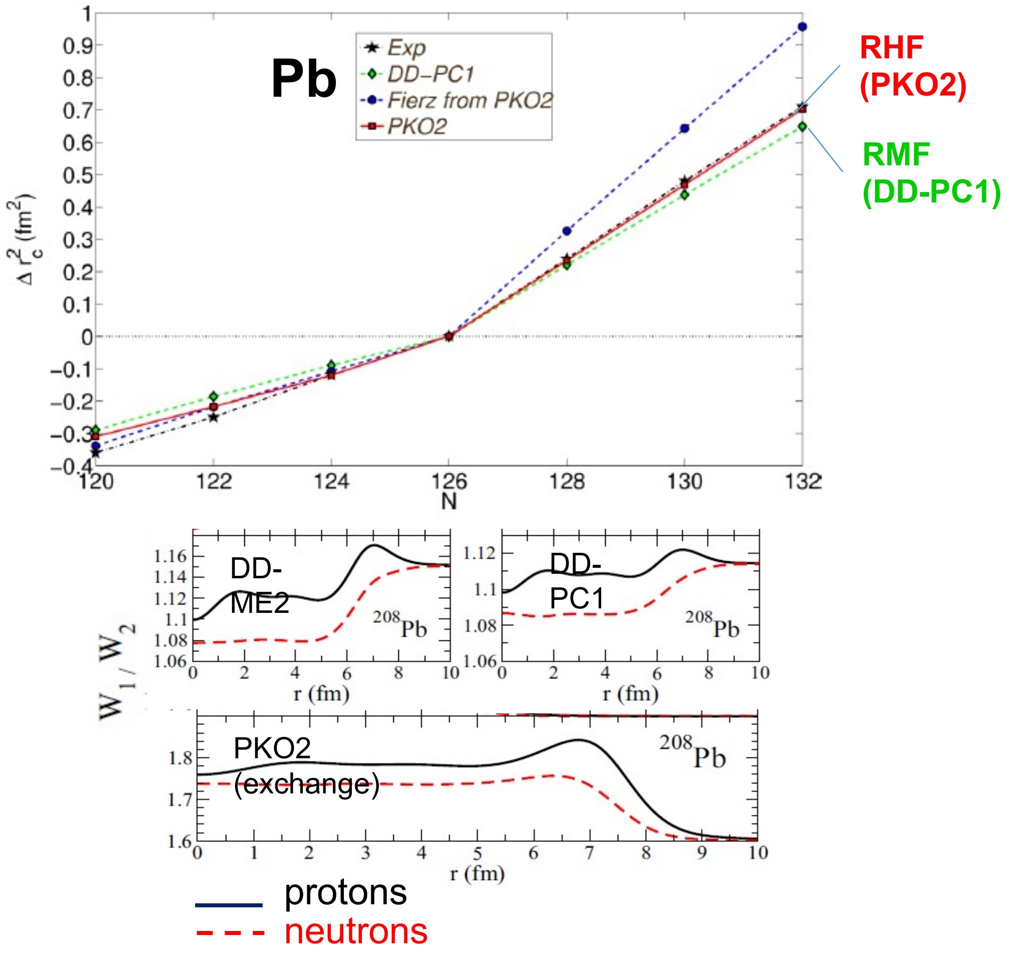
A bit of « kinkology »

Skyrme and Gogny forces do not reproduced 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)

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

$\frac{W_1}{W_2}^{(q)} (\alpha_\sigma, \alpha_\omega, \alpha_\rho)$ determines the isospin dependence of the SO potential

=2 in Skyrme parameterization

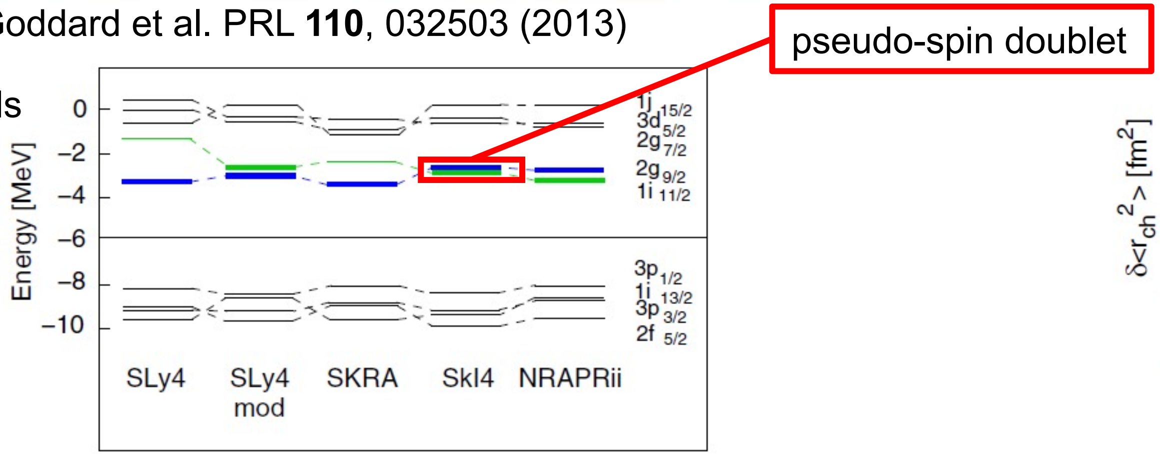


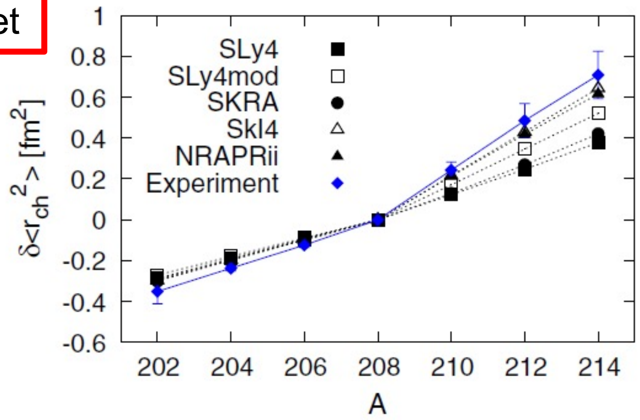
A bit of « kinkology »

N=126

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

Neutron orbitals

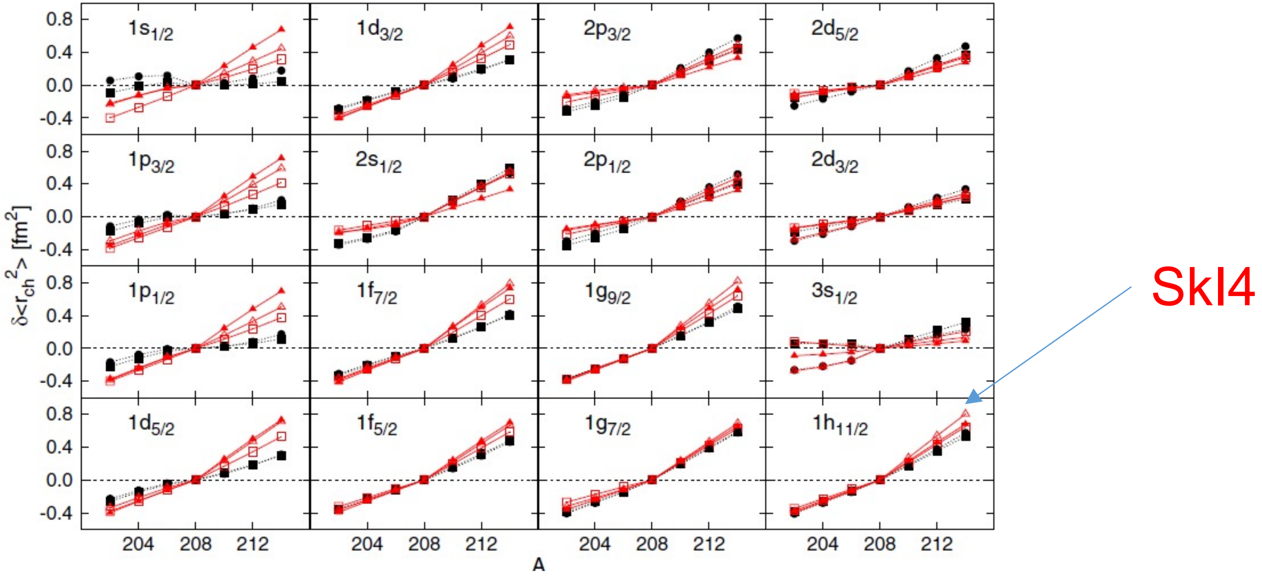




Lead isotope shift of individual proton orbitals

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

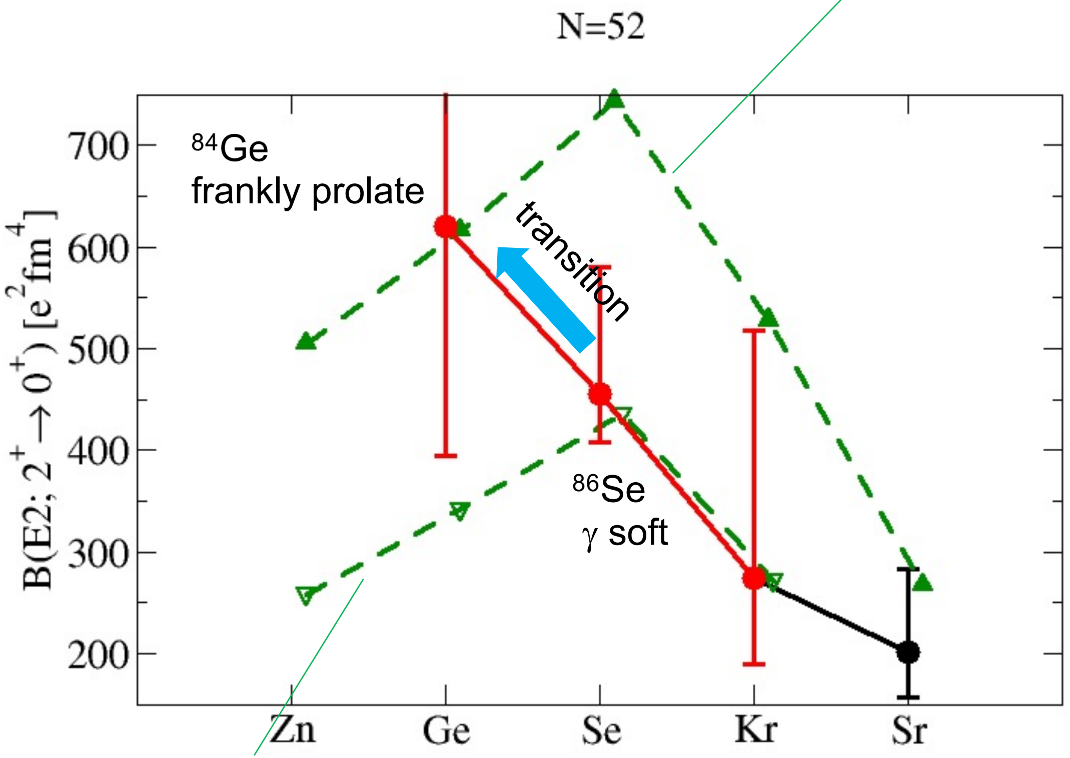
orbits with the same nodal structure (n=1) contribute in an essential way

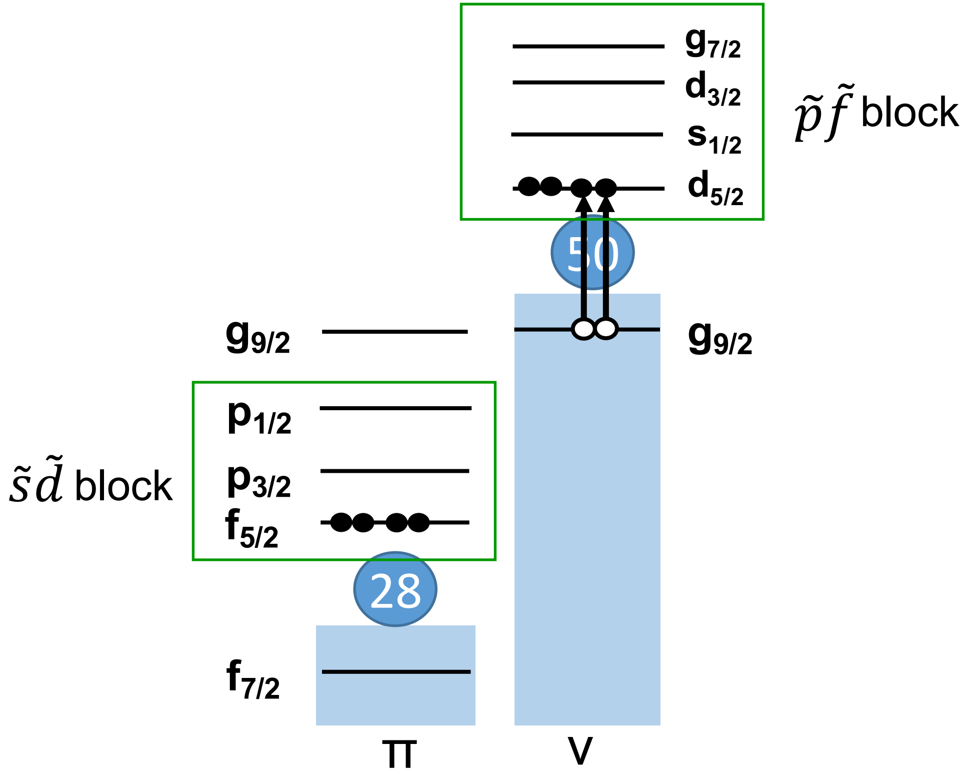


Pseudo-spin symmetry : the hidden architect of shape coexistence in the N=50 region ?

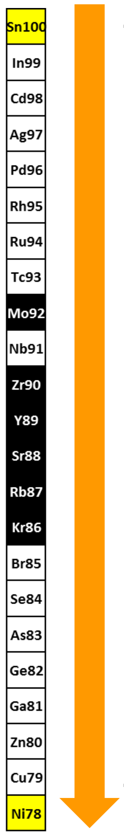
^{84}Ge 2^+ lifetime measurement :
plunger AGATA + VAMOS – Exp. E669 GANIL
C. Delafosse et al. PRL 121, 192502 (2018)

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



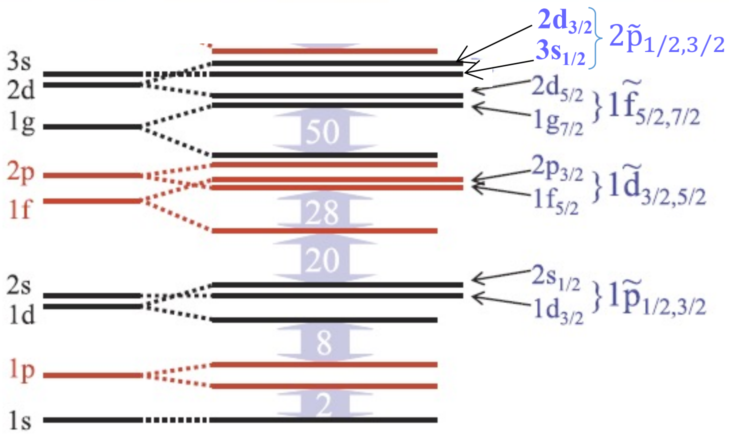
T=1/2

Σ_n ↘

R ↘

neutron diffusivity ↗

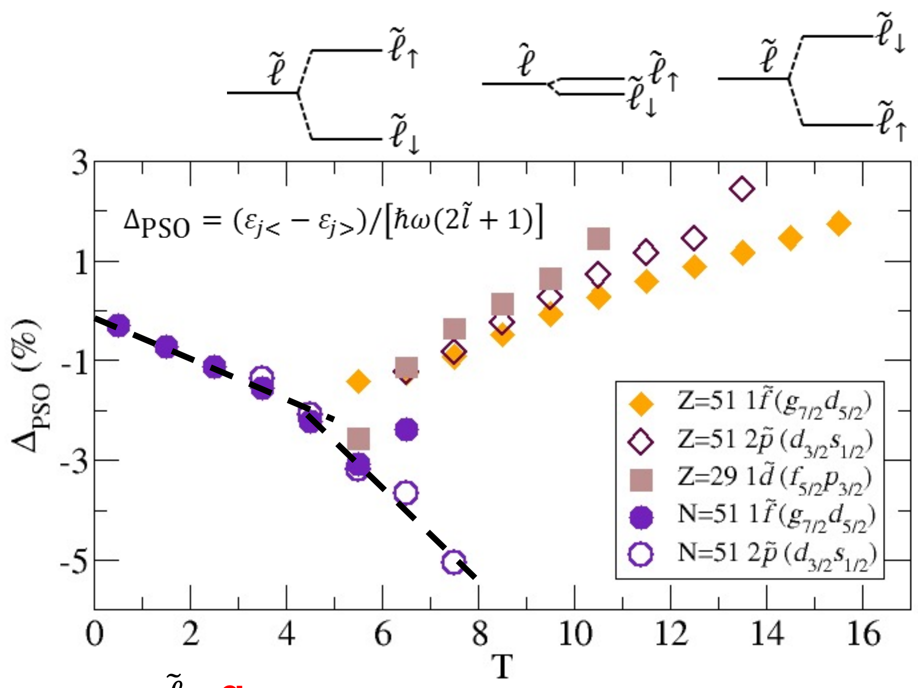
T=23/2

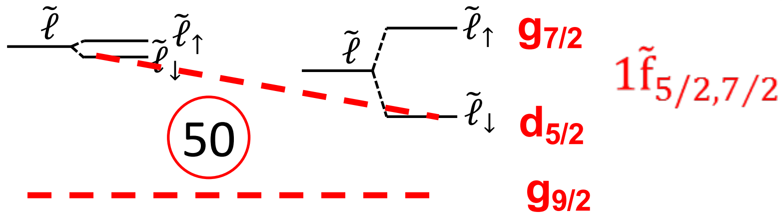


isospin dependence of the pseudospin symmetry

ρ **meson interaction**,
in neutron rich nuclei :
- repulsive for the neutrons
- attractive for the protons

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

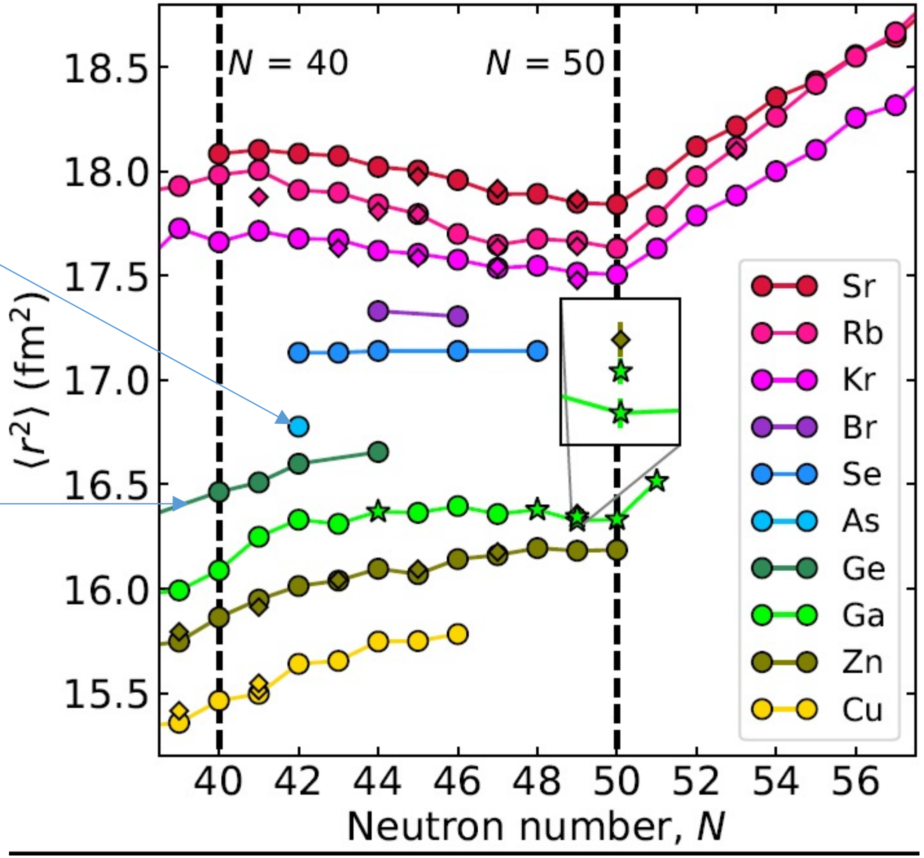




Future plans on this topic

Laser spectroscopy of neutron-rich As isotopes (IGISOL, Jyväskylä)

Laser spectroscopy of neutron-rich Ge isotopes (ALTO, Orsay)
-> Ge beams now accessible via sulfurination (GeS^+)



G. Farooq-Smith, PhD Thesis (KU Leuven)

Other electromagnetic probes

- ion manipulation with EM fields: mass measurements
- interaction with the hyperfine field : laser spectroscopy, nuclear orientation $\rightarrow$ $I^{(\pi)}$, μ, Q_s, $\delta\langle r^2_c\rangle$
- γ-spectroscopy : lifetimes, $B(E\lambda)$, $B(M\lambda)$

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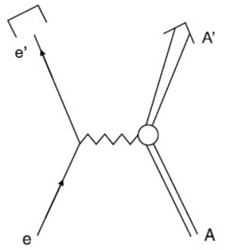
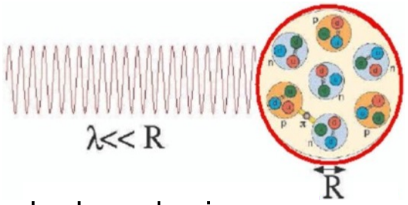
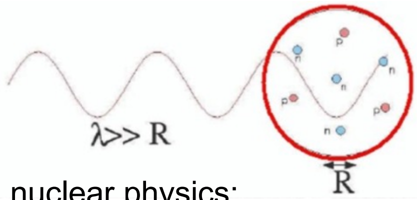
Theoritical interpretations gives a critical role to density distribution of nuclear matter : we have to dive inside the nucleus : e^- scattering





hadron physics:
structure of the nucleon



nuclear physics:
internal structure of the nucleus
E_e= 500 MeV → ≈0.5 fm scale

e momentum transfer q ≈ $1/\lambda$

A(e,e) elastic cross section

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

point charge nucleus

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

form factor

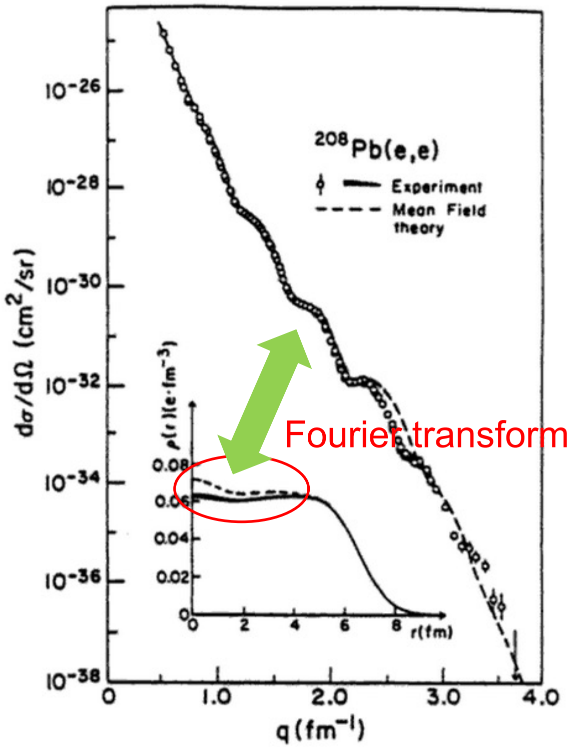
Fourier transform

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

charge distribution
"model independent"

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

The e-probe revolution



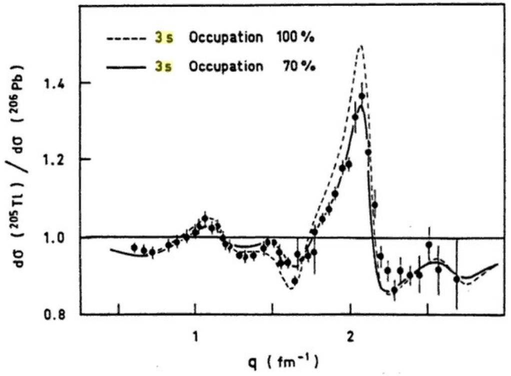
12 orders of magnitude !

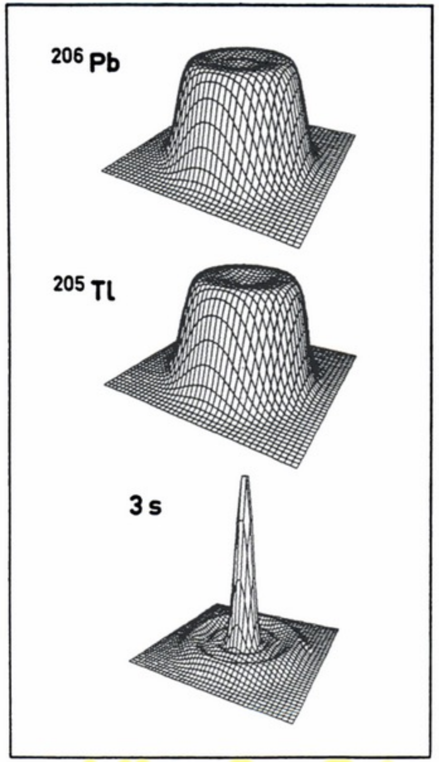
B. Frois and Papanicolas
Ann. Rev. Nucl. Part. Sci 37 (1987)

Dechargé and Gogny
PRC 81 (1980)

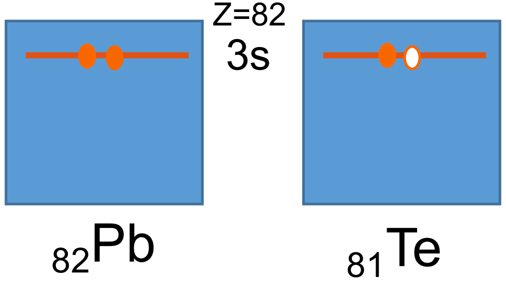
Cavedon, Frois, Goutte et al.
PRL 49 (1982)

etc…





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



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

→ $\delta\langle r^2_c\rangle$ kinks, neutron skin and giant haloes formation ?
→ shell evolution ?

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

recoil factor

longitudinal form factor

transverse form factor

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

charge transition density

$$J_{\lambda\lambda'}(r) = \frac{i}{c} \int \langle \psi_f \| \mathbf{J}_{op}(\mathbf{r}) \cdot \mathbf{Y}_{\lambda\lambda' 1}(\hat{\mathbf{r}}) \| \psi_i \rangle \, d\hat{r}$$

current transition density

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

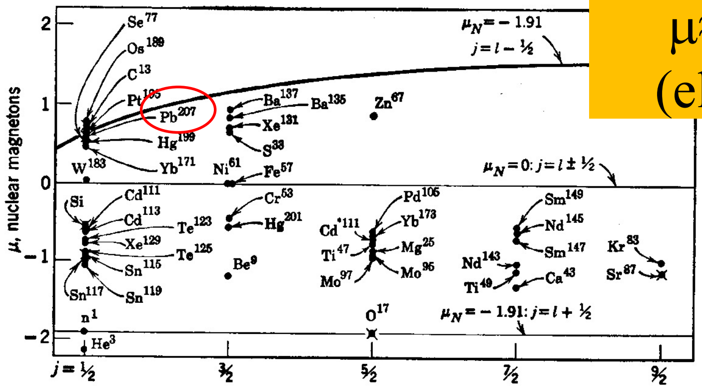
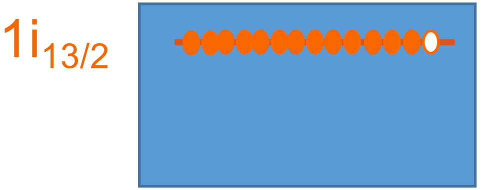


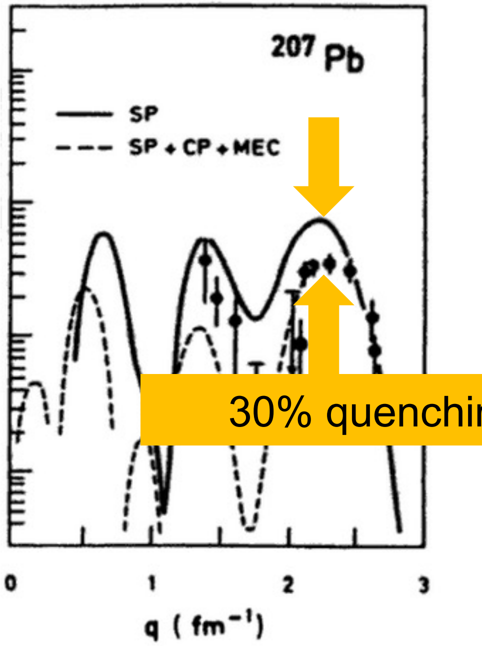
Fig. I.5. Magnetic moments of nuclei with odd N plotted against the spin.

$\mu \approx F_M$ for $q \to 0$ (elastic at 180°)

N=126



$^{207}Pb_{125}$



30% quenchi

Next step : e-scattering on radioactive nuclei : a vast program

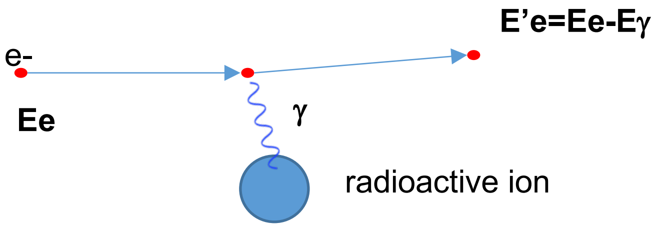
- radius, diffusivity

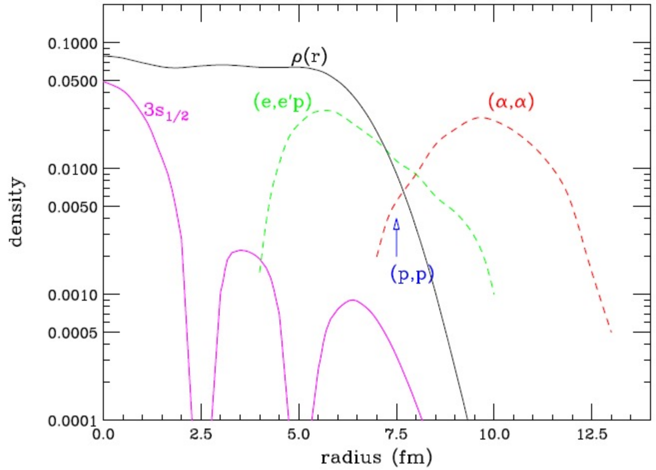
- perfect coulomb excitation : forward electron scattering (no multi-step process)

- “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)



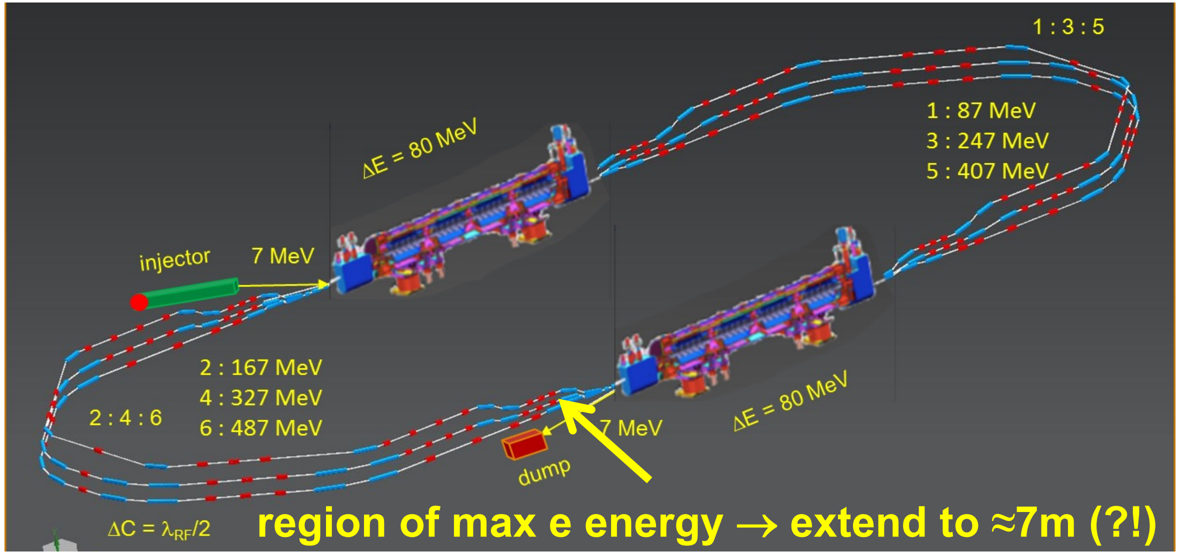


The possible physics program spans exactly the physics interests of the vast majority of the low-energy nuclear physics community in Orsay-Saclay and in France (and elsewhere)

… **with a much more powerful probe**!

The DESTIN project

injection of ALTO-like RIBS into the ERL



More detail about ERL : see W. Kaabi's presentation

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

Largely inspired by the pioneering SCRIT example

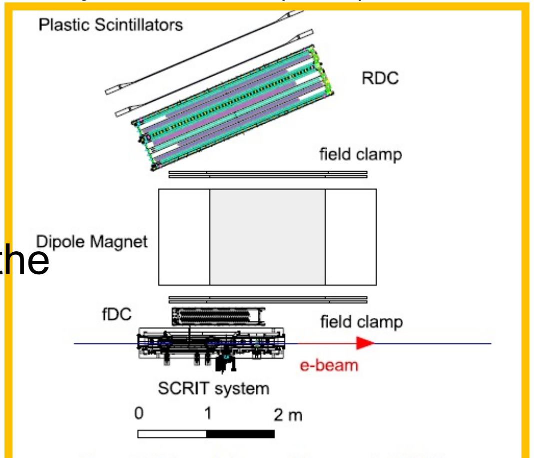
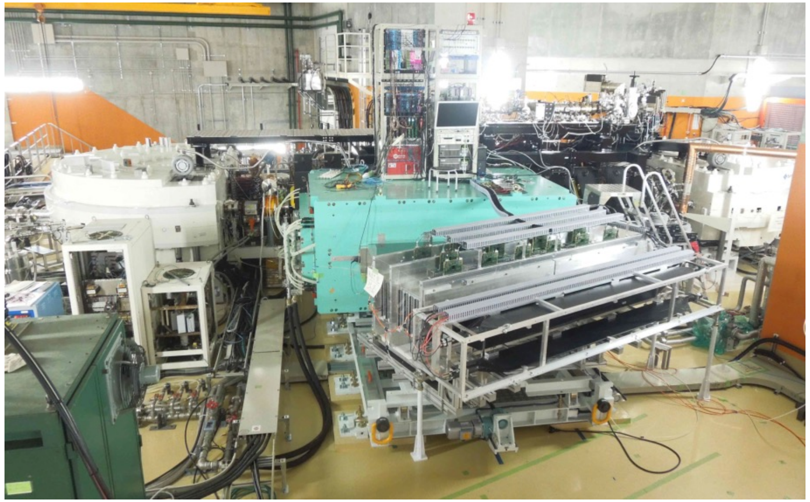


Figure 2. Schematic layout of detectors in WiSES.



The DESTIN project

- 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 $\boldsymbol{E_e \simeq 500}$ **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} cm^{-2}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 [cm^{-2}s^{-1}]
Elastic scattering at small q	r.m.s. charge radii	Light	10^{24}
First minimum in elastic form factor	Density distribution with 2 parameters	Light Medium Heavy	10^{28} 10^{26} 10^{24}
Second minimum in elastic form factor	Density distribution with 3 parameters	Medium Heavy	10^{29} 10^{26}
Pygmy/Giant resonances	Position, width, strength, decays	Medium Heavy	10^{28} 10^{28}
Quasi-elastic scattering	SF, spectral strength	Light	10^{29}

- **strategy: fixed target $\rightarrow$ trapped RI population 10^6-10^8**

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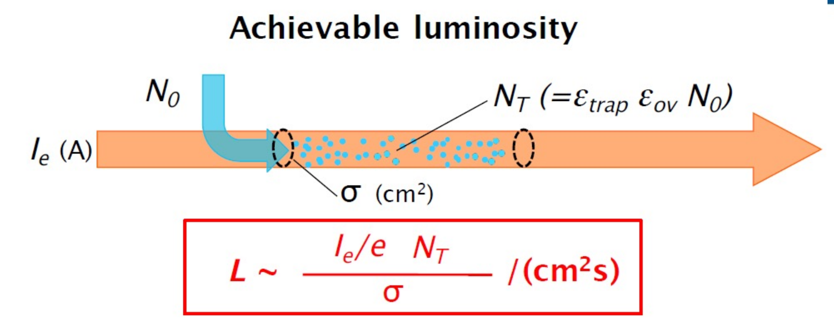
The DESTIN project

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

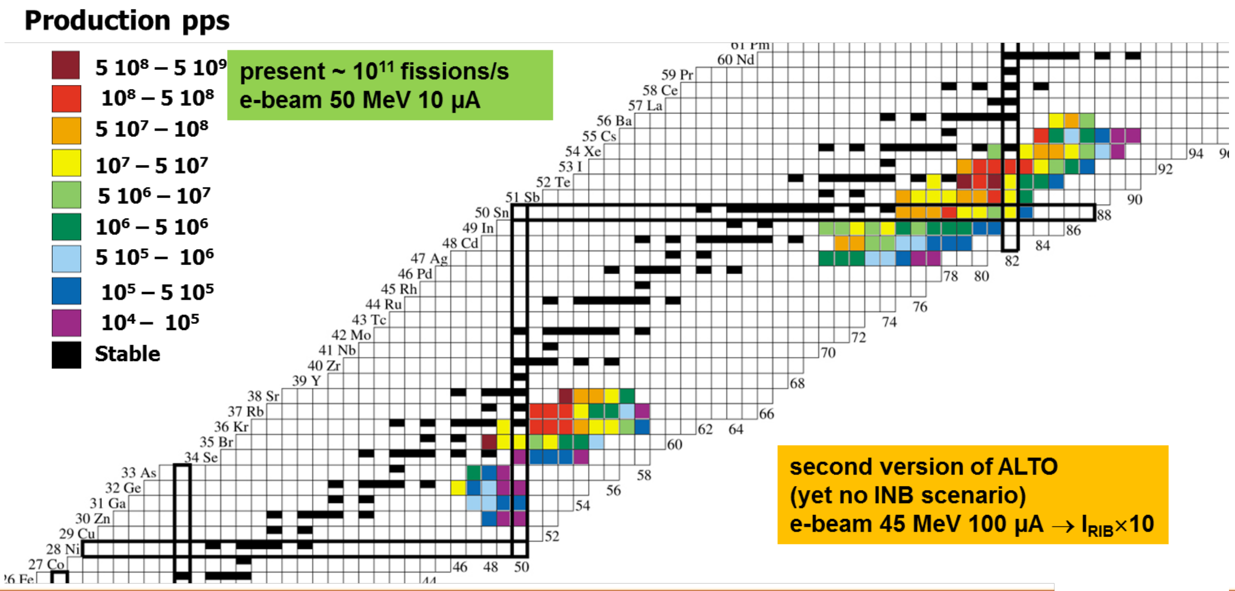
I_e=200 mA N_A=10^6 trapped ions: $\mathcal{L} \simeq 10^{29}$ should be achieved

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**

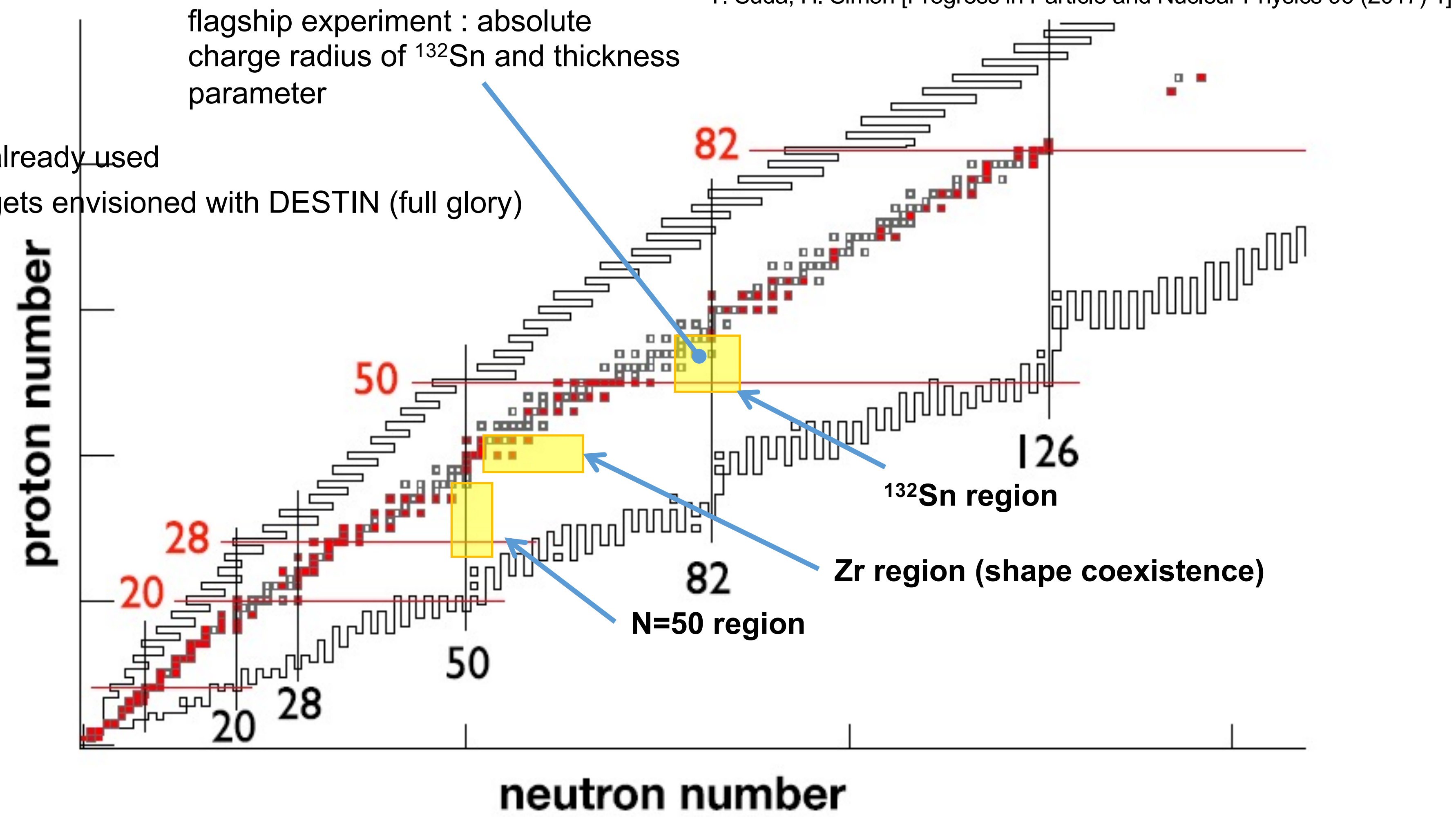
but the dynamical e-beam-RI coupling should be investigated : first time with a ERL time structure
e-beam instabilities ? impact on ERL operation ?



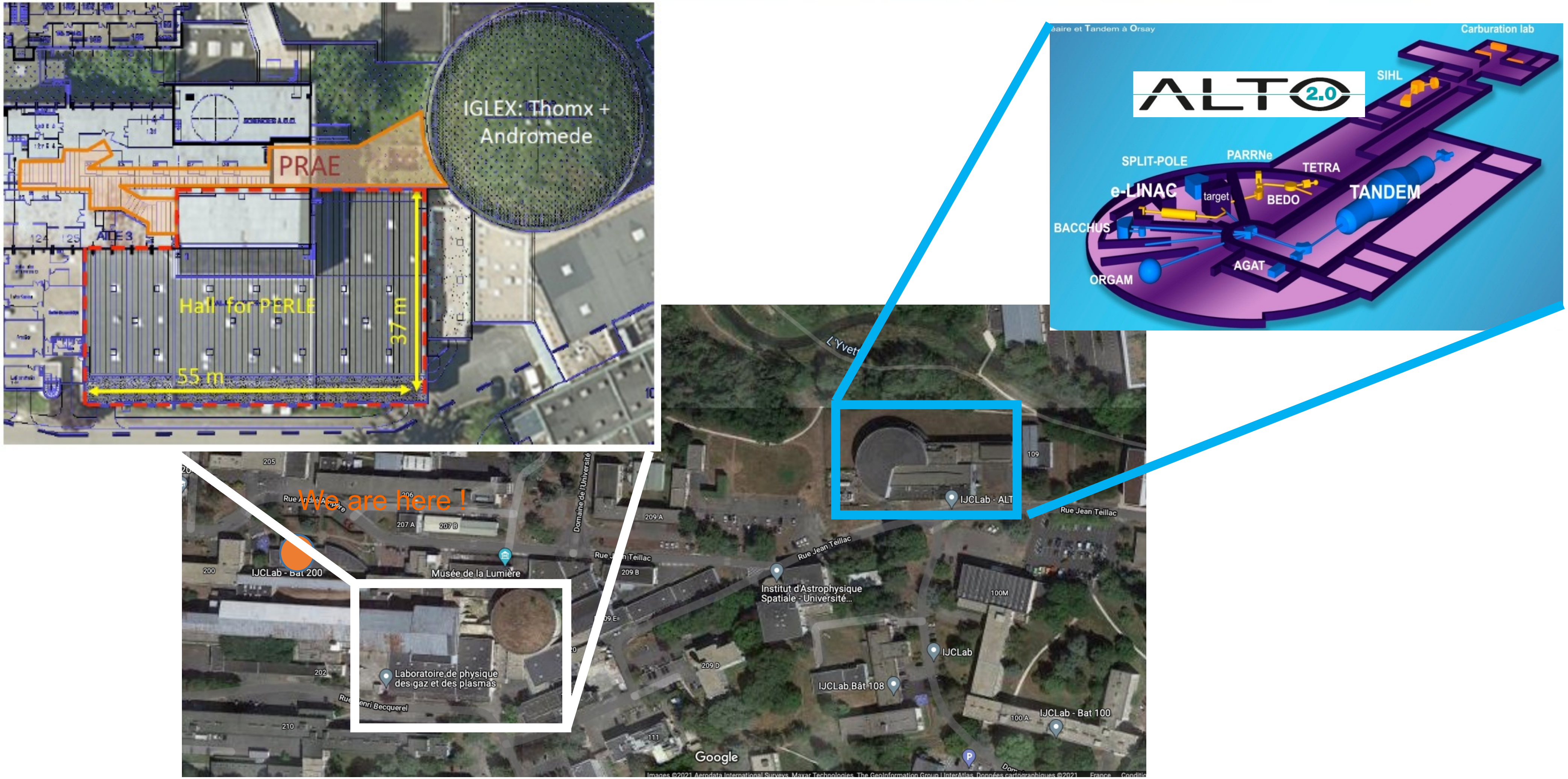
The DESTIN project

T. Suda, H. Simon [Progress in Particle and Nuclear Physics 96 (2017) 1]

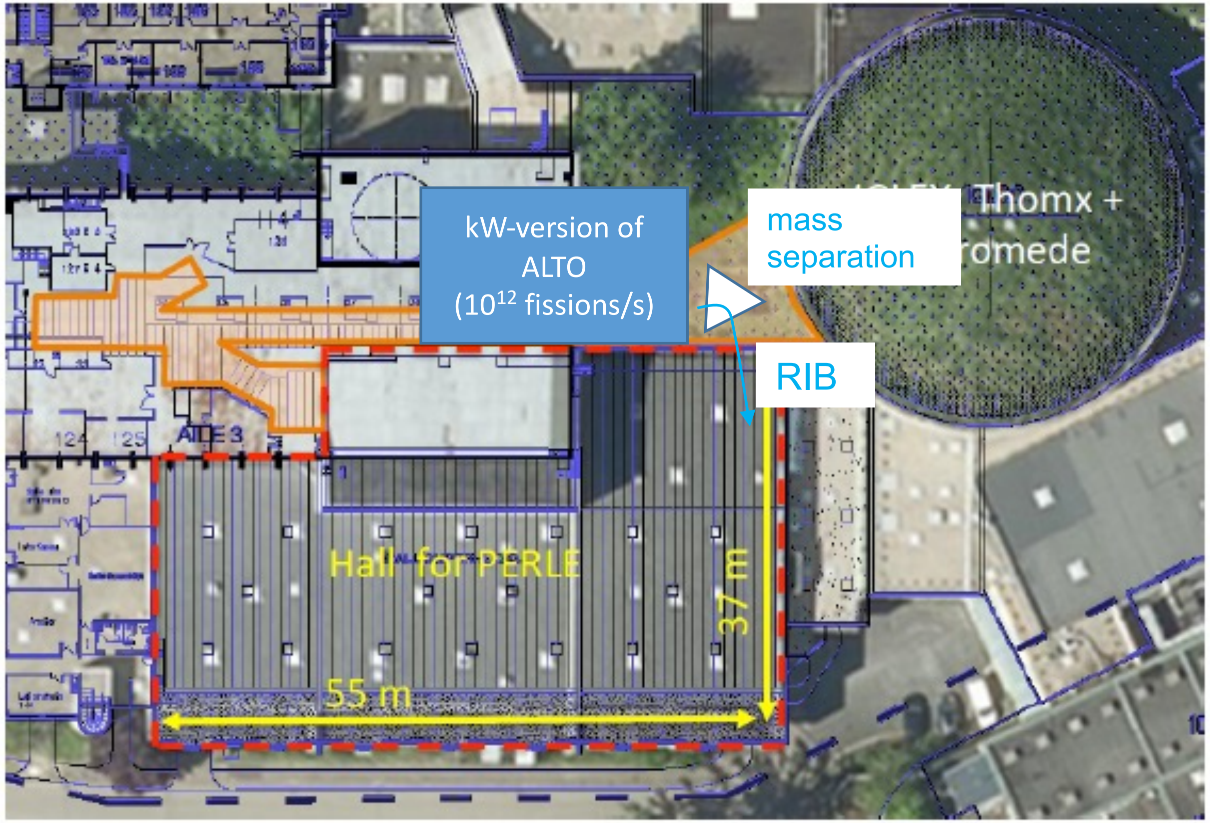
- stable targets already used
- radioactive targets envisioned with DESTIN (full glory)

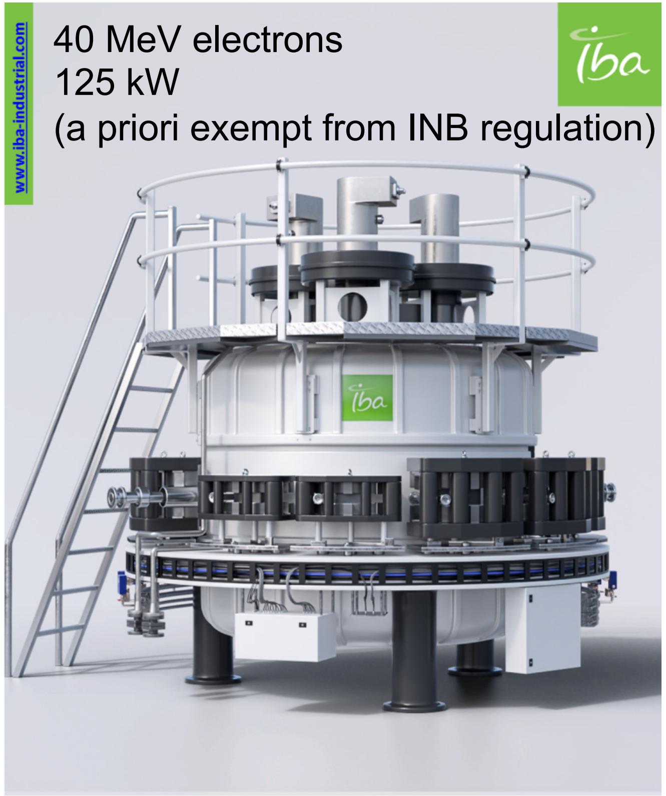


The DESTIN project



The DESTIN project





Rhodotron® TT300-HE
High Energy Electron Generator

Conclusion

- EM probes associated to ISOL low energy beams are powerful tools to study nuclear structure;
- We (IJCLab nuclear physicist) have build and maintain an expertise on both ISOL production and laser spectroscopy for almost 50 years;
- The adventure continues with the study of the neutron-rich N=50 region via laser spectroscopy;
- The ^{132}Sn region can and must be studied using e- scattering for better understanding of correlation between radius and binding energy of nuclei.