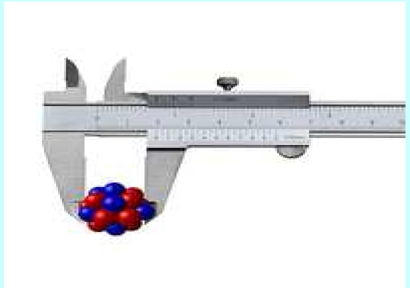
LEES 2024
28 Oct. -1 Nov.
Sendai

Low-Energy Electron Scattering for Nucleon and Exotic Nuclei

Tohoku University
東北大学知の館

New structure observables in a future GANIL facility for electron-radioactive ion scattering

Context of the RIB physics & physics questions
The (femto)scopes of the experimental program
→ SCRIT-inspired project ←
Physics cases & Beams
Spirit of the project ←→ Nuclear density observables



Valérie Lapoux CEA Saclay
On behalf of the e-RIB group (CEA, GANIL, LPC Caen, IJCLab)
Pierre Delahaye (GANIL), Vittorio Somà (CEA), *et al.*
→ *Fruitful discussions with the SCRIT-Riken-Tohoku group*

cea irfu

Nuclear physics at the extremes

High Tz, high I, high Ex, high Z

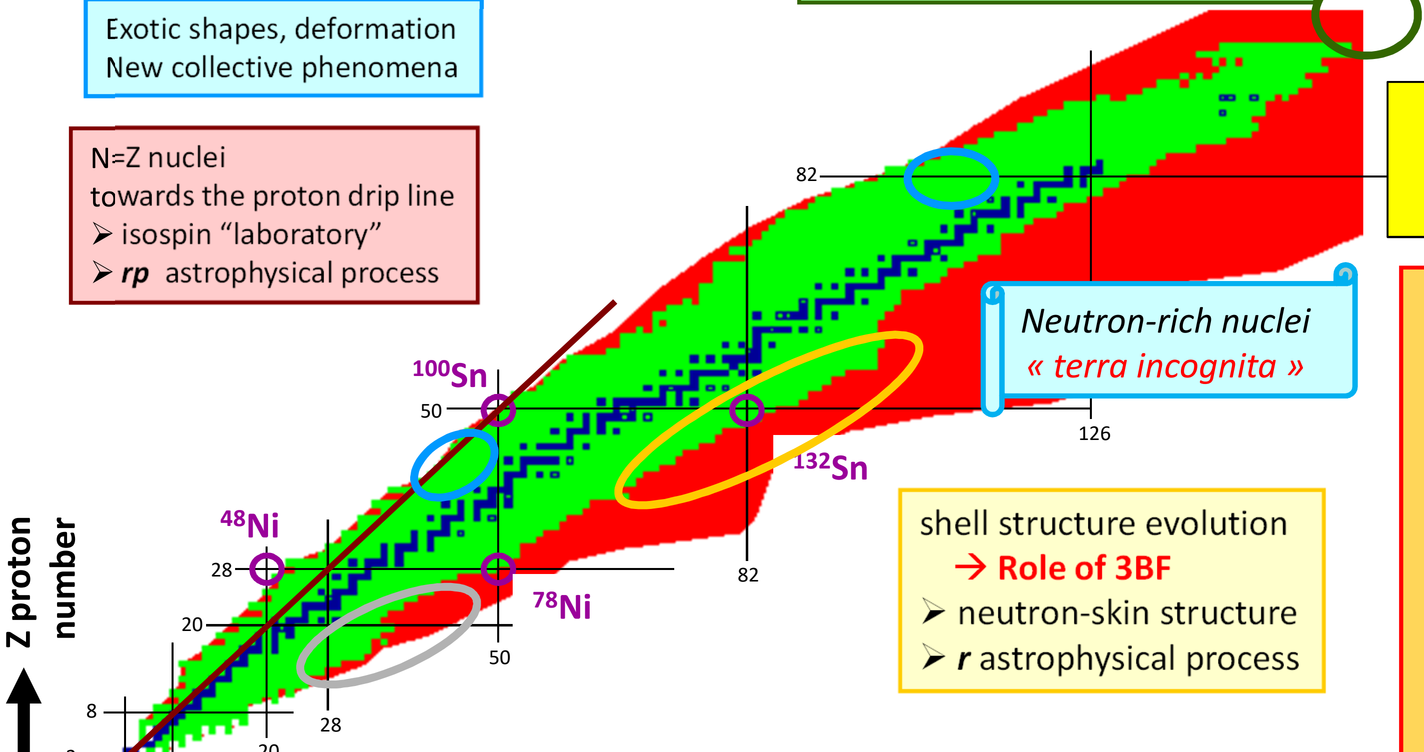
From the 1980s to 2010, article introduction:
« with the advent of the RIBs… »

Exotic shapes, deformation
New collective phenomena

Exotic nuclei → Testing ground for theories
From stable to weakly-bound at large asymmetry (N-Z)/A
→ constraints on the nuclear models

Neutron-rich superheavy nuclei
→ Towards a new island of stability?
→ Spectroscopy towards Z=108

N=Z nuclei
towards the proton drip line
- isospin "laboratory"
- ***rp*** astrophysical process

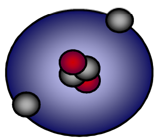


How can we improve our knowledge on nuclear interactions ?

Neutron-rich nuclei
« terra incognita »

shell structure evolution
→ **Role of 3BF**
- neutron-skin structure
- ***r*** astrophysical process

+ Extension of the neutron dripline
Up to ^{24}O
[^{31}F] *(Sakurai, PLB 1999)*
RIKEN / MSU
Up to ^{34}Ne *(Ahn PRL 2019)* **[^{37}Na]**
+ New isotopes at RIBF
+ Shell effects at doubly magic exotic nuclei
N = 50 ^{78}Ni *Nature 2019*
Beyond dripline N=20
^{28}O *Nature 2023*



Weakly-bound nuclei towards the neutron drip-line, up to Z ≈ 25
Halo phenomena

Relevant observables & probes?

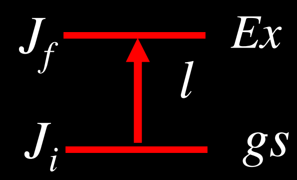
Interaction field between nucleus and particle probes

Transition multipole matrix element M

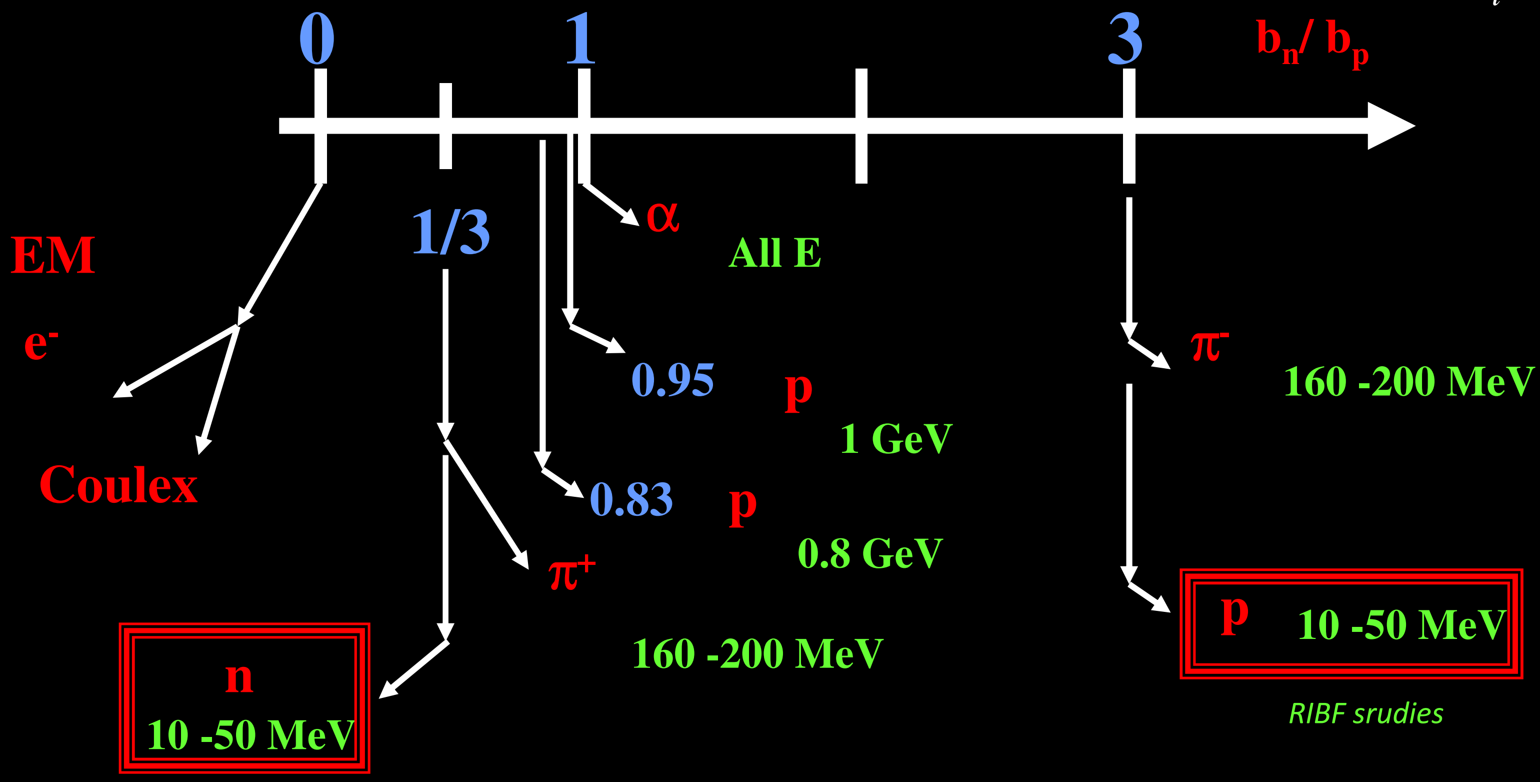
$$M = b_n M_n + b_p M_p$$

$b_{n,p}$ interaction strengths between the external field and n,p of the nucleus*

* bn/bp : A. Bernstein, V. Brown and V. Madsen, PLB 103, 255 (1981)



Phenomenological overview



RIBF srudies

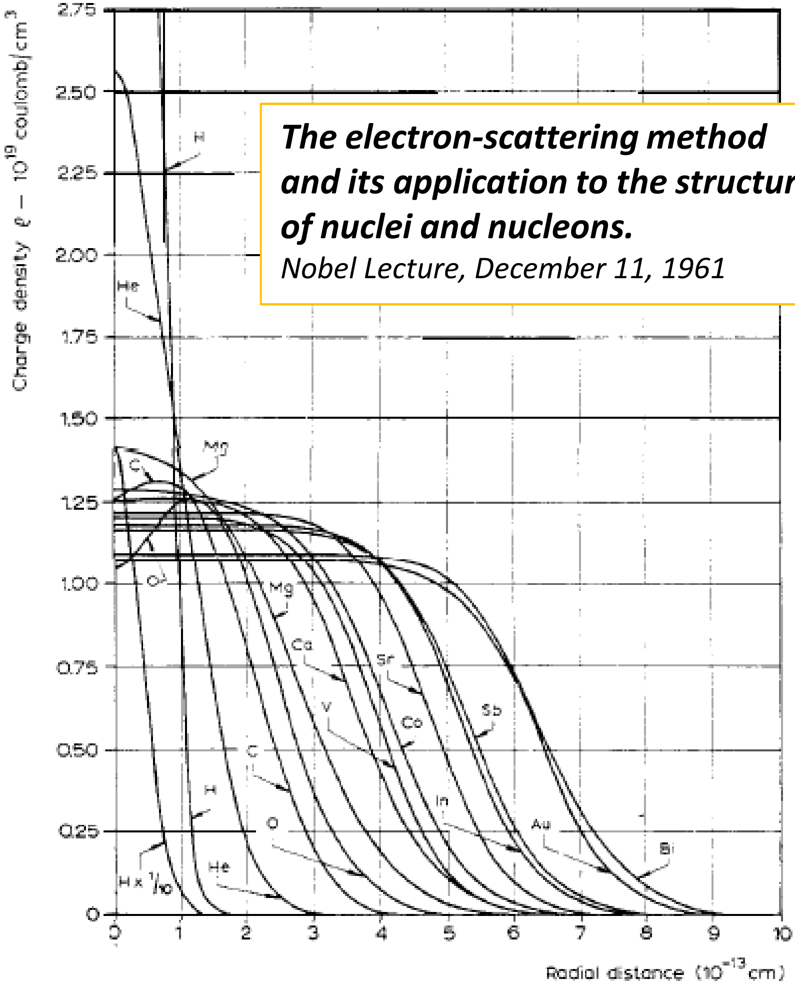
Dreaming of nuclear interactions… measuring densities

Verdi « Sometimes the progress is to look back in the past. ».

Voltaire, *Éléments de la philosophie de Newton* (1738) :
« L'homme n'est pas fait pour connaître la nature intime des choses ; il peut seulement calculer, mesurer, peser et expérimenter ».

Micromégas et le nain Saturnien rencontrent des Terriens
Micromégas de M. de Voltaire. 1778 BnF

1961 R.HOFSTADTER



The electron-scattering method and its application to the structure of nuclei and nucleons.
Nobel Lecture, December 11, 1961

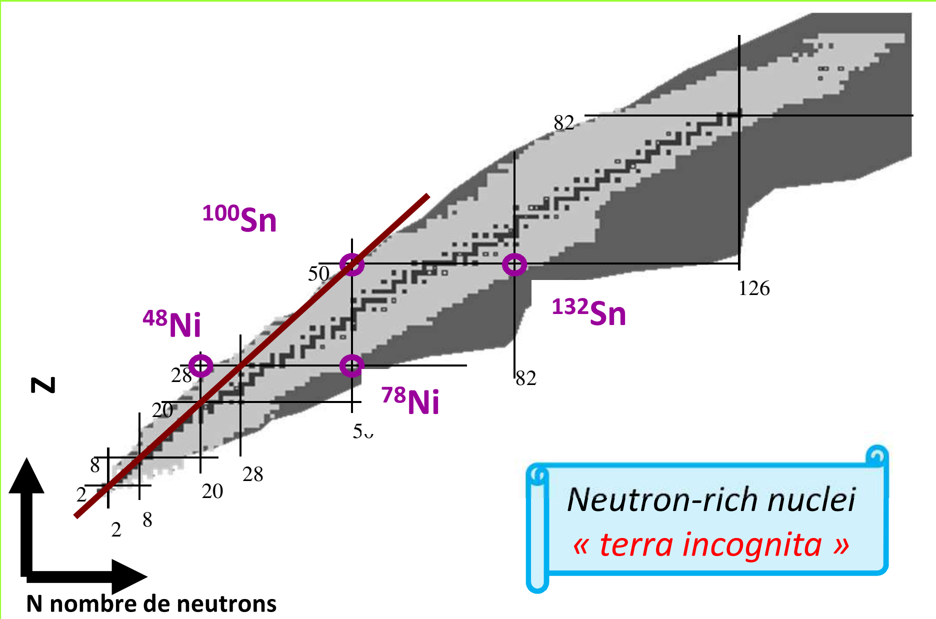
Direct Structure observables from electron –radioactive ion collisions at GANIL

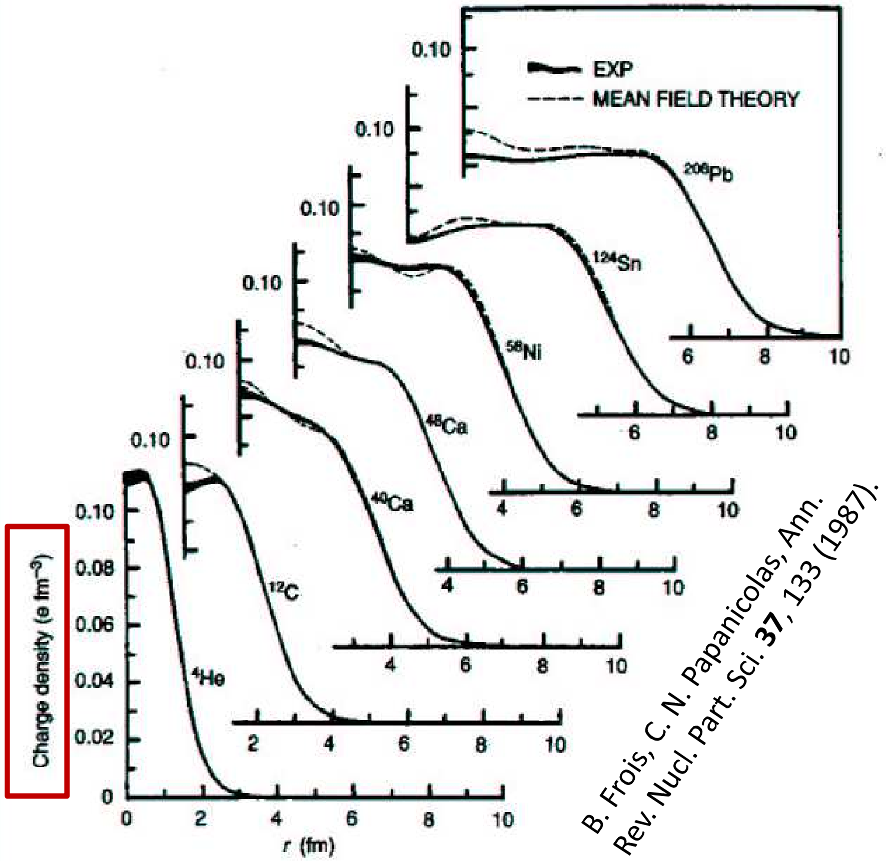
Main long-standing questions of the nuclear physics – cf NuPECC 2017 Long Range Plans

How can we improve our knowledge on nuclear interactions ?

How to understand and to model the structure of the nucleus?
Shell structure evolution? Nuclear sizes and densities?
What are the (effective) interactions between nucleons inside the nucleus?

Building blocks of our knowledge on nuclei → charge distributions
form factors → ρ_{ch}, ρ_p





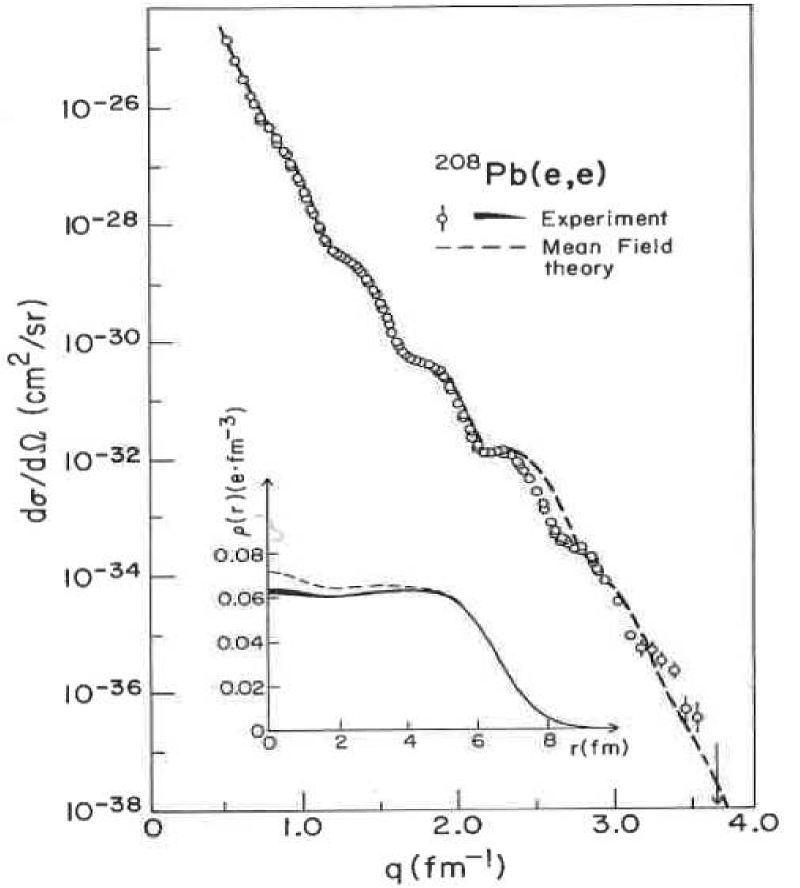
B. Frois, C. N. Papanicolas, Ann. Rev. Nucl. Part. Sci. **37**, 133 (1987).

*Direct comparison between experiment and theory on **observables** : nuclear densities*
→ e- RIB measurements in the 2030s?

GOAL: Proton densities for RIB via (e,e) exp.

From (e,e) form factors
→ ρ_{ch}, ρ_p

Goals for Nuclear matter densities: charge density profiles for RI as done for stable nuclei



B. Frois, C. N. Papanicolas,
Ann. Rev. Nucl. Part. Sci. **37**, 133 (1987).

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}} |F(q)|^2$$

$$F(\vec{q}) = \int d^3 r \rho_{ch}(\vec{r}) e^{i\vec{q}\vec{r}}$$

Extraction of densities

(e,e) scattering observables ←→ nuclear density fit
+ Assuming various density shapes, with parameters fitted on (e,e) data
+ Parameterization from theory
+ Model-independent (FB expansion,…) functions for the nuclear densities

Tables encoding knowledge on nuclear densities since the 50ies - Observables

H.De Vries, C. W.De Jager, and C.De Vries,
At. Data Nucl. Data Tables 36 (1987) 495-536
Nuclear charge density distribution parameters from electron elastic scattering

Works by Hofstadter *et al.* (1950s)
Ee ~150 MeV
N_{beam} ~ 1nA (~10^9 /s) ~10^{28} /cm²/s

Observables, sizes and densities

(e,e) and (p,p) → ρ_p and ρ_m → ρ_n

Elastic and inelastic electron scattering
→ Determination of nuclear **charge** sizes and shapes

From (e,e) **for stable nuclei**
form factors → ρ_{ch}, ρ_p

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott} |F(q)|^2$$

$$F(\vec{q}) = \int d^3r \rho_{ch}(\vec{r}) e^{i\vec{q}\vec{r}}$$

$^{16-18}$O(e,e)

For exotic nuclei: up to now, only r_{ch}
Few cases, cf data from laser spectroscopy
F(q) → ρ_{ch} ?
Electron-ion: SCRIT at RIKEN.
On-going projects for **RI-electron collisions:**
→ Physics cases in NuPECC LRP 2017
→ Future e-RI colliders; Elise@FAIR...

Back to basics

$$\rho(r) = \langle \Psi_{gs} | \delta(\vec{r} - \vec{r'}) | \Psi_{gs} \rangle$$

Elastic and inelastic proton scattering
to probe details of the densities ρ_m,
and to infer ρ_n properties

$^{16-18}$O(p,p)

From (p,p)
form factors → ρ_m

$$\frac{d\sigma}{d\Omega} = \frac{m_i m_f}{(2\pi\hbar^2)^2} \frac{k_f}{k_i} \left| \langle \varphi_f | V | \varphi_i \rangle \right|^2$$

$$U(\rho_p, \rho_n, E_p) = \lambda_v V(\rho, E_p) + i\, \lambda_w W(\rho, E_p)$$

Optical Model Potential microscopic analysis
E, ρ ({ρ_p, ρ_n}) density-dependent nucleon-nucleus pot.
e.g. **JLM local microscopic complex OMP**
from g-matrix calculations
E_p ~10-160 MeV extended to 200 MeV (CEA-DAM)
*J.P. Jeukenne, A. Lejeune, C. Mahaux, PRC **16**, 80 ('77)*

Neutron-rich RI beams (p,p) → test the validity of calculated ρ_p, ρ_m, ρ_n
→ check possible **neutron-skin via exp/theory comparison**
N.B. Here, we DO NOT EXTRACT ρ_m but rm radii

Oxygen isotopes radii via (p,p)

observables, sizes and densities

From (e,e) form factors → ρ_{ch}, ρ_p

$^{16-18}$O(e,e)

From (p,p) form factors → ρ_m

$^{16-18}$O(p,p)

^{20,22}O(p,p)

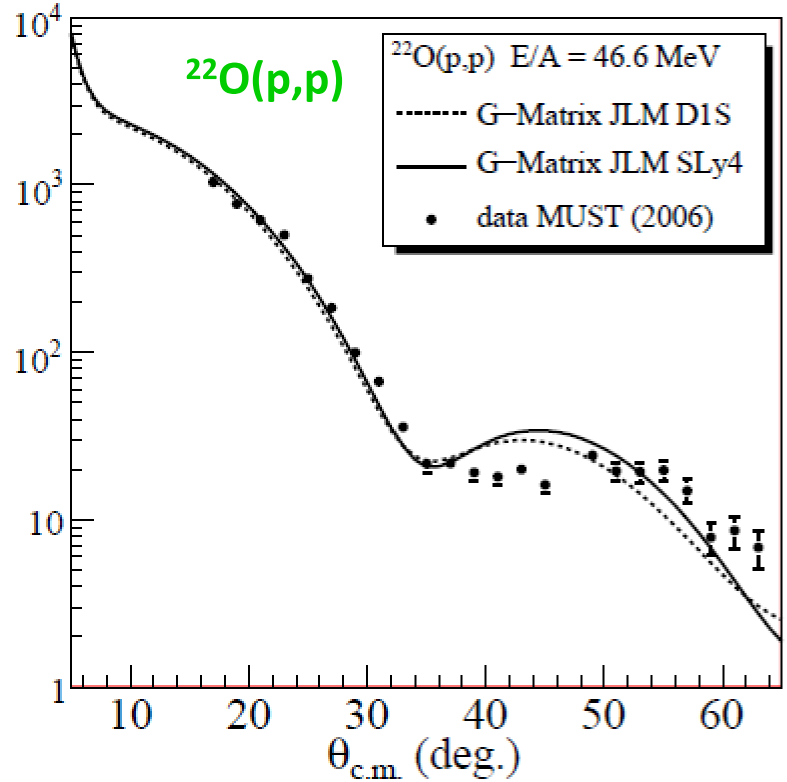
Cf (p,p) exp. methods MUST1 & 2, + calculation with microscopic OMP p + nucleus U(ρ,E) for: ^{6,8}He(p,p) in EPJA 51, 91 (2015)

(p,p) scattering

$$\frac{d\sigma}{d\Omega} = \frac{m_i m_f}{(2\pi\hbar^2)^2} \frac{k_f}{k_i} \left|\langle \varphi_f | U | \varphi_i \rangle\right|^2$$

Proton-nucleus potential

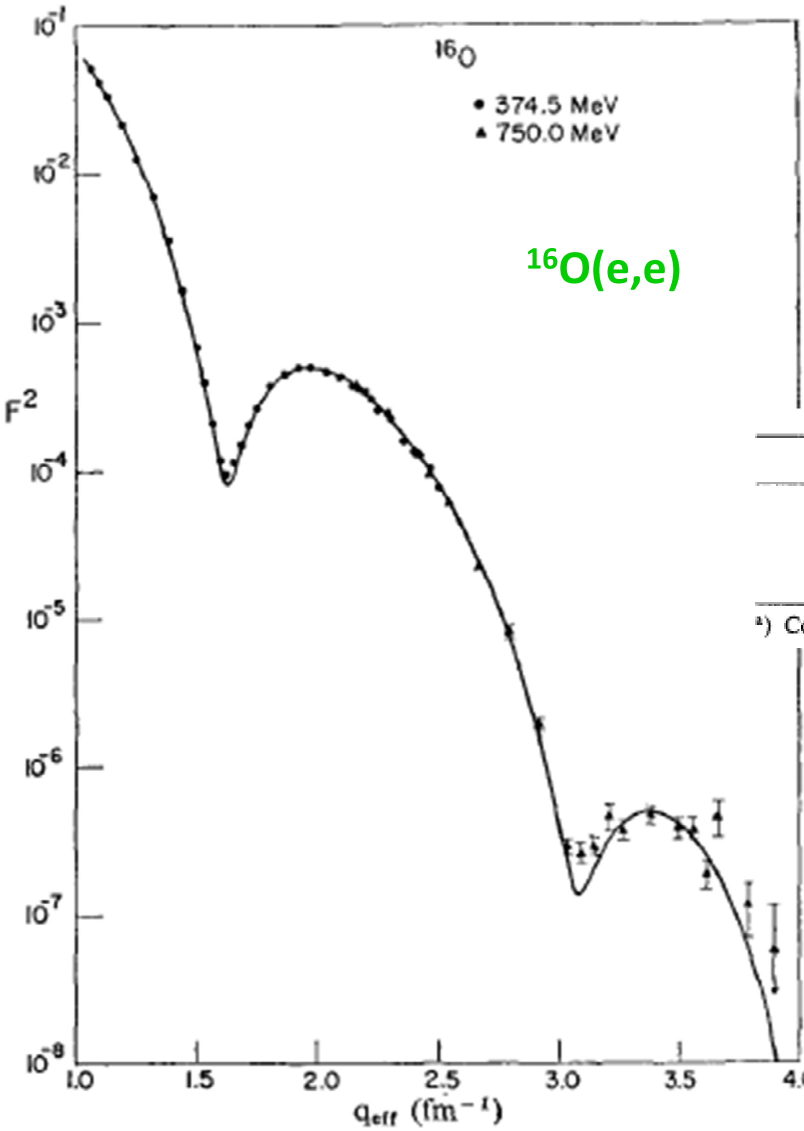
$$U(\rho_p, \rho_n, E) = \lambda_V V + i \lambda_W W$$



MUST data @GANIL: ^{20}O PLB **490**, 45 ('00) ; ^{22}O PRL **96,** 012501 ('06); *(p,p) JLM calc. + rms* PRL **117**, 052501 (2016)

Neutron-rich RI beams from (p,p) scattering → extraction of r_m, test of ρ_m

^{16}O(e,e) scattering measurements to extract charge density profiles



ELASTIC ELECTRON SCATTERING FROM ^{12}C AND ^{16}O

I. SICK and J. S. McCARTHY

High Energy Physics Laboratory, Stanford University, Stanford, California 94305 †

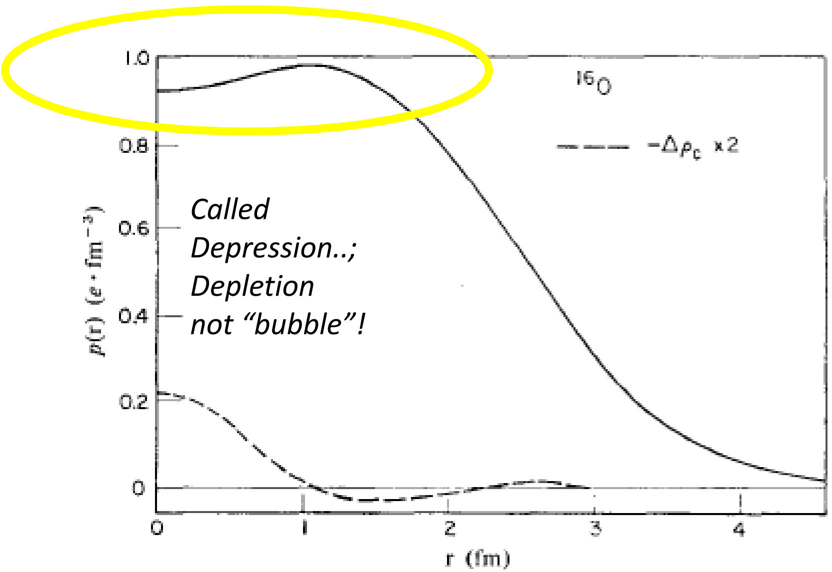
Nucl. Phys. ***A 150*** (1970) 631-654

$$\rho(r) \propto \frac{1+Wr^2/C^2}{1+\exp\left(\frac{r-C}{z}\right)},$$

rms radii

	Type	Oxygen
present exp.	high q	2.73 ±0.025 fm
Benz [8])	low q	2.666±0.035 fm
Crannell [5])	high q	2.65 ±0.04 fm [a])

[a]) Computed in PWBA.



Comparison : Experiment- *ab-initio* calculations to test interactions between nucleons

Benchmarks of structure models & interactions?
How to improve our knowledge & description?
Relevant observables probes?

Study from stable to weakly-bound nuclei
→ constraints on the nuclear models

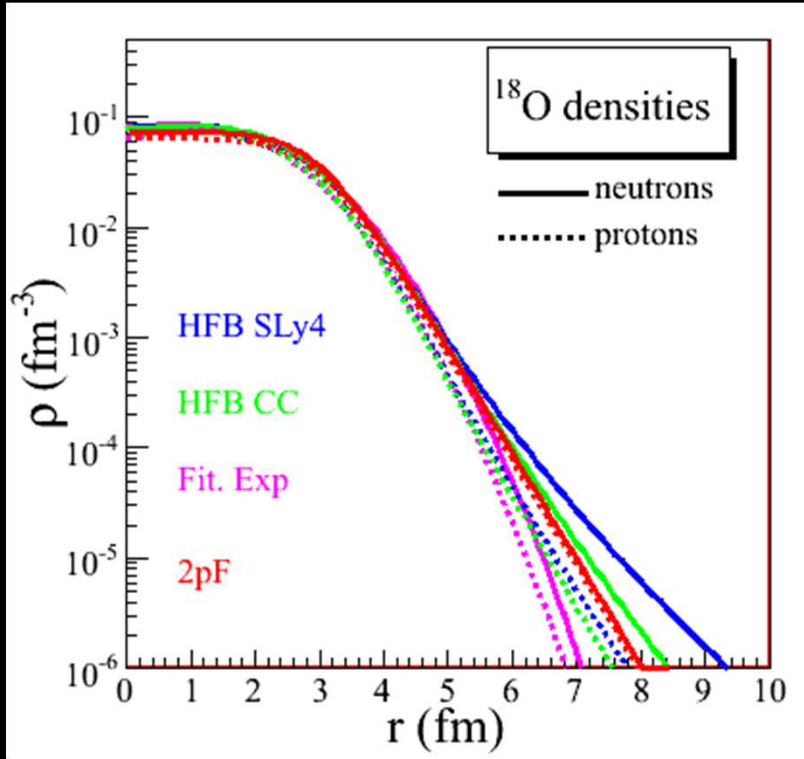
Masses ←→ Binding energies

Sizes ←→ Nuclear rms radii r_{ch}, r_m

From (e,e) form factors → ρ_{ch}, ρ_p

From (p,p) form factors → ρ_m

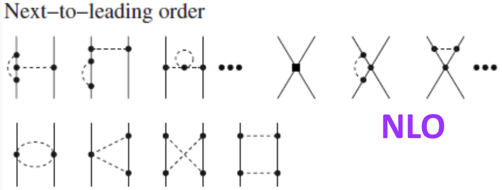
Nuclear matter radii
Nuclear densities



ab-initio

2 Nucleon Forces

Leading Order



NLO

N^2LO and N^3LO diagrams ….

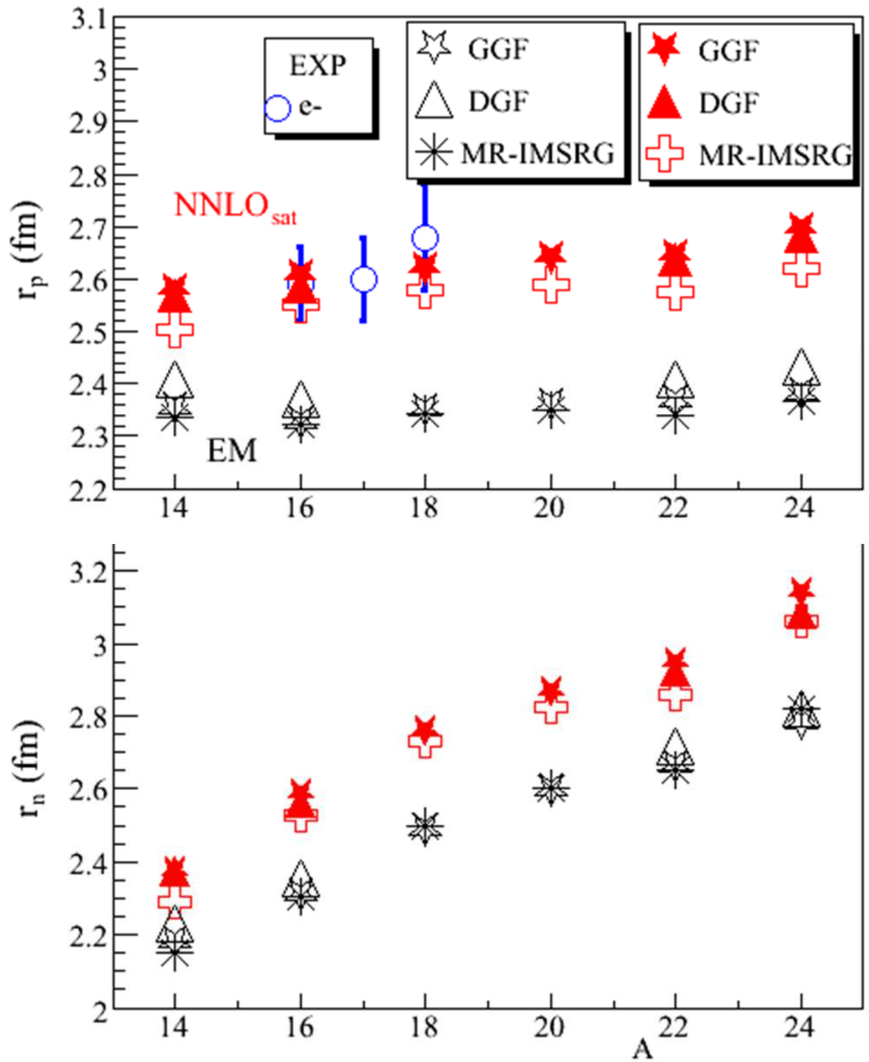
3NF

Leading order + NLO + N^2LO

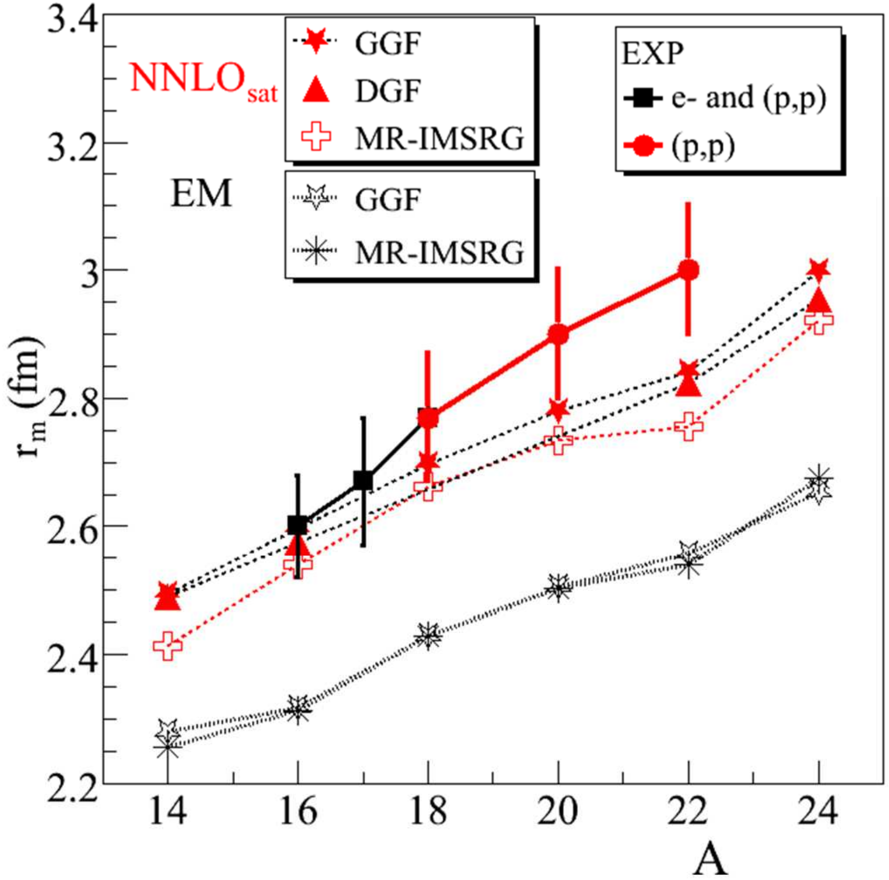
Calculated observables : binding energies, sizes and densities

Comparison between EXP & THEORY
→ Necessary step to reach a quantitative theory approach

Calculated versus experimental proton, neutron and matter radii



State-of-the-art *ab initio* calculations: V. Somà, C. Barbieri, H. Hergert J.D. Holt, S.R. Stroberg



PRL **112**, 052501 (2016)
V. Lapoux, V. Somà, C. Barbieri, H. Hergert J.D. Holt, S.R. Stroberg

Possible explanations?
Missing terms in the (N^2LO, N^3LO) developments of the EFT chiral forces…

Check nuclear charge DENSITIES
→powerful constraints on various approaches of the nuclear interactions ab initio side, EDF-type, Skyrme-like…

ACTIONS – COLLABORATIONS – STUDIES

End of 2019 International committee Scientific council (SC) for the future of GANIL mandated by CEA & CNRS dir
Jan. 2020 → Starting the e-RIB working group, collaboration « electron-RIB for GANIL future »
16th March 2020 → Contribution on « *Nuclear structure from electron-ion collisions* »
Main institutes : CEA Irfu, CNRS IN2P3, + SCRIT group +TUD, …
June 2020 Selection of two contributions by the SC asking for detailed reports *(2 other groups formed afterwards)*.

Working core group → Report sent Dec 2nd 2020.
Working group report *HAL (cea-03176547, v1)*
https://hal-cea.archives-ouvertes.fr/cea-03176547v1

SC collected other reports in 2021. *Decision steps for GANIL future? On-going process.*
April 2021 *Letter of synthesis sent to the SC chairman with updates on the technical choices (synchrotron versus ERL)*
2022 NuPECC The Nuclear Physics European Collaboration Committee Long Range Plan 2024 -Community input - 30 May - 30 oct.2022
A unique probe for nuclear structure in a future European radioactive ion –electron collider
https://indico.ph.tum.de/event/7050/contributions/6314

2020-2023 e-RIB working groups
https://esnt.cea.fr/Phocea/Page/index.php?id=110 […Projet ESNT 2018/2019]

The e-RIB core group
CEA-Saclay IRFU Antoine Chancé (DACM), Valérie Lapoux (DPhN), Vittorio Somà (DPhN)
GANIL Pierre Delahaye, LPC Caen Adrien Matta and Freddy Flavigny
With collaborators from GANIL, LPC, IJCLab, CENBG, IKP.
Experts contacted: T. Suda (Tohoku Univ) T. Wakasugi (RIKEN) and the SCRIT group

Electron-RI beam facility in progress (the only one)

→ SCRIT *Self-Contained Radioactive Ion Target at RIKEN*

L limited to 10^{28} cm^{-2} s^{-1} for 10^7 trapped ions,

RI limits: long lifetimes (~100 ms)

Feasibility of the SCRIT concept demonstrated in **2008**.

Obtained L: **10^{27} cm^{-2} s^{-1}** with SCRIT target-like 10^9 cm^{-2} *(introducing 10^8 part.) & e- beam of 200 mA (10^{18} /s)*

→**2023** *"First Observation of Electron Scattering from Online-Produced Radioactive Target"*

^{137}Cs L average ~0.9 10^{26} cm^{-2} s^{-1} for 2x 10^7 trapped ions

Alternative long-term hypothetical projects

*→ELISe FAIR **10^{28} cm^{-2} s^{-1}** ; e beam 10^{18} /s;*

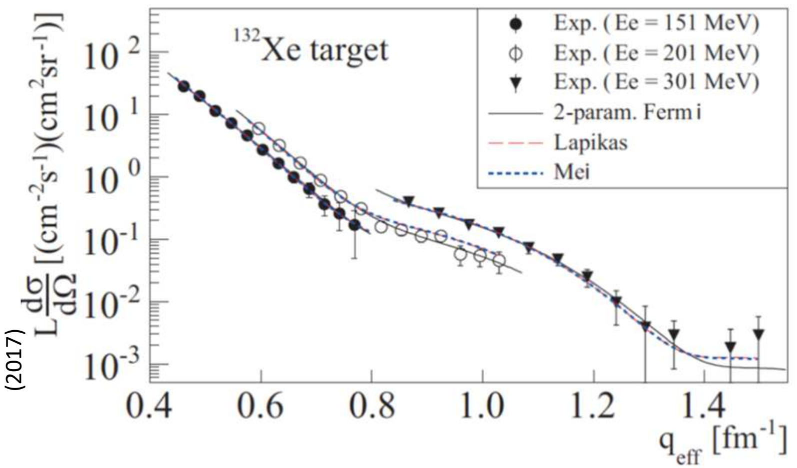
→E = 125 to 500 MeV e- linac stored in the EAR.

→ Ion ring NESR E~ 0.2 -0.74 GeV/ n. Postponed

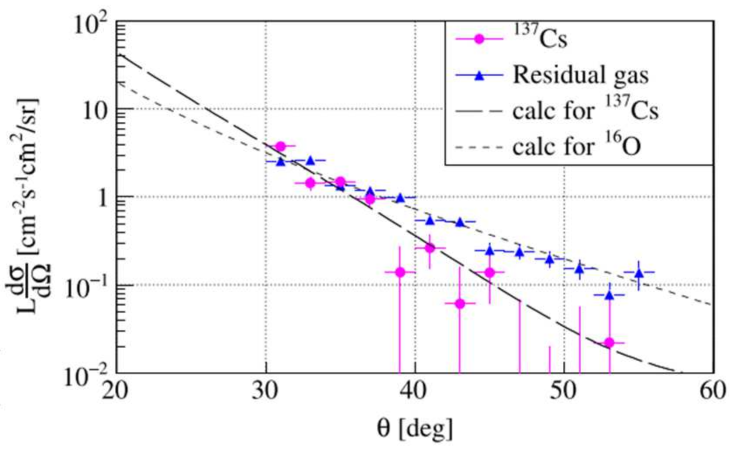
*→ DERICA Dubna **10^{28} cm^{-2} s^{-1}**; Ee ~ 500 MeV e- linac; Erib 300 A.MeV –not considered in the 1st stage of the Dubna project*

?EIC…JLAB (L 10^{36} ; e beam 10^{15} /s ; target-like 10^{21} cm^{-2})

Tsukada *et al.*, PRL **118**, 262501 (2017)



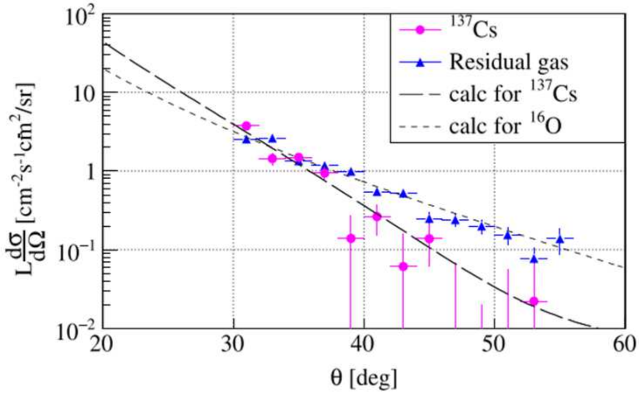
Tsukada *et al.*, PRL **131**, 092502 (2023)



[Scrit04] M. Wakasugi, T. Suda, and Y. Yano, NIM A 532, 216 (2004).
[Scrit05] T. Suda, M. Wakasugi, Prog. Part. Nucl. Phys. 55, 417 (2005).
[Scrit17] K. Tsukada et al., Phys. Rev. Lett. 118, 262501 (2017).

Writing to our directors about the international context of (e,e) scattering off RI beams

Tsukada *et al.*, PRL **131**, 092502 (2023)



Electron-RI beam facilities

Emblematic successful unique worldwide project: SCRIT
2023 First RI ^{137}**Cs** (e,e) scattering
^{137}**Cs L average ~0.9 10^{26} cm^{-2} s^{-1}**
for 2x 10^7 trapped ions

2nd November 2023 –writing to GANIl & IRFU &IJCLab to require (some) decision steps
« Les physiciens au cœur du programme de SCRIT ont été pleinement associés à nos prospectives, aussi bien dans le cadre du projet pour l'avenir du Ganil qu'à l'échelle européenne dans le cadre de la proposition soumise au comité de NuPECC pour le plan à long terme de 2024. »

[Scrit23] ***(Radioactive ^{137}Cs ; average L ~ 0.9 10^{26} cm^{-2} s^{-1} with around only 2.7 x 10^7 trapped ions)***
First Observation of Electron Scattering from Online-Produced Radioactive Target
K. Tsukada, Y. Abe, A. Enokizono, T. Goke, M. Hara, Y. Honda, T. Hori, S. Ichikawa, Y. Ito, K. Kurita, C. Legris, Y. Maehara, T. Ohnishi, R. Ogawara, T. Suda, T. Tamae, M. Wakasugi, M. Watanabe, and H. Wauke
Phys. Rev. Lett. **131**, 092502 (2023) https://doi.org/10.1103/PhysRevLett.131.092502

[ScritArt] Références des travaux de R&D et de tests SCRIT
"Proof of principle studies": Nucl. Instrum. Methods **A 532** (2004) 216 ; PRL **100**, 164801 (2018) ; PRL **102**, 102501 (2019).
SCRIT facility: Nucl. Instrum. Methods B **317** (2013) 668.
ERIS facility (photofission of U) Nucl. Instrum. Methods B **317** (2013) 357.

+ ***(Stable ^{132}Xe ; L over 10^{27} cm^{-2} s^{-1} with around 10^8 trapped target ions)***
First Elastic Electron Scattering from 132Xe at the SCRIT Facility,
K. Tsukada, A. Enokizono, T. Ohnishi, K. Adachi, T. Fujita, M. Hara, M. Hori, T. Hori, S. Ichikawa, K. Kurita, K. Matsuda, T. Suda, T. Tamae, M. Togasaki, M. Wakasugi, M. Watanabe, and K. Yamada, Phys. Rev. Lett. **118**, 262501 (2017)
+ ***(Stable ^{133}Cs ; L over 10^{26} cm^{-2} s^{-1} with around only 10^6 trapped ions)***
First Demonstration of Electron Scattering Using a Novel Target Developed for Short-Lived Nuclei,
T. Suda, M. Wakasugi, T. Emoto, K. Ishii, S. Ito, K. Kurita, A. Kuwajima, A. Noda, T. Shirai, T. Tamae, H. Tongu, S. Wang, and Y. Yano, Phys. Rev. Lett. **102**, 102501 (2009)
+ ***(Stable ^{133}Cs ; L ~ 2.4 (8) 10^{26} cm^{-2} s^{-1} with around only 7 x 10^6 trapped ions)***
Novel Internal Target for Electron Scattering off Unstable Nuclei,
M. Wakasugi, T. Emoto, Y. Furukawa, K. Ishii, S. Ito, T. Koseki, K. Kurita, A. Kuwajima, T. Masuda, A. Morikawa, M. Nakamura, A. Noda, T. Ohnishi, T. Shirai, T. Suda, H. Takeda, T. Tamae, H. Tongu, S. Wang, and Y. Yano,
Phys. Rev. Lett. **100**, 164801 (2008). https://doi.org/10.1103/PhysRevLett.100.164801

[ScritKyo] Kyo TSUKADA (Kyoto Univ.) *https://irfu.cea.fr/Phocea/Vie_des_labos/Seminaires/index.php?id=4917*

[Talk23] **ESNT seminar talks** https://esnt.cea.fr/Phocea/Page/index.php?id=110
En 2023 deux séminaires ont été donnés au DPhN sur les avancées des travaux du groupe SCRIT, par les physiciens qui collaborent avec ceux de RIKEN pour développer le programme expérimental.
15 Feb. 2023 11h-11h45 - Kyo TSUKADA (Kyoto Univ.) *Present status and future prospects of the SCRIT project*
15 Feb. 2023 11h45-12h - Hikari WAUKE (Tohoku Univ.) *Recent results of electron scattering at SCRIT facility*

Physics program - from nuclear size to density profile

Goals for nuclear matter densities: charge density profiles for RI as done for stable nuclei

+ Scientific motivations: nuclear charge, electromagnetic transition, magnetic current densities

Background: textbook experiments on stable nuclei done in the 50s to 90s

+Pioneer program with SCRIT at RIKEN

→ **Choice of a SCRIT-like project with innovative Ion Trap and [I ~ 100-200 mA, E~500-700 MeV] electron accelerator (synchrotron)**

→ *Studies of the feasible cases with RI optical conditions:*
(Less) constraints on the electron- ion beam Interaction vertex ion cloud size, ~0.2mm^2

Observables and quantities of interest	**Reactions** *(q: momentum transfer)*	**Type of nucleus**	**Required luminosity L**
rms charge radii	**(e,e)** *elastic at small q*	Light ($Z^2 \leq 100$)	L: 10^{24} cm^{-2}s^{-1}
Charge density distribution with 2 parameter Fermi function (2pF) ρ_{ch}	**(e,e)** *First min. in elastic form factor*	Light Medium Heavy	**L: 10^{28} 10^{26} cm^{-2}s^{-1} 10^{24}**
Charge density distribution with 3pF ρ_{ch}	**(e,e)** *2nd min. in elastic form factor*	Medium Heavy	**L: 10^{29} cm^{-2}s^{-1} 10^{26}**
F_L, F_T Magnetic form factors→ Proton, neutron transition densities *Direct access to neutron-skin*	**(e,e)** *2nd min. in elastic form factor*	Odd-even Medium Heavy	**L: 10^{30}cm^{-2}s^{-1} 10^{29}**
Energy spectra, width, strength, decays, collective excitations	**(e,e')**	Medium-Heavy	L: $10^{28\text{-}29}$ cm^{-2}s^{-1}
Extraction of the density distribution *using functionals (series of Fourier-Bessel functions …)*	**(e,e)** **(e,e')**	Light Medium-Heavy	**(e,e) (e,e') L : $10^{30\text{-}31}$ (e,e) (e,e') L ~$10^{29\text{-}30}$**
Spectral functions, correlations	**(e,e'p)**		**$10^{30\text{-}31}$ cm^{-2}s^{-1}**

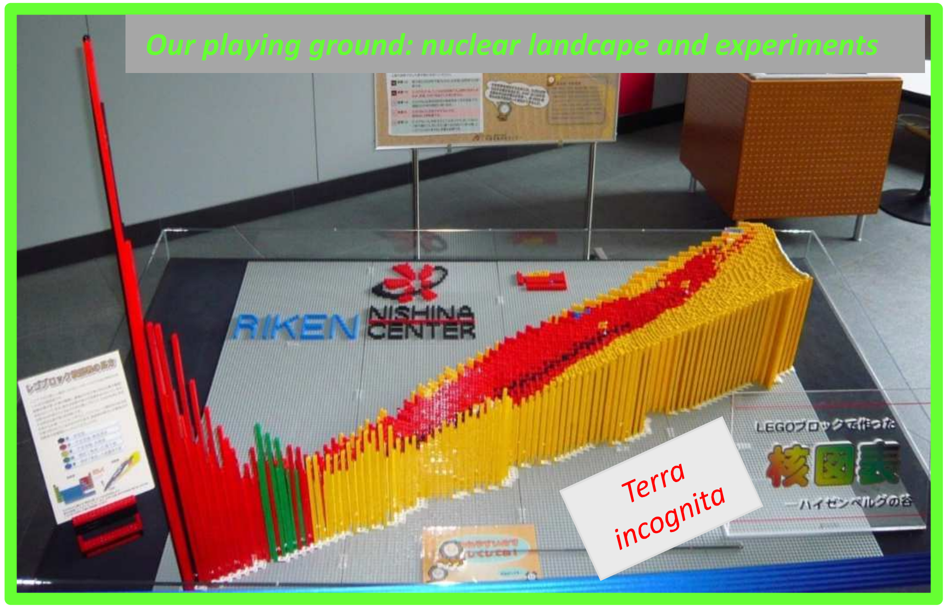
Program for nuclear densities at GANIL

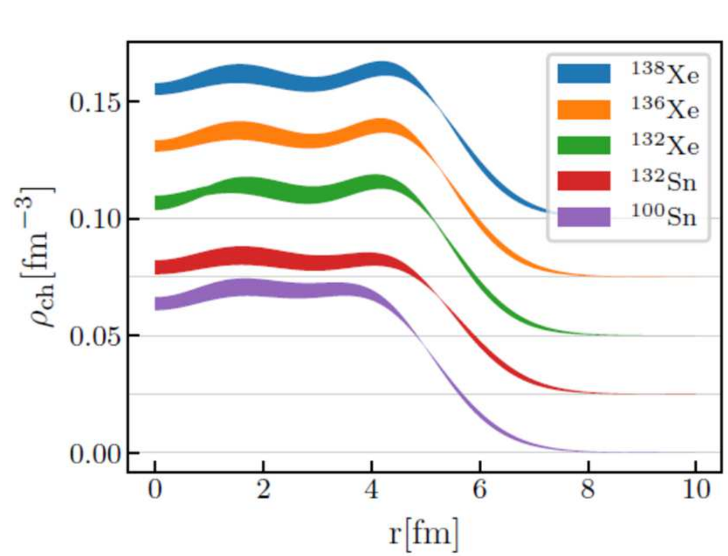
Building blocks of our knowledge on nuclei

Nuclear densities

Measure nuclear density observables
Benchmark of nuclear interactions
Data tables & constraint on theories

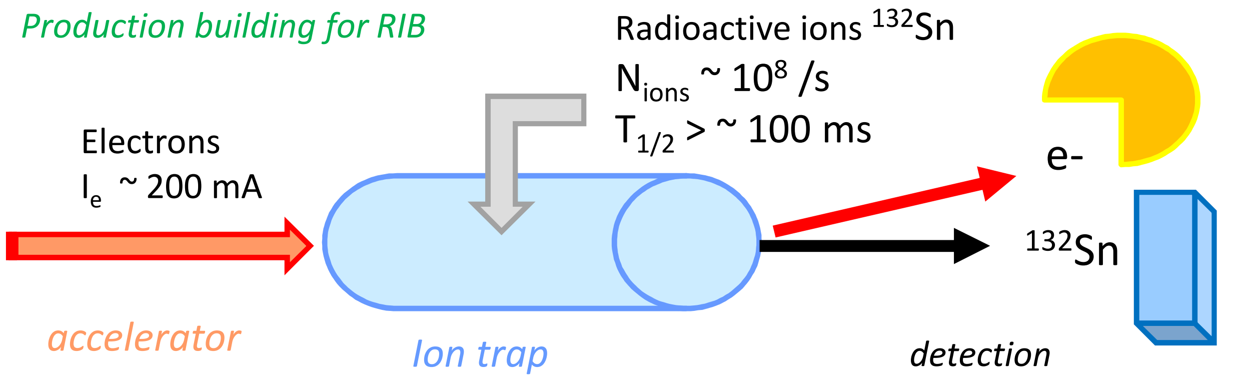
Our playing ground: nuclear landcape and experiments





P. Arthuis, C. Barbieri ,M. Vorabbi, P. Finelli
ArxiV:2002.02214v2 PRL **125**, 182501 (2020)

Production building for RIB

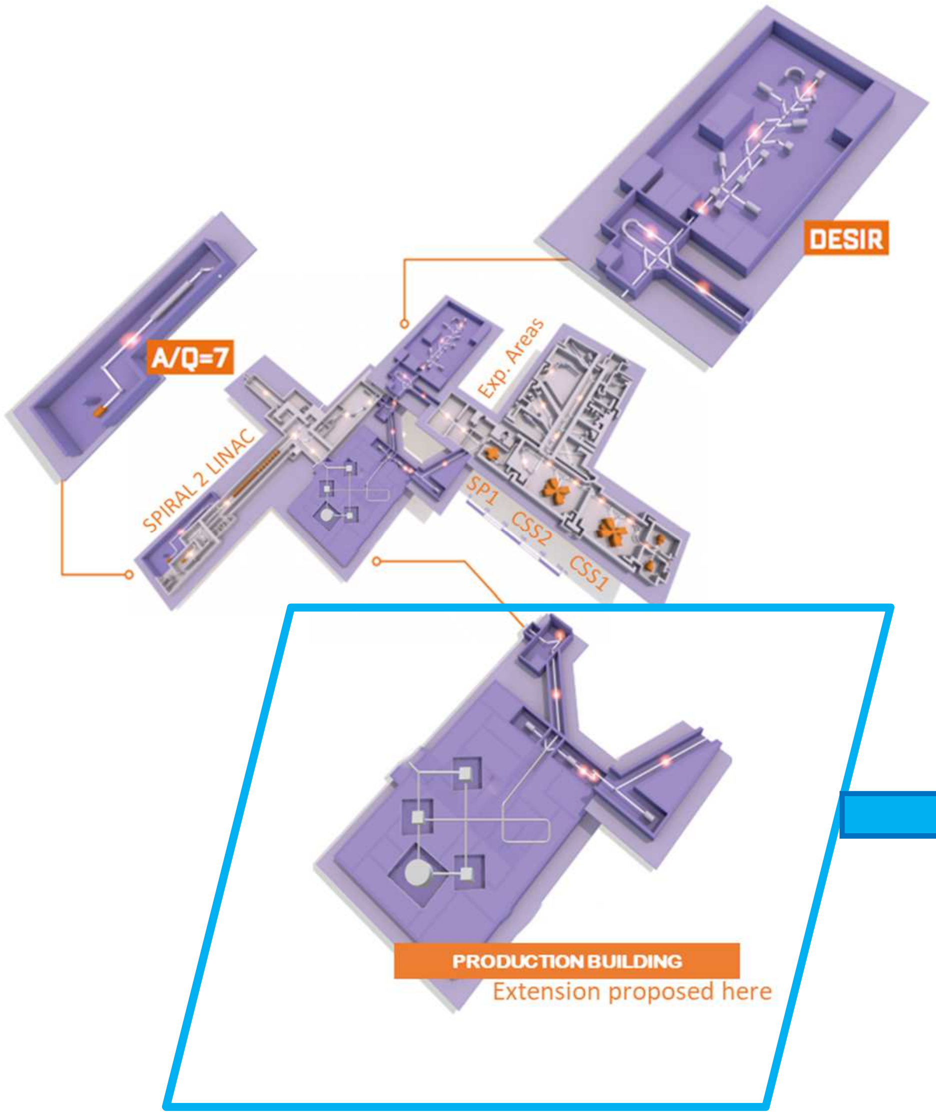


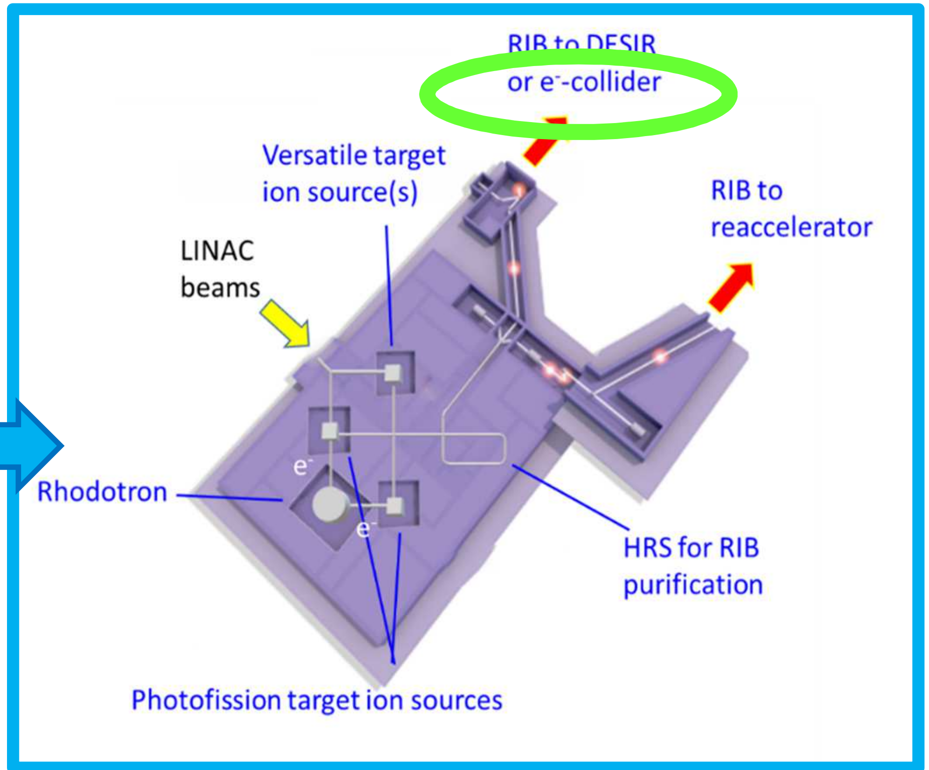
In the context of "GANIL future"

Spirit of the project
→ Nuclear density observables via (e,e) & (p,p) programs
→ Renewal of the RIB physics
→ Focusing on questions related to the tests of nuclear interactions
→ Identify the "feasible" cases

A multi-user facility

A production building with several production caves
ISOL / gas cell with dedicated driver to complement the LINAC
• Fusion and transfer reactions with the LINAC beams (including A/Q=7)
• Photofission or light particle induced fission (p,d, ^{3}He/^{4}He): up to ~10^{13} fissions/s



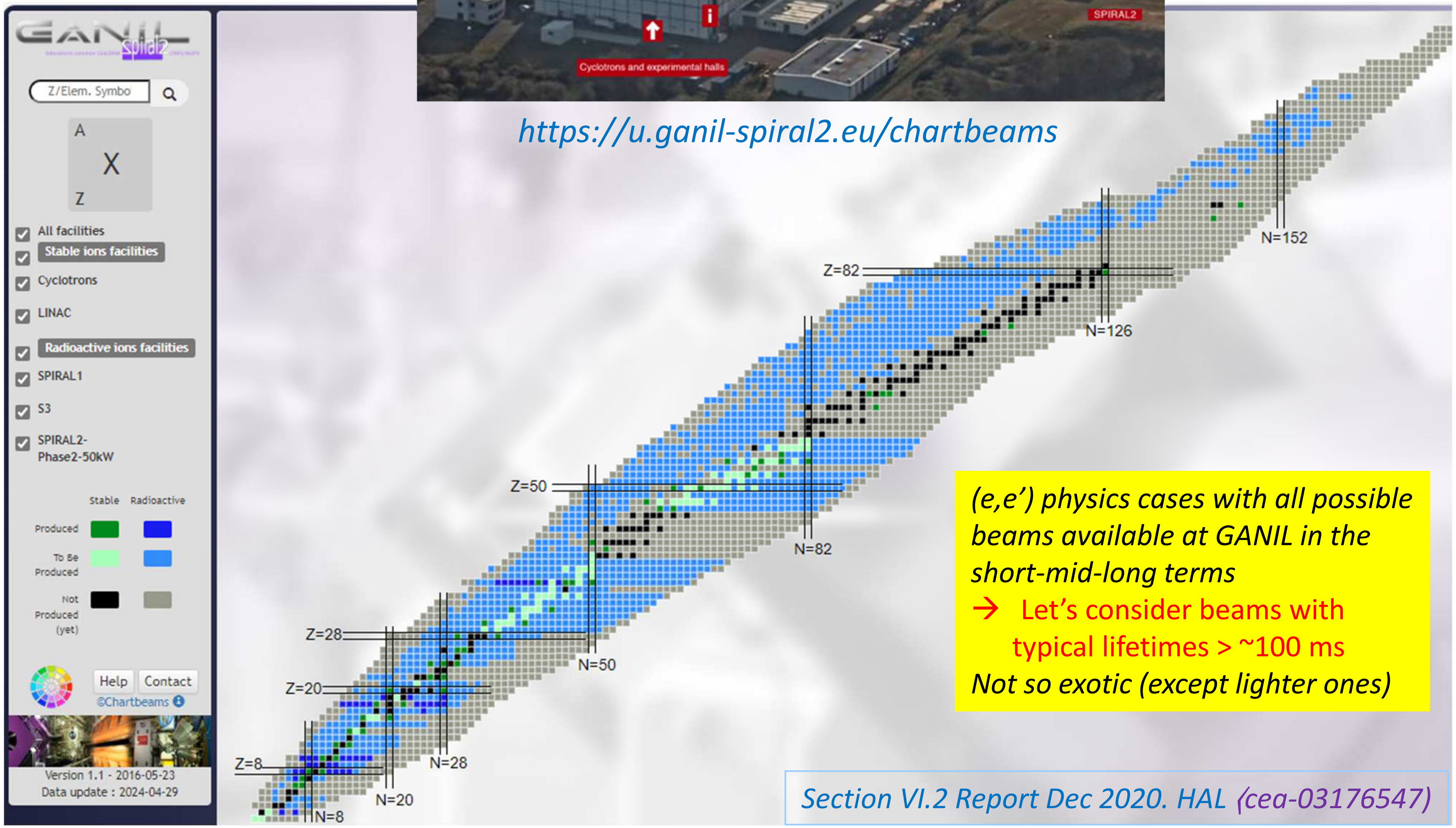


HAL CEA (cea-03176547)

GANIL beams

All production modes:
SPIRAL1, LINAC, S3 MNT
(or tentative project SPIRAL2)

https://u.ganil-spiral2.eu/chartbeams



(e,e') physics cases with all possible beams available at GANIL in the short-mid-long terms
→ Let's consider beams with typical lifetimes > ~100 ms
Not so exotic (except lighter ones)

Section VI.2 Report Dec 2020. HAL (cea-03176547)

Physics program – direct structure observables

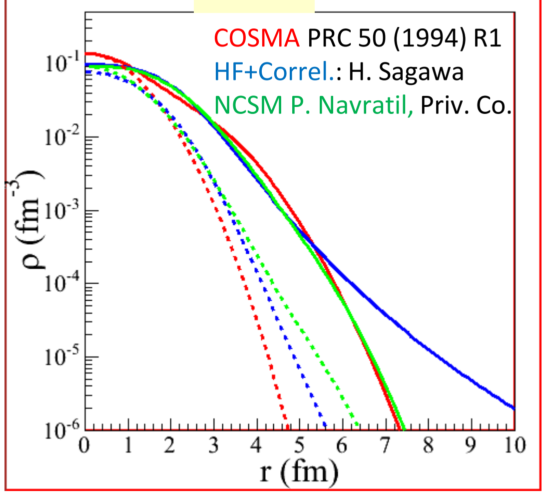
Examples of First Day experiments of the e-RIB machine at GANIL
with the existing/ present SPIRAL1 beams
Not so exotic except very light RIB
-typical RI lifetimes >~ 100 ms, better test cases with I ~ 10^8 part/s

In the spirit of the project → Nuclear density observables & tests of nuclear interactions

(e,e) experiments (with sensitivity to the shape of the density)

Kr Z = 36	^{74}**Kr** 11.5min **> 1.5 10^6/s**	^{76}**Kr** 14.8h **> 4. 10^7/s**	*2pF par from (e,e) up to 2.5 fm^{-1} with I ~10^7*
Ar Z = 18	^{44}**Ar** 11.87 min >10^6/s ^{45}Ar 21.5 s > 8. 10^5/s	^{46}Ar *N= 28 8.4 s* > 10^5/s	
Mg Z = 12	^{23}**Mg** 11.3 sec **2·10^8**		*Form factors from (e,e) q ~0.5-3 fm^{-1} with I ~10^8*
Ne Z = 10	^{18}Ne 1.7 sec **1.7 x 10^7/s**	^{19}**Ne** 17.3 sec **1.5 x 10^8/s**	
O Z = 8	^{14}**O** 70 s 10^7/s	*^{22}O 2.25 s ^{21}O 3.4 s* *^{20}O 13.5 s ^{19}O 2.4 s* *Yields to be studied*	
He Z = 2	^{6}**He** 806 ms **2 x 10^8 /s** ($5 x 10^7$)	*^{8}He 119 ms* *10^5 /s*	

p & n



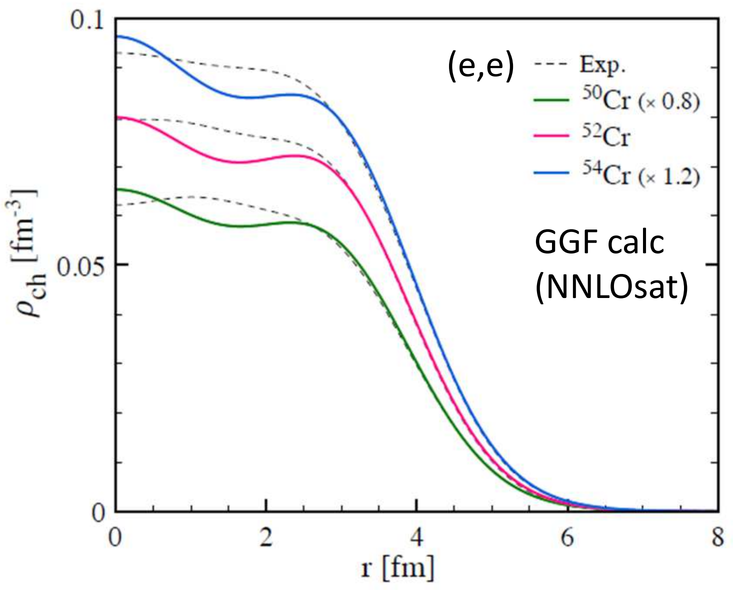
Test of nuclear density models for ^{6,8}He via proton target reactions Eur. Phys. J. A (2015) 51: 91

Table VI.1.D - 2020 report HAL (cea-03176547)

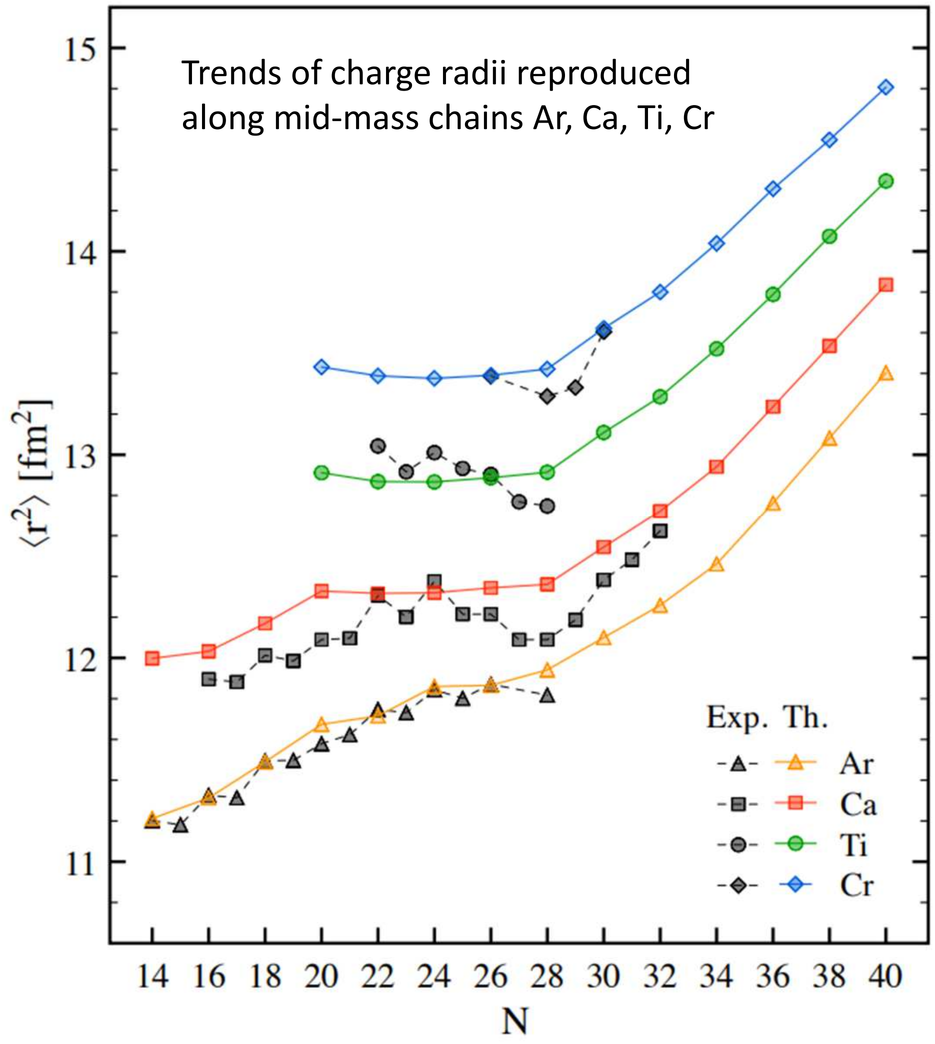
Direct Structure observables

Example of structure calculations
V. Somà, C. Barbieri, T. Duguet, *et al.*
Moving away from singly-magic nuclei with Gorkov Green's function theory.
Eur. Phys. J. A **57**, 135 (2021).

Sensitivity to the shape of the density



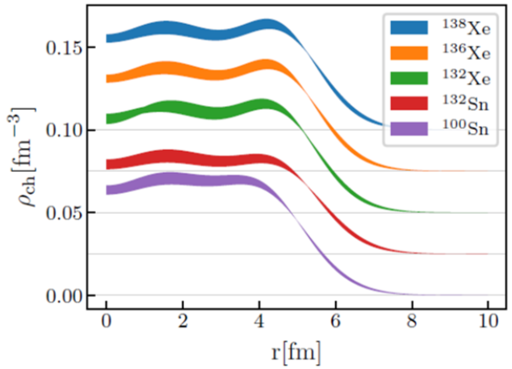
V Somà et al EPJA 2021
GGF calc. of doubly open-shell nuclei



Examples and test cases with foreseen or prospective production modes of RIBs
– mid and long-term plans - Beam T > ~ 100 ms
+ LEBd for LEB DESIR (postAcc for post-acceleration yields) and PhF for photofission;
+ isotopes produced via S3-LEB or MNT techniques

Sn Z=50	^{104}Sn 20.8 s 10^5/s ^{108}Sn 10.3 min 5 x 10^5/s	^{130}Sn 3.72 min > 10^9 /s *(LEBd)* *(PhF)* ^{131}Sn 56.0 s	^{132}Sn N=82 39.7s 9 x 10^8 /s *(LEBd)* $3 \cdot 10^9$ /s *(PhF)* ^{133}Sn 1.45s	^{134}Sn 1.05 s 3 x 10^6 /s *(LEBd)* > 10^7 /s *(PhF)* ^{135}Sn 530 ms
Kr Z=36	^{90}Kr N=54 32.3 s 6.4 x 10^8/s > 10^9 /s *(PhF)*	^{92}Kr 1.84 s 2.6 x 10^8/s > 10^9 /s *(PhF)*	^{94}Kr 212 ms 1.2 x 10^7/s > 10^9 /s *(PhF)*	^{96}Kr N=60 *80 ms* ~$5 \cdot 10^9$ /s *(PhF)*
Se Z=34	^{84}Se N=50 3.1 min *(LEBd)* 9.5 x10^7/s *(postAcc* 1.2 x 10^6)	^{86}Se 14.3 s *(LEBd)* 3.1x10^7/s *(postAcc* 3.9 x 10^5)	^{88}Se N=54 1.5 s	

Elastic scattering on mid-heavy neutron-rich nuclei to measure charge distributions



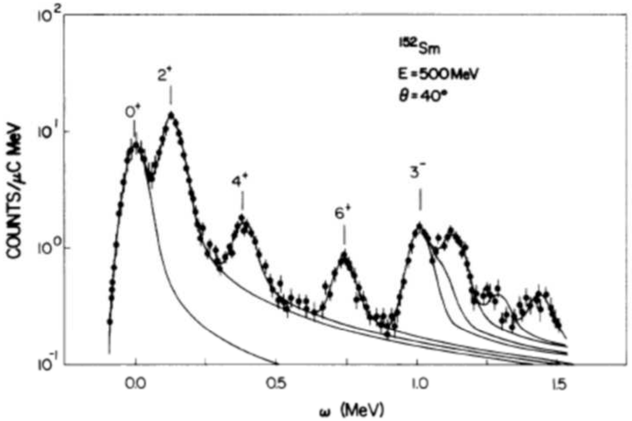
PRL **125**, 182501 (2020)

Am Z=95 ^{239}Am N=144 11.9 h $2 \cdot 10^6$ /s *(S3-LEB)*		*Bk Z=97* ^{248}Bk N=151 >9 y $3.3 \cdot 10^6$ /s *(MNT)*	*Ra Z=88* ^{214}Ra N=126 2.44 sec $6.3 \cdot 10^9$ /s *(MNT)*
Sm Z=62	*^{160}Sm N=98 9.6sec (?S3-LEB)*	*^{162}Sm N=100 9.6 sec*	*^{164}Sm N=102 1.43s*
Cs Z=55 ^{118}Cs N=63 14 sec $3 \cdot 10^6$ /s *(S3-LEB)*		*Xe Z=54* ^{116}Xe N=62 59 s 1.2 x 10^5/s	*Te Z=52* ^{112}Te N= 60 2 min 3.4 x 10^5/s

Nuclear studies of charge densities and of alpha cluster states in the neutron-rich isotopes.

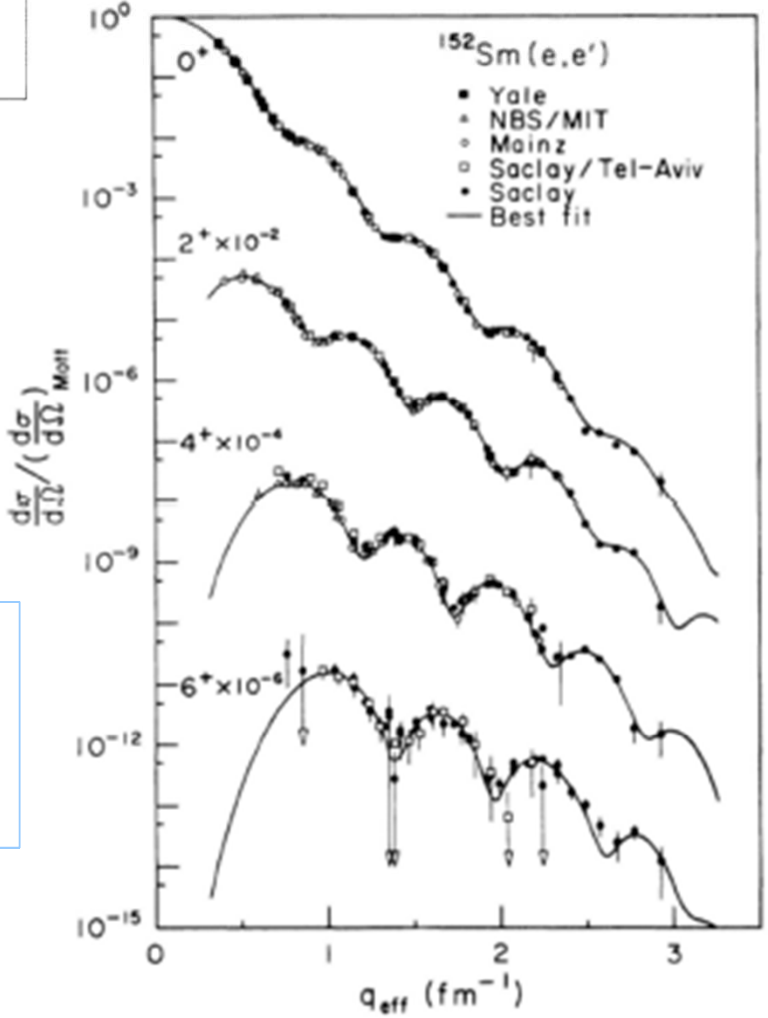
Tables - 2020 report HAL (cea-03176547)

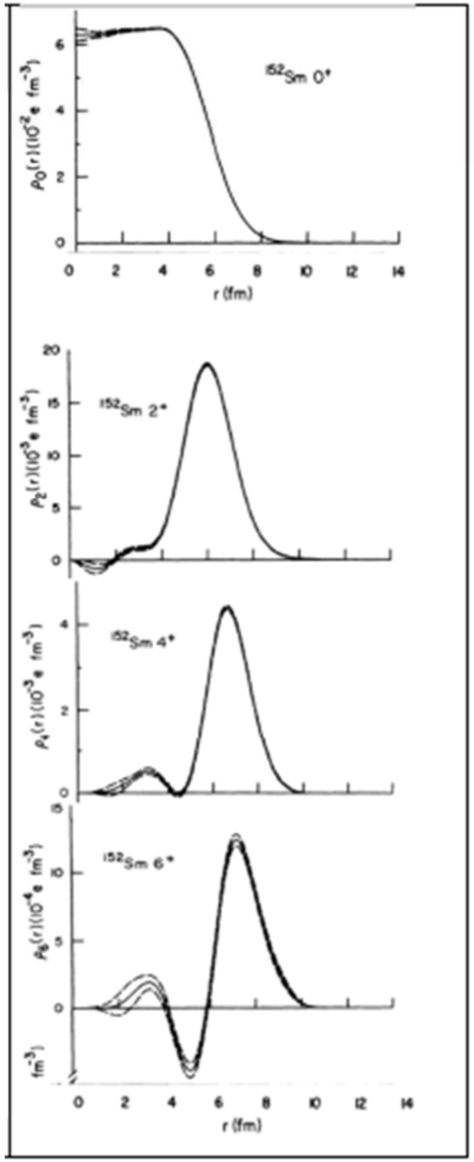
Transition densities & gs rotational bands



^{152}Sm 0+ gs
2+ 121.7818 keV 1.403 ns
4+ 366.4793 9 57.7 ps
0+ 684.751 21 6.10 ps
6+ 706.928 17
2+ 810.453 5
3- 1041.122 4

^{152}Sm (e,e) spectroscopic studies
*Text book case: X.H. Phan et al., Electron scattering studies of the ground state rotational band of ^{152}Sm, Phys. Rev. C **38**, 1173 (1988).*





NEXT WITH SCRIT? ^{154}Sm deformation issues → T. Otsuka's talk

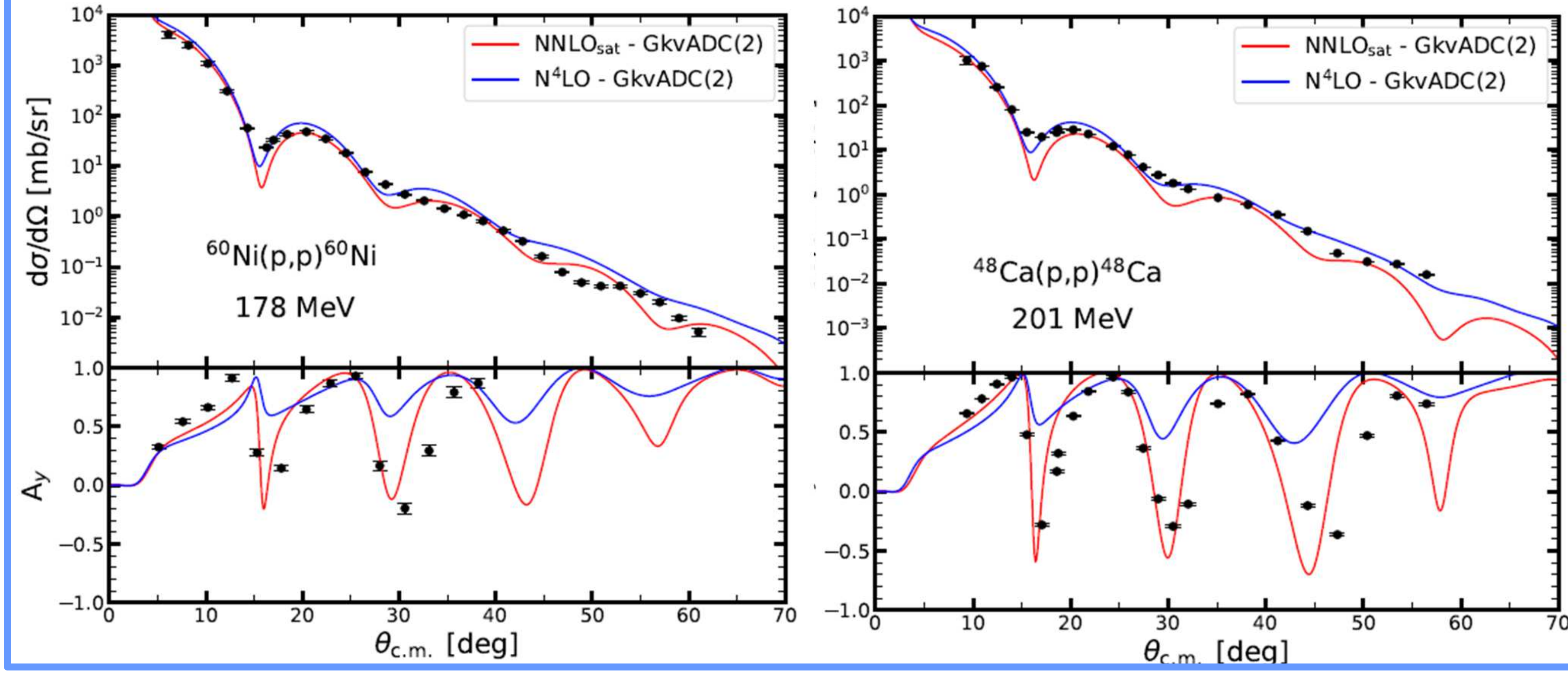
Direct structure observables via (e,e) and (p,p) programs with RIBs

GOAL: proton densities and rm matter radii by combining (e,e) ($\rho_{ch} \rightarrow \rho_p$) and (p,p) data ($\rightarrow r_m$)
N.B. Suda-san et al. : PTP about 4th momentum of the ρ_{ch} from (e,e) → reaching r_n

H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. 2019, 113D01 doi:10.1093/ptep/ptz121
H. Kurasawa, T. Suda and T. Suzuki, PTEP., 2021, 013D02 doi:10.1093/ptep/ptaa177

(p,p) data → r_m + density profile tests using state-of-the-art *ab initio* structure-reaction approaches

Microscopic optical potentials for medium-mass isotopes derived at the first order of the Watson multiple scattering theory
M. Vorabbi, C. Barbieri, V. Somà , P. Finelli, and C. Giusti arXiv:2309.04226v2 21 Mar 2024



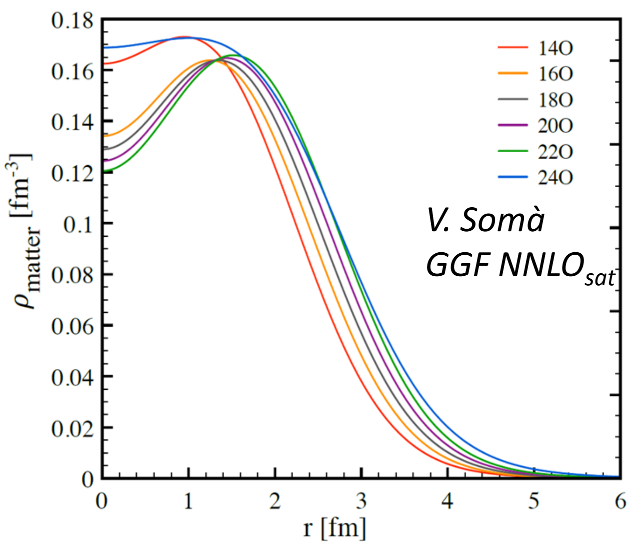
(p,p) exp at RIKEN for OMP studies → TRIP/MESA program by H. Baba et al. - during 9 years from FY2023
→ Check possible extraction of rms matter radii for near-stability radioactive isotopes (e.g. Ti, Ni)

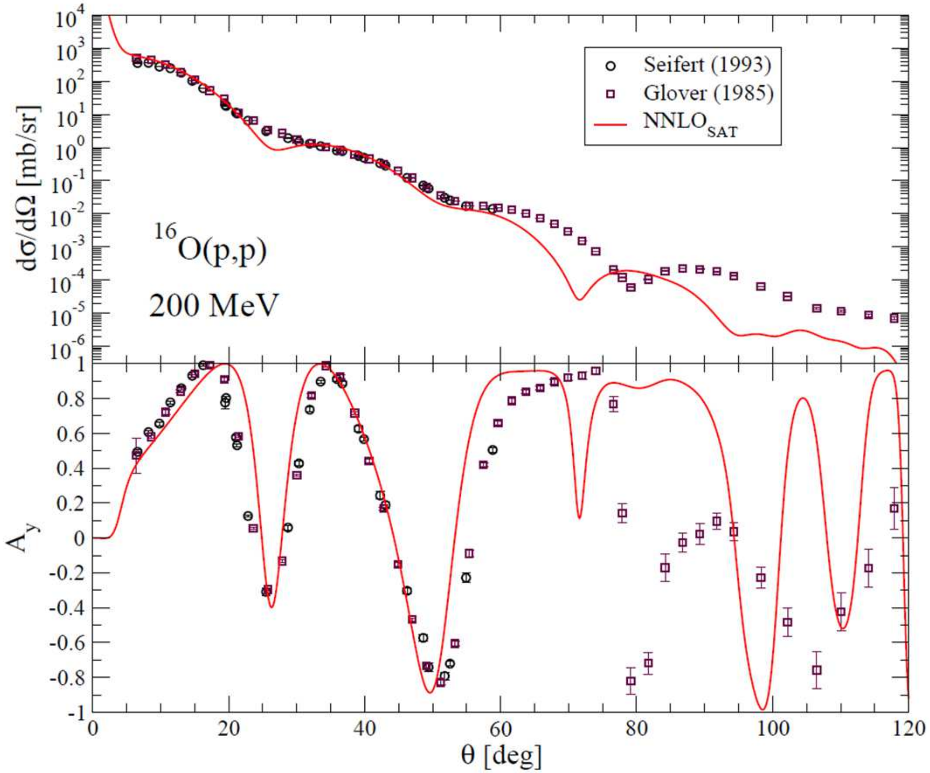
Direct Structure observables –exp-theory comparison on (e,e) & (p,p)

GOAL: improve our knowledge on the interactions using (e,e) and (p,p) combined analysis for proton &matter nuclear densities

*N.B. **Golden age of the ab initio calculations** possibly extrapolated to main regions of the nuclear chart*
Robust approach done on systematical basis with uncertainty propagation associated to the results
→ Cf P. Arthuis's talk

+ Reaction framework of the (p,p) elastic scattering + extraction of the r_m
& test of ***nuclear matter densities*** *using state-of-the-art OMP analysis*





→ Same for RI beams
Long term perspectives (2030-2045)
From nuclear size to density profiles
→ Nuclear database

Electron-RI project at GANIL: summary & perspectives

OBSERVABLES OF NUCLEAR DENSITIES → DATA TABLES
→ Direct comparison to nuclear theories

Precise and extended physics cases
→ Femtoscope project - eRIB at Ganil²
*Electron scattering on **radioactive ions** at GANIL²*
Grand Accélérateur National d'Ions Lourds et de Leptons
Not so exotic -typical RI lifetimes >~ 100 ms
→ SCRIT-inspired project ←

Pathway to new observables at GANIL - R&D & collaborative works - step by step, to 2035-2040
2020-2024 Exploration works by the e-RIB core group *(CEA-Irfu, GANIL, LPC Caen, IJCLab)*
→ *Strong physics cases extensively defined* - taking advantage of the **variety of present (SPIRAL1,...) future beams**
→ Benefiting from discussions with the SCRIT-Riken-Tohoku group
Building blocks & strategy –not (yet) in the conceptual design report phase!
–redefining teams (to be reinforced) & agenda
Electron accelerator of synchrotron type (DACM design): no technical issue.
Beam tests → see with IJCLab prototype accelerator
Ion trap device *Main issues: building a SCRIT-like demonstrator at* L ~ 10^{28} cm^{-2}s^{-1} *for GANIL... at GANIL?*
From L ~ 10^{28-29} cm^{-2}s^{-1} to 10^{30-31} cm^{-2}s^{-1}
→**Concept of ion recirculation in the trap** *(P. Delahaye et al.): needs for simulations, benchmark tests, demonstrator*
→ *On going - need to build a task force GANIL- IRFU-IJCLab-LPC Caen & to gather expertise*
→ ***We need SCRIT group experience and help during all the (future) R&D for eRIB at GANIL***

cea irfu cnrs IN2P3 GANIL

From Spring to Autumn season of the electron-nucleus & RIB physics

Address via (e,e) with RIBthe main (long-standing) questions of the nuclear physics

+ Shapes and deformation from (e,e') (stable) and Coulex (RI)
+ Shell structure from hadronic probes (transfer)

SPRING Scientific heritage of (e,e')

→ Hofstadter period: Stanford univ., ALS (CEA Saclay) Mainz
→ Database of nuclear densities + spectroscopy via (e,e')

→ *Yukawa's spirit: vision of the nuclear interaction*

SUMMER Radioactive ion physics

Nuclear physics questions at the extremes
Hadronic probes
→ the nuclear interaction & potentials?

Light exotic nuclei
Neutron-halo or skin structures
Resonances

Interaction potentials

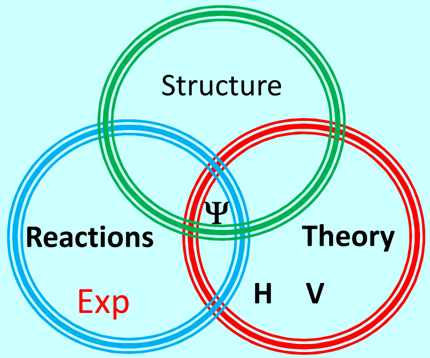
Microscopic OM potential

Rms matter radii via (p,p) scattering

AUTUMN Low-Energy Electron Scattering for Radioactive Nuclei

Goals
OBSERVABLES OF NUCLEAR DENSITIES
for RI as done for stable nuclei
→ DATA TABLES
→ Direct comparison to nuclear theories
→ Testing ground for effective & state-of-the-art nuclear *ab initio* interactions

Towards main advances in the knowledge & improvement of nuclear interactions



Electron-RIB groups

The-RIB group (CEA-Irfu, GANIL, LPC Caen, IJCLab)
CEA-Saclay IRFU - Antoine Chancé (DACM), Vittorio Somà (DPhN), Valérie Lapoux (DPhN)
GANIL - Pierre Delahaye ; LPC Caen – Adrien Matta, Freddy Flavigny *et al.*
→ *SCRIT-Riken-Tohoku group T. Suda, M. Wakasugi*

Collaboration "Electron scattering on radioactive ions at GANIL" [Research Report] 1st Dec. 2020 Hal-CEA. ⟨cea-03176547, v1⟩
https://hal-cea.archives-ouvertes.fr/cea-04062929

Contribution to the NuPECC Long Range Plan (LRP) 2024
for Nuclear Physics in Europe - *29 September 2022*
https://indico.ph.tum.de/event/7050/contributions/6314
A unique probe for nuclear structure in a future European radioactive ion –electron collider
Authors and main contributors for the electron-ion project
CEA-Saclay, Irfu *valerie.lapoux@cea.fr; vittorio.soma@cea.fr; antoine.chance@cea.fr*
GANIL *pierre.delahaye@ganil.fr*
LPC Caen *flavigny@lpccaen.in2p3.fr;matta@lpccaen.in2p3.fr*
TU Darmstadt *aobertelli@ikp.tu-darmstadt.de*
Tohoku University *suda@lns.tohoku.ac.jp*
RIKEN Nishina Center, Kyoto University *wakasugi.masanori.8z@kyoto-u.ac.jp*
IJCLab. *verney@ijclab.in2p3.fr*

cea irfu cnrs IN2P3 GANIL *RIKEN*