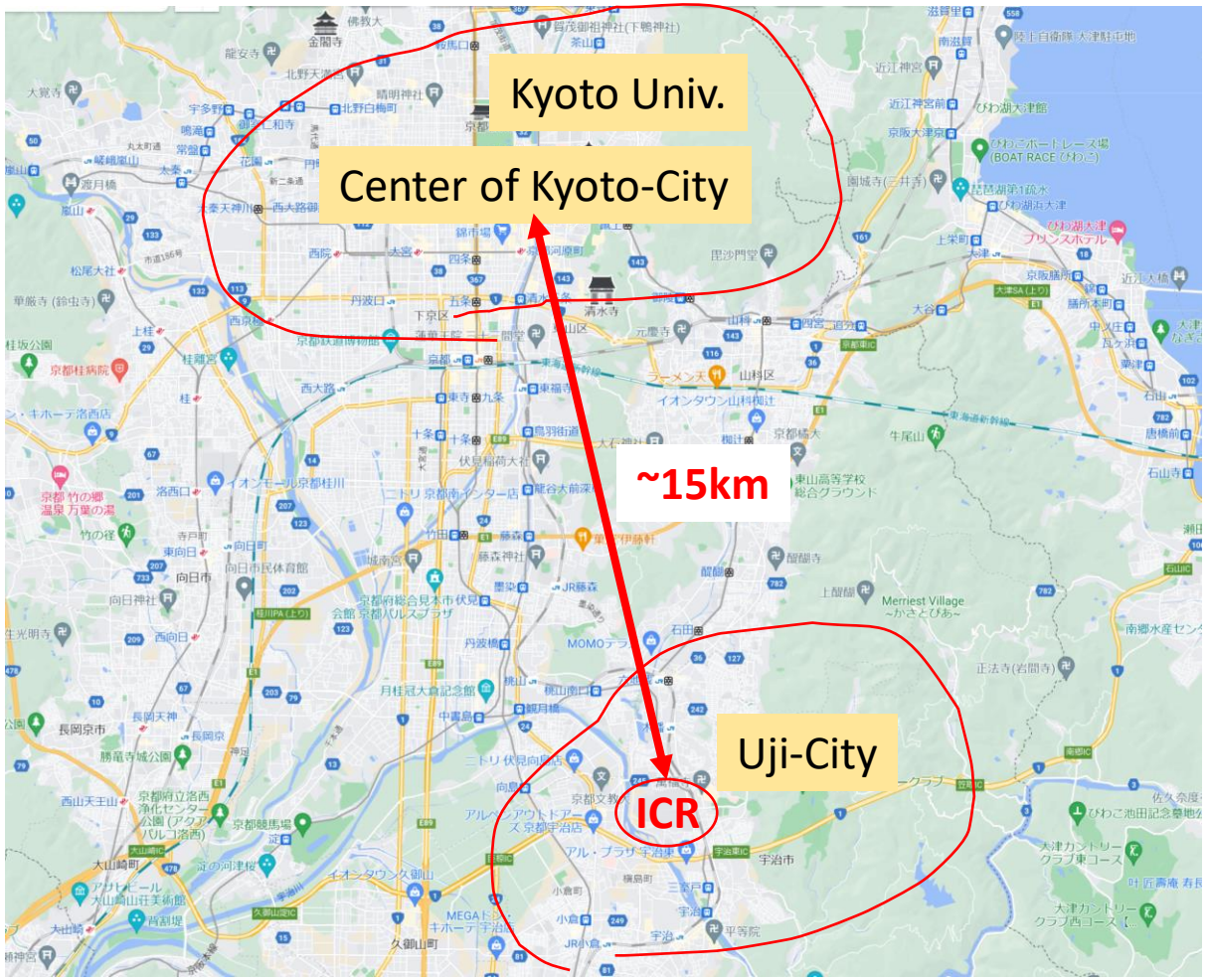
Electron scattering from unstable nuclei at SCRIT facility

ICR, Kyoto University

Kyo Tsukada

for SCRIT collaboration

Institute for Chemical Research (ICR), Kyoto Univ.



Institute for Chemical Research (ICR), Kyoto Univ.

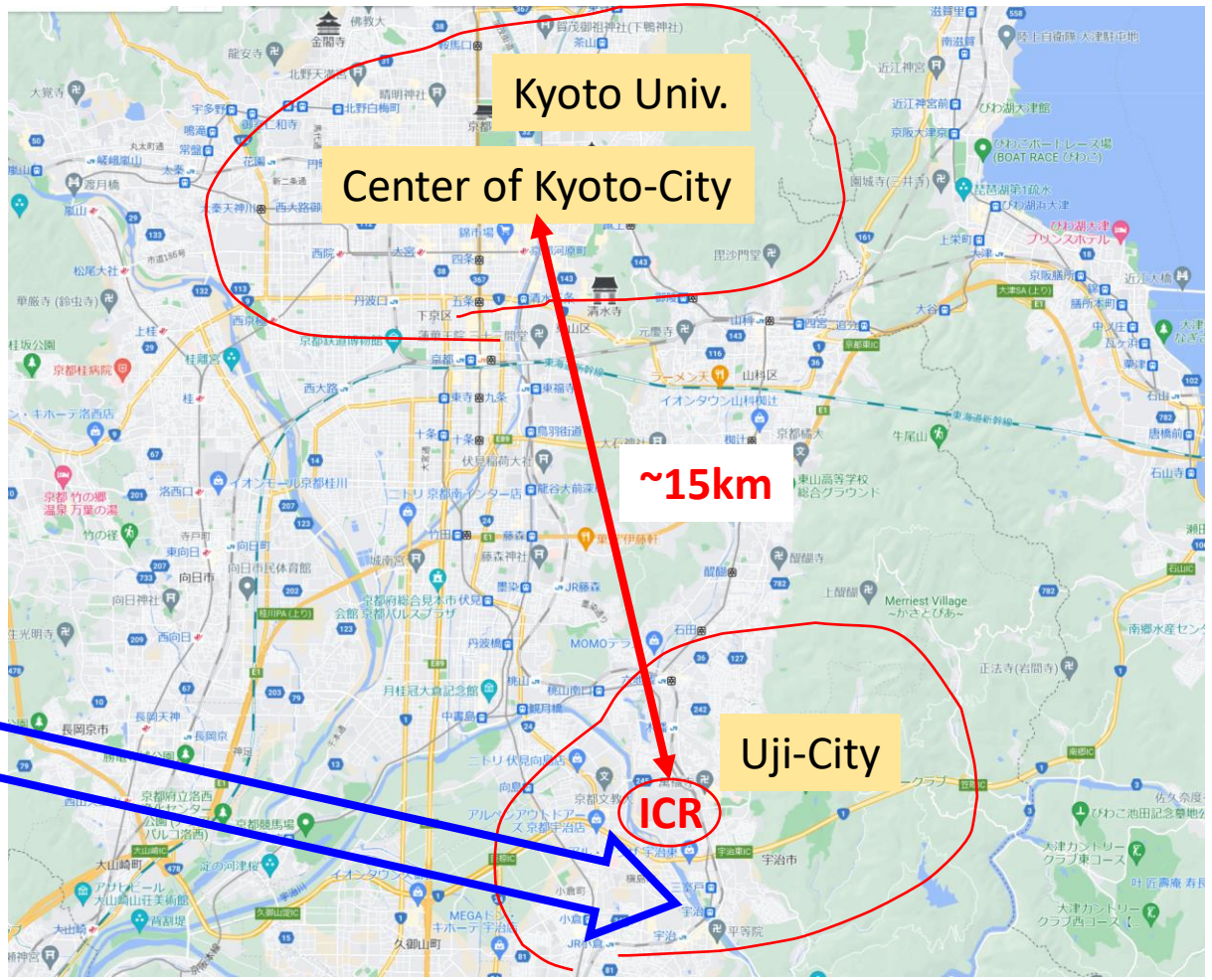
宇治茶

Uji-cha (green tea)

平等院

Byodo-in Temple
(World Heritage)

10 yen coin



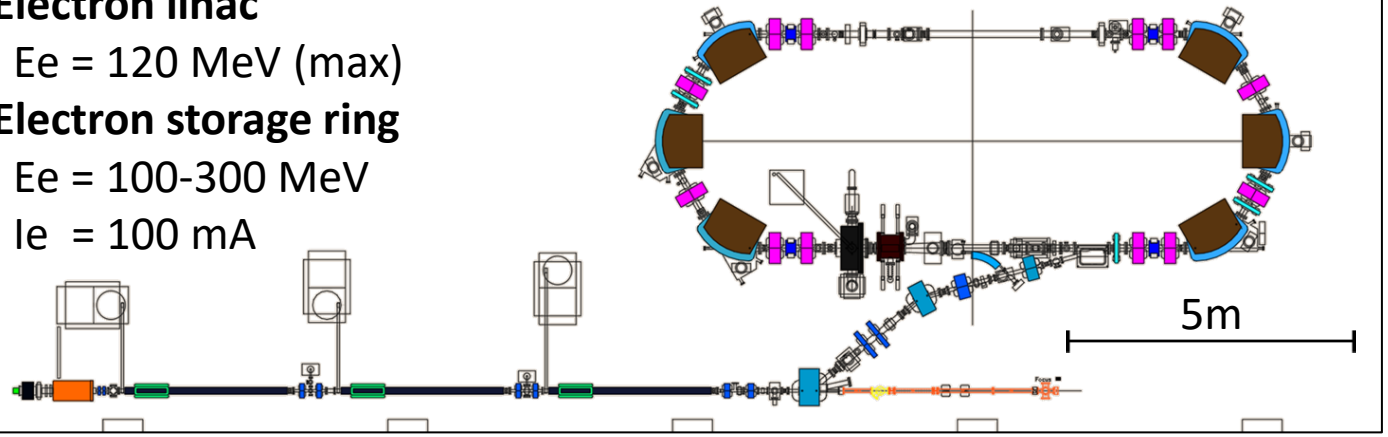
Institute for Chemical Research (ICR), Kyoto Univ.

KYOTO UNIVERSITY
Institute for Chemical Research
ICR

Particle Beam Science Lab.

3 staffs
1 technical staff
1 secretay
2~3 students

Electron linac
Ee = 120 MeV (max)
Electron storage ring
Ee = 100-300 MeV
Ie = 100 mA



- **Principle study of the SCRIT method** was conducted here.
- These accelerators have been shut down for a long time.
- Recovery work is ongoing to begin the nuclear physics research.

Contents

- Introduction to e-RI scattering
  - Motivation
  - Electron scattering
  - SCRIT method
- SCRIT electron scattering facility
  - Facility
  - SCRIT and previous results
- Latest results
  - Years of developments
  - First results of e-RI scattering
  - Isotope, isotone measurements

} Presented by Wauke-san in the next talk

- Related topics to future of SCRIT method
  - Possibility to access neutron information in nucleus by electron scattering
- Summary

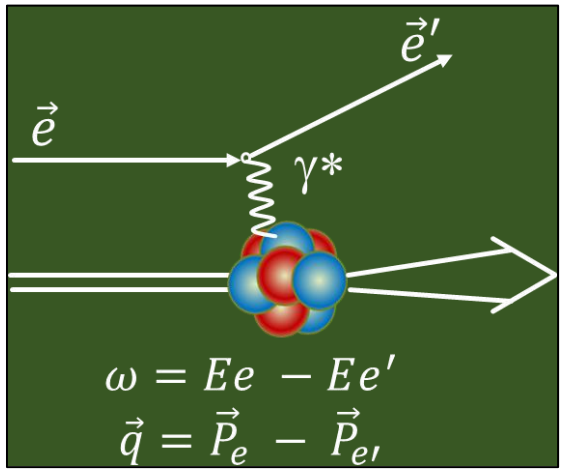
Contents

Motivation

Electron scattering off unstable nuclei

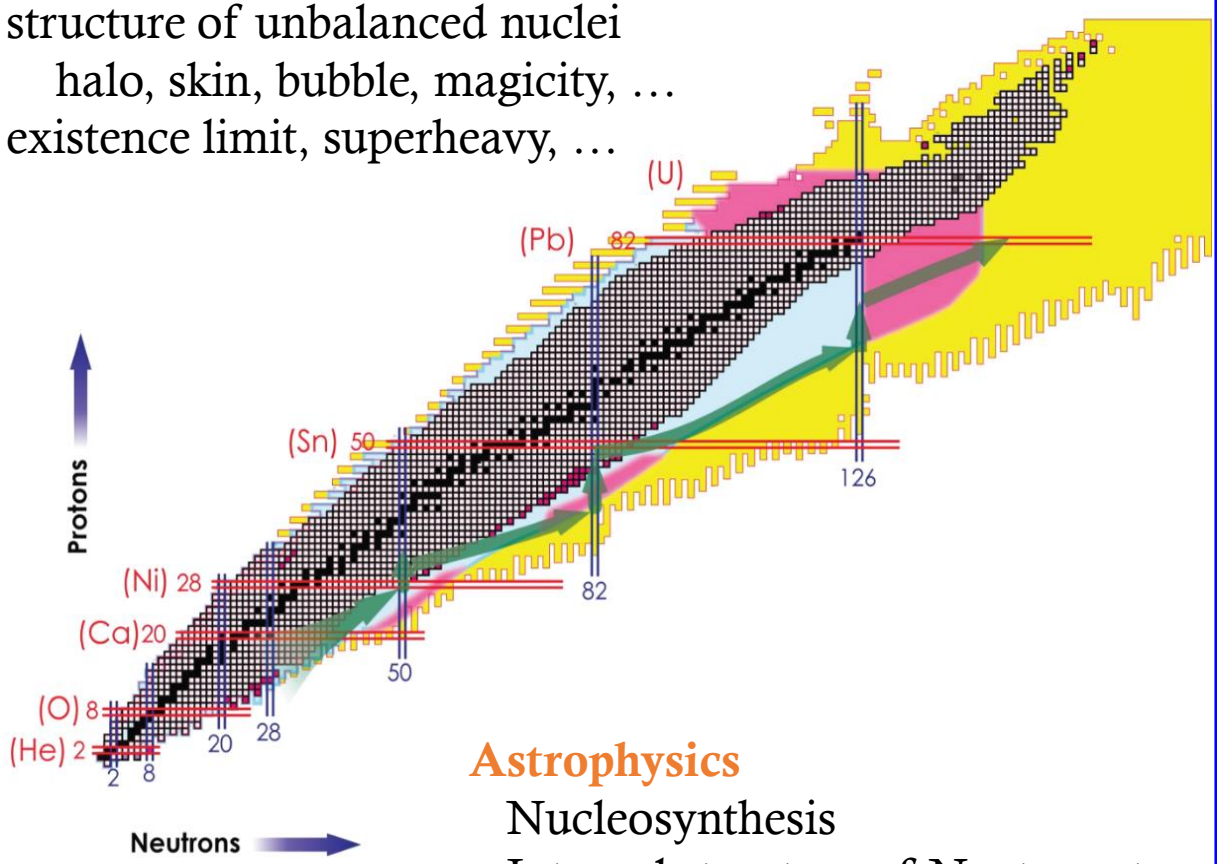
Direct and unambiguous information for structure study of atomic nuclei:

- Elementary point particle probe
- Well known electromagnetic interaction
  - EM structure of nucleus
  - probing whole volume of nucleus
  - one photon exchange approximation
- Independent variable q and ω



Nuclear physics

structure of unbalanced nuclei
halo, skin, bubble, magicity, …
existence limit, superheavy, …

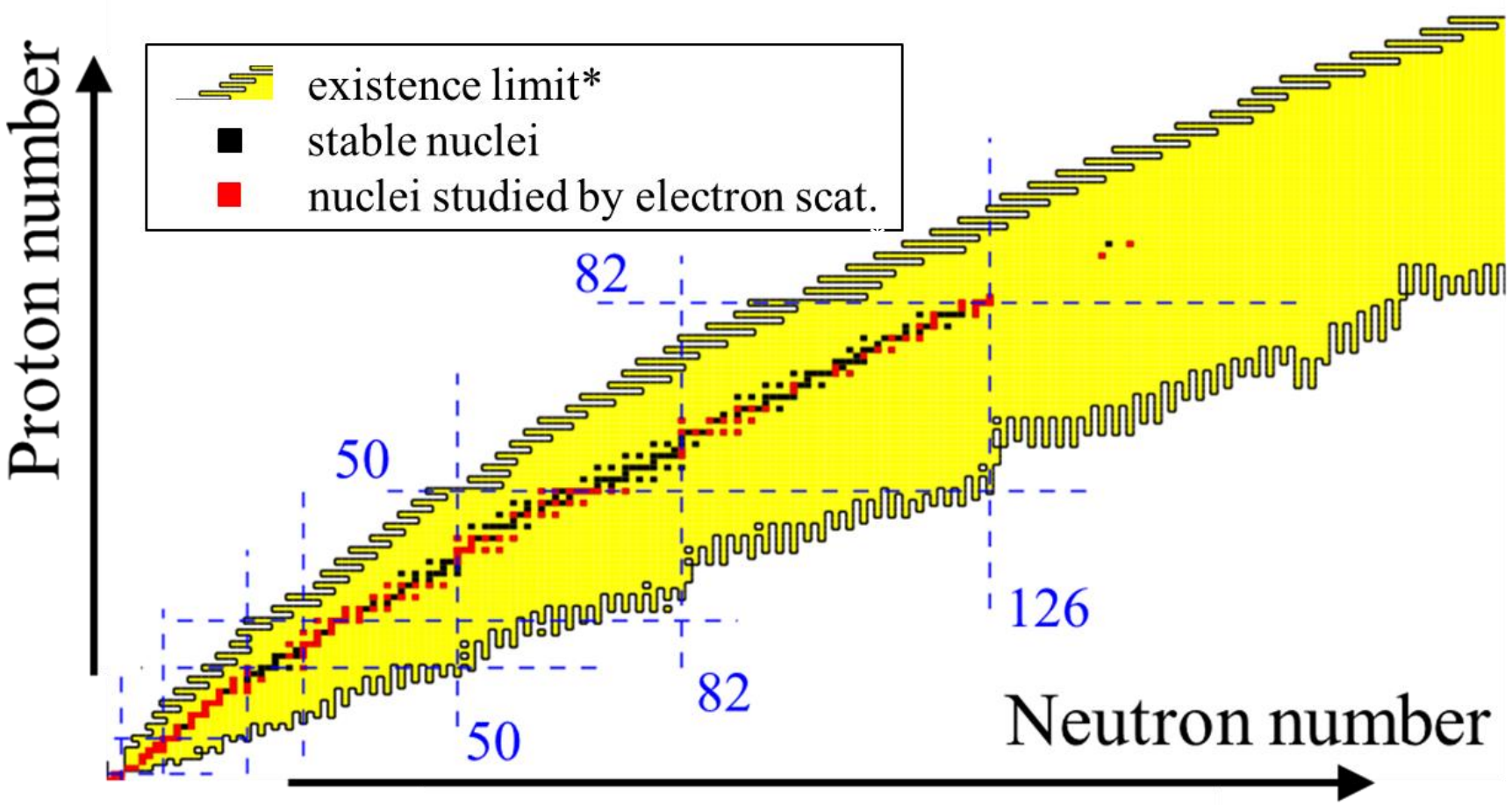


Astrophysics

Nucleosynthesis
Internal structure of Neutron star
…

Nuclei studied by electron scattering

Never applied for short-lived exotic nuclei



*KTUY mass formula, Progr.Theoret.Phys. 113(2005) 305

** H. deVries et al., At. Data Nucl. Data Tables 36, 495 (1987)
G. Fricke et al., At. Data Nucl. Data Tables 60, 177 (1995)

Electron scattering for stable nuclei

Yield = CrossSection($\propto Z^2$) × Luminosity × $d\Omega$

Luminosity : overlap between beam and target

Required Luminosity [/cm^2/s]
for mid-heavy nuclei

10^{27} 10^{29} 10^{31}

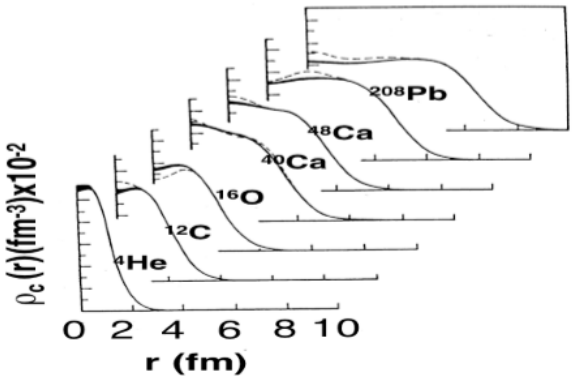
elastic scattering

inelastic scattering

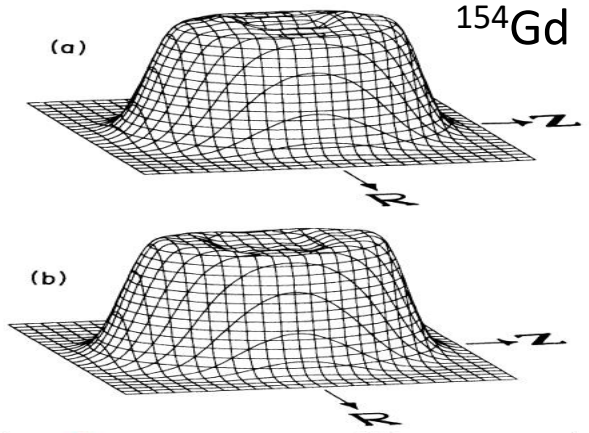
quasi-elastic (e,e'p

magnetic sc

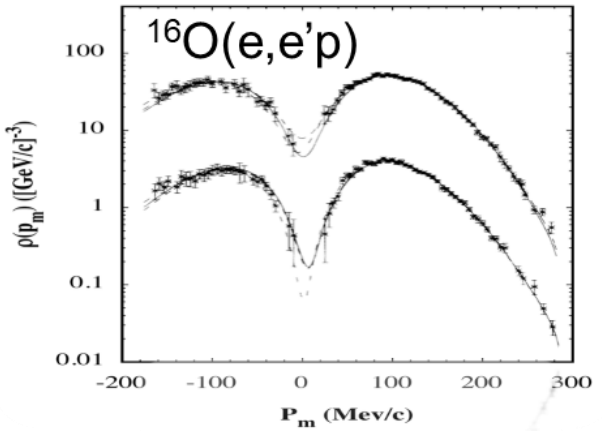
elastic scattering
→ charge distribution



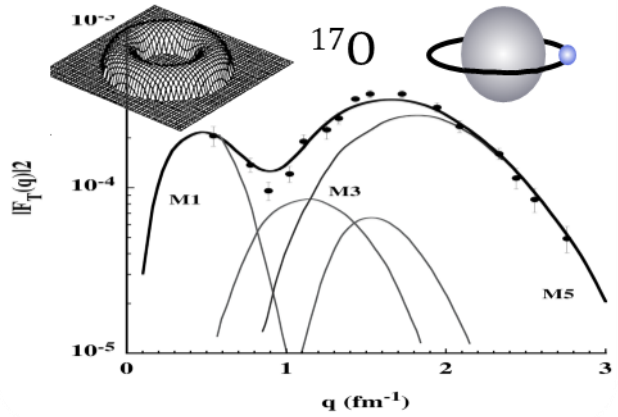
elastic + inelasticscattering
→ deformation



quasi-elastic (e,e'p)
→ S-factor



magnetic scattering
→valence neutron



Elastic electron scattering for spin-less nuclei

- Largest cross section among e-scatterings
- Gross shape of charge distribution $\rho_c(r)$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot |Fc(q)|^2$$

Cross section of Mott scattering

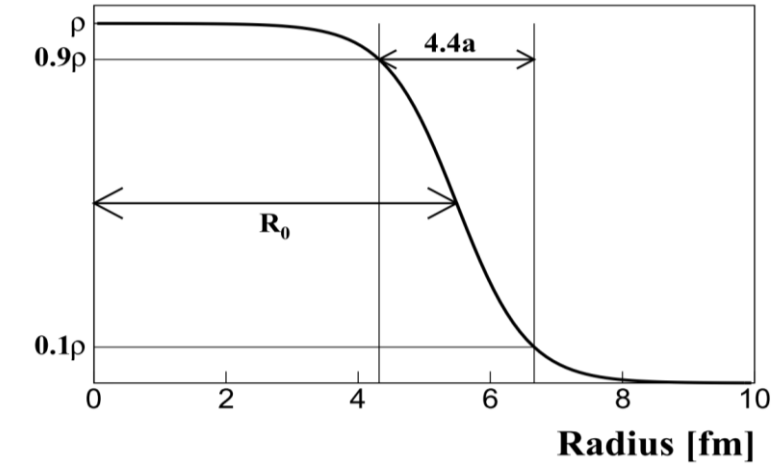
Form factor

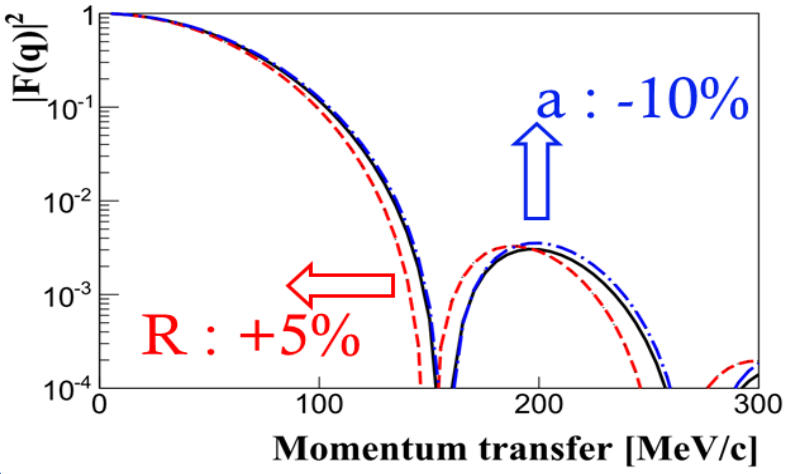
$$Fc(q) = \int \rho_C(\vec{r}) e^{i\vec{q}\vec{r}} d\vec{r}$$

Charge density distribution

L=10^{27} [$cm^{-2}s^{-1}$] is required
to determine the radius and diffuseness
of Z~50 medium-heavy nuclei

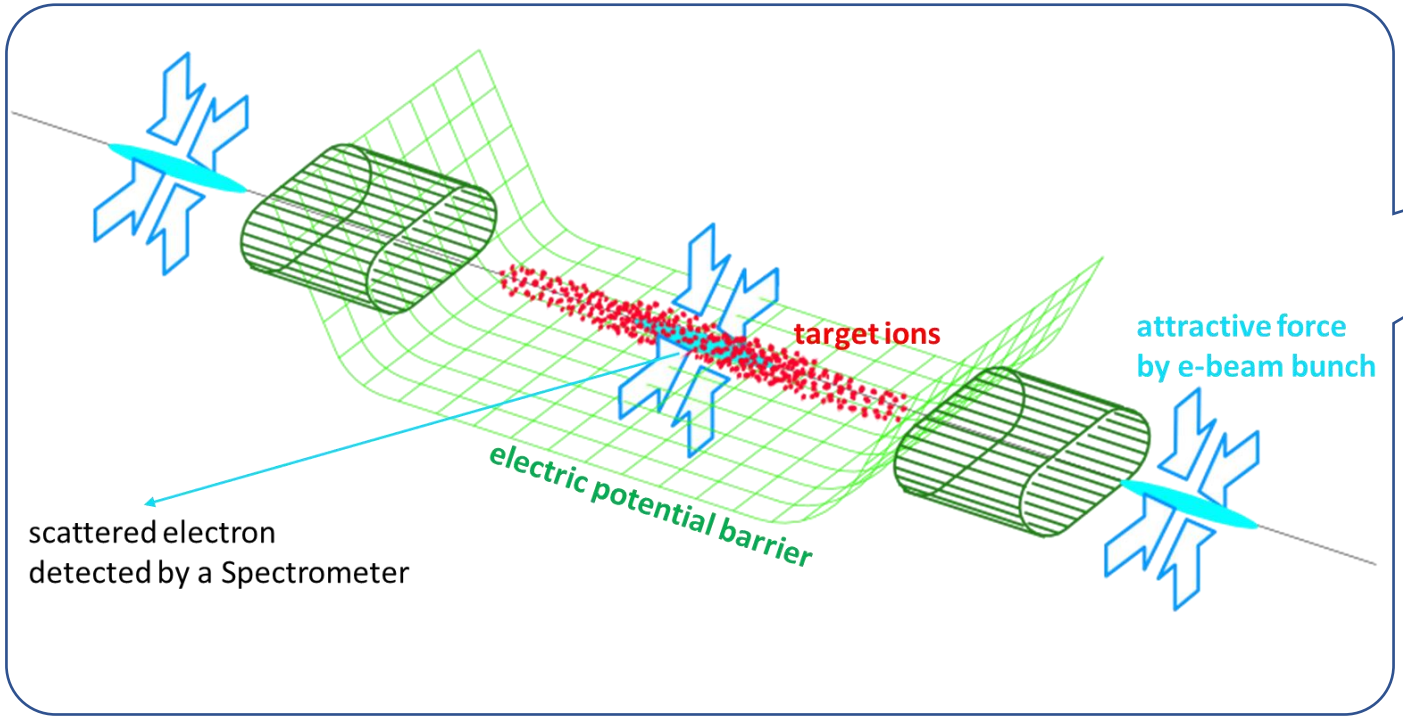
$$\rho_C = \rho/(1 + e^{(r-R)/a})$$

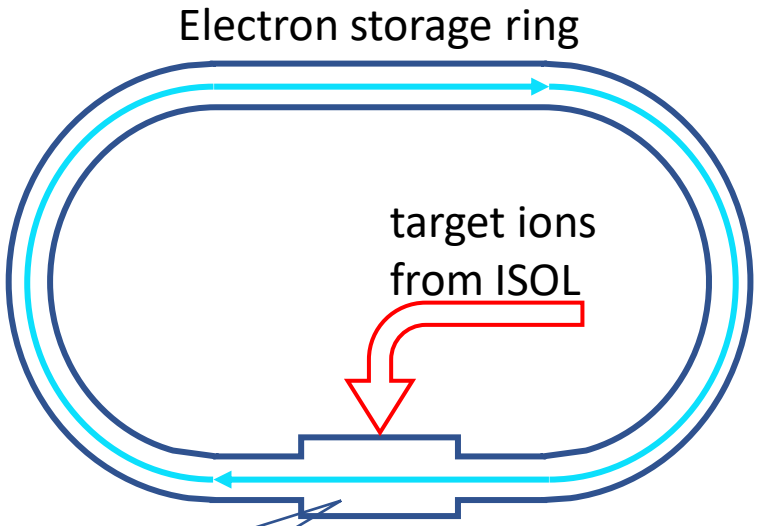




SCRIT (Self-Confining Radioactive isotope Ion Target)

Ion trapping phenomena : Transverse trapping
(known as a serious problem of e-storage ring)
+
Electric potential barrier : Longitudinal trapping





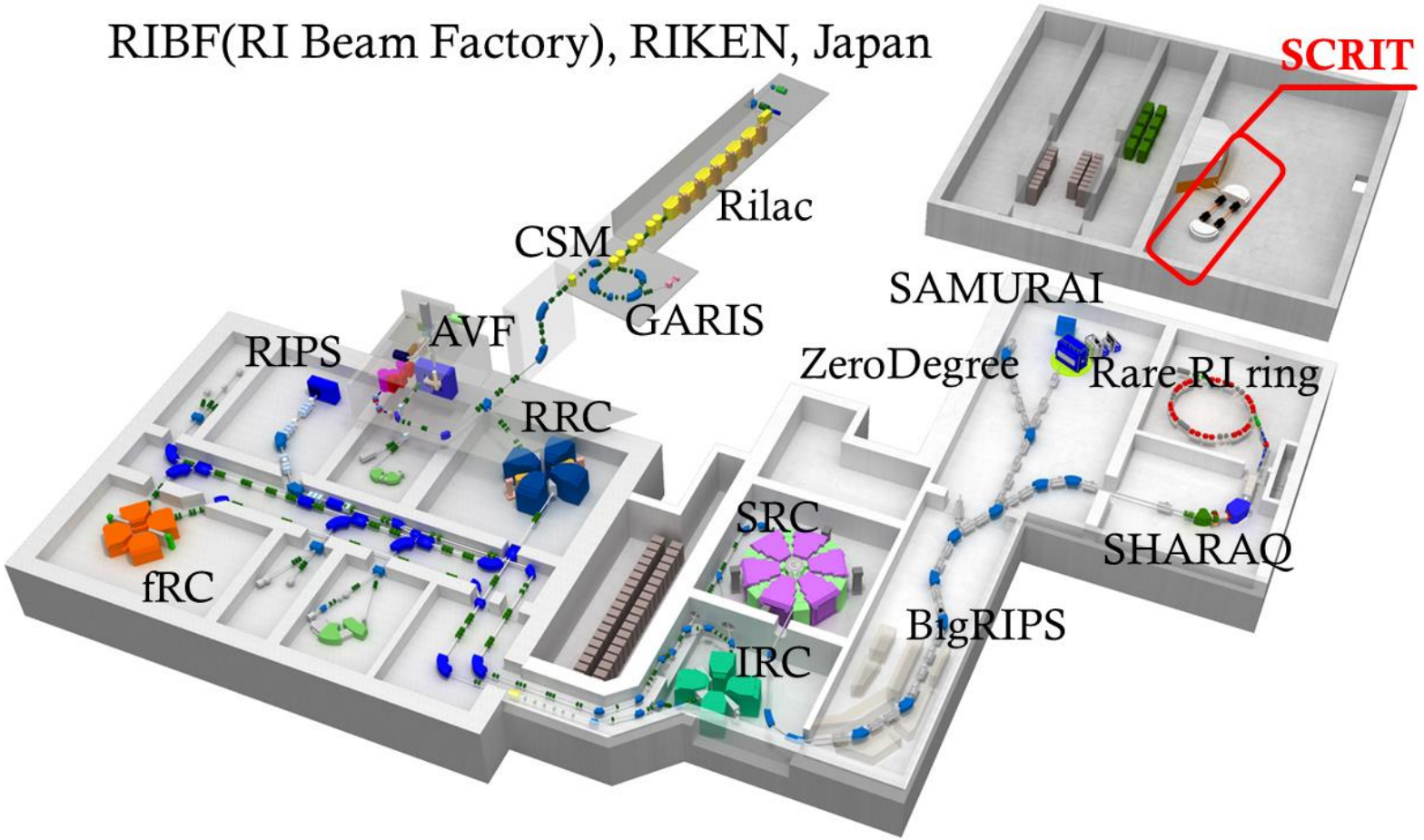
Beam : Ie~200 mA, size~mm^2
10^8 RI ions introduced
Target thickness ~ 10^9 cm^{-2}
} **L~$10^{27}$$cm^{-2}$$s^{-1}$**

⇔ ~ 10^{20} cm^{-2} for usual e-scattering

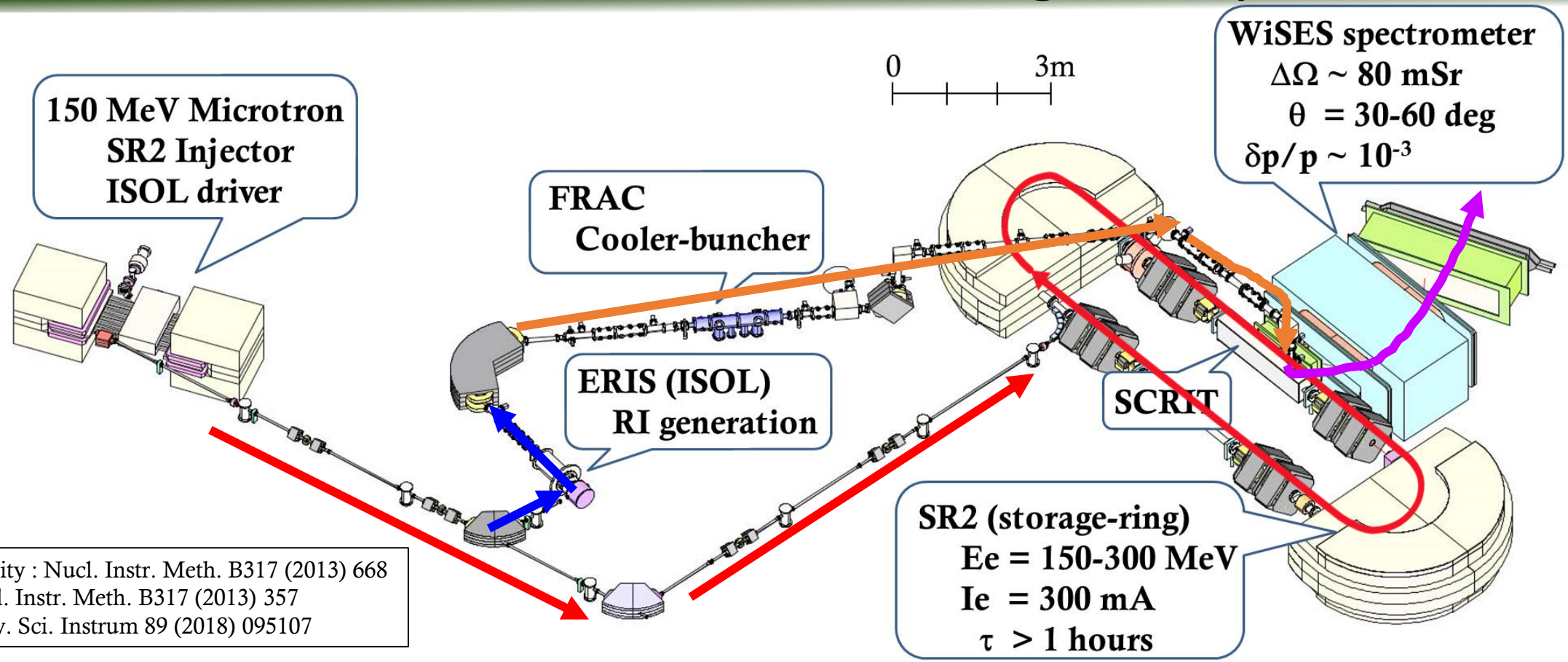
Contents

SCRIT electron scattering facility at RIKEN RIBF

The world's first and unique facility dedicated to electron scattering off unstable nuclei.



Overview of SCRIT electron scattering facility



SCRIT facility : Nucl. Instr. Meth. B317 (2013) 668
ERIS : Nucl. Instr. Meth. B317 (2013) 357
FRAC : Rev. Sci. Instrum 89 (2018) 095107

Injection to SR2
Ee=150-300MeV
Ie=250mA

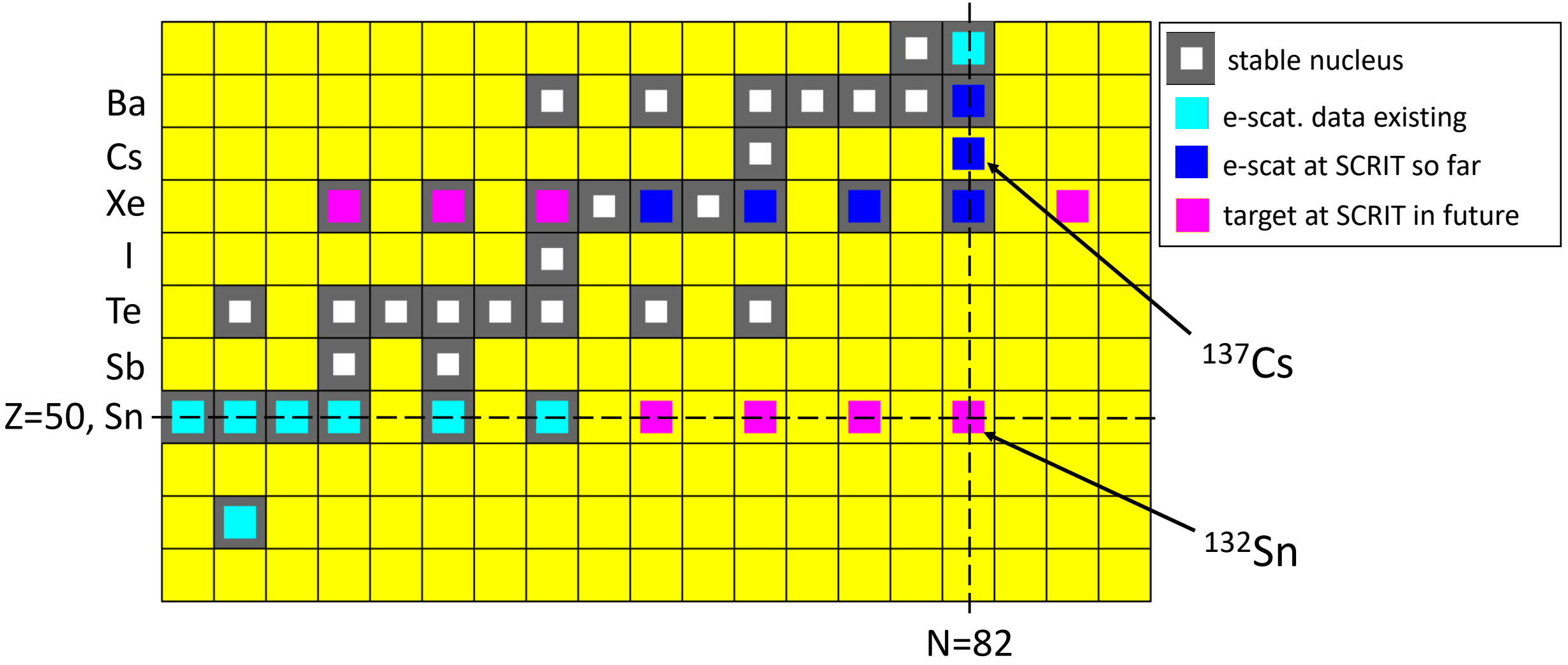
RI generation
via Uranium
photo-fission

Transporta
tion and
trapping

Measuring
scattered
electrons

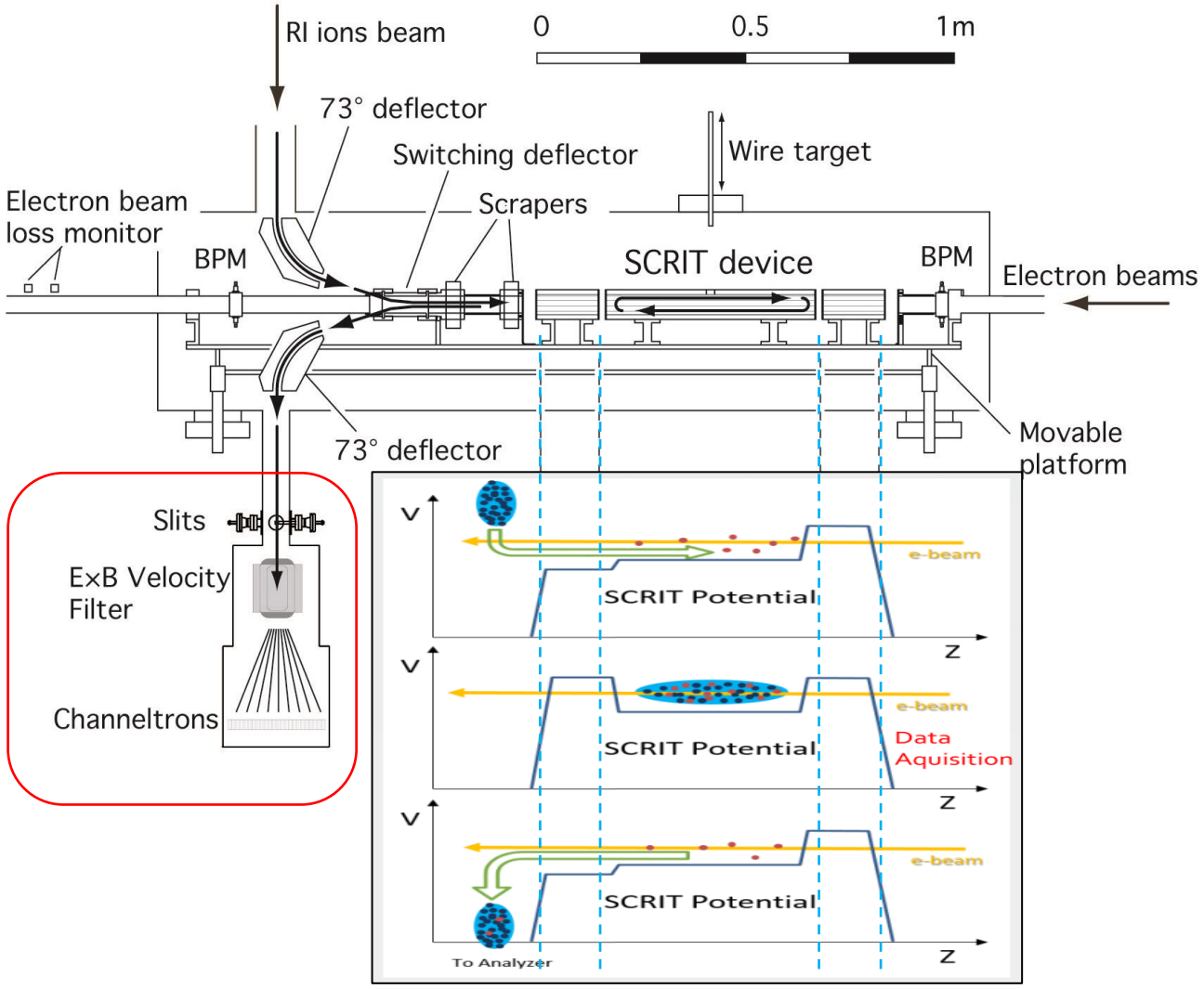
Generation, **Transportation** and **Trapping** have been developed for the last several years.

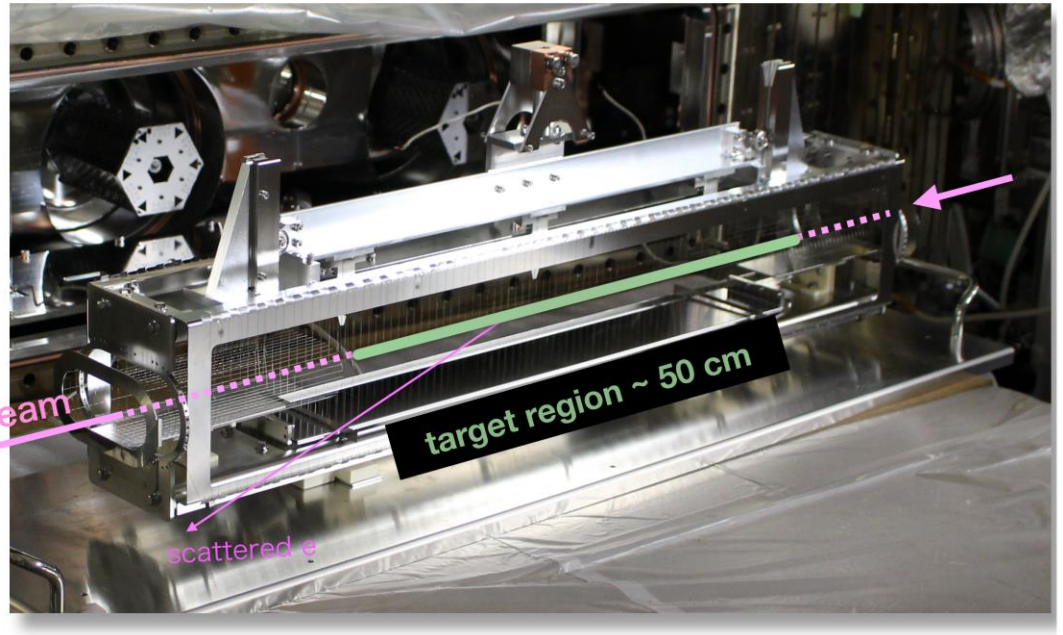
e-scattering at the SCRIT facility



Characteristics of the SCRIT system and the transportation have been also studied and developed at these experiments.

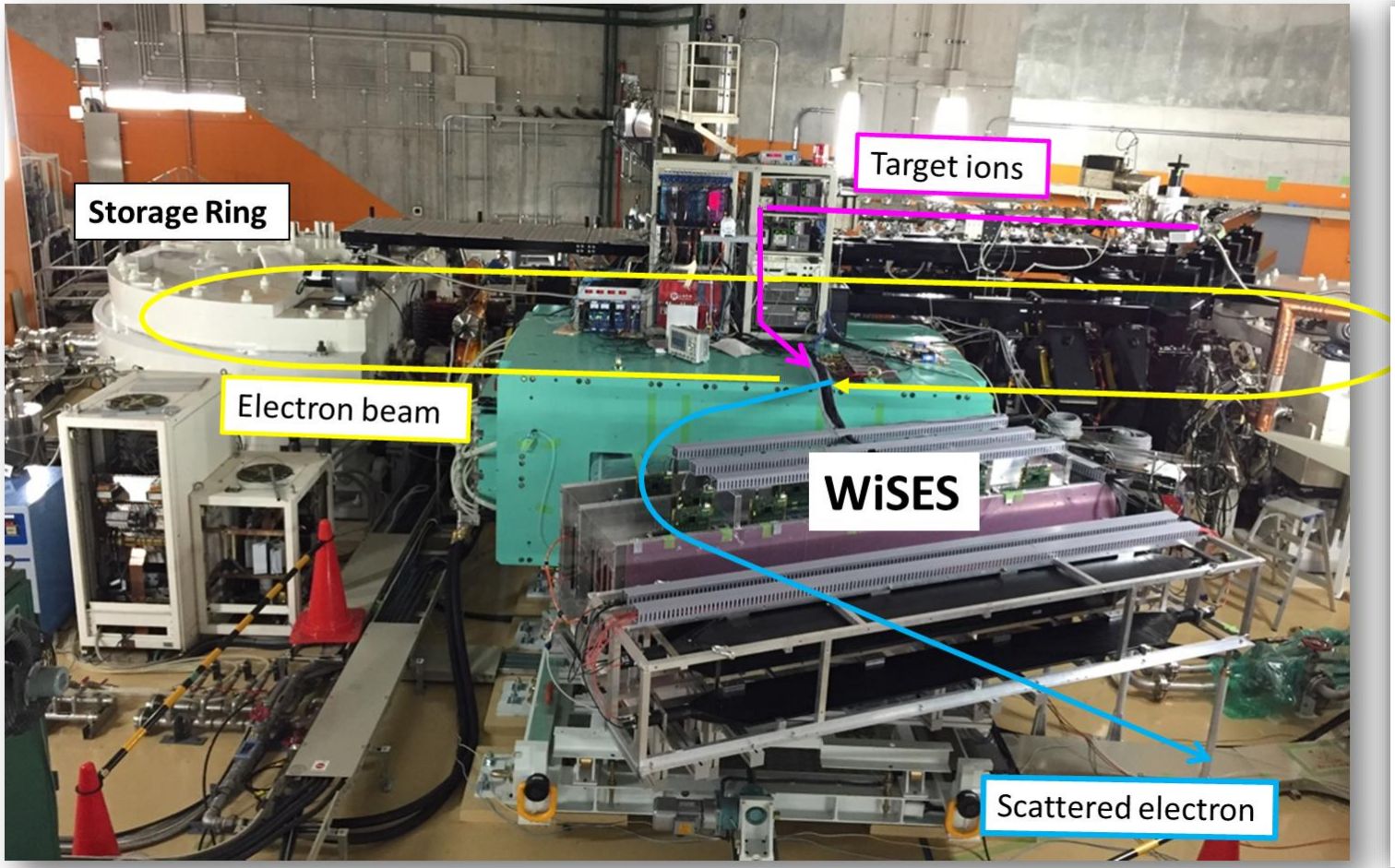
SCRIT system

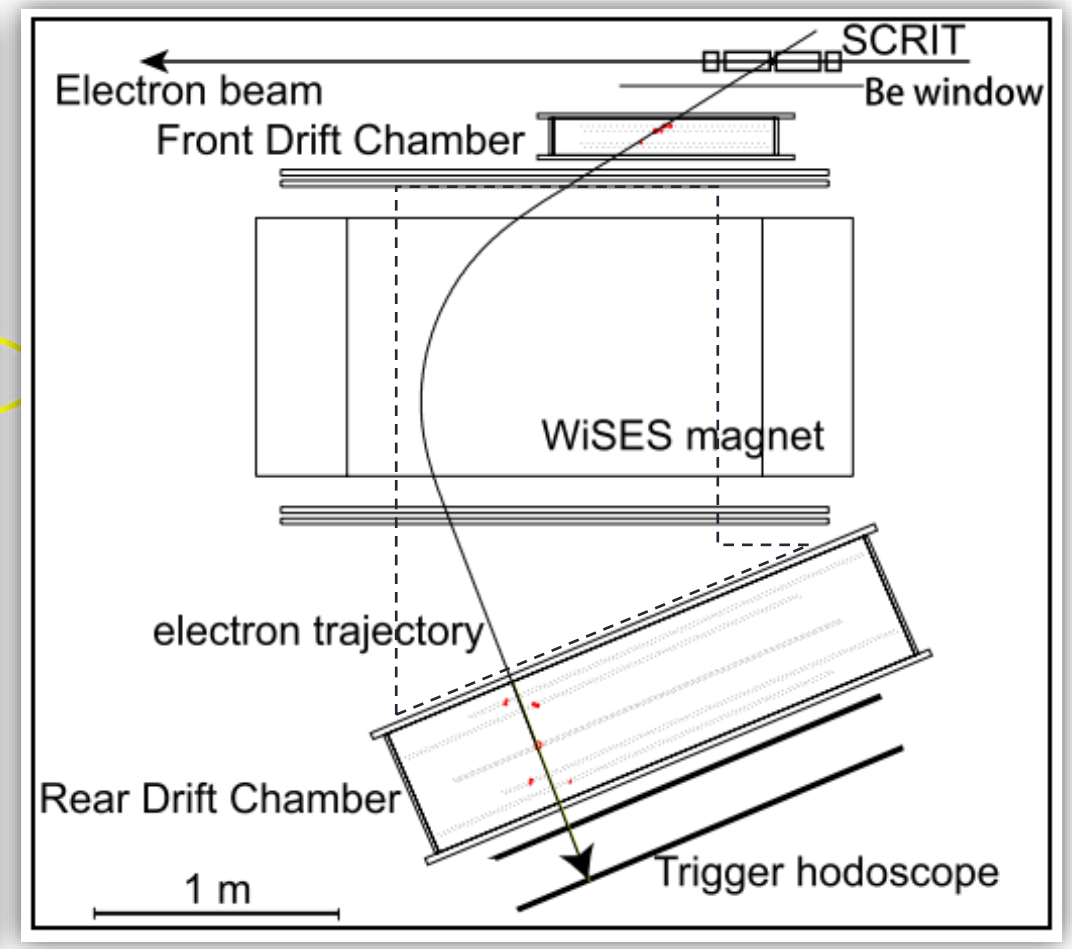




Frequency ~ Hz

WiSES (Window-frame Spectrometer for Electron Scattering)





First physics run at SCRIT facility

^{132}Xe target : stable, never studied by e-scat.

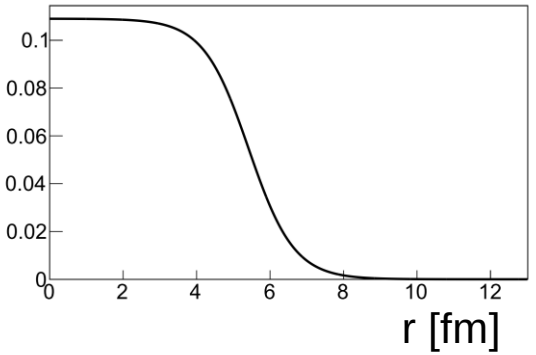
L ~ 10^{27} cm^{-2}s^{-1} with $N_{trapped}$ ~ 10^{8} ions/pulse

Ee = 150, 200, 300 MeV

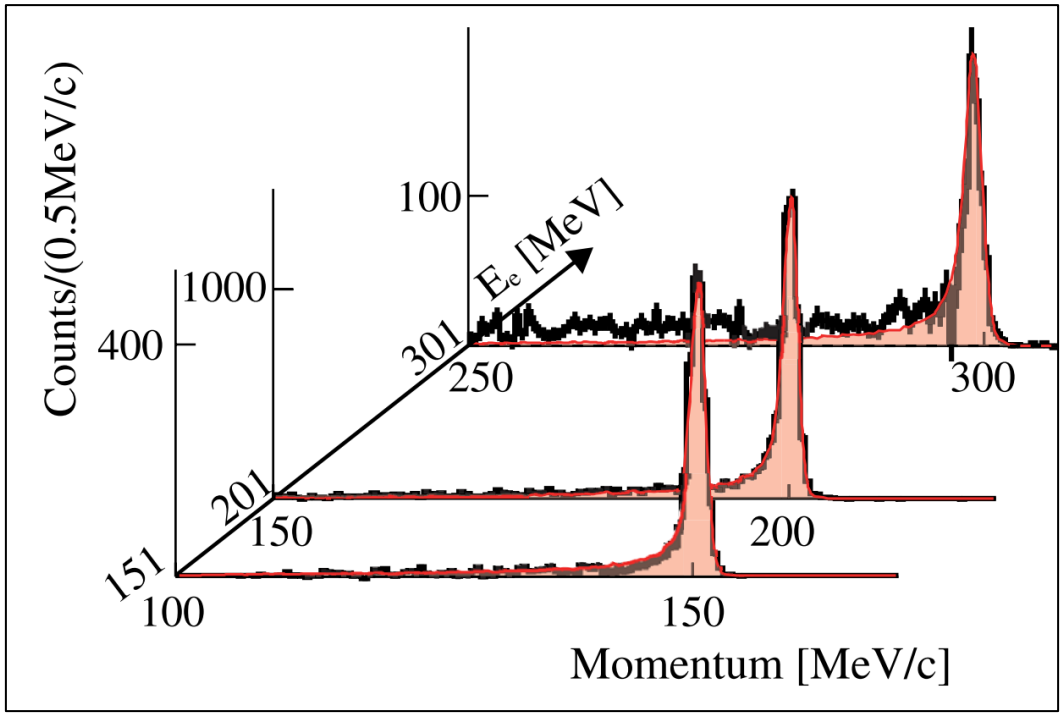
θ = 30 - 60 deg

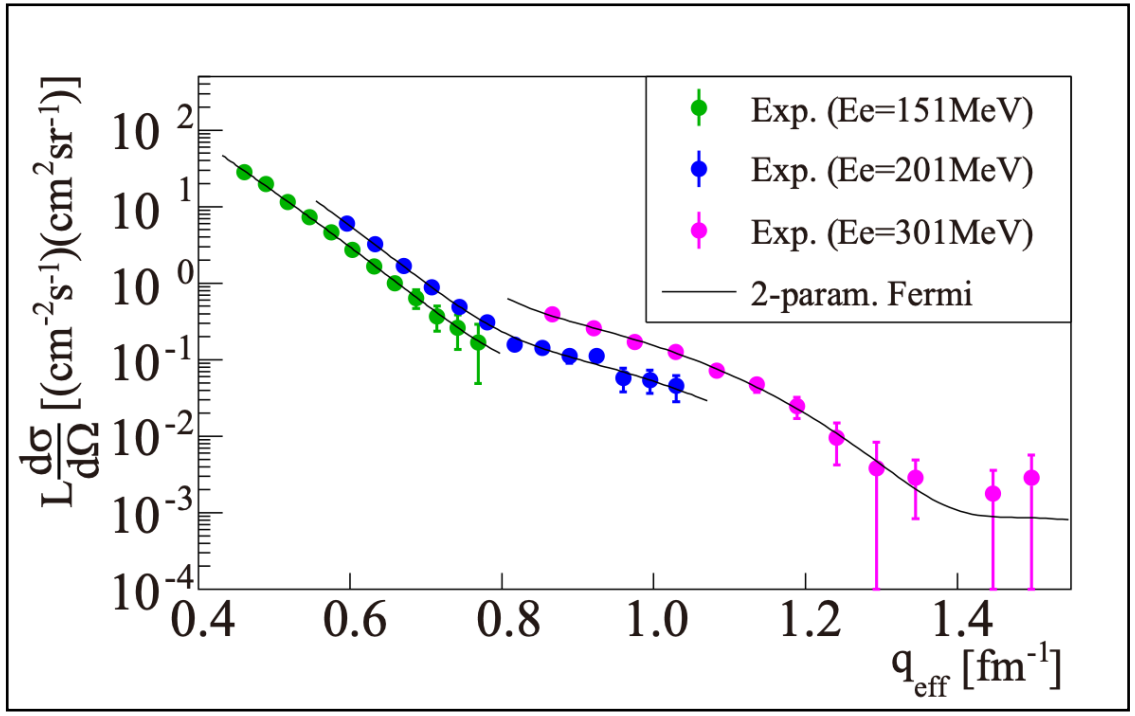
} q = 0.4 – 1.5 fm^{-1}

$$\rho_C = \rho/(1 + e^{4.4(r-C)/t})$$



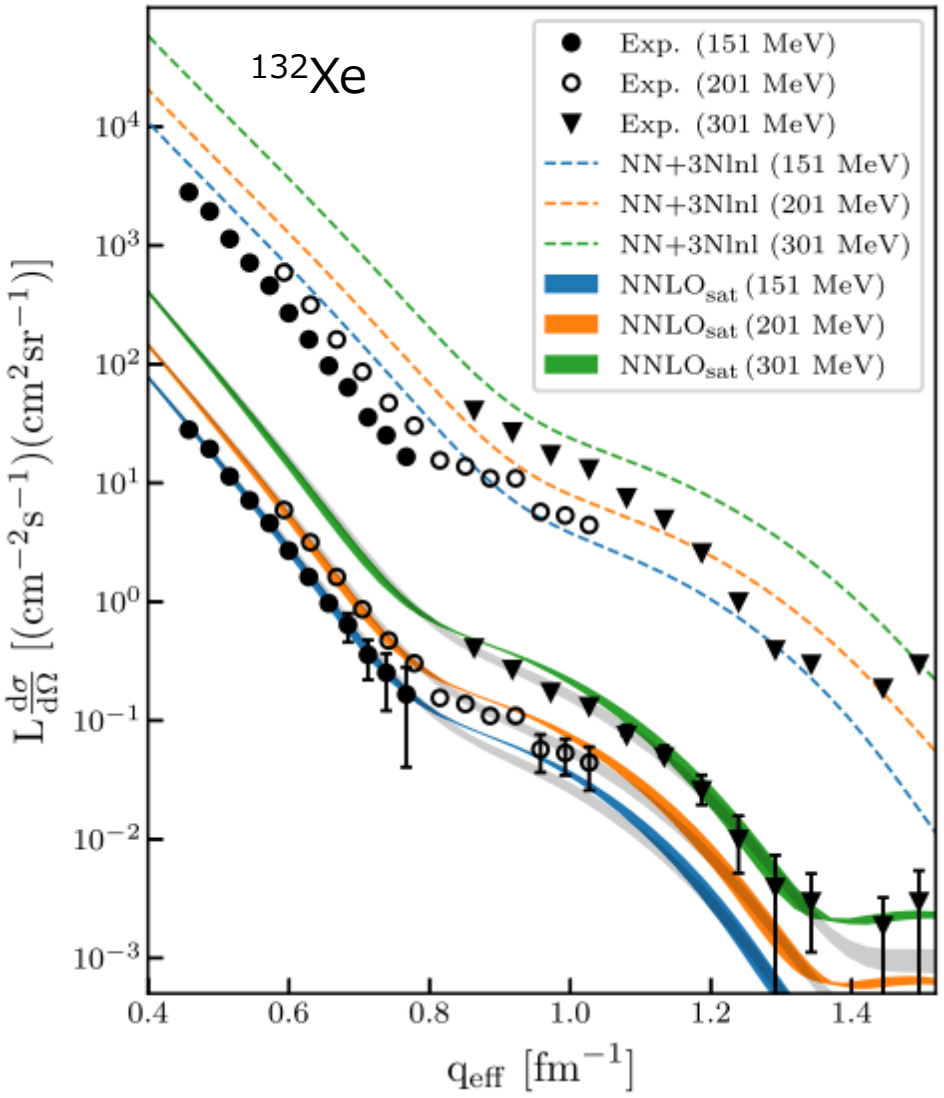
$$C = 5.42^{+0.11}_{-0.08}$$
$$t = 2.71^{+0.29}_{-0.38}$$
$$\langle r \rangle^{1/2} = 4.79^{+0.12}_{-0.10}$$



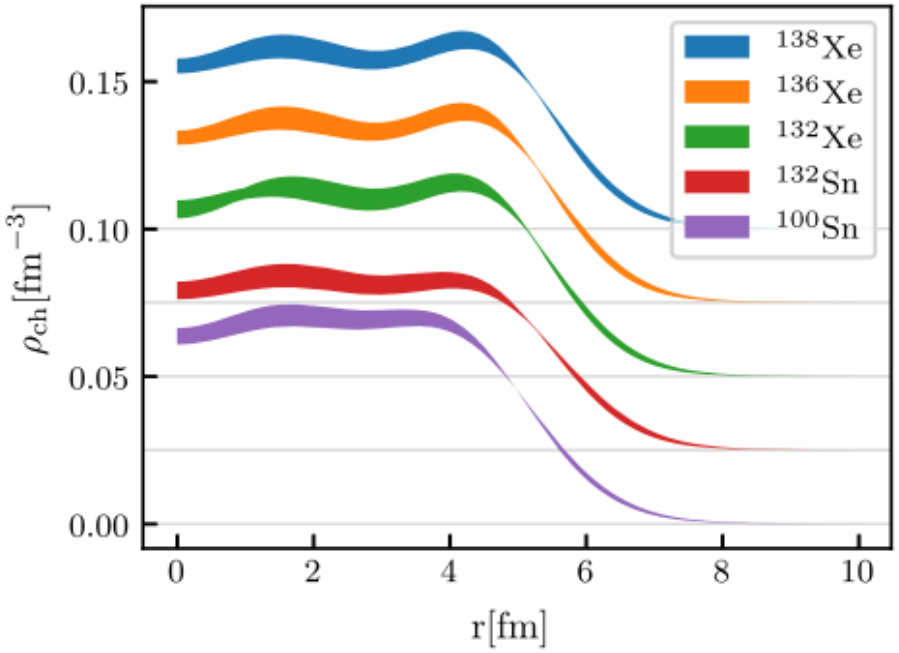


K. Tsukada *et. al*, Phys.Rev.Lett. 118 (2017) 262501

Comparison with calculation



- Recently, *ab initio* calculations for A~130 nuclei become available.
- Calculated Cross sections with NNLO$_{sat}$ chiral interaction almost agree with our results.
- Direct comparison between exp. data and theory can be realized including unstable nuclei near future.



P. Arthuis *et. al*, Phys.Rev.Lett. 125 (2020) 182501

Contents

Contents

n-th moments of charge distribution (ρ_c) and neutron distribution

based on:

- H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. (2019) 113D01
- H. Kurasawa, T. Suda and T. Suzuki, Prog. Theor. Exp. Phys. (2021) 013D02
- H. Kurasawa, T. Suzuki, Prog. Theor. Exp. Phys. (2022) 023D03

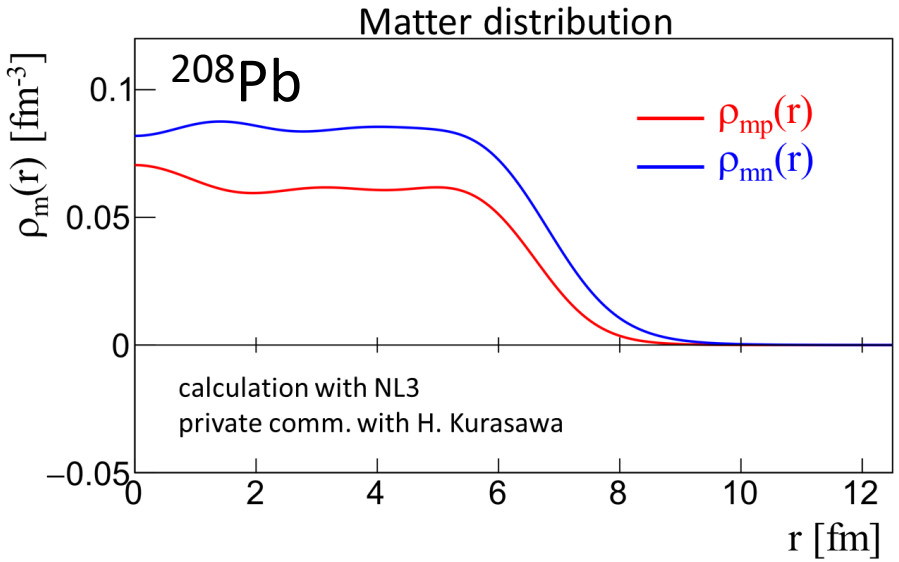
Nucleon distribution in Nucleus

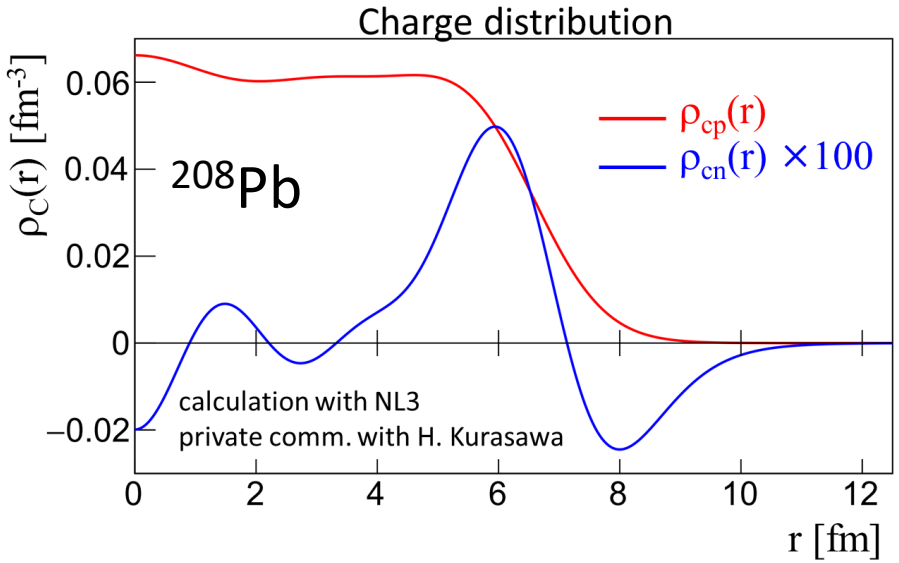
Proton and Neutron density distributions :
basic information of nuclear structure study

$\rho_{mp}(r) \sim \rho_c(r)$: precisely determined by e-scat.

$\rho_{cn}(r)$: too small

$\rho_{mn}(r)$: reaction c.s., p-scat., …





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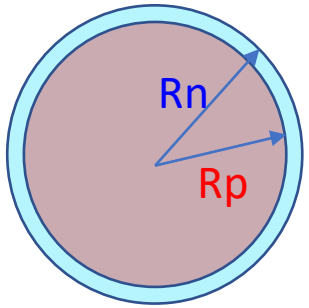
$\rho_{mp}(r) \sim \rho_c(r)$: precisely determined by e-scat.

$\rho_{cn}(r)$: too small

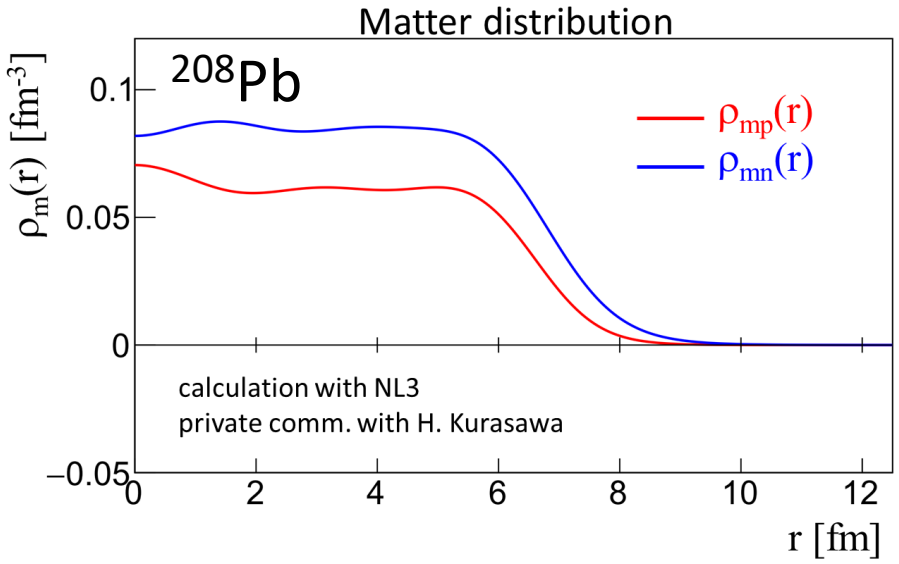
$\rho_{mn}(r)$: reaction c.s., p-scat., …

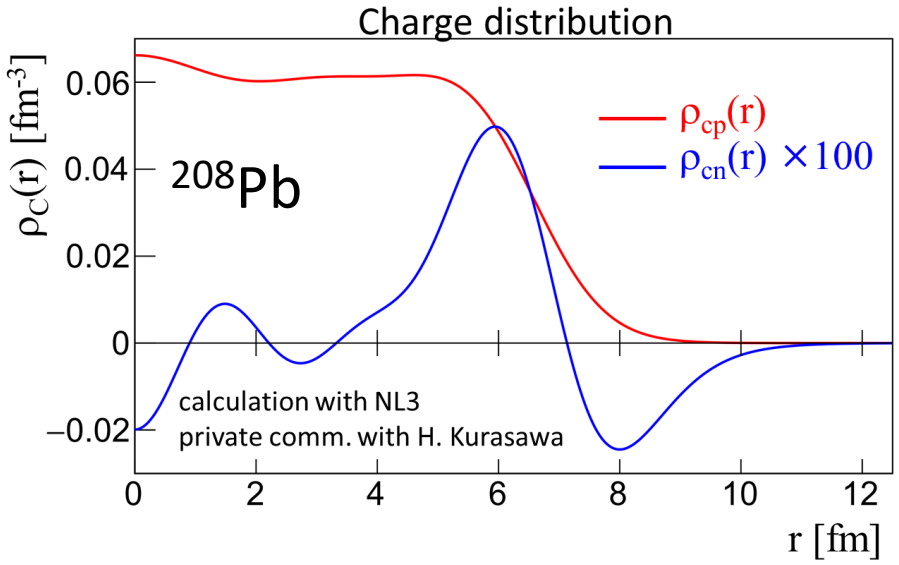
Strong correlation between Neutron skin and symmetry energy of the EOS of nuclear matter.



neutron skin δR = Rn – Rp
δR = 0.2-0.3 fm
Rp = 5.5 fm for ^{208}Pb

A less ambiguous method is desired.



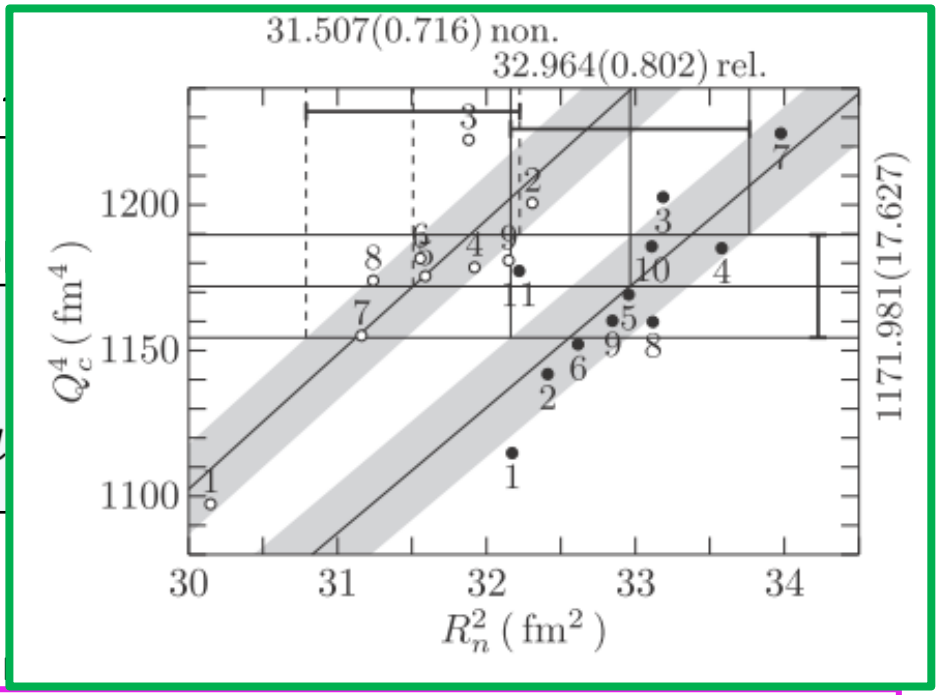


Neutron contribution in nucleus

Higher moments of nuclear charge density provide information of radius of neutron distribution.

H. Kurasawa, T. Suda and

Regression analysis



2nd moment

Full re

$$< r_c^2 > = \int r^2 \rho_C(r) d^3r$$

$$= < r^2_{p(point)} > + < r_p^2 > + \frac{N}{Z} < r_n^2 > + (rela$$

constraint for nuclear structure model

4th moment

Full relativistic

$$< r_c^4 > = \int r^4 \rho_C(r) d^3r$$

$$= < r^4_{p(point)} > + \frac{10}{3} < r^2_{p(point)} >< r_p^2 >$$

$$+ \frac{10}{3} < r^2_{n(point)} >< r_n^2 > \frac{N}{Z}$$

$$+ (relativistic\ corr.)$$

Radius of neutron dist. explicitly appears!

4th moment from ρ_c

Charge density dist. of ^{208}Pb and ^{48,40}Ca are well known by electron scattering.

$$< r_c^4 > = \int r^4 \rho_c(r) d^3r$$

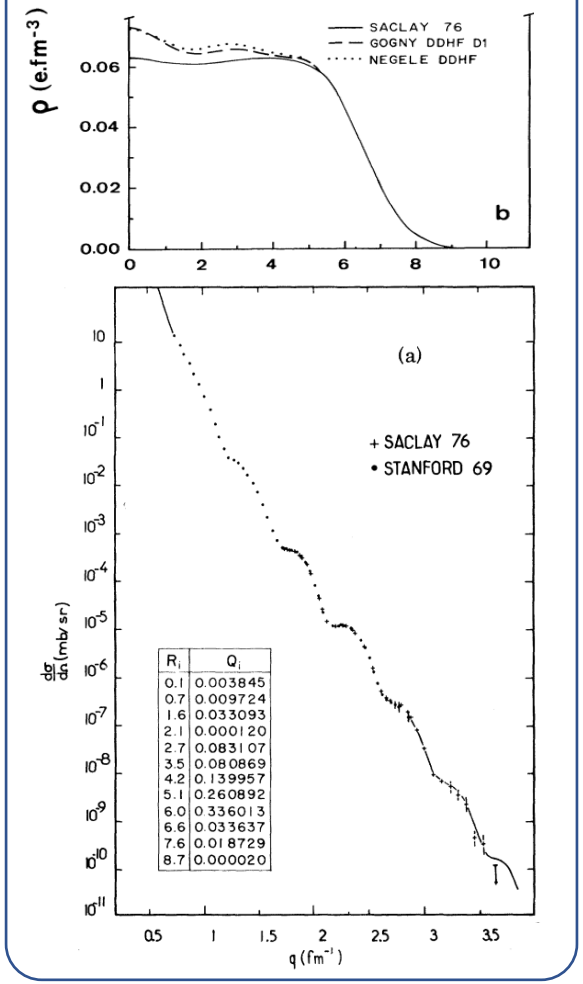
	Rp [fm]	Rn [fm]	δRn [fm]	δRn [fm]
^{208}Pb	5.454(0.013)	5.728(0.057)	0.282(0.024)	0.283(0.071)
^{48}Ca	3.378(0.005)	3.597(0.021)	0.219(0.013)	0.121(0.026)
^{40}Ca	3.346(0.002)	3.296(0.002)	-0.050(0.004)	-
	KS-method			CREX, PREX

H. Kurasawa, T. Suda and T. Suzuki, PTEP 2021 (2021) 1, 013D02

- Precise determination of ρ_C is also not easy.
- Other targets, especially RI are more hopeless.

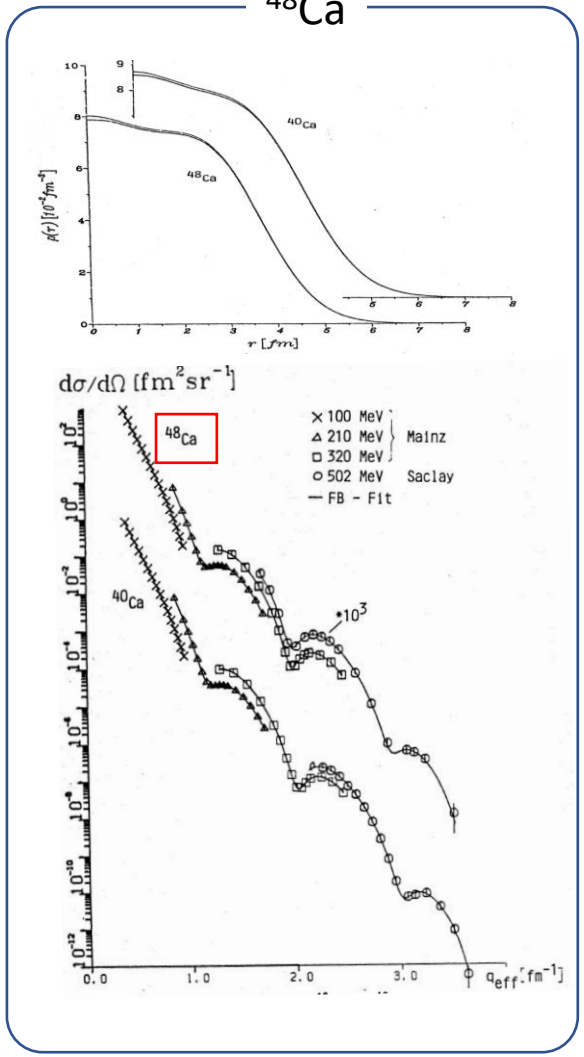
→ Direct measurement of $<r_C^4>$

^{208}Pb



B. Frois *et. al.*, Phys.Rev.Lett.38,152 (1977)

^{48}Ca



H. J. Emrich, PhD thesis, Johannes-Gutenberg-University, Mainz (1983)

Direct measurement of 4th moment in low-q

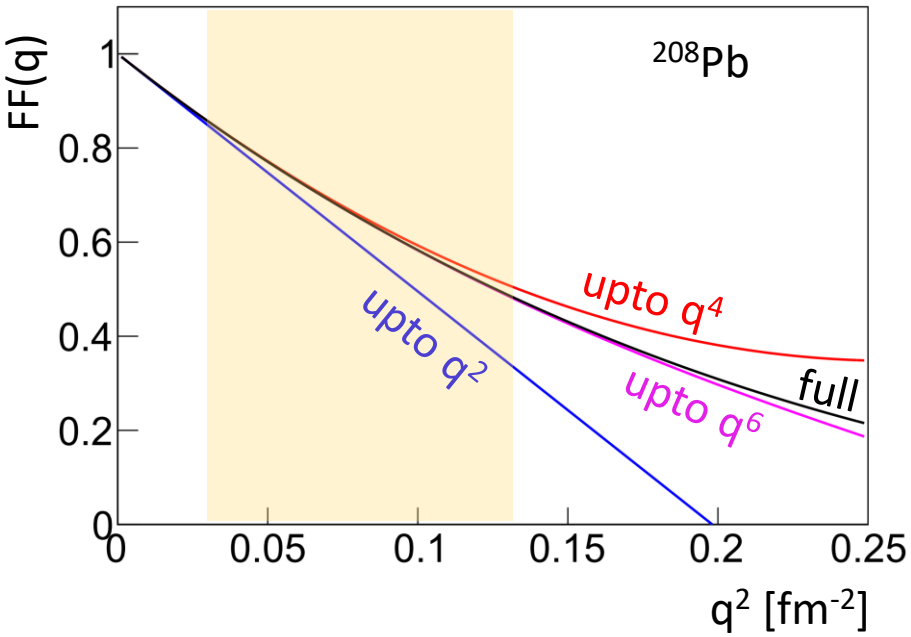
- q-dependence of the cross section,

$$\frac{d\sigma_{Mott}}{d\Omega} \propto 1/q^4$$ ⇨ Huge cross section in low-q region

- Series expansion

$$F_C(q) = \int \rho_C(\vec{r}) e^{-i\vec{q}\vec{r}} d^3r$$

$$\sim 1 - \underbrace{\frac{\langle r_C^2 \rangle}{3!} q^2}_{\text{isotope shift}} + \underbrace{\frac{\langle r_C^4 \rangle}{5!} q^4}_{\text{wanted}} - \underbrace{\frac{\langle r_C^6 \rangle}{7!} q^6}_{\text{disregarded}} + \cdots$$

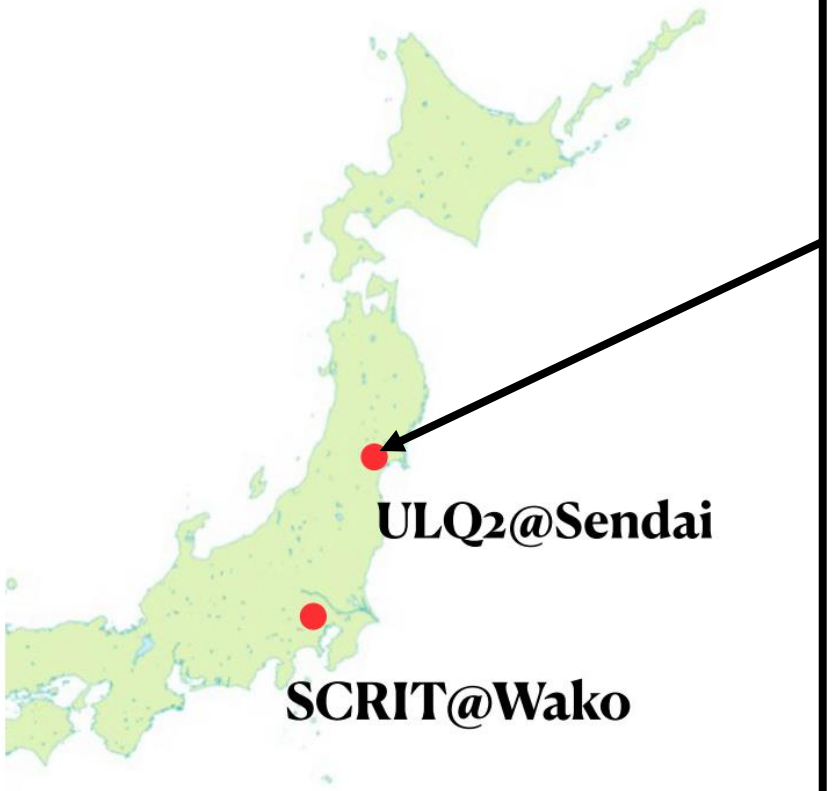


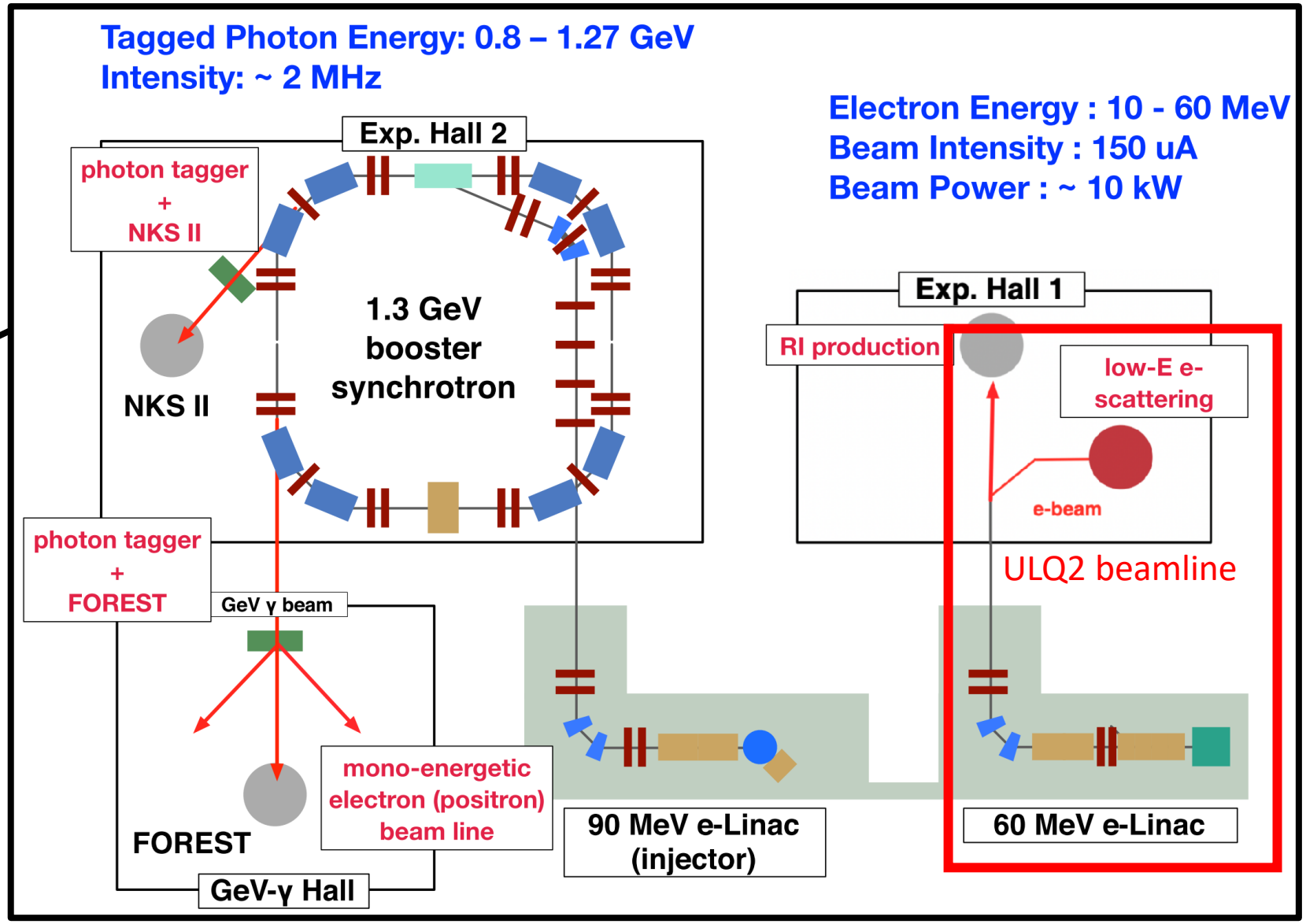
Possibility of e-RI scattering with low-luminosity

e.g. ^{132}Sn target @SCRIT

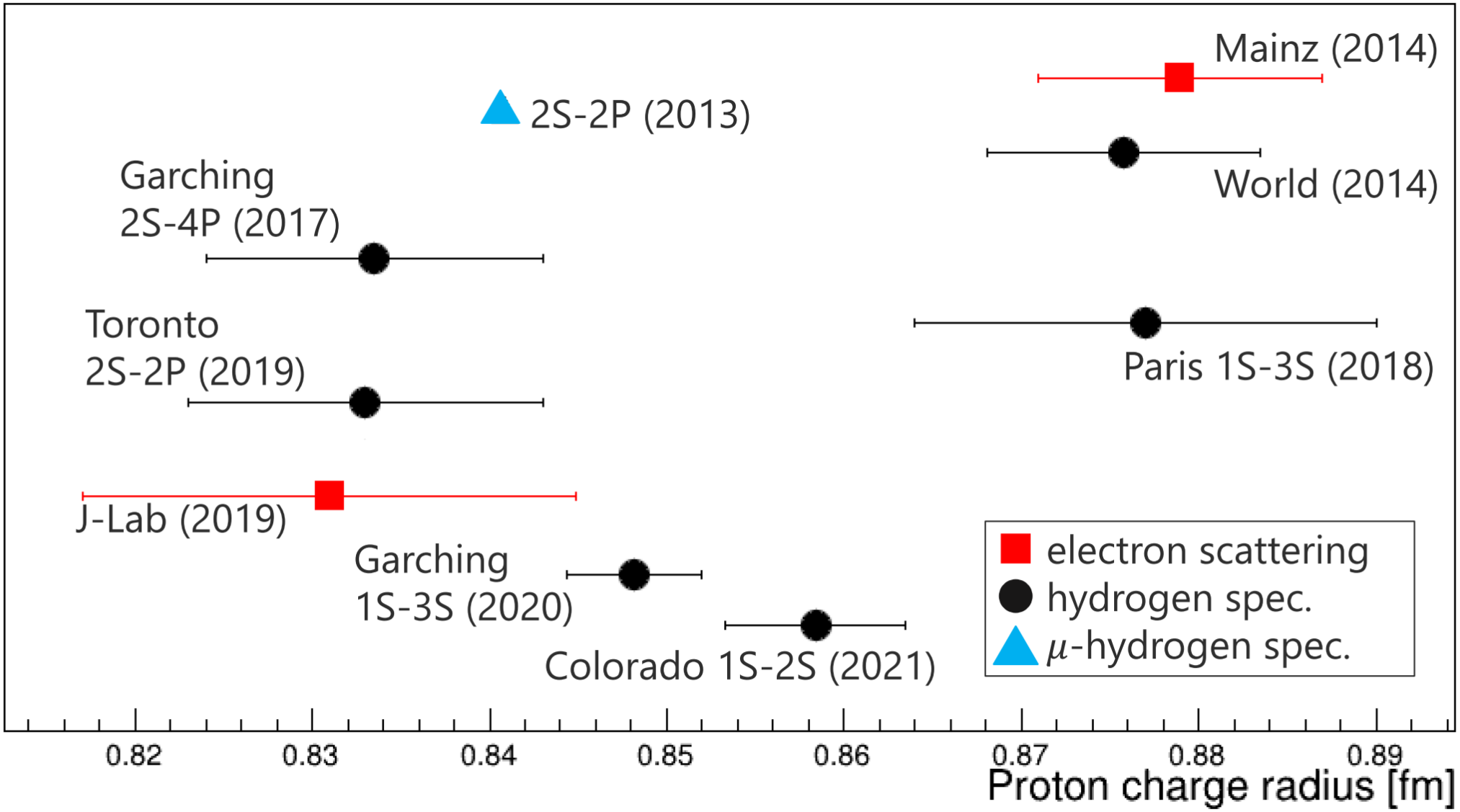
We already started a feasibility study.

Research Center for ELectron-PHoton Science (ELPH), Tohoku University





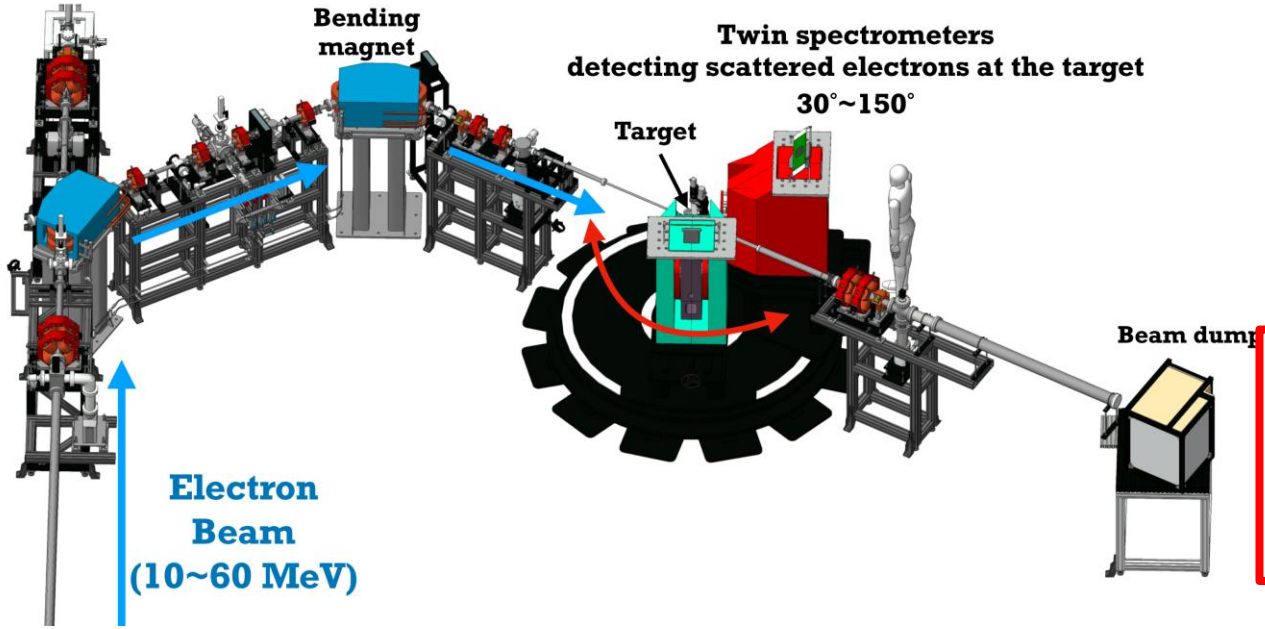
Present status of proton radius puzzle

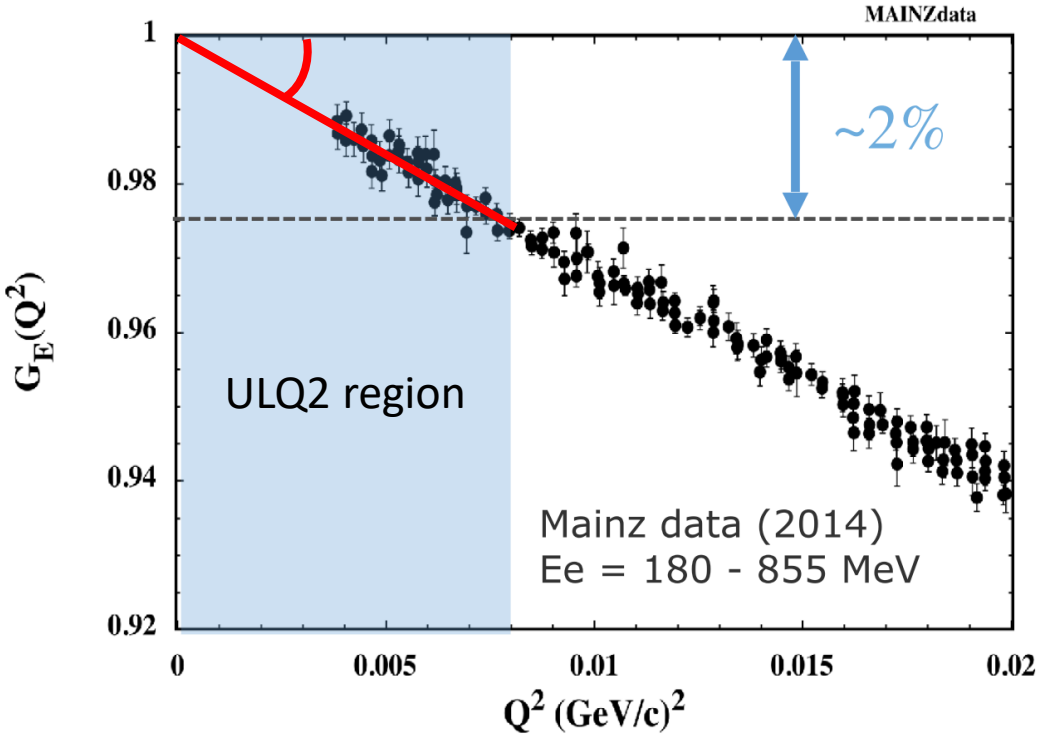


ULQ2 (Ultra Low-Q^2) project

Purpose : Determination of proton radius: $r_p^2 \equiv -6\frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2\to 0}$

1. Extreme low-Q^2 , $0.0003 \le Q^2 \le 0.008$ $(GeV/c)^2$
2. Absolute cross section with 10^{-3} accuracy
   by relative measurement of e+C and e+H with CH_2
3. Separation of G_E and G_M by Rosenbluth method
   → Ee = 10-60 MeV, θ = 30-150°





Performance studies are almost finished.
Physics RUN will be performed within a year.
CD_2 target is also planned.

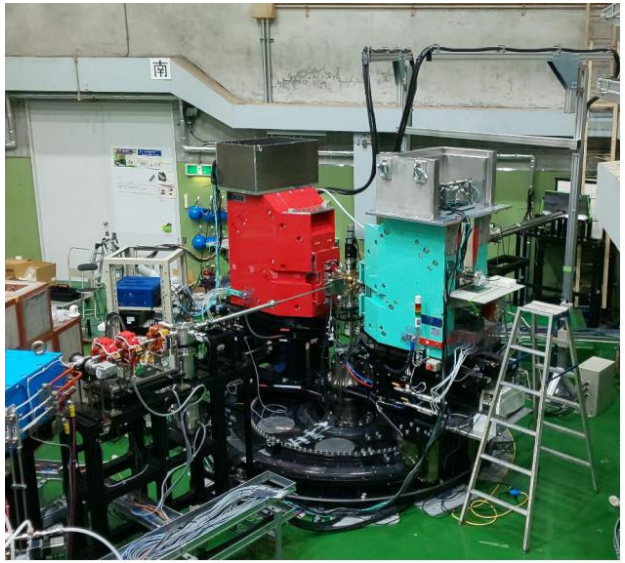
LEEP (Low Energy Electron scattering for ^{208}Pb) experiment

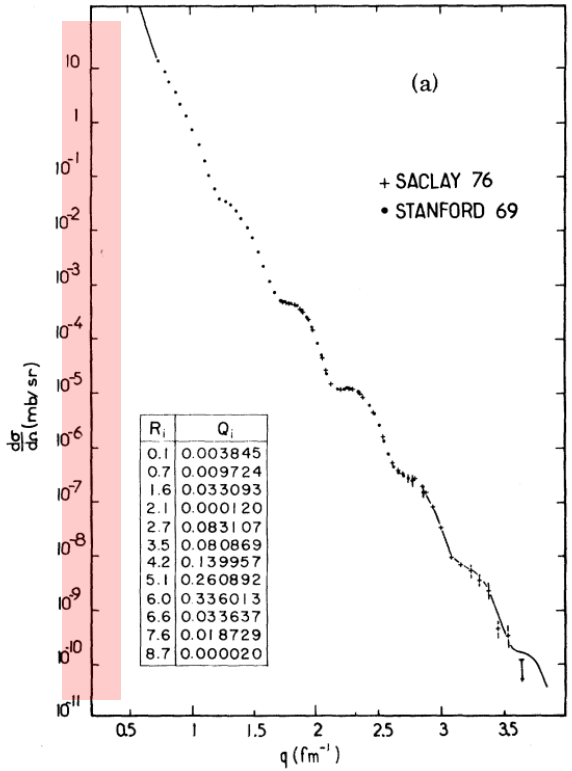
^{208}Pb(e,e) at the ULQ2 beam line

Ee : 10 – 50 MeV

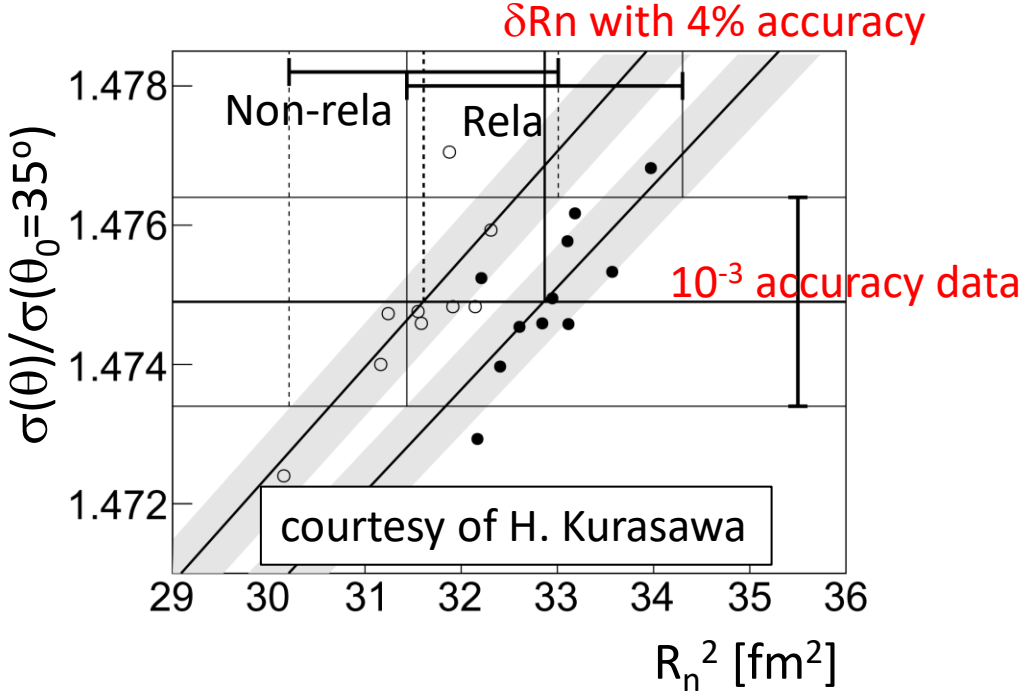
θ : 30 – 150°

q : 0.17 – 0.36 fm^{-1}





$\sigma(\theta)/\sigma(\theta_0)$ vs R_n^2

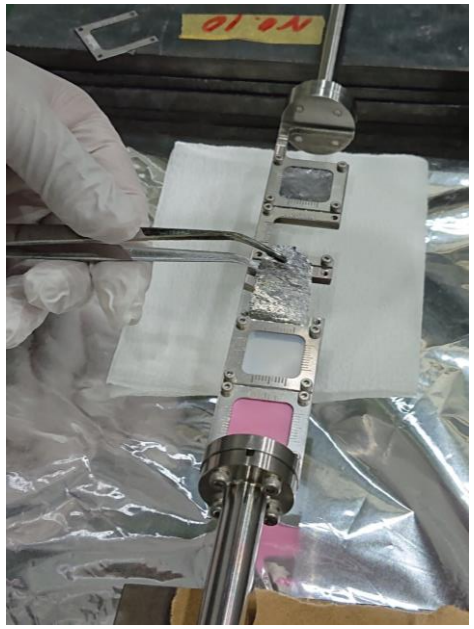


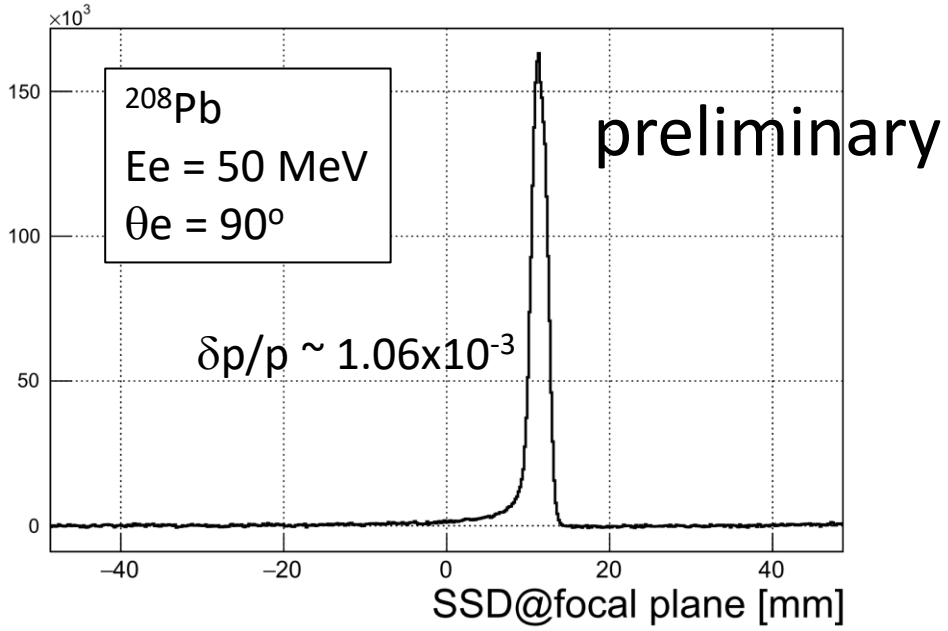
- Ratio of Cross sections $\sigma(\theta)/\sigma(\theta_0)$ instead of the absolute values
- By changing angle, systematic studies to reduce the error
- Coulomb distortion effect is incorporated by phase shift calculation.

^{208}Pb target and commissioning exp.

^{208}Pb foil made by ourselves at RCNP, Osaka Univ.

Target : 25x25x0.01 mm^3, >99% enrich





Performance studies of twin spectrometers started last October.
Precisions of angles, acceptances, … are ongoing.
After the feasibility study with ^{208}Pb, ^{48}Ca could be the next target if we can get it.

in future ⇨ Rn from e-RI scat. at SCRIT facility

Summary

- We are aiming to perform electron scattering off short-lived unstable nuclei.
- SCRIT electron scattering facility is the world's first facility dedicated for exotic nuclei.
- The first experiment with unstable nucleus, ^{137}Cs, was successfully carried out after years of developments.
- The upgrade of the power of ISOL driver and related works will be accomplished in a few years.

- New method for measuring neutron radius by elastic scattering.
  - $\langle r_C^4 \rangle$ includes the information of neutron radius
  - possible determination of proton and neutron radii by e-RI scattering

SCRIT collaboration

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Thank you for your attention!