Nuclear radii
and
density distributions

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- Proton elastic scattering from stable nuclei
- <u>E</u>lastic <u>S</u>cattering of <u>P</u>rotons with <u>RI</u> beams
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- **Introduction**

Nuclear radii and density distributions

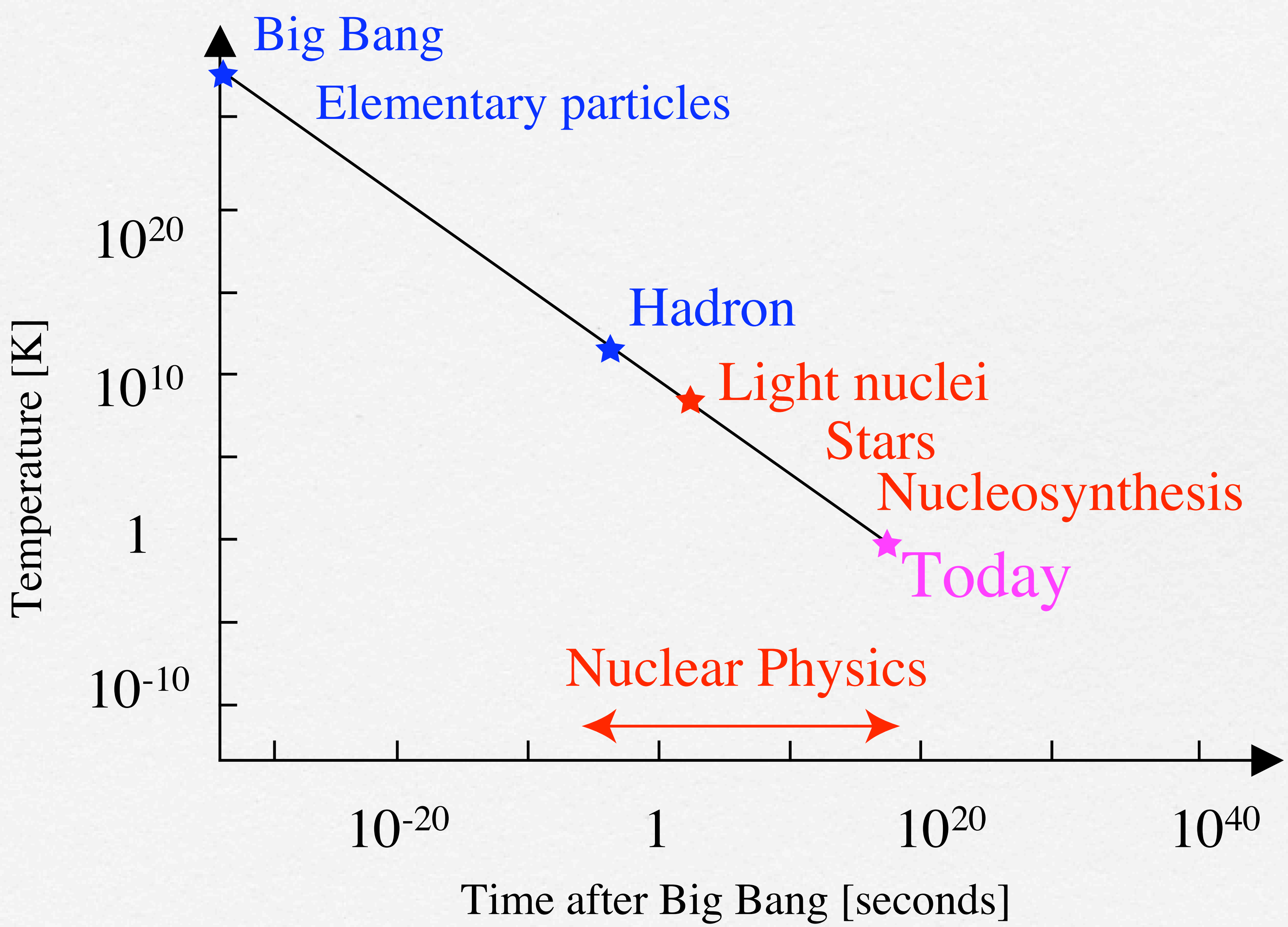
- Fundamental properties of nuclei
- Inputs and/or guidelines to describe the nuclear reactions and structures

	Stable nuclei
Charge radius	**Muonic atom**
Proton distribution	**Electron scattering**
Neutron distribution	**Proton elastic scattering**

By unfolding the charge distribution

By using the well inferred proton distribution

History of Universe

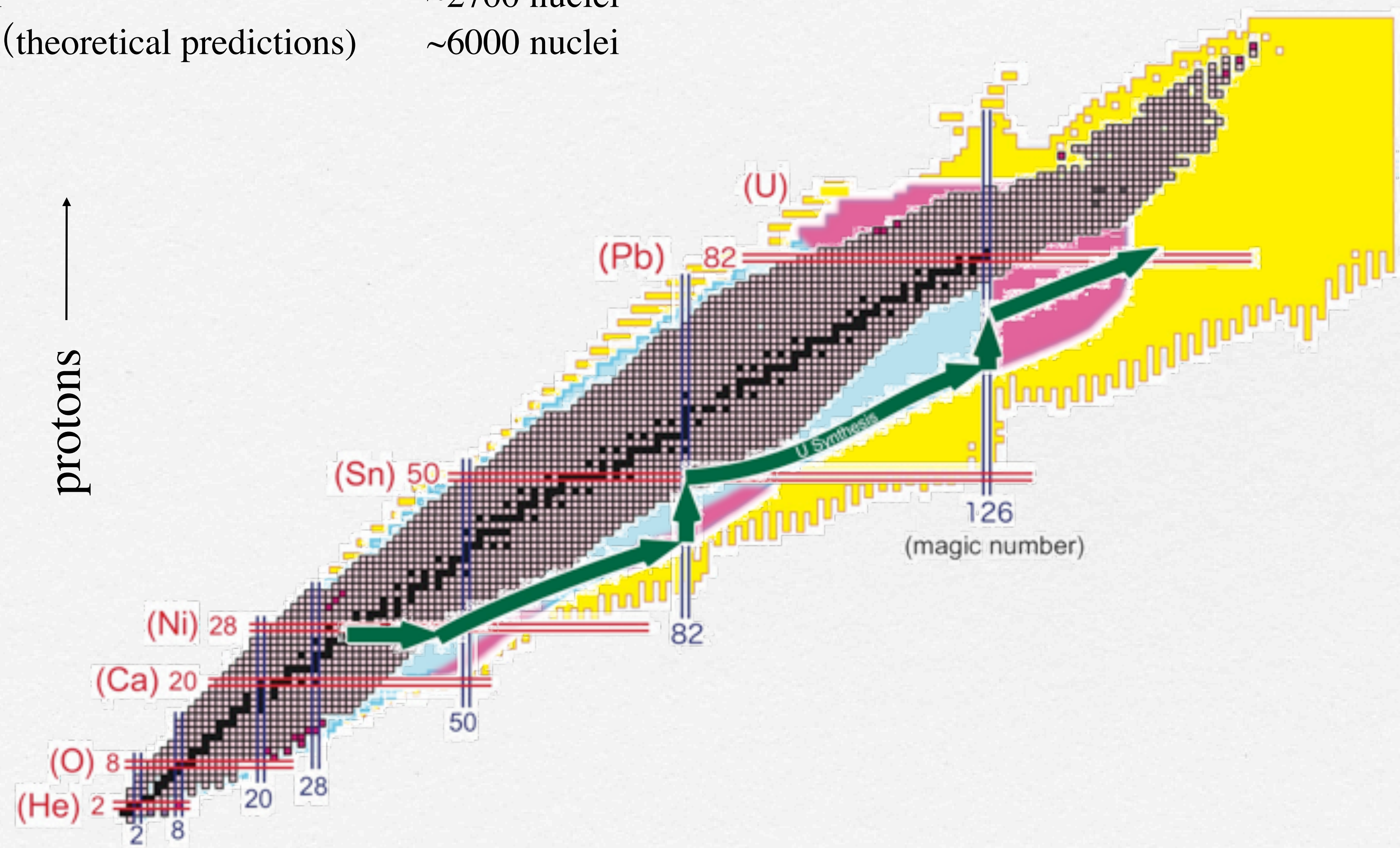


Background: http://www.nscl.msu.edu/~austin/nuclear-astrophysics.pdf

Nuclear chart

■	stable nuclei	~300 nuclei
□	unstable nuclei observed so far	~2700 nuclei
—	drip-lines (limit of existence) (theoretical predictions)	~6000 nuclei
=	magic numbers	
	Projectile Fragmentation	
	In-flight U fission & P.F.	

protons



neutrons

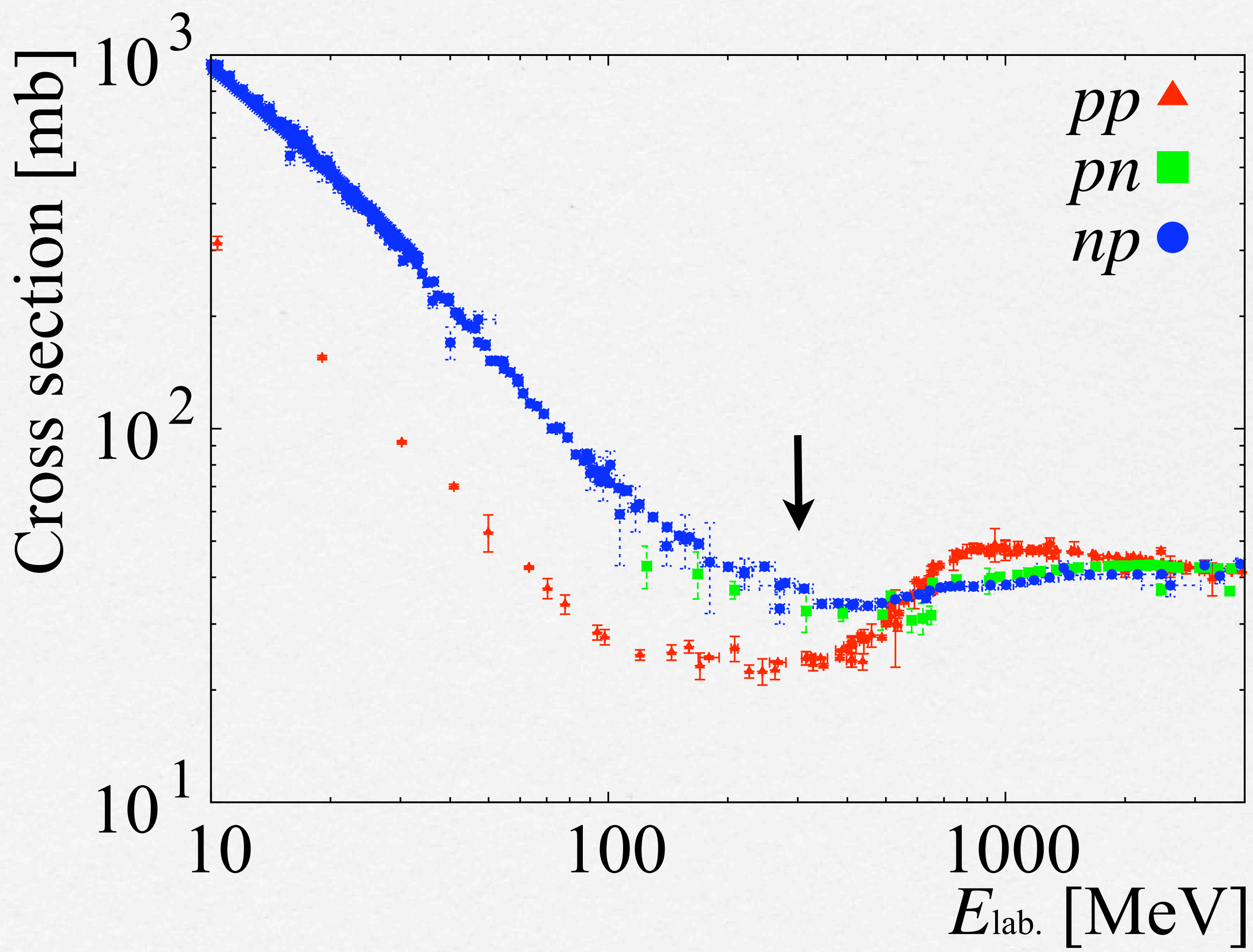
http://www.nishina.riken.go.jp

- Introduction
- **Proton elastic scattering from Stable nuclei**

Proton elastic scattering

E_p=200 - 400 MeV

The longest mean free path in nuclei (2 fm^{-1})



Relativistic Impulse Approximation

D. P. Murdock and C. J. Horowitz, Phys. Rev. C 35, 1442(1987).

Relativistic Love-Franey model:

$$F = F^S + F^V \gamma^{\mu}_{(0)} \gamma_{(1)\,\mu} - F^{PV} \frac{\not{q}\,\gamma^5_{(0)}}{2M} \frac{\not{q}\,\gamma^5_{(1)}}{2M} + F^T \sigma^{\mu\nu}_{(0)} \sigma_{(1)\,\mu\nu} + F^A \gamma^5_{(0)} \gamma^{\mu}_{(0)} \gamma^5_{(1)} \gamma_{(1)\,\mu}$$

L = S, V, PV, T, A

$$F^L(q, E_c) = i \frac{M^2}{2E_c k_c} \left[F^L_D(q) + F^L_X(Q) \right]$$

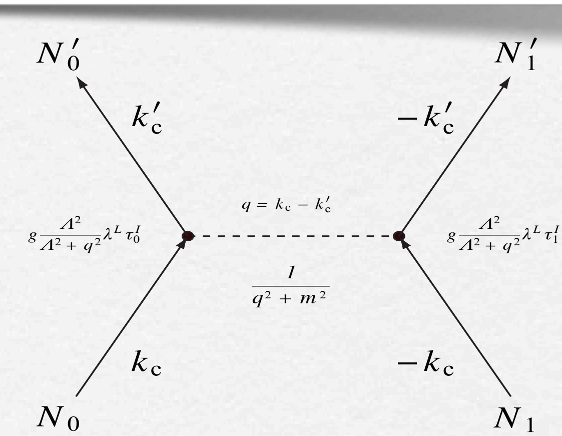
$$F^L_D(q) = \sum_j \delta_{L,L(j)} \{\tau_0 \cdot \tau_1\}^{I_j} f^j(q)$$

$$F^L_X(Q) = (-1)^T \sum_j B_{L(j),L} \{\tau_0 \cdot \tau_1\}^{I_j} f^j(Q)$$

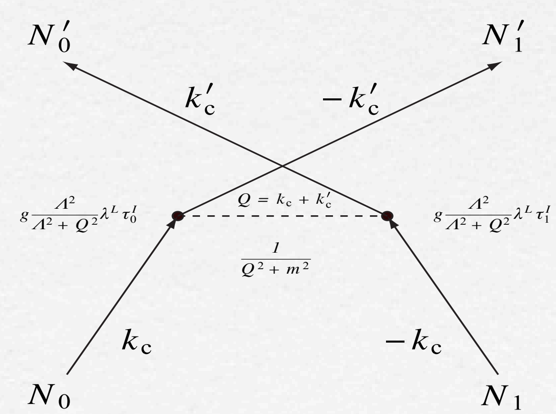
$$f^j(q) = \frac{g_j^2}{q^2 + m_j^2} \left(\frac{\Lambda_j^2}{\Lambda_j^2 + q^2} \right)^2 - i \frac{\overline{g}_j^2}{q^2 + \overline{m}_j{}^2} \left(\frac{\overline{\Lambda}_j^2}{\overline{\Lambda}^2 + q^2} \right)^2$$

$$F^L(pp) = F^L(T = 1)$$

$$F^L(pn) = \frac{1}{2} \left[F^L(T = 0) + F^L(T = 1) \right]$$



Direct



Exchange

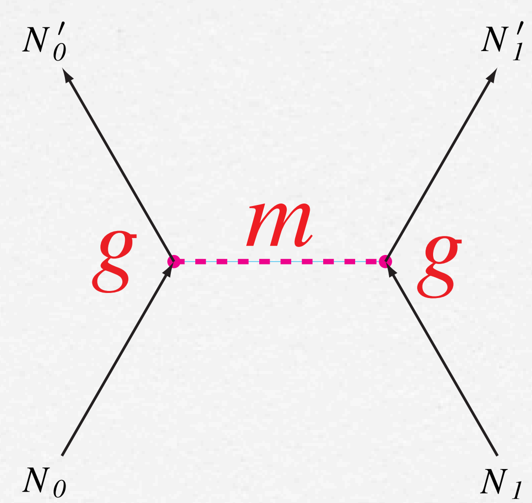
Relativistic Impulse Approximation

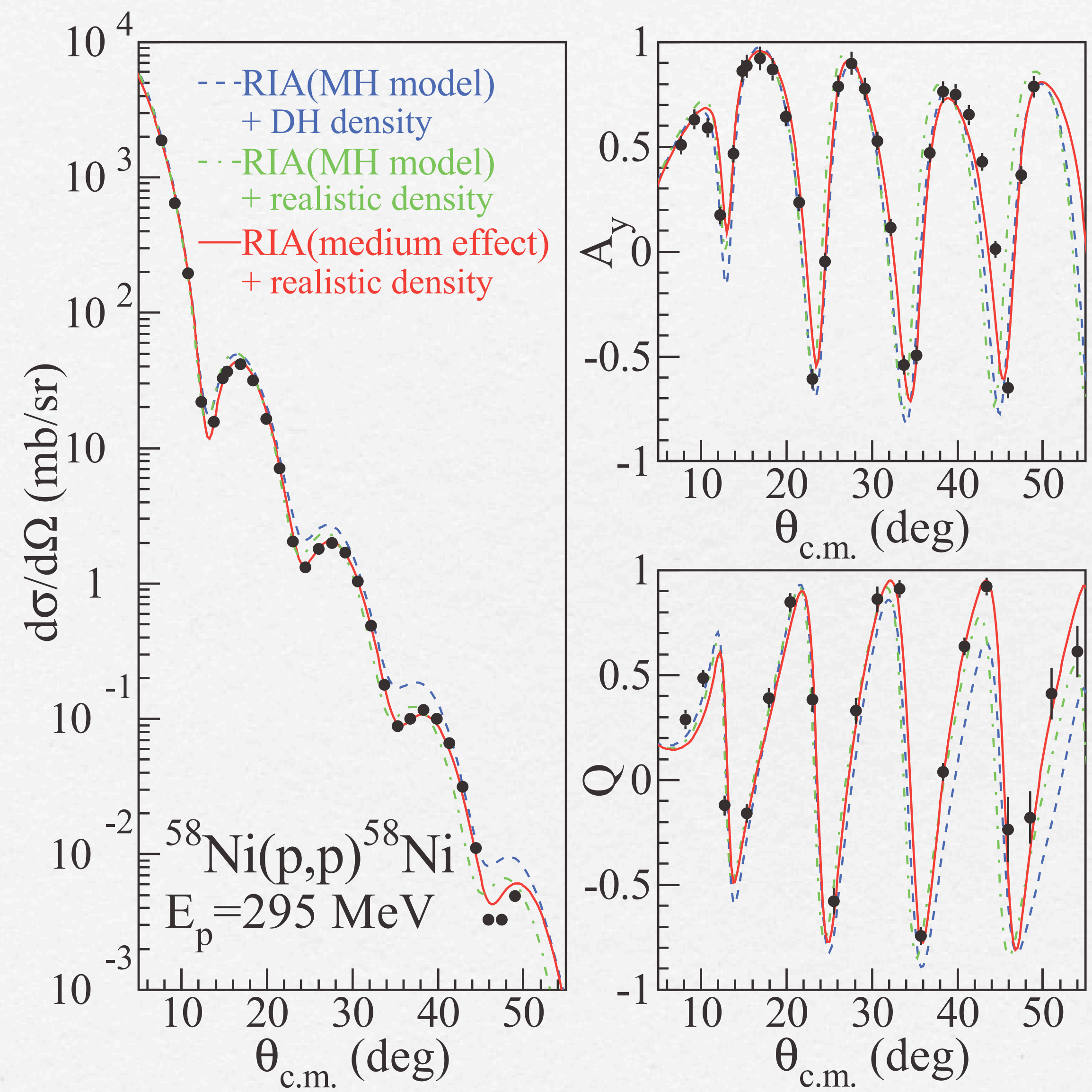
Phenomenological medium modification

H. Sakaguchi et al., Phys. Rev. C 57, 1749 (1998).

$$g_j^2 \rightarrow \frac{g_j^2}{1 + \underline{a_j} \frac{\rho(r)}{\rho_0}},$$

$$m_j \rightarrow m_j \left[1 + \underline{b_j} \frac{\rho(r)}{\rho_0}\right],$$

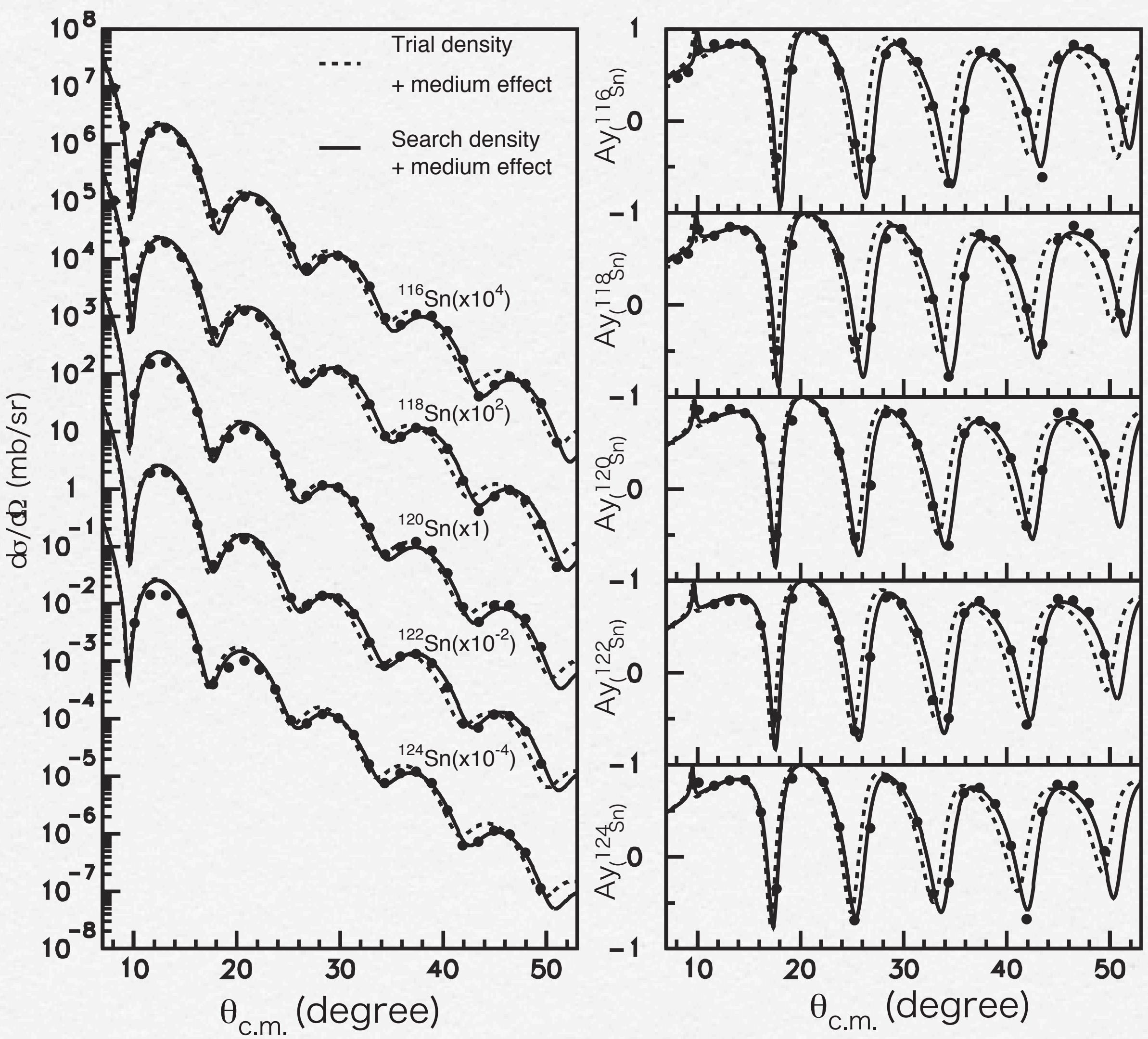




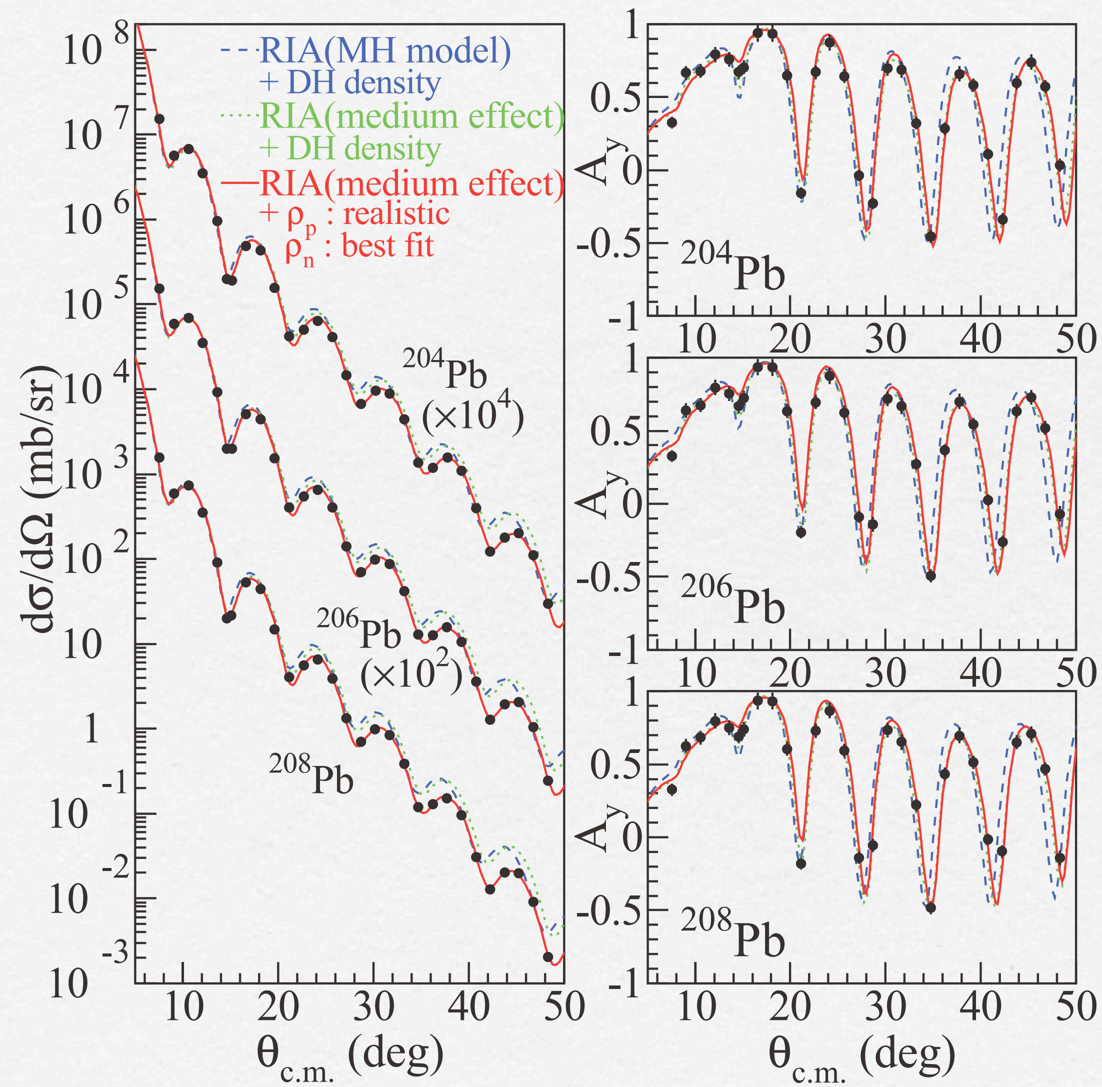
J.Zenihiro et al.,
Phys. Rev. C 82, 044611 (2010)

Proton elastic scattering form stable nuclei

Experimental data at RCNP, Osaka University



S.Terashima et al.,
Phys. Rev. C 77, 024317 (2008)



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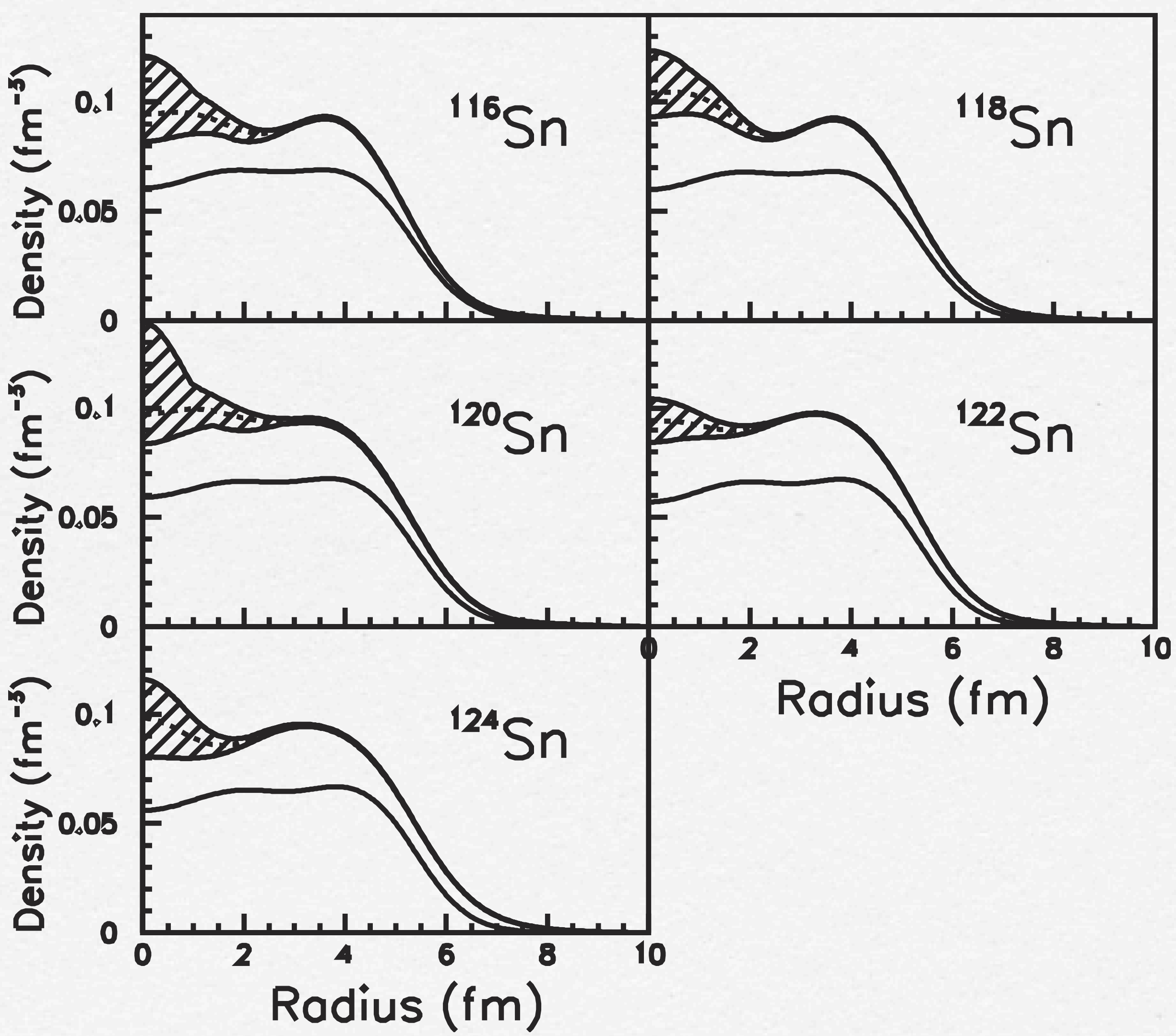

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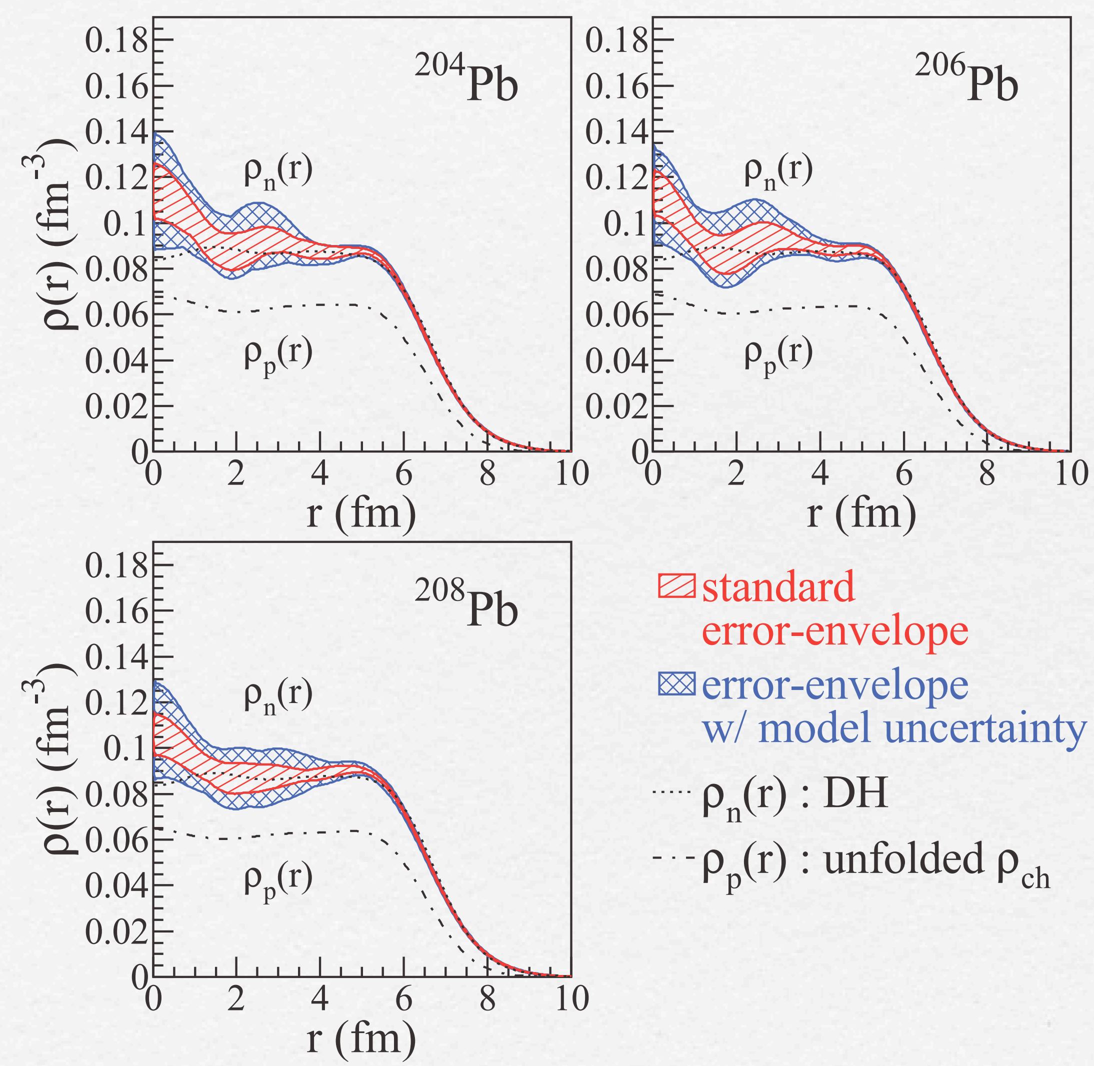

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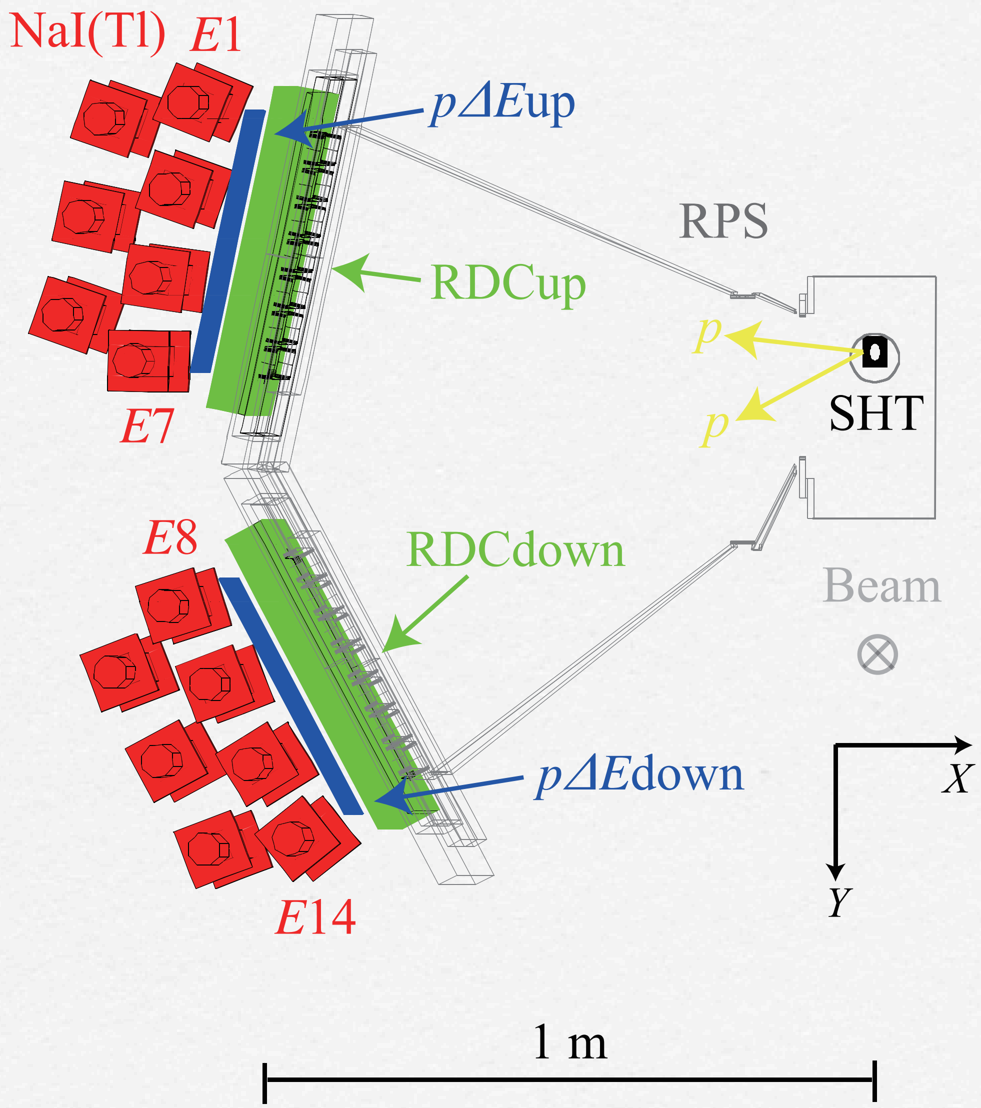
- Introduction
- Proton elastic scattering from Stable nuclei
- **<u>E</u>lastic <u>S</u>cattering of <u>P</u>rotons with <u>RI</u> beams**

Recoil Proton Spectrometer (RPS)



	Solid H_2 (SHT)	RDC	*pΔE*	*E*
material	Para H_2	$Ar+C_2H_6$	Plastic	NaI(Tl)
effective area	ϕ 30 mm	436 x 436 mm²	440 x 440 mm²	431.8 x 45.72 mm²
thickness	1 mm	69.4 mm	2.53 / 3.09 mm	50.8 mm
Resolution		500 μm	TOF : 0.1 nsec	0.3 %(80 MeV)

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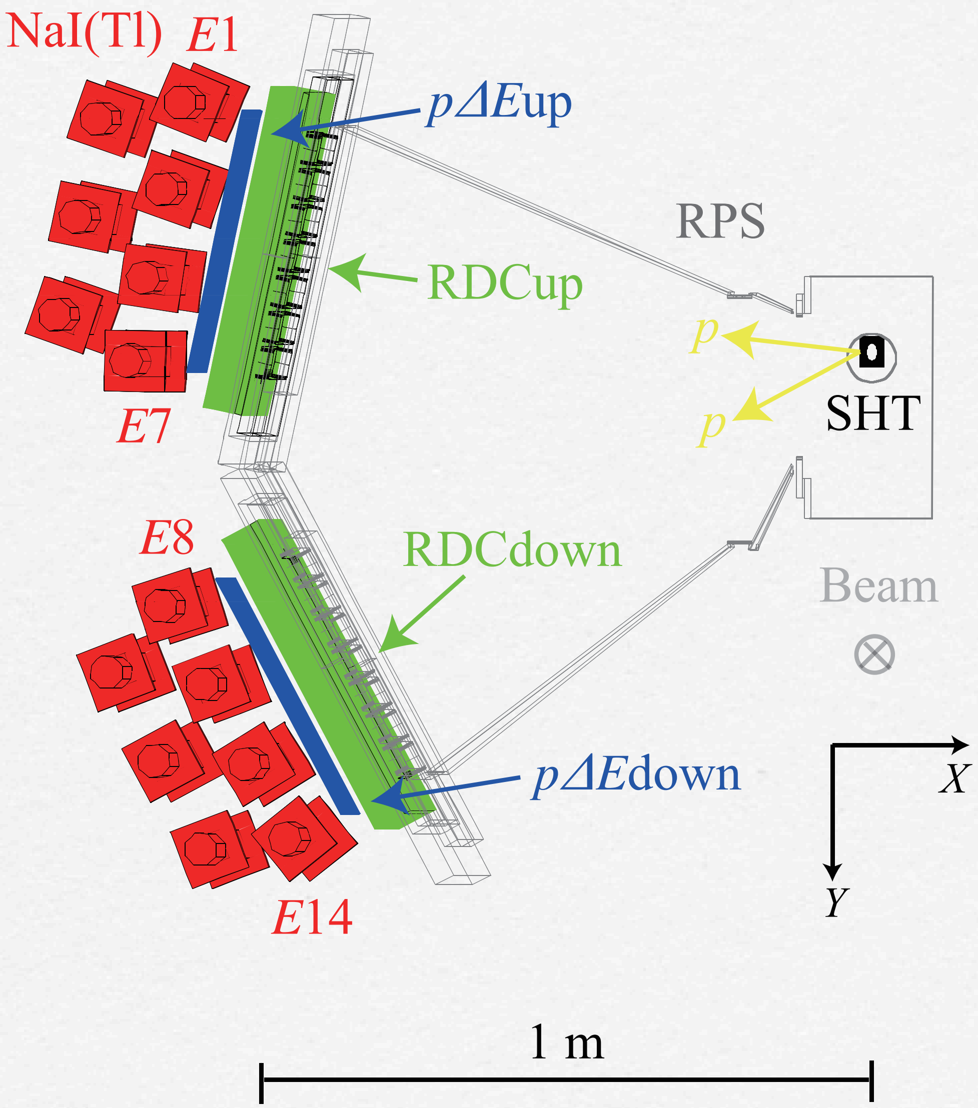

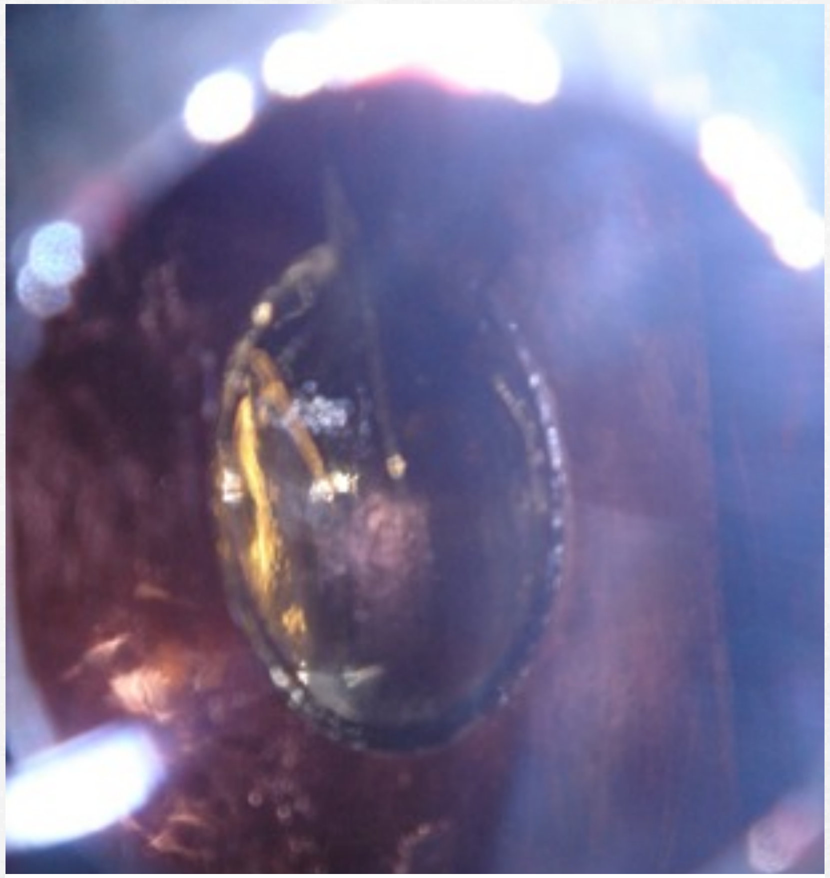

Solid para hydrogen target
ϕ30 mm, 1 mm^t

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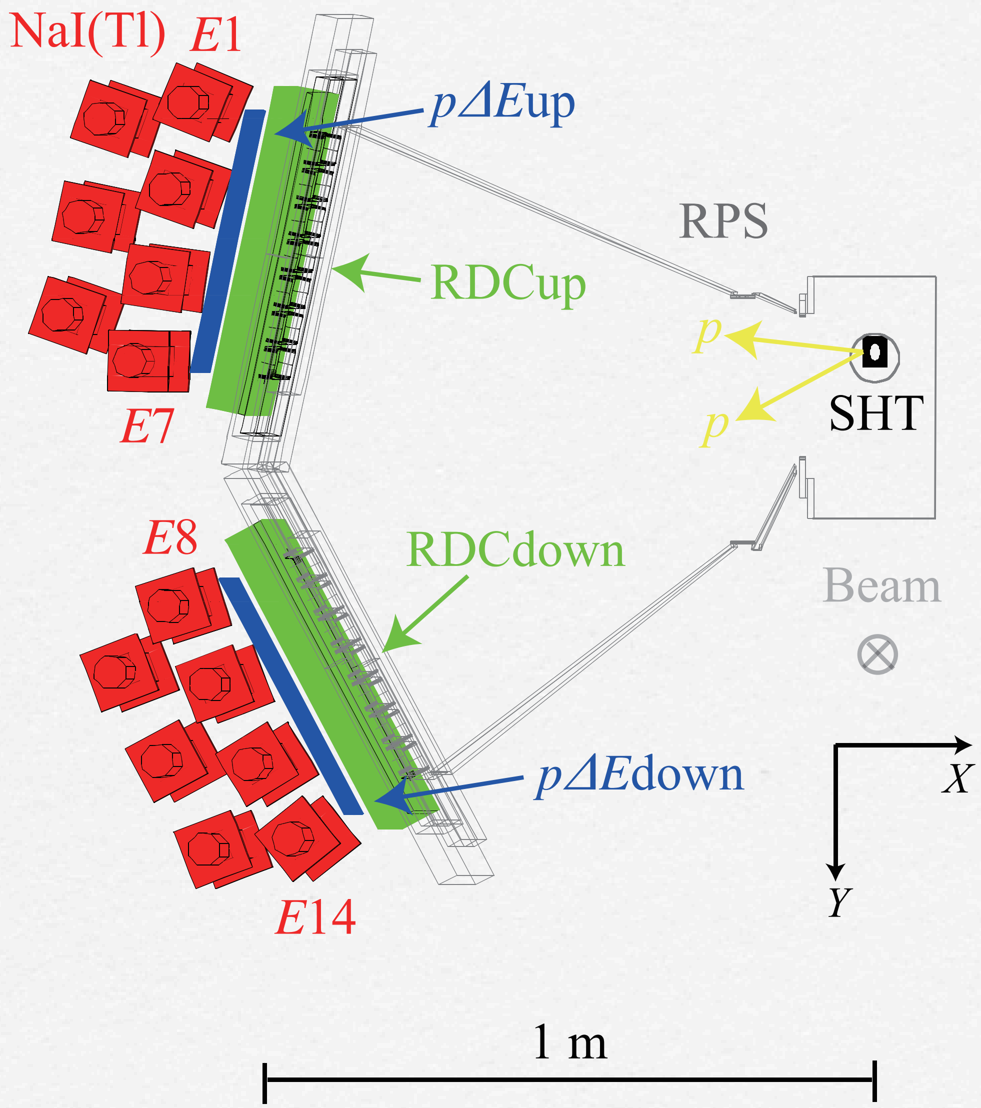
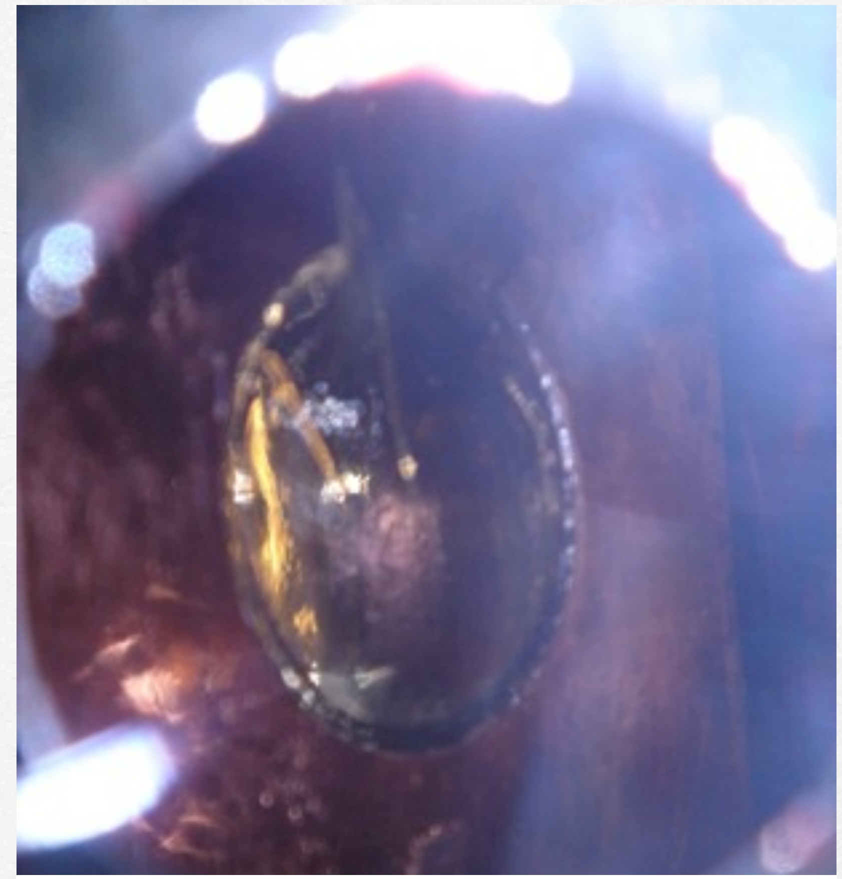
effective area	ϕ 30 mm	436 x 436 mm^2	440 x 440 mm^2	431.8 x 45.72 mm^2
thickness	1 mm	69.4 mm	2.53 / 3.09 mm	50.8 mm
Resolution		500 µm	TOF : 0.1 nsec	0.3 %(80 MeV)

Recoil Proton Spectrometer (RPS)



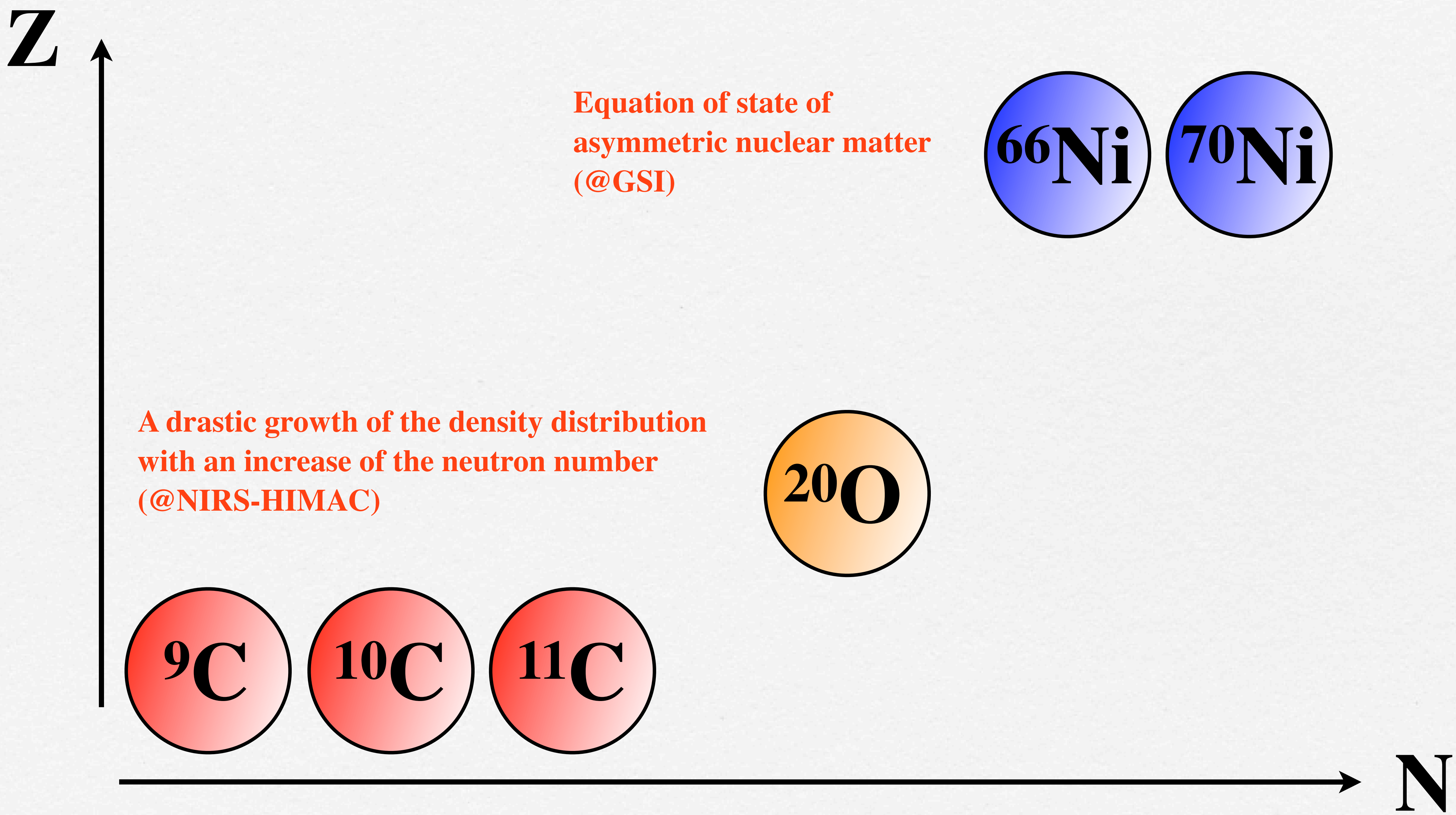


Solid para hydrogen target
ϕ30 mm, 1 mm^t

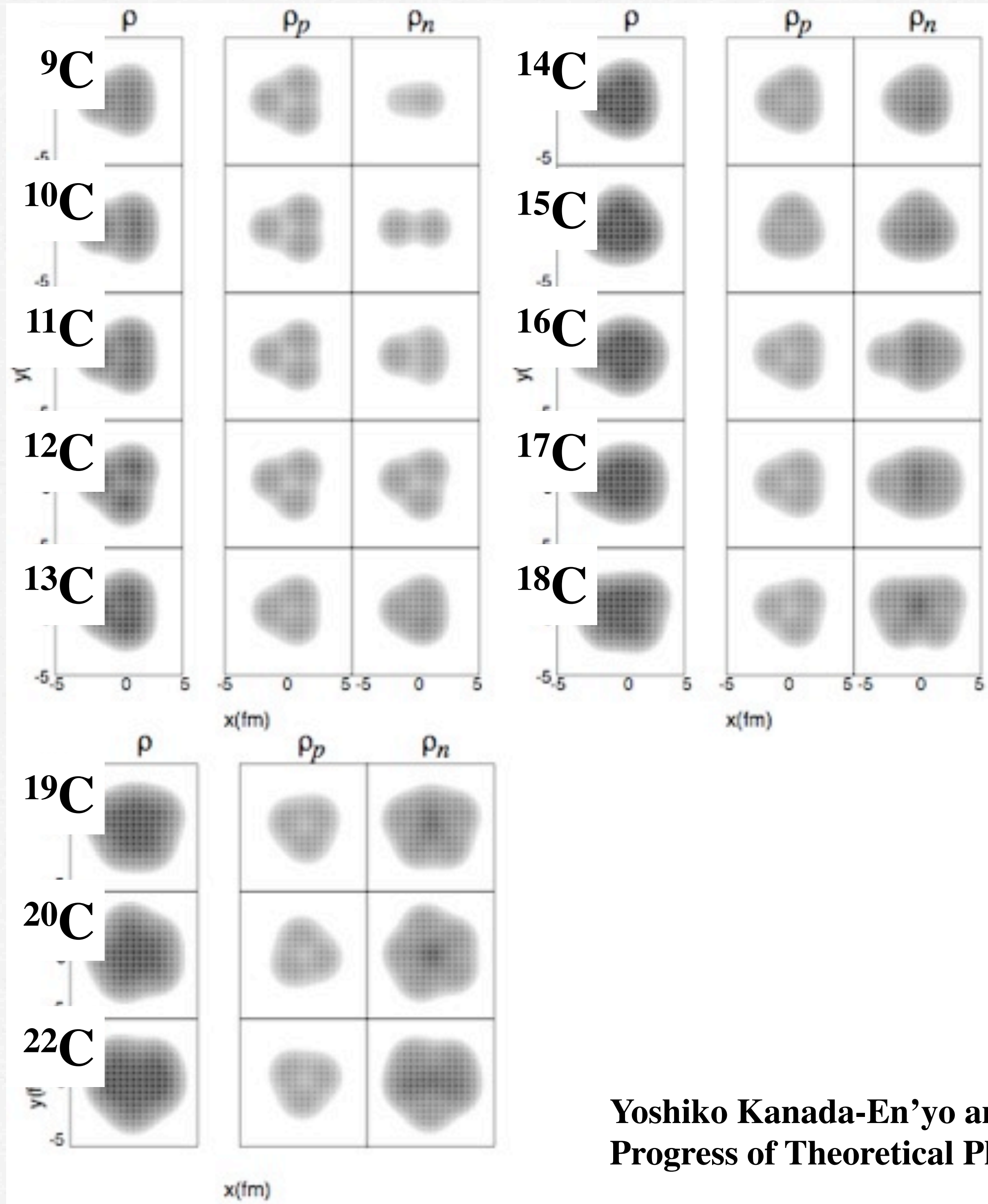
Large, thin solid hydrogen target using para-H_2,
Y. Matsuda et al., Nucl. Instr. and Meth. A 643 6-10 (2011).

Scintillating fiber detector for momentum tagging light nuclei at intermediate energies,
Y. Matsuda et al., Nucl. Instr. and Meth. A 670 25-31 (2012).

Elastic Scattering of Protons with RI beams

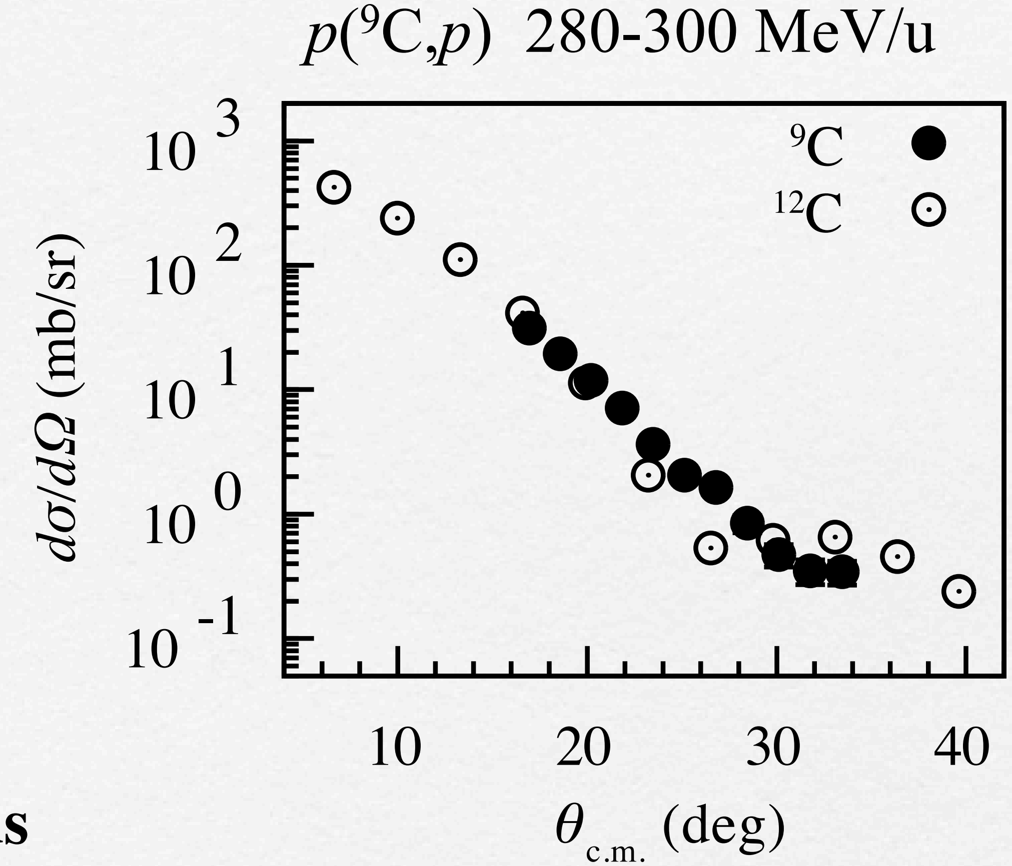


Antisymmetrized Molecular Dynamics (AMD) density



Yoshiko Kanada-En'yo and Hisashi Horiuchi,
Progress of Theoretical Physics Supplement, 142 (2001) 205

Matter radius of ^{9}C



Application of our previous work

H. Sakaguchi et al., Phys. Rev. C 57, 1749 (1998).
S.Terashima et al., Phys. Rev. C 77, 024317 (2008)
J.Zenihiro et al.,Phys. Rev. C 82, 044611 (2010)

We need to

(1) tune the scattering amplitude with scattering for a nearby *N* = *Z* nucleus

(2) deduce both proton and neutron density distributions

(1) tune the scattering amplitude with scattering for a nearby $N = Z$ nucleus: ^{12}C

Phenomenological medium modification

H. Sakaguchi et al., Phys. Rev. C 57, 1749 (1998).

$$g_j^2 \rightarrow \frac{g_j^2}{1 + \underline{a_j}\frac{\rho(r)}{\rho_0}},$$

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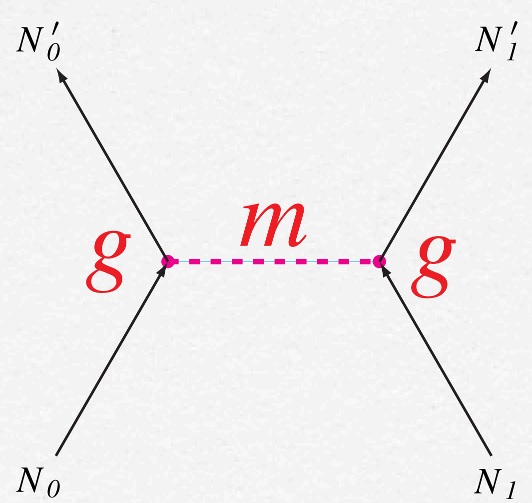
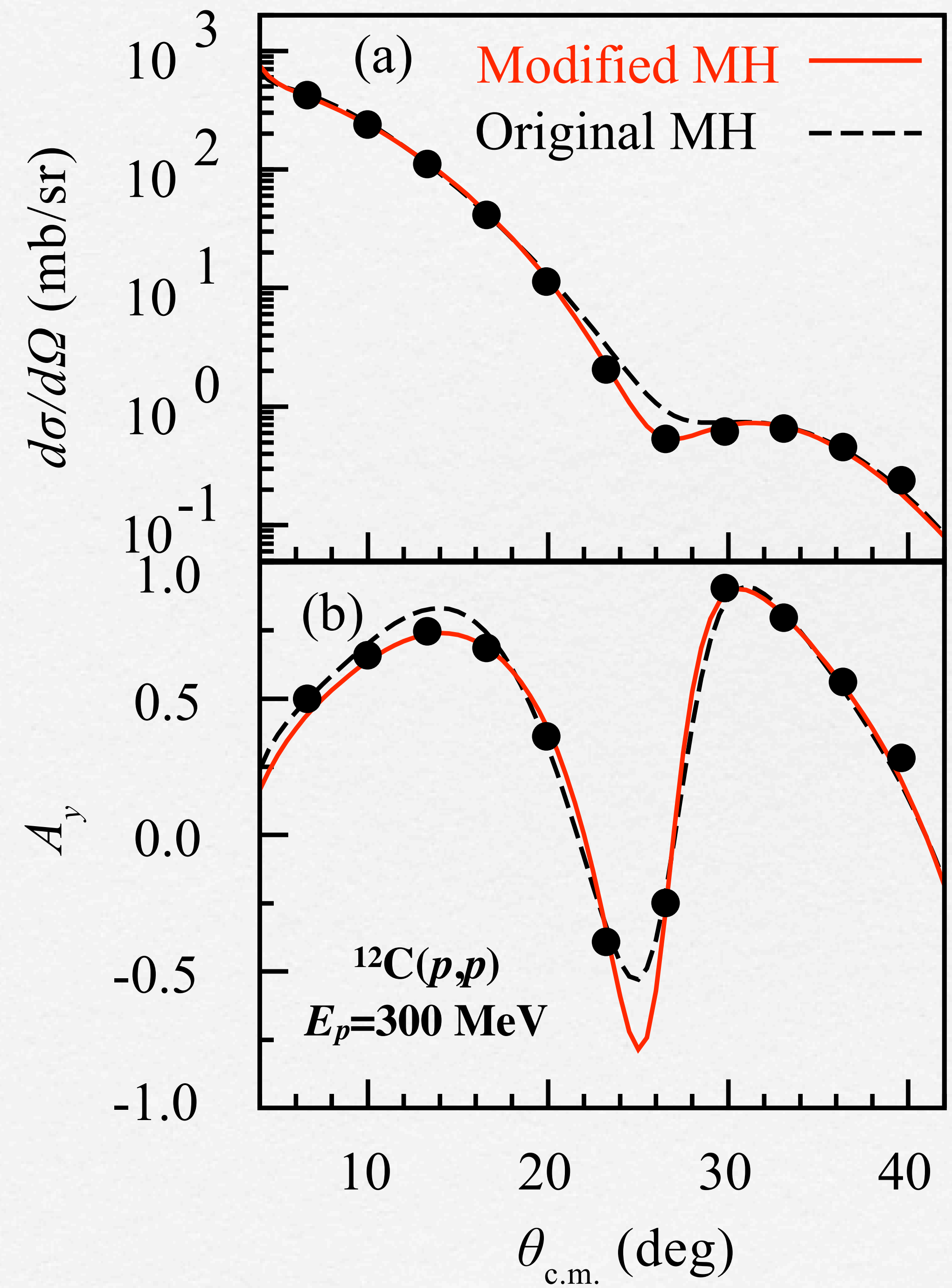




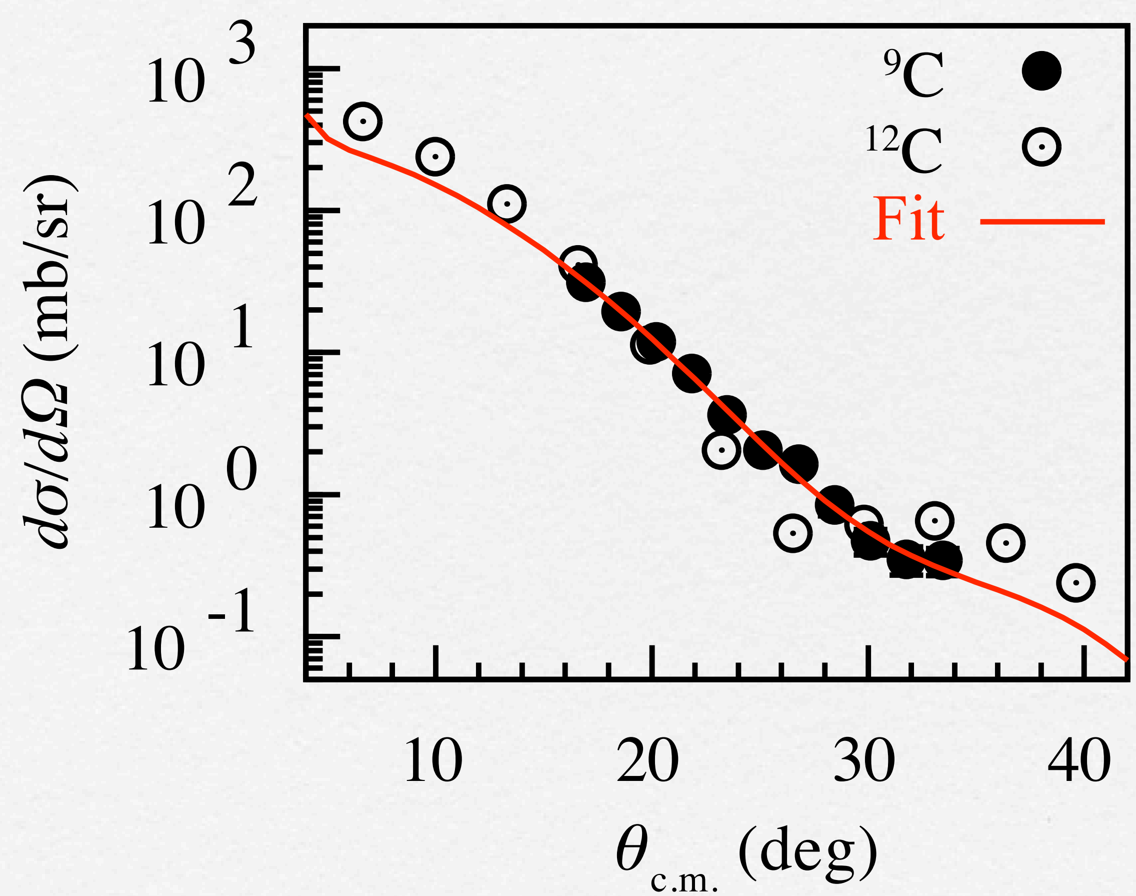
(2) deduce both proton and neutron density distributions

Two parameter Fermi distribution

$$\rho_i(r) = \frac{N_i}{1 + exp\{(r - R_i)/a_i\}}, i = p, n,$$

Deduced rms matter radius,
best-fit χ^2, and geometry parameters (fm)

$\langle r_m^2 \rangle^{1/2}$	χ^2	R_p	R_n	a_p	a_n
$2.43^{+0.55}_{-0.28}$	5.15	3.345	1.647	0.307	0.070



Experimental matter radii (fm) of ^{9}C and ^{9}Li.

	(p, p)	σ_I	σ_R
^{9}C	$2.43^{+0.55}_{-0.28}$ a	2.42(3) b	2.75(34), 2.71(32) c
^{9}Li	2.44(6) d	2.32(2) b	2.534(25) e

a: Preset work
b: A. Ozawa et al., Nucl. Phys. A 693, 32 (2001).
c: R. E. Warner et al., Phys. Rev. C 74, 014605 (2006).
d: A. V. Dobrovolsky et al., Nucl. Phys. A 766, 1 (2006).
e: E. Liatard et al., Europhys. Lett. 13, 401 (19900.

Summary

- Proton elastic scattering at 300 MeV is one method of studying nuclear radii and density density distributions.

- We have succeeded in extracting neutron density distributions of medium-heavy stable nuclei.

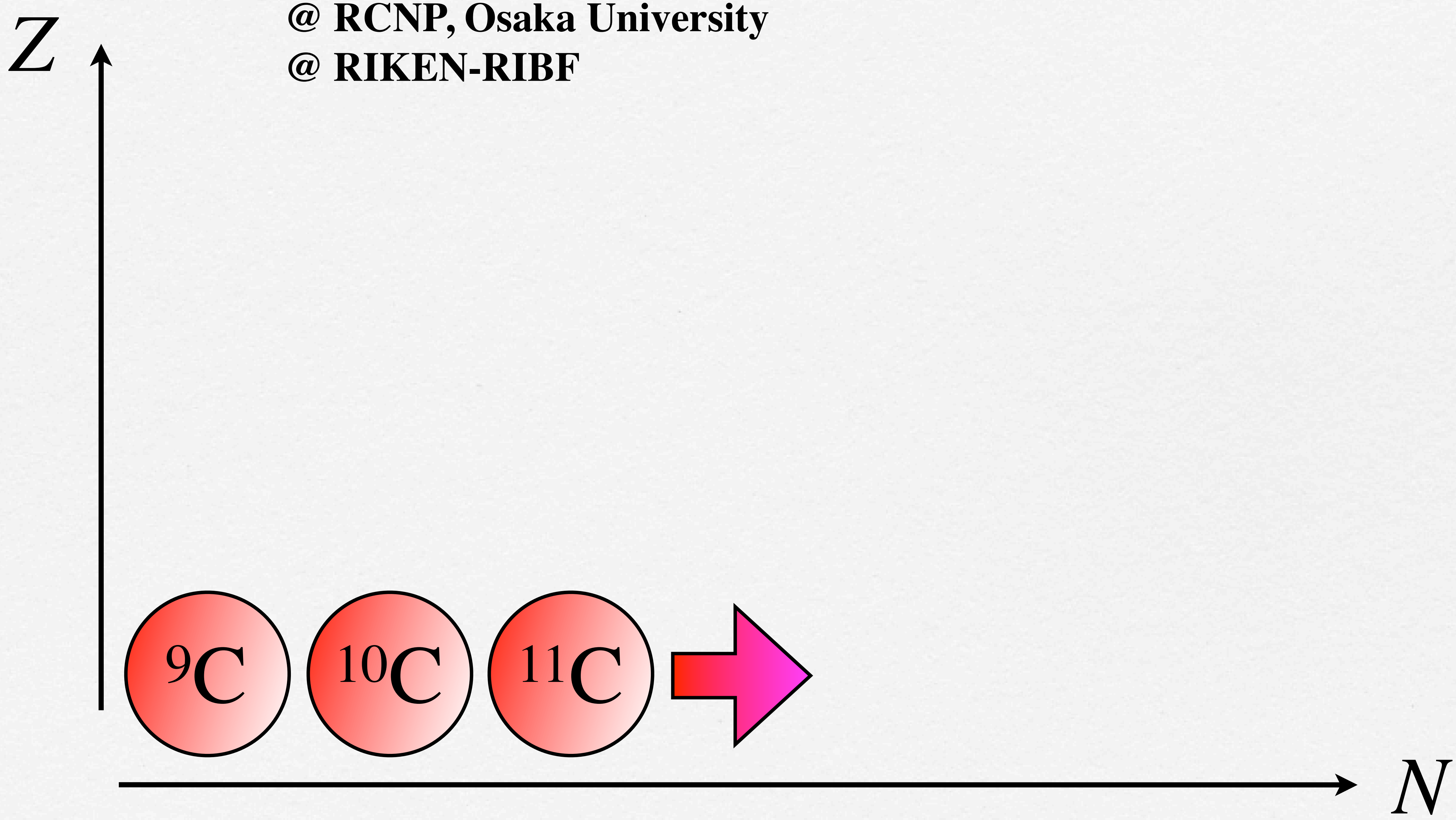
- We planed "Elastic Scattering of Protons with RI beams (ESPRI)" and constructed a Recoil Proton Spectrometer to measure unstable nuclei.

- We have measured following unstable nuclei:
  - $^{9,10,11}C$
  - $^{66,70}Ni$

- The root-mean-square matter radius of ^{9}C was deduced to be 2.43 (-0.28/+0.55) fm.

Present work

- **Measurements of neutron-rich carbon isotopes: ^{14,16}C**
  @ RCNP, Osaka University
  @ RIKEN-RIBF



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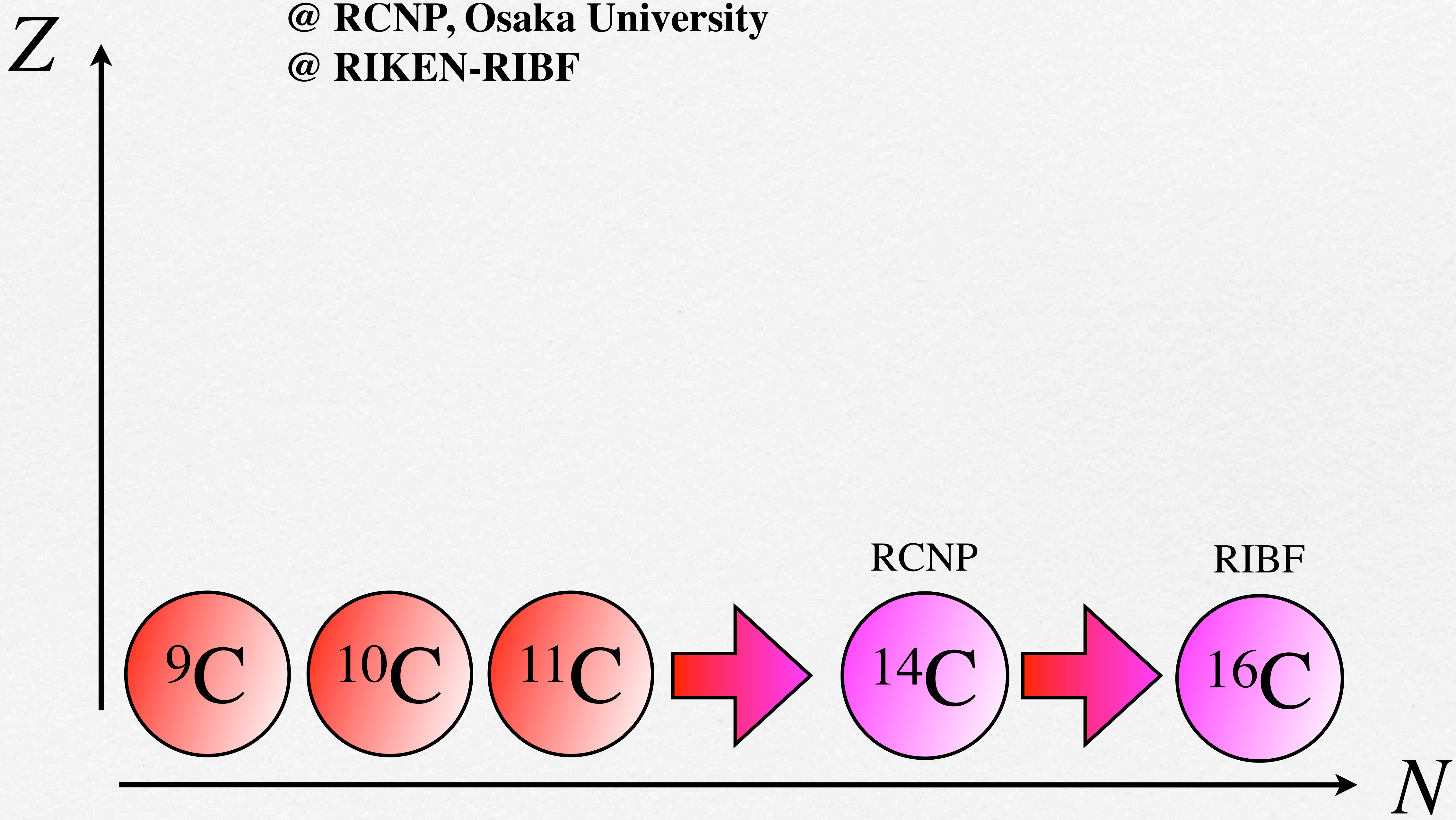

Thank you for your attention

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Souel Univ.	Y. Sato
SAGA HIMAT	M. Kanazawa
GSI	S272 collaborators, M. Takechi