Proton elastic scattering
and
the radius of ^{9}C

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Motivation

Nuclear size

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

	Stable nuclei
Charge radius (Matter radius)	Muonic atom
Charge distribution	Electron scattering
Neutron distribution	Proton elastic scattering

Proton elastic scattering

H.Feshbach, Ann.Phys.5(1958)357

$$(H_0 + U)|\psi >= E|\psi >$$

$$\begin{aligned} U &\equiv < 0|V|0 > + < 0|PVQ\frac{1}{E - QHQ + i\epsilon}QVP|0 > \\ &\sim < 0|V|0 > \end{aligned}$$

U : optical potential
$|0\rangle$: grand state wave function of target nucleus
V : NN effective interaction

$P \equiv |0\rangle\langle 0|$: projection operator to the elastic channel
$Q \equiv 1\text{-}P$: projection operator to the other channels
$|\Psi\rangle$: total wave function of the flame
$|\psi\rangle$: wave function of the relative motion of the elastic channel

$$(PHP + PHQ)|\Psi >= EP|\Psi >$$
$$(QHP + QHQ)|\Psi >= EQ|\Psi >$$
$$\left(PH_0P + PVP + PVQ\frac{1}{E - QHQ + i\epsilon}QVP\right)P|\Psi >= EP|\Psi >$$

Stable nuclei

Polarized proton elastic scattering ($d\sigma/d\Omega$, Ay, Q)

↳Relativistic Impulse Approximation (RIA)

D. P. Murdock and C. J. Horowitz, PRC35, 1442.

↳Phenomenological medium modification

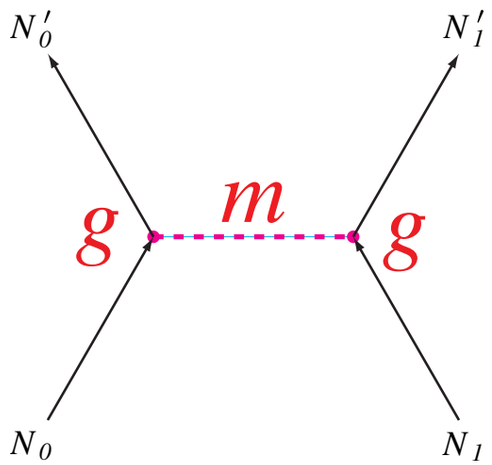
H. Sakaguchi et al., PRC57, 1749.

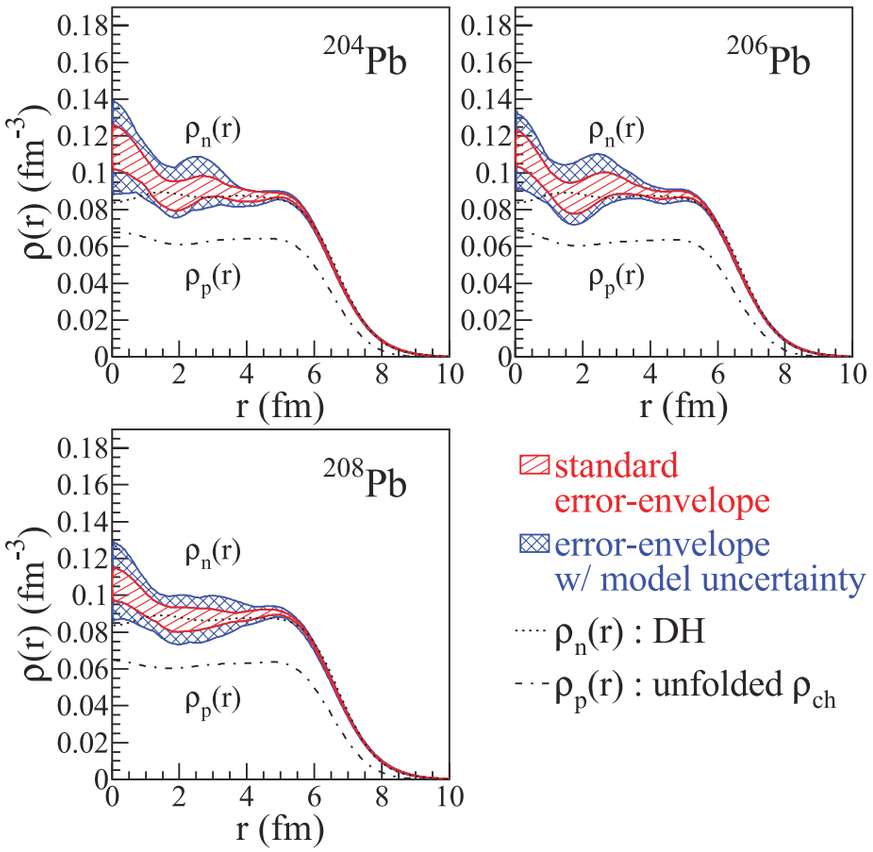
↳Extraction of ρ_n ($^{116\text{-}124}$Sn, $^{204\text{-}208}$Pb)

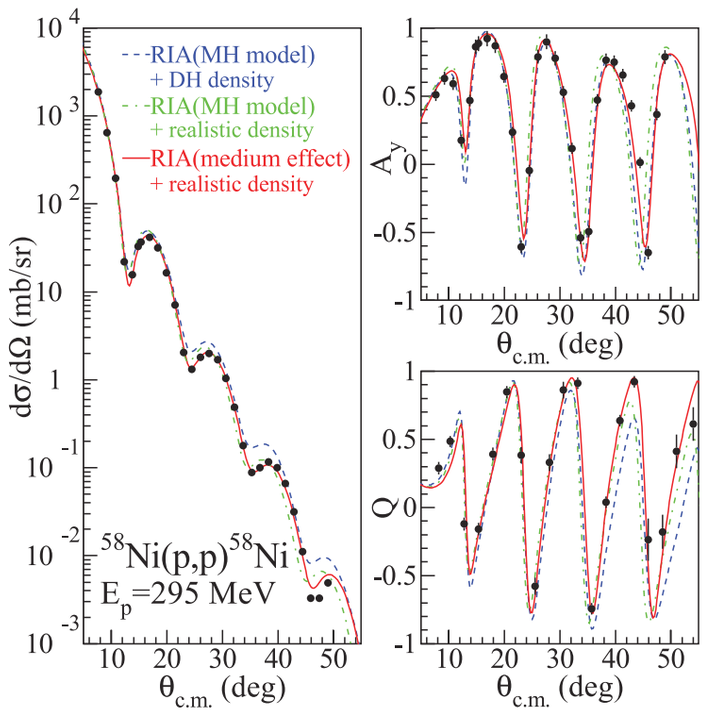
S. Terachima et al., PRC77, 024317.
J.Zenihiro et al., PRC82, 044611.

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

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







Motivation

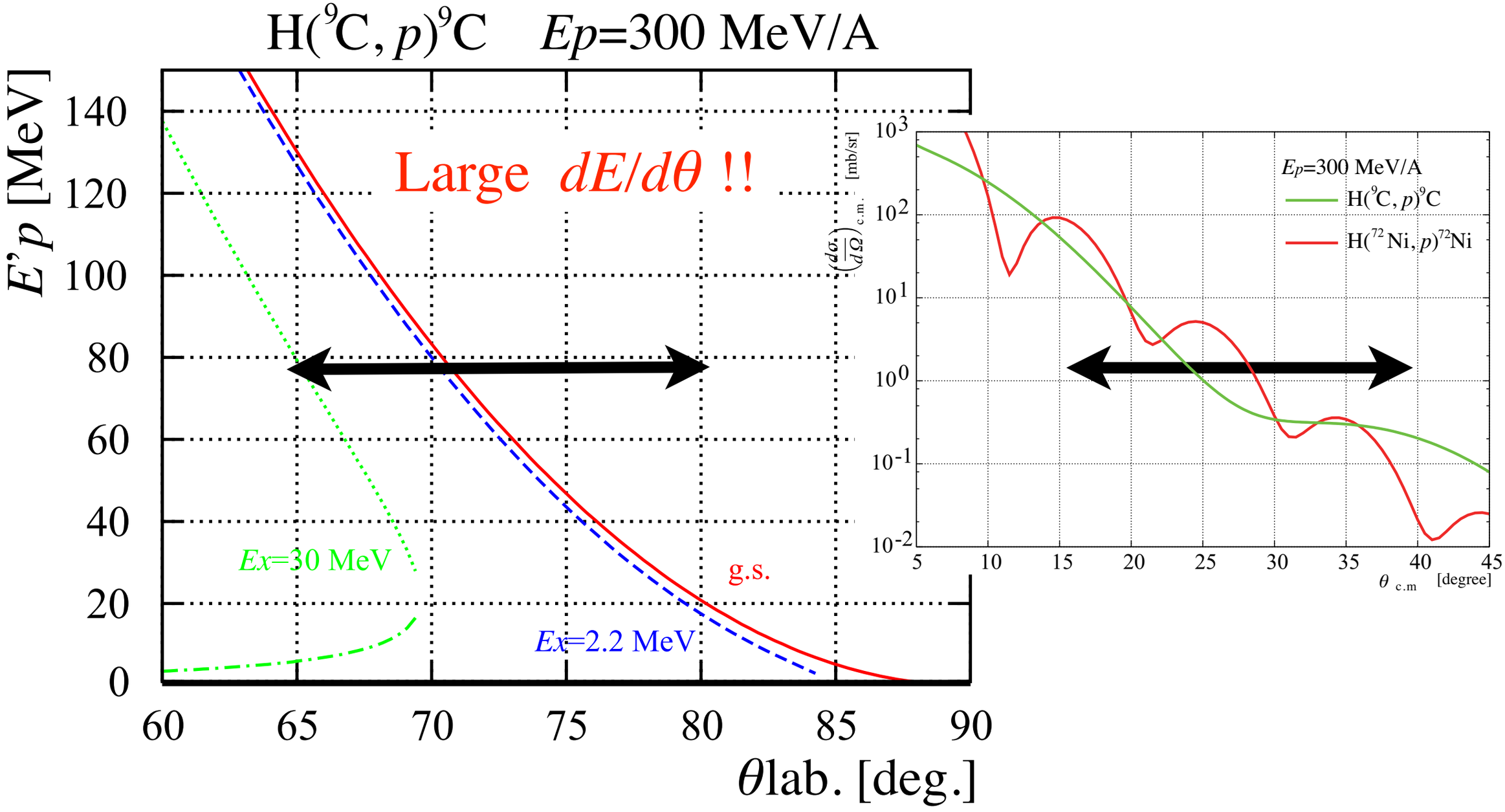
Nuclear size

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

	Stable nuclei	Unstable nuclei
Charge radius (Matter radius)	Muonic atom	Isotope shift (Interaction cross section)
Charge distribution	Electron scattering	
Neutron distribution	Proton elastic scattering	

Concerning the density distribution, experimetal data is rare !!

Unstable nuclei



It has been difficult to measure in a wide momentum transfer region.

Experiments in the lower momentum transfer region (<1 fm^{-1}) have been done so far.

- RIKEN, GANIL,MSU : <100 MeV/A
- GSI (He, Li isotope) : 700 MeV/A

Elastic Scattering of Protons with RI beam (ESPRI) project

Collaborators

S.Terashima (Beihang Univ.)
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H.Sakaguchi (Osaka Univ.)
H.Otsu (RIKEN)
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Kyoto Univ.
T.Murakami

Miyazaki Univ.
Y.Maeda

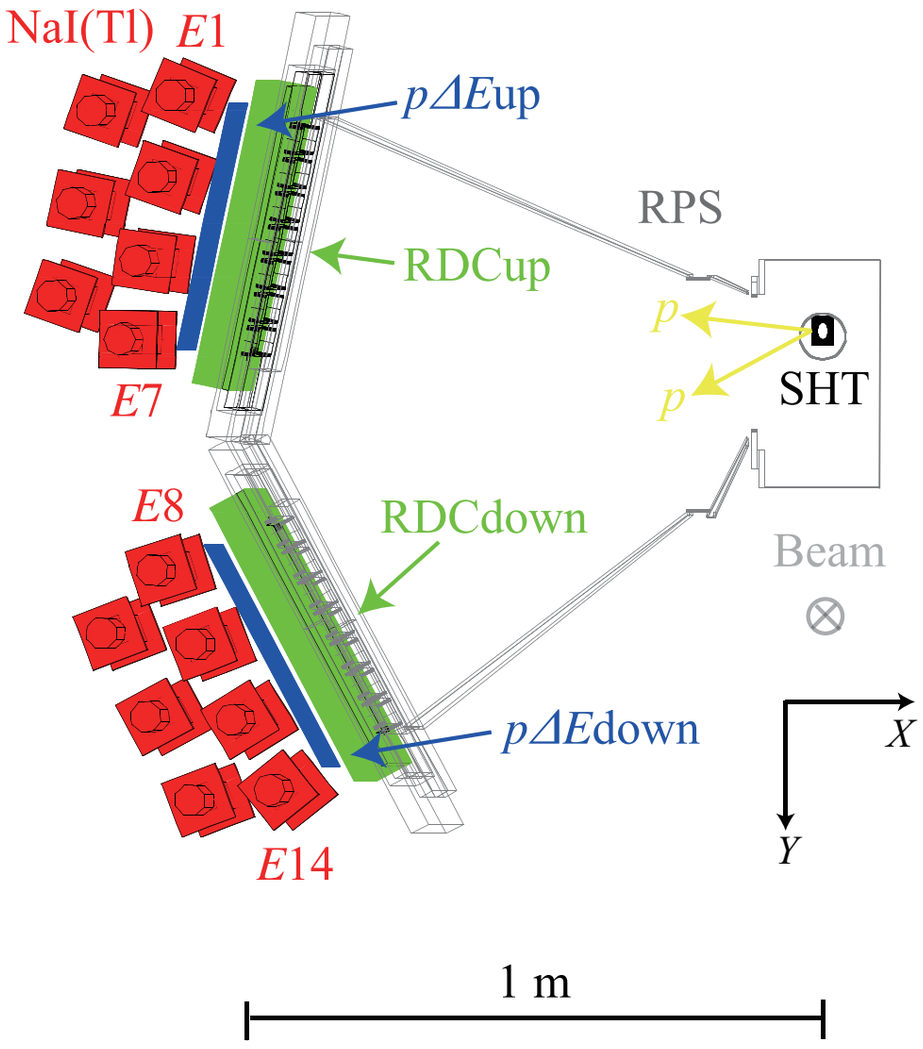
Souel Univ.
Y.Sato

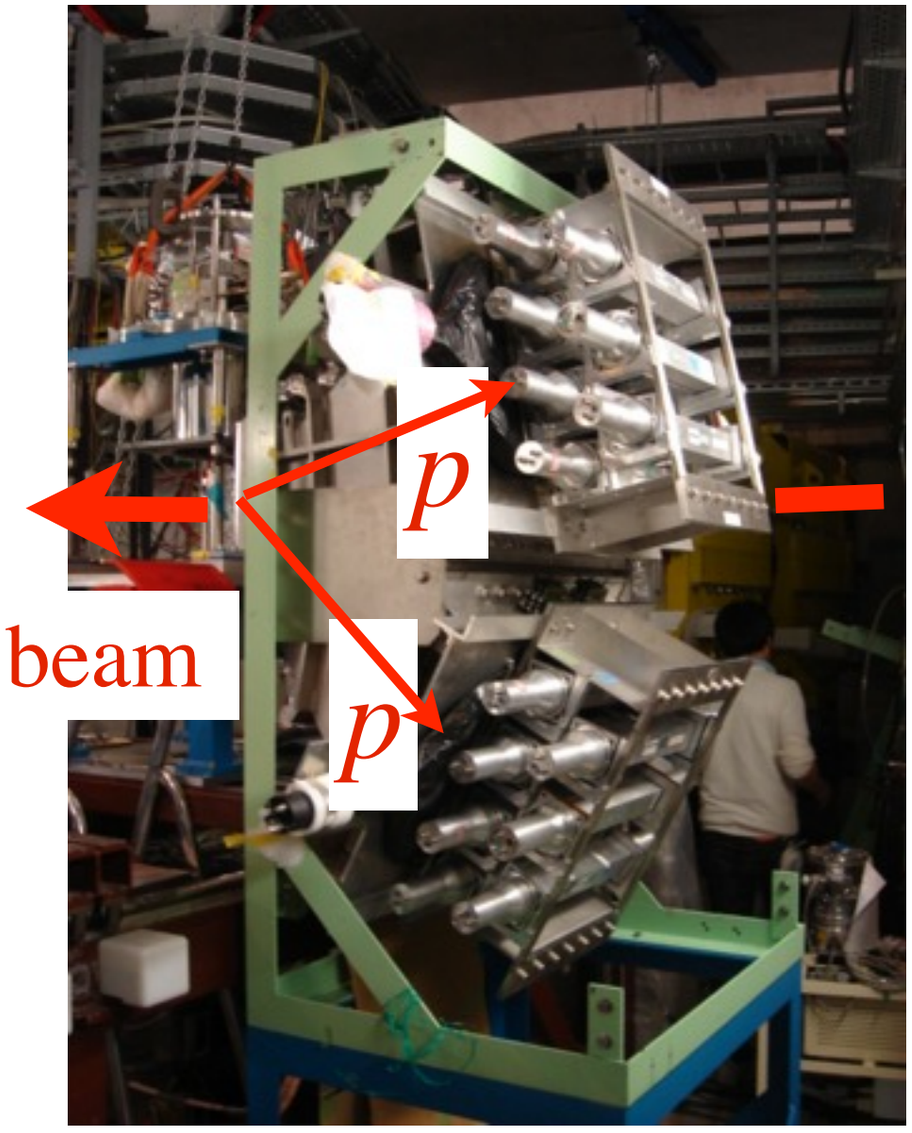
Osaka Univ.
I.Tanihata
O.H.Jin

GSI
M.Takechi
S272 collaborators

NIRS
M.Kanazawa

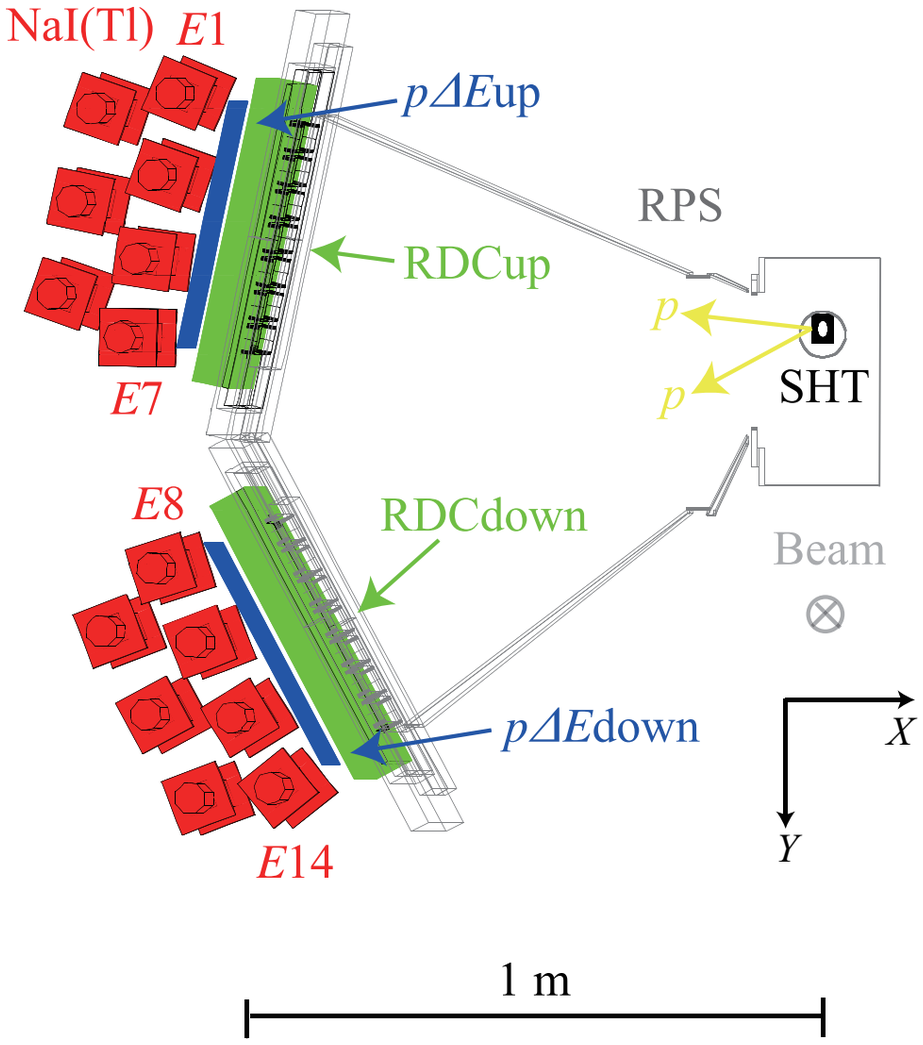
Recoil Proton Spectrometer (RPS)

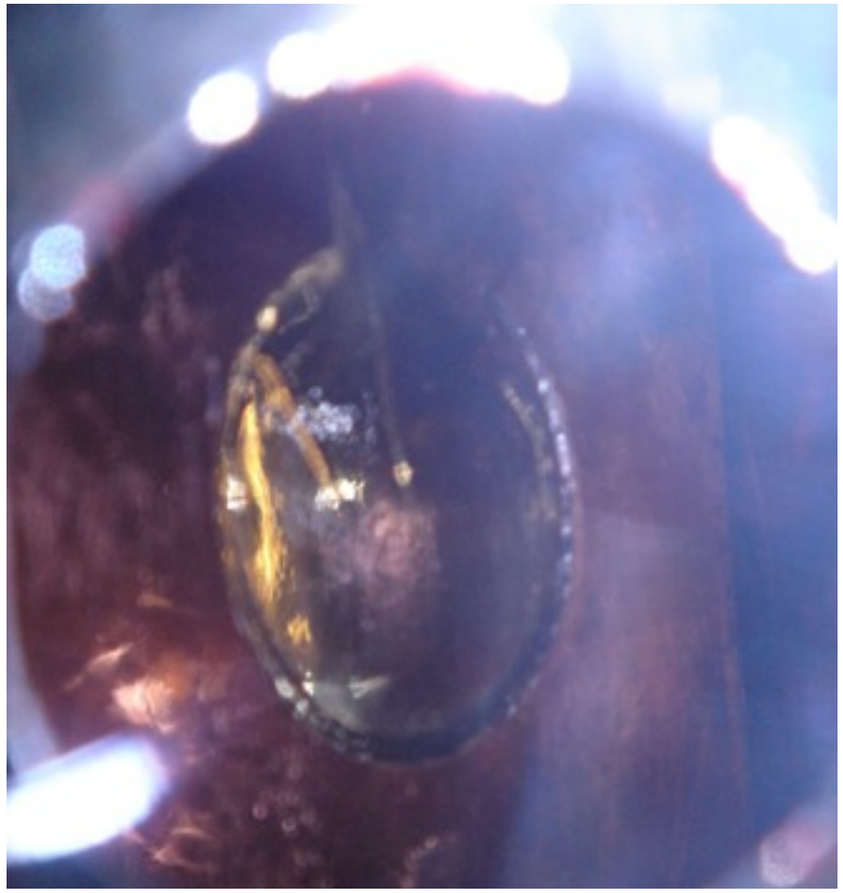




	Solid H_2 (SHT)	RDC	$p\Delta E$	E
material	Para H_2	Ar+C_2H_6	Plastic	NaI(Tl)
effective area	ϕ 30 mm	436 x 436 mm^2	440 x 440 mm^2	431.8 x 45.72 mm^2
thickness	1 mm	69.4 mm	2.53 / 3.09 mm	50.8 mm
Resolution		500 μm	TOF : 0.1 nsec	0.3 %(80 MeV)

Recoil Proton Spectrometer (RPS)



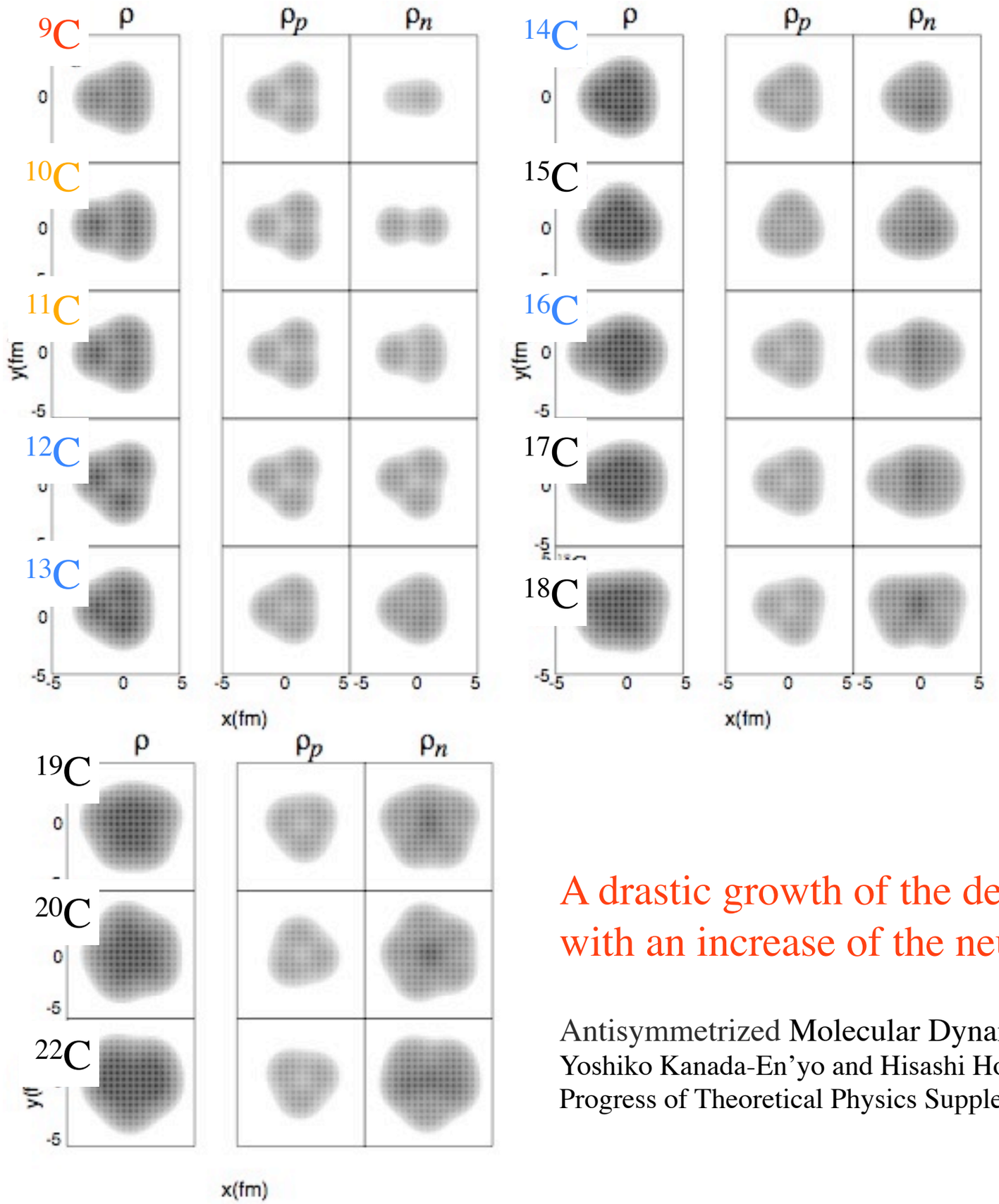


Solid para hydrogen target

ϕ30 mm, 1 mm^t

	Solid H_2 (SHT)	RDC	$p\Delta E$	E
material	Para H_2	Ar+C_2H_6	Plastic	NaI(Tl)
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)

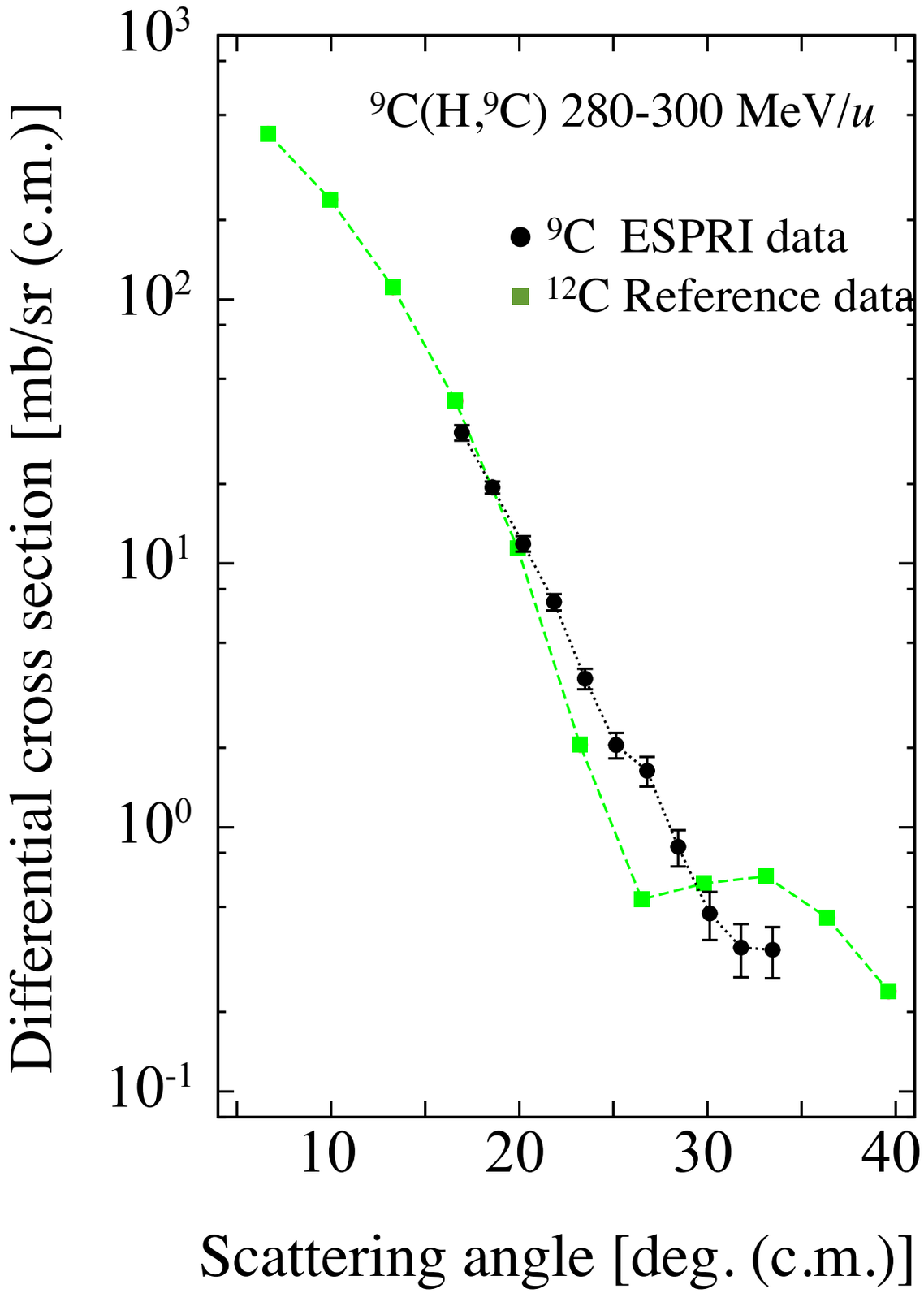
Experiments of ESPRI



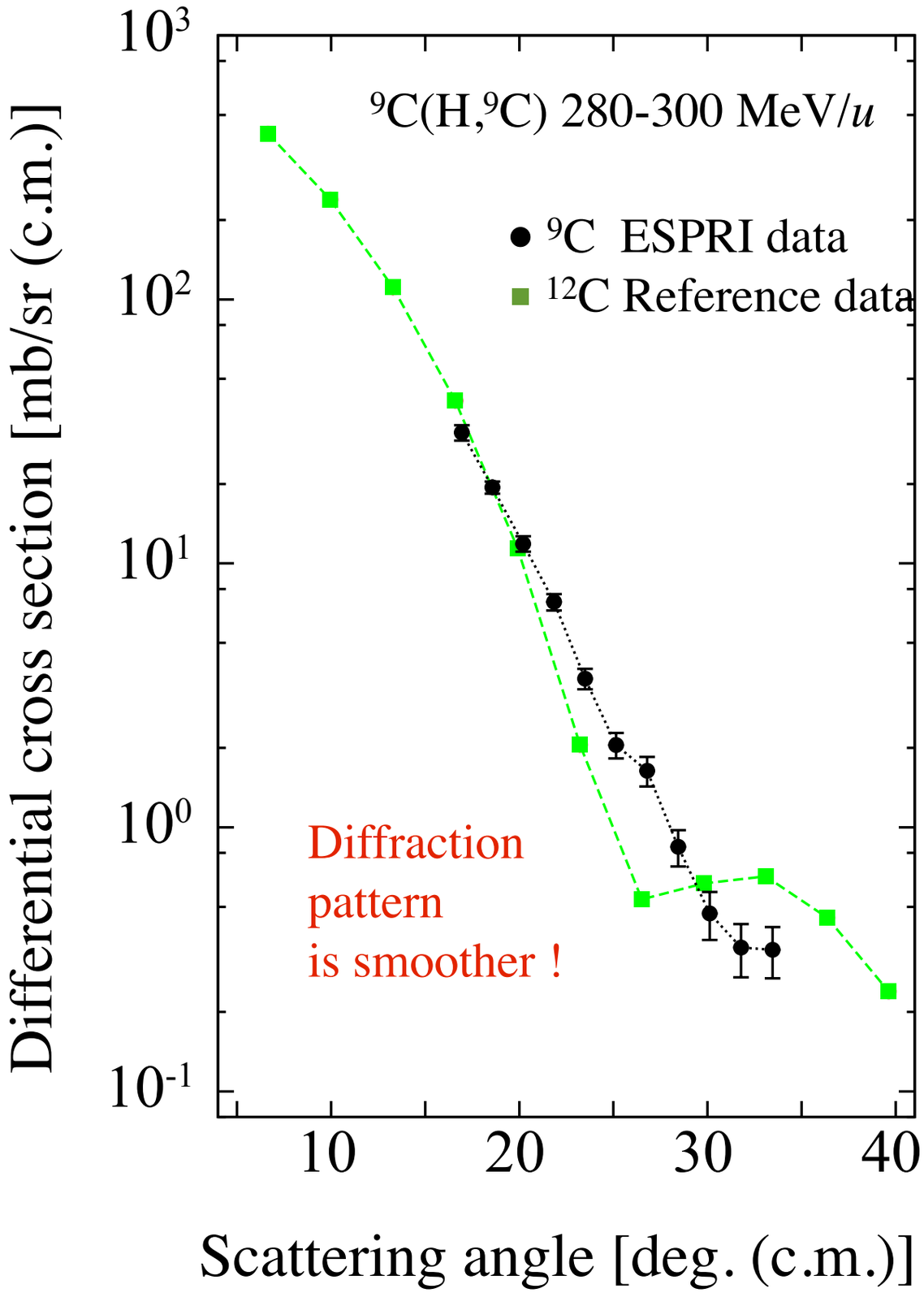
A drastic growth of the density distribution with an increase of the neutron number.

Antisymmetrized Molecular Dynamics (AMD) density:
Yoshiko Kanada-En'yo and Hisashi Horiuchi,
Progress of Theoretical Physics Supplement, 142 (2001) 205

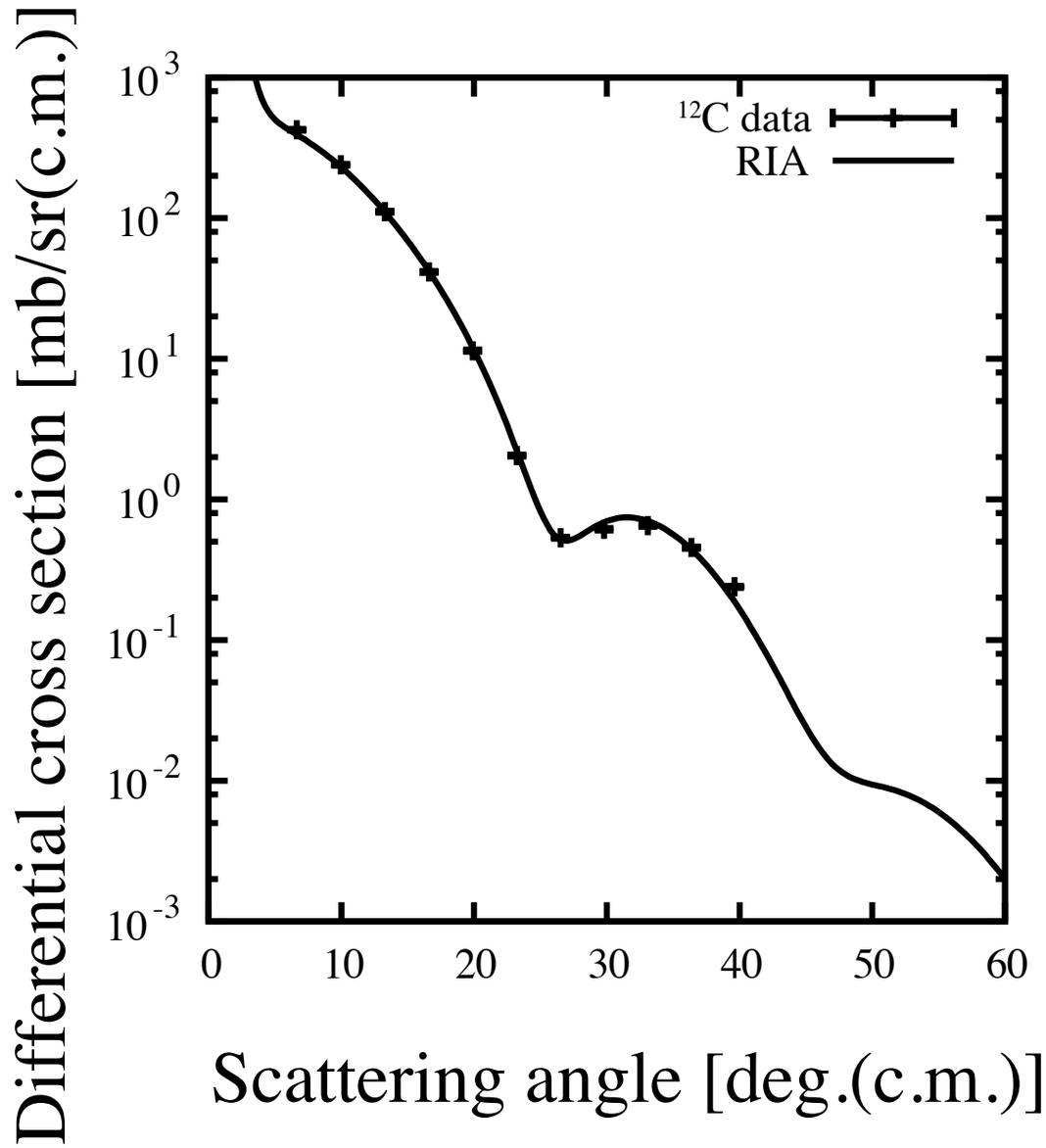
^{9}C data analysis

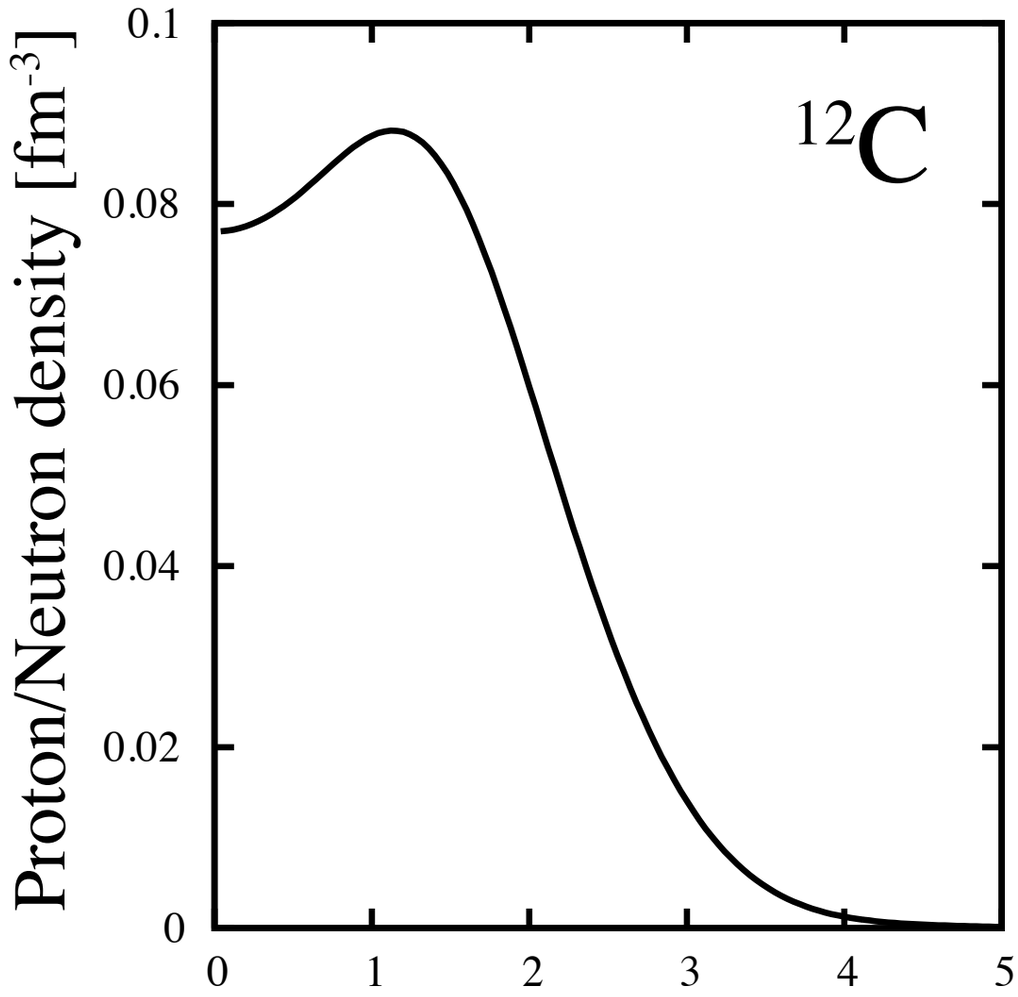


^{9}C data analysis



^{9}C data analysis



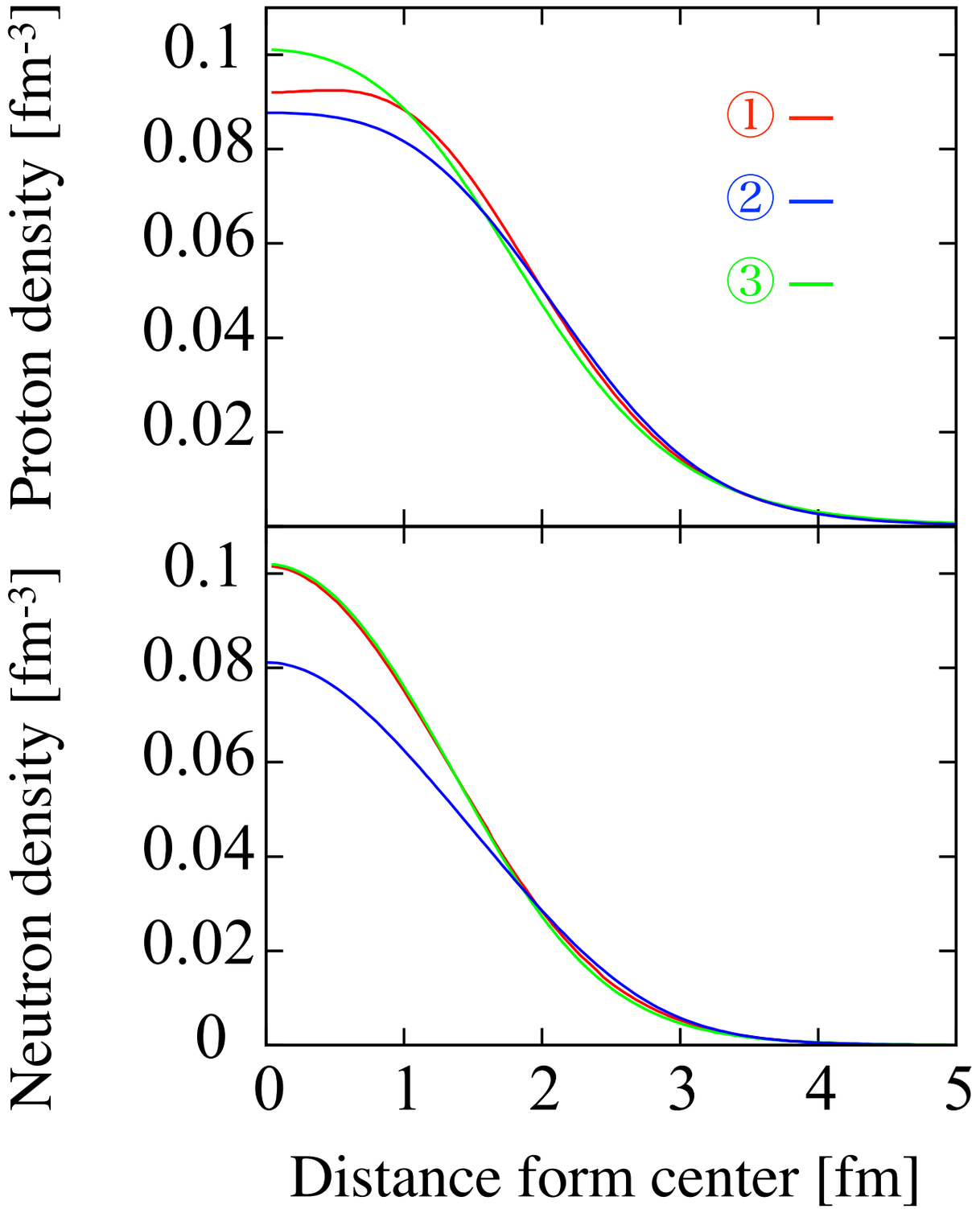


$$g_j^2 \rightarrow \frac{g_j^2}{1+a_j\frac{\rho(r)}{\rho_0}},$$

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

a_σ	-0.391
a_ω	-0.529
b_σ	0.356
b_ω	0.477

^{9}C data analysis

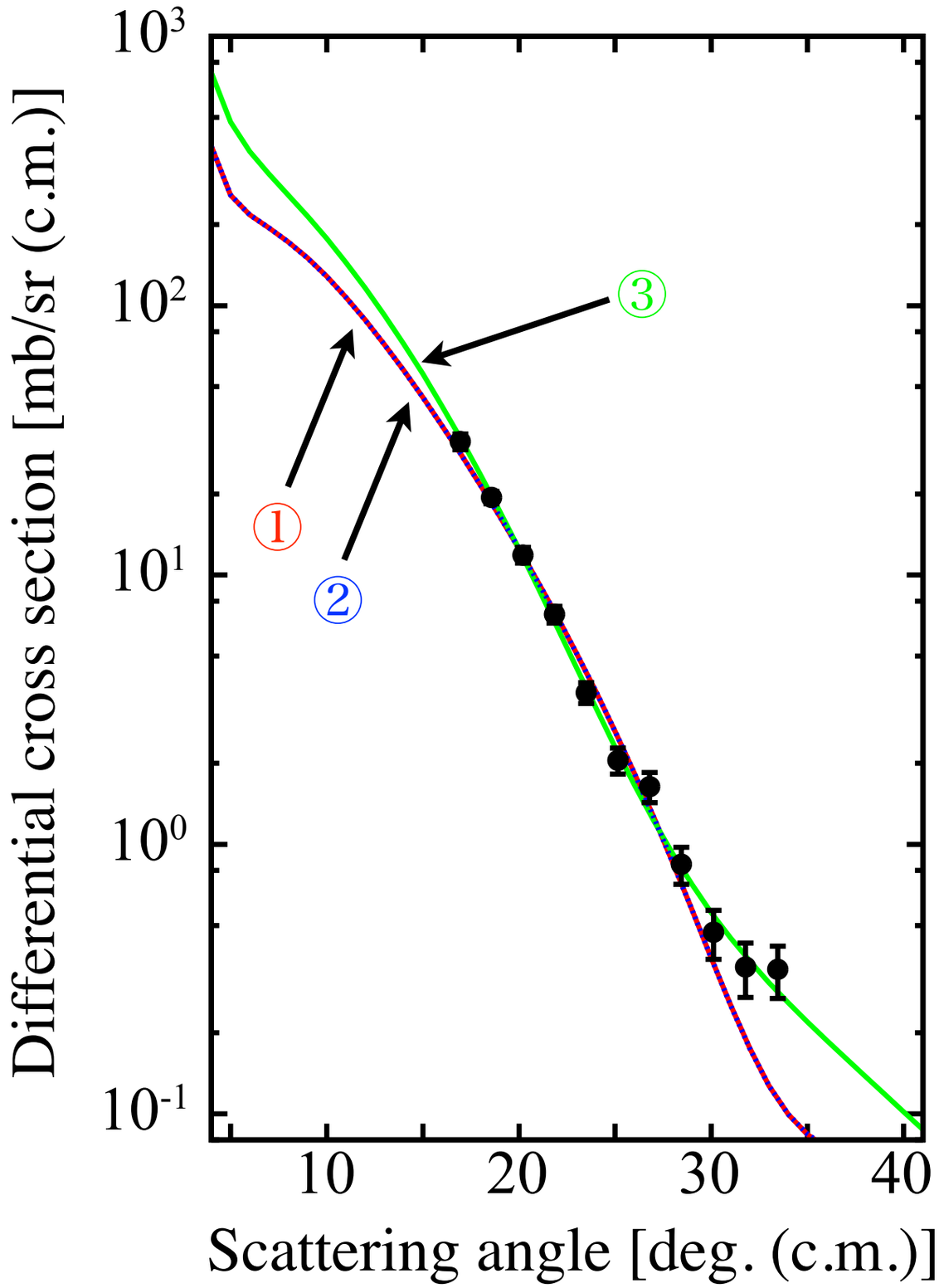


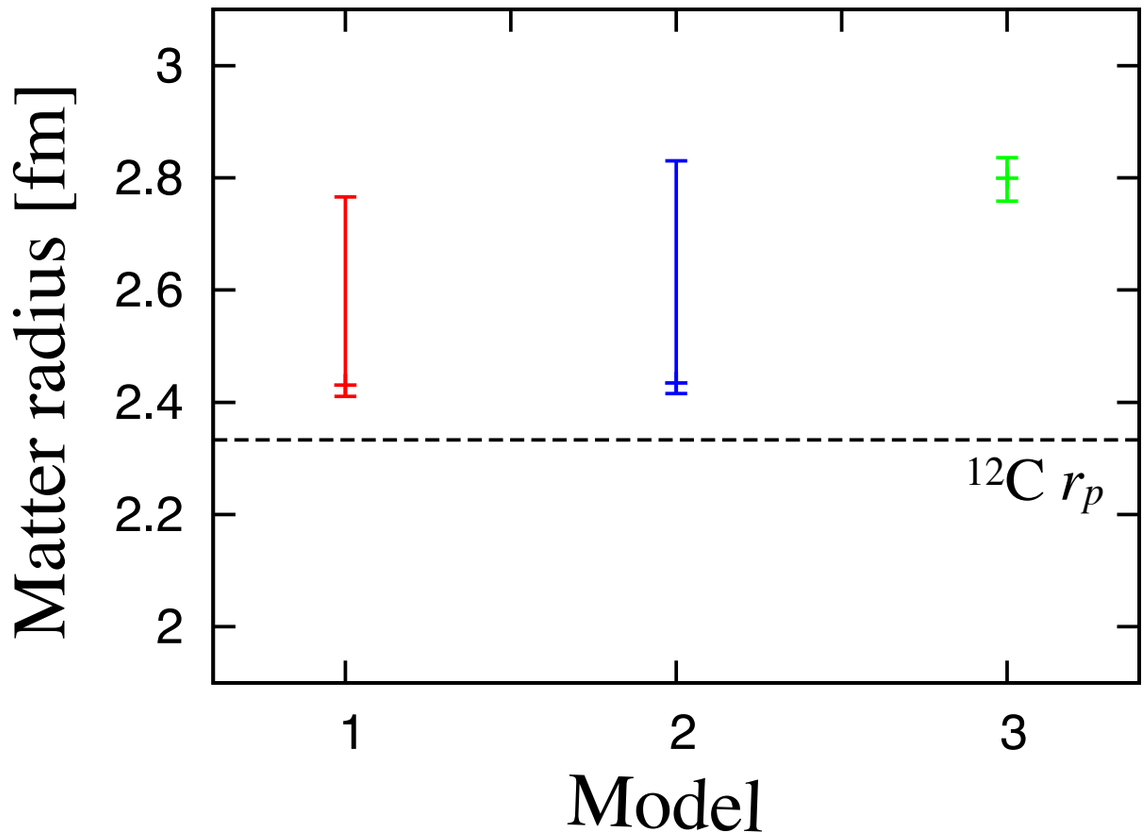
$$\rho_{p,n}(r) \quad \propto \quad \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}$$

	a_p	a_n	Model
1	0.541	0.526	AMD
2	0.540	0.538	SLy4
3	0.608	0.512	RMF

1. N.Furutachi et al., PTP 121(2009) 586.
2. Comp. Nucl. Phys. 1, Chap. 2.
3. Comp. Nucl. Phys. 1, Chap. 7.

^{9}C data analysis





※ H. De.Vries et al. Atomic and Nuclear Data Tables, 36, 495 (1987).

Summary

- We proposed a project, “Elastic Scattering of Protons with RI beams (ESPRI)”.
  - Size and density distributions of unstable nuclei
  - Related topics: asymmetric nuclear matter, weakly bound systems, modification of shell structure.

- We have developed a Recoil Proton Spectrometer.
  - Thin and large solid hydrogen target
  - Extensive momentum transfer region: up to about 2 fm^{-1}
  - Excitation energy resolution : about 400 keV(rms)

- We have measured following unstable nuclei:
  - $^{9,10,11}C$ @NIRS-HIMAC
  - ^{20}O @NIRS-HIMAC (not introduced in this talk)
  - $^{66,70}Ni$ @GSI (not introduced in this talk)

- The radius of ^{9}C:
  - 2.4-2.8 fm
  - Larger than the radius of ^{12}C

Future plan

- We are preparing to measure following nuclei:
  - $^{12,13,14}C$ @RCNP, Osaka Univ.
  - ^{16}C @RIKEN-RIBF

End