

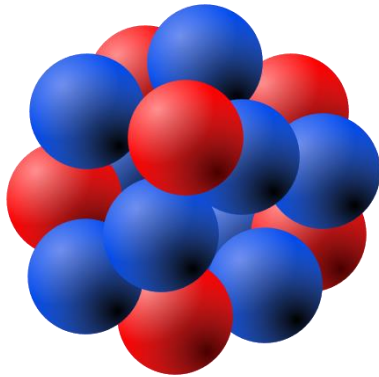
EOS study in nuclear physics

Juzo Zenihiro

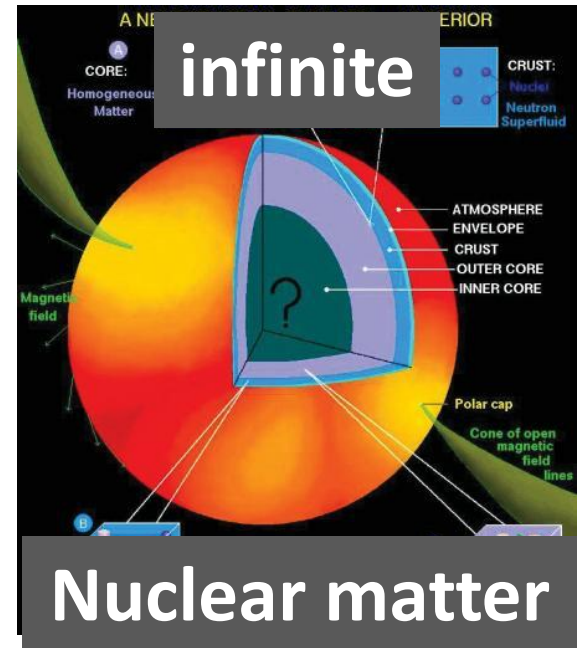
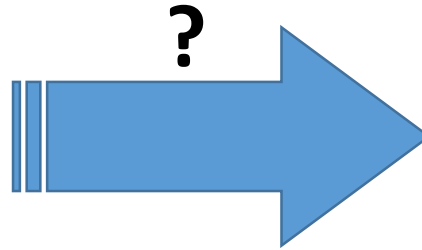
前回のおさらい: EOSのこれまでとこれから

- **ここ5年**のEOS研究: $E(\rho, \delta) = E(\rho, 0) + S(\rho)\delta^2$ これだけ。
 - 少なからずいまだ核構造モデルの不定性に縛られている。
 - しかし近年では**スキンや密度分布、非圧縮率(incompressibility)、電気双極分極率(dipole polarizability)**を、モデル依存を出来るだけ排除して決める方法論が開発されてきている。
 - Sum ruleが活躍
 - EOSの特にSymmetry energyに対してある程度の制限を課すことができつつある。
 - 舞台は不安定核へ
- **これから5年**は? 完璧な J, L, K_{sym} を目指して。
 - 最早大雑把な制限ではなく、モデルを構築するための確固たるインプットとしての**系統的**なsurveyが必須。(荷電半径、結合エネルギーなどに続く。)。
 - アイソスピン→スキン、非圧縮率、電気双極分極率、質量 → ESPRI, CAT, R3,
 - 密度→重イオン衝突による、 $2\rho_0$ での π^+/π^- ratio、核子間相互作用の密度依存→ SPIRIT, HI elastic
 - RCNP並の精密測定を不安定核で目指す!
 - 100(!)-132SnやCa、Niを含む中重核を一網打尽にする。
- **10年(以上)**を見据えると? EOSってそもそも。。。
 - 本当のところNeutron Star Matter ($\delta \rightarrow 1, \rho > 2\rho_0$)をどのようにして観るのか?
 - 核物質の新たな側面を見るには新しい軸でもって見る。アイソスピン、密度に加えて。
 - p と n 以外の構成要素の寄与(クラスター自由度?)、 d, t, a, π, \dots などの核物質中での確率分布(原子核版パートン分布): **Cluster, Parton**
 - 有限温度核物質のEOS(基底状態でない): **Temperature**
 - 中性子星物質とは何なのか? (not中性子物質?、ハイペロン含むハドロン相、クォーク相、EMC効果?): **Phase shift**
 - マグネターも新しい原子核物理のモデルケースになりうるか? 核物質中で高磁場を生み出すダイナミクス。原子核のダイナモ理論。高スピンの核物質に及ぼす寄与: **Magnetic moment? High Spin? (classical nuclear matter?), Spin Susceptibility?**
 - といった新しい自由度を含むEOSの構築。

finite



Nucleus



Nuclear structure

- ρ_p & ρ_n , neutron skin
- ISGMR
- Dipole polarizability
- ...

Basic input \rightarrow EOS

$$: E(\rho, \delta) = E(\rho, 0) + S(\rho)\delta^2$$

$\delta=0$: Symmetric matter

$\delta=1$: Neutron matter

Nuclear matter EOS with isospin asymmetry δ

- EOS of nuclear matter $\mathcal{E}(\rho, \delta)$: the energy per nucleon

$$\mathcal{E}(\rho, \delta) = \mathcal{E}(\rho, 0) + \mathcal{S}(\rho)\delta^2 + O(\delta^4)$$

- EOS of symmetric nuclear matter $\mathcal{E}(\rho, 0)$:

$$\mathcal{E}(\rho, 0) = \mathcal{E}(\rho_{\text{sat}}, 0) + \frac{K_0}{2}\varepsilon^2 + O(\varepsilon^3)$$

$$\rightarrow \mathcal{E}(\rho_{\text{sat}}, 0) \sim -16 \text{ MeV},$$

$$K_0 \sim 240 \text{ MeV}$$

- The symmetry energy $\mathcal{S}(\rho)$:

$$\mathcal{S}(\rho) = \mathcal{S}(\rho_{\text{sat}}) + L\delta + \frac{K_{\text{sym}}}{2}\varepsilon^2 + O(\varepsilon^3)$$

\rightarrow Still less certain !

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}, \quad \varepsilon = \frac{\rho - \rho_{\text{sat}}}{3\rho_{\text{sat}}}$$

EOS study: Symmetry energy exp.

ESPRI : ρ_p, ρ_n & **Skin** thickness : L , **saturation**

(p, p) elastic for stable & unstable nuclei

$^{204-208}\text{Pb}$, $^{116-124}\text{Sn}$, ^{90}Zr , $^{40-48}\text{Ca}$ (RCNP)

^{132}Sn , $^{66,70}\text{Ni}$, ^{16}C (RIBF, GSI)

CAT : **Incompressibility** of nuclear matter: K_{sym}

GMR by (d, d') or (a, a') around 0 degree

^{132}Sn (RIBF)

SAMURAI-TPC (SPiRIT) : EOS at $2\rho_0$

π^+/π^- ratio by HI collision (Sn isotope?) (RIBF)

A-A HI elastic scattering : EOS at $2\rho_0$

Theory : H. Sakuragi, T. Furumoto

Planned ; $^{12}\text{C}-^{12}\text{C}$ at 100, 200, 300 (RCNP, RIBF)

(p, p') at 0 degree : **Dipole Polarizability** : L

proton inelastic scattering (^{208}Pb , ^{120}Sn , ^{90}Zr) (RCNP)

PREX-II, CREX at J-lab : neutron radius & skin thickness : L

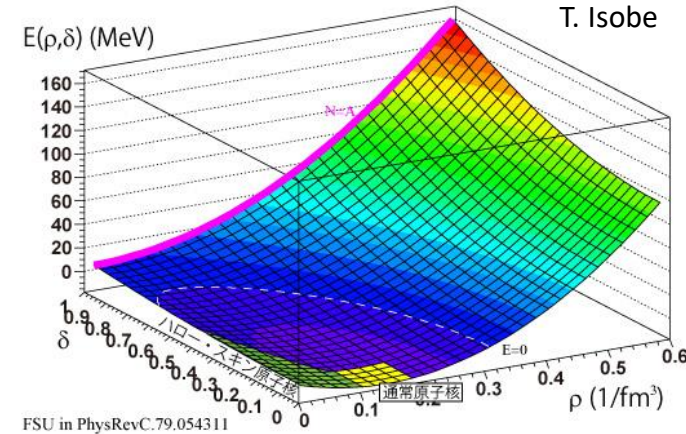
parity-violating electron elastic scattering

2015/10/27

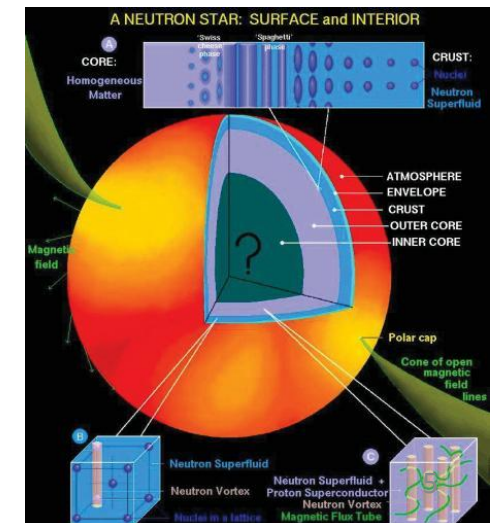
Stable nuclei : ^{208}Pb , ^{48}Ca

3D NM EOS

Drawn by
T. Isobe



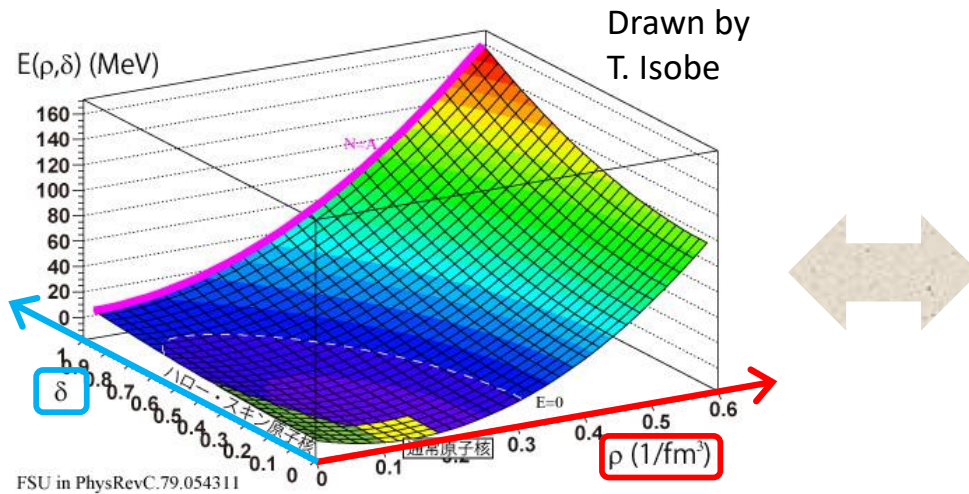
Neutron Star Structure



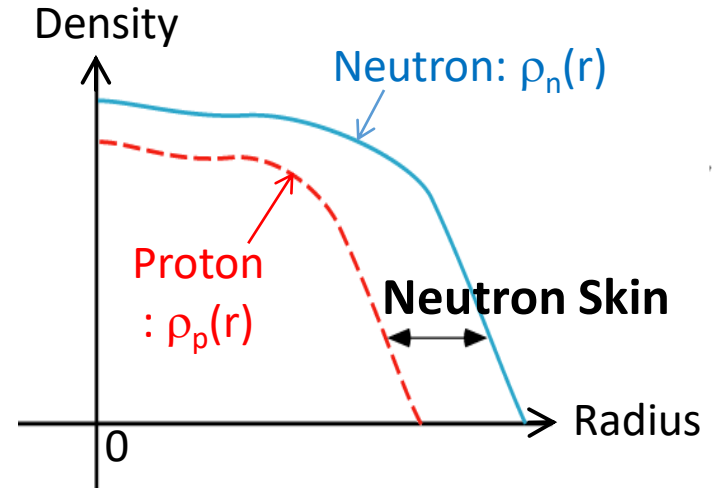
Neutron skin

EOS vs neutron skin : simple picture

Nuclear matter EOS



Finite nucleus



$$E(\rho, \delta) = E(\rho, 0) + \underline{S(\rho)}\delta^2 + O(\delta^4)$$

Symmetry
energy

Density: ρ

Asymmetry: δ

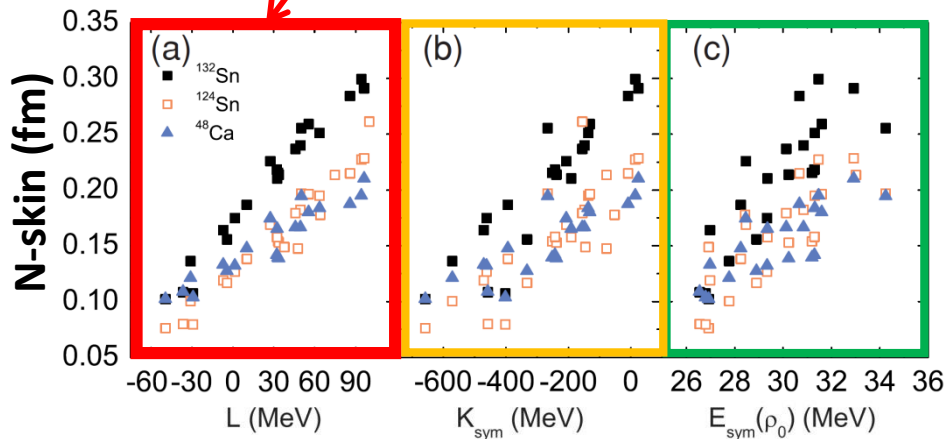
Symmetry energy vs. Neutron skin

$$E(\rho, \delta) = E(\rho, 0) + S(\rho)\delta^2 + O(\delta^4)$$

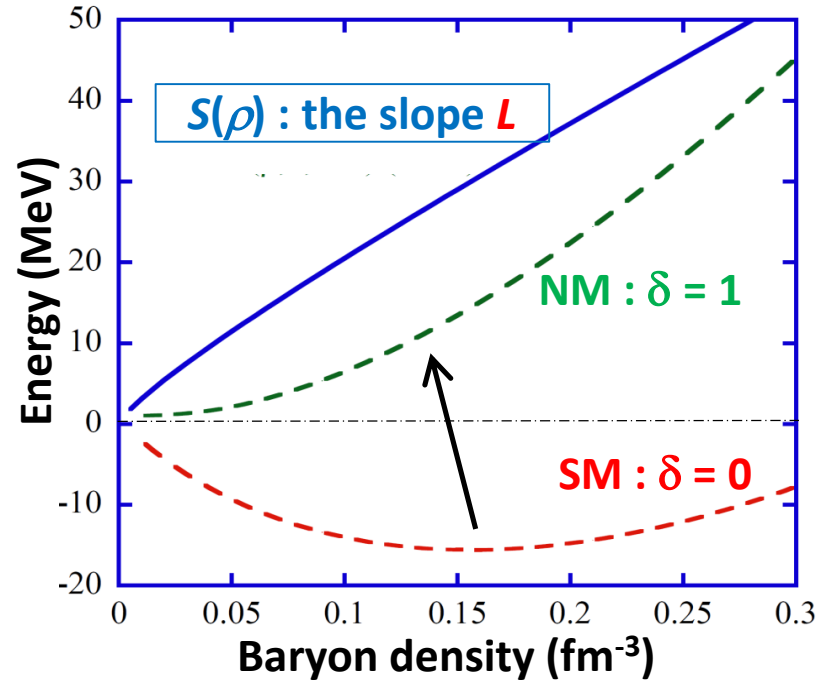
$$S(\rho) = S(\rho_{\text{sat}}) + L\varepsilon + \frac{K_{\text{sym}}}{2}\varepsilon^2 + O(\varepsilon^3)$$

Strong correlation!

$$\varepsilon = \frac{\rho - \rho_{\text{sat}}}{3\rho_{\text{sat}}}$$



Taken from L.-W. Chen et al., PRC72, 064309.



Determine the slope coefficient L of $S(\rho) \rightarrow$ **neutron matter EOS**

Impact on **neutron star** structure

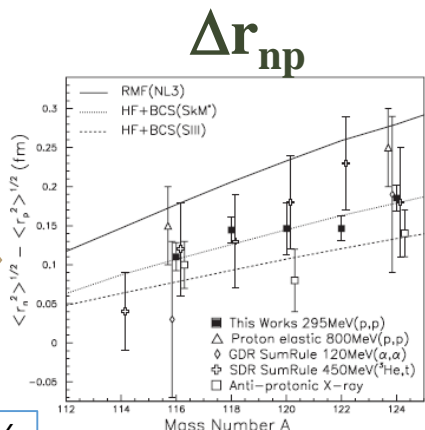
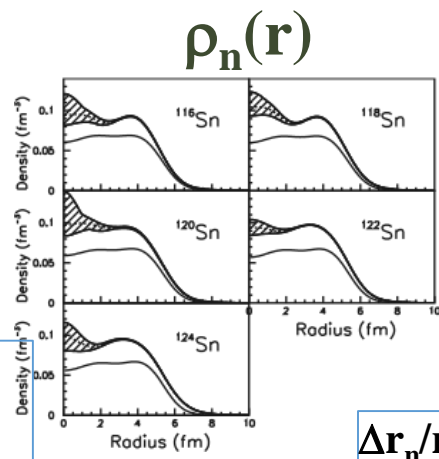
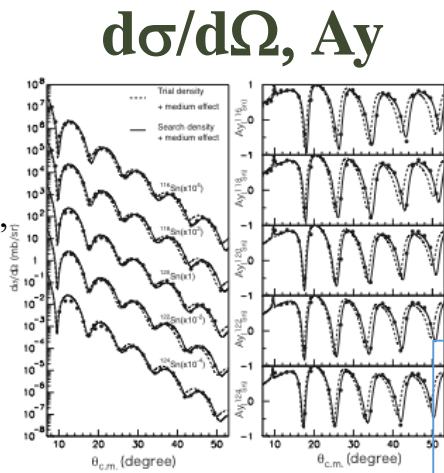
- Radius, cooling system, etc.

Neutron density and skin study (1)

Stable nuclei → **RCNP, Osaka Univ.**

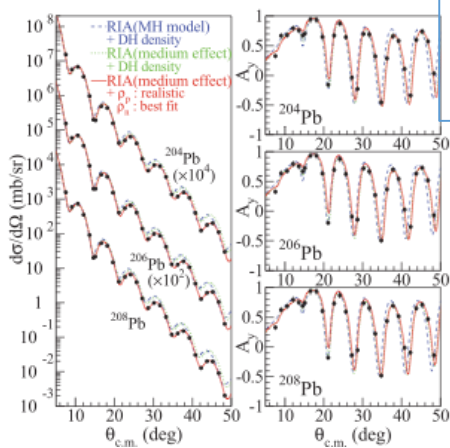
Sn

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

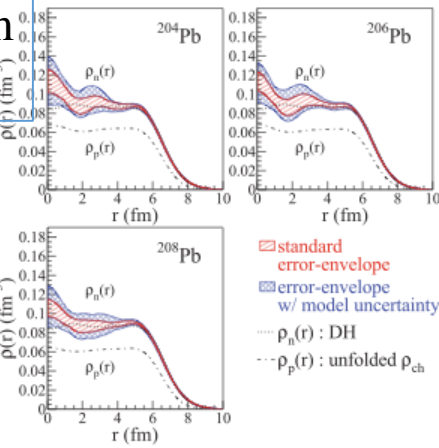


Pb

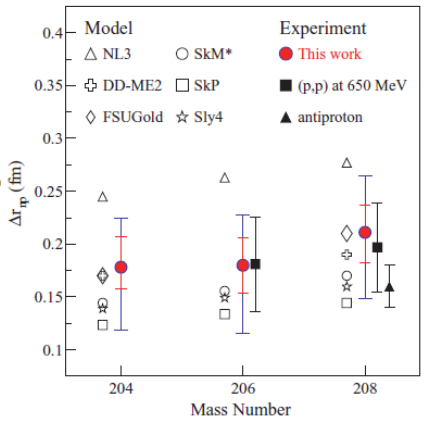
J.Zenihiro et al.,
Phys. Rev. C 82,
044611 (2010)



RIA
+
Medium
Effect



$\Delta r_n / r_n < 0.5\%$

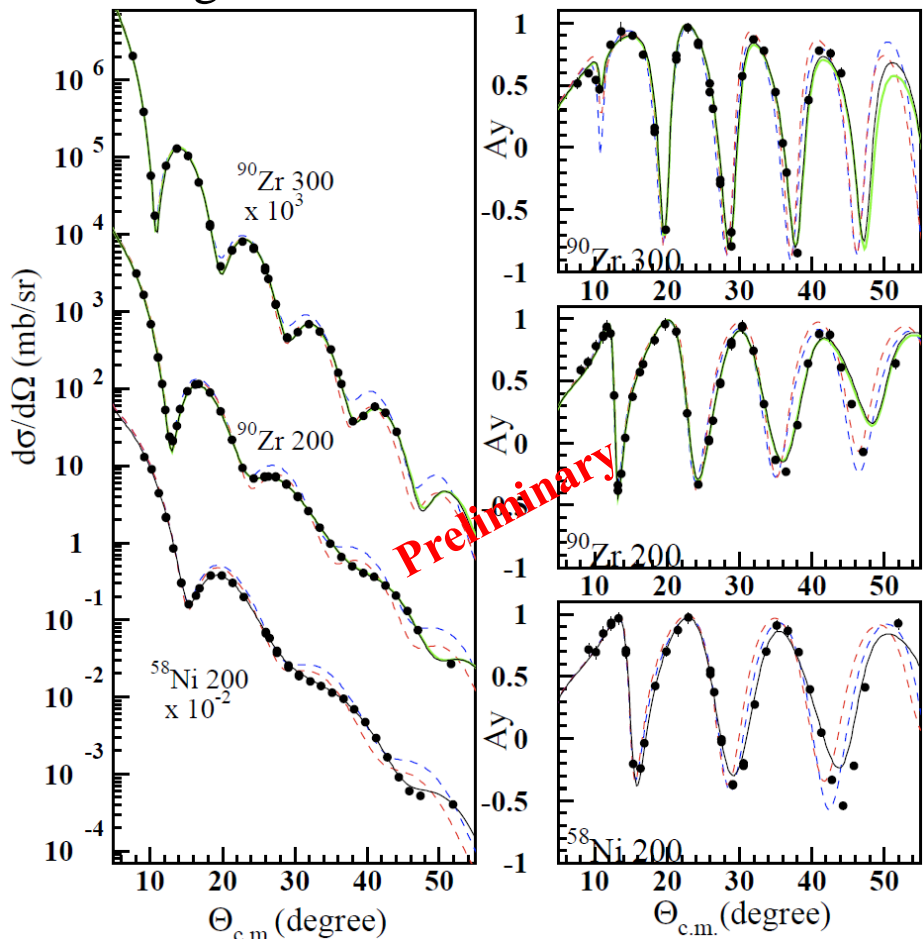


Ongoing work :

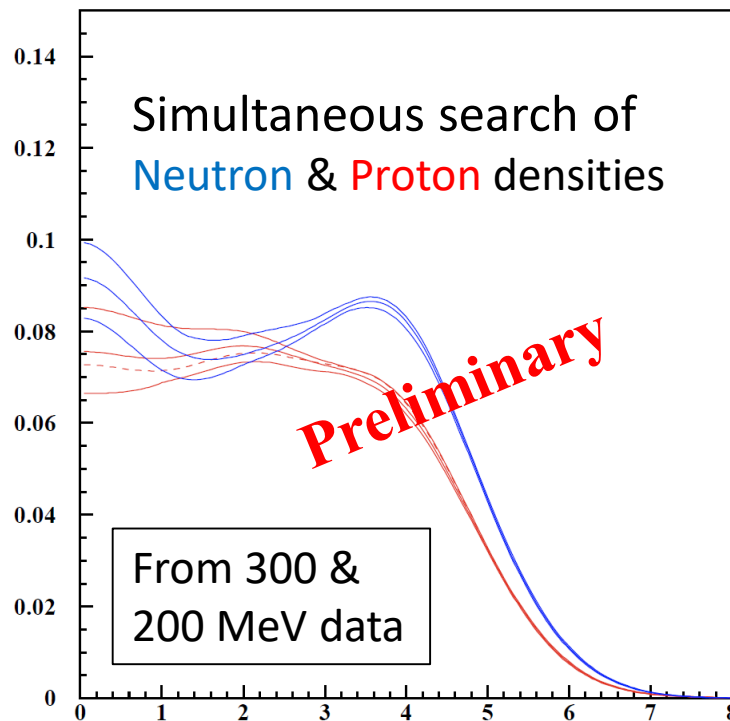
$40,42,44,48\text{Ca}$ and $90,92,94\text{Zr}$

Simultaneous extraction of ρ_p & ρ_n from two-energy p-elastic data @ 200 & 300 MeV

Fitting results for ^{90}Zr @ **200 & 300 MeV**



Extracted densities of ^{90}Zr



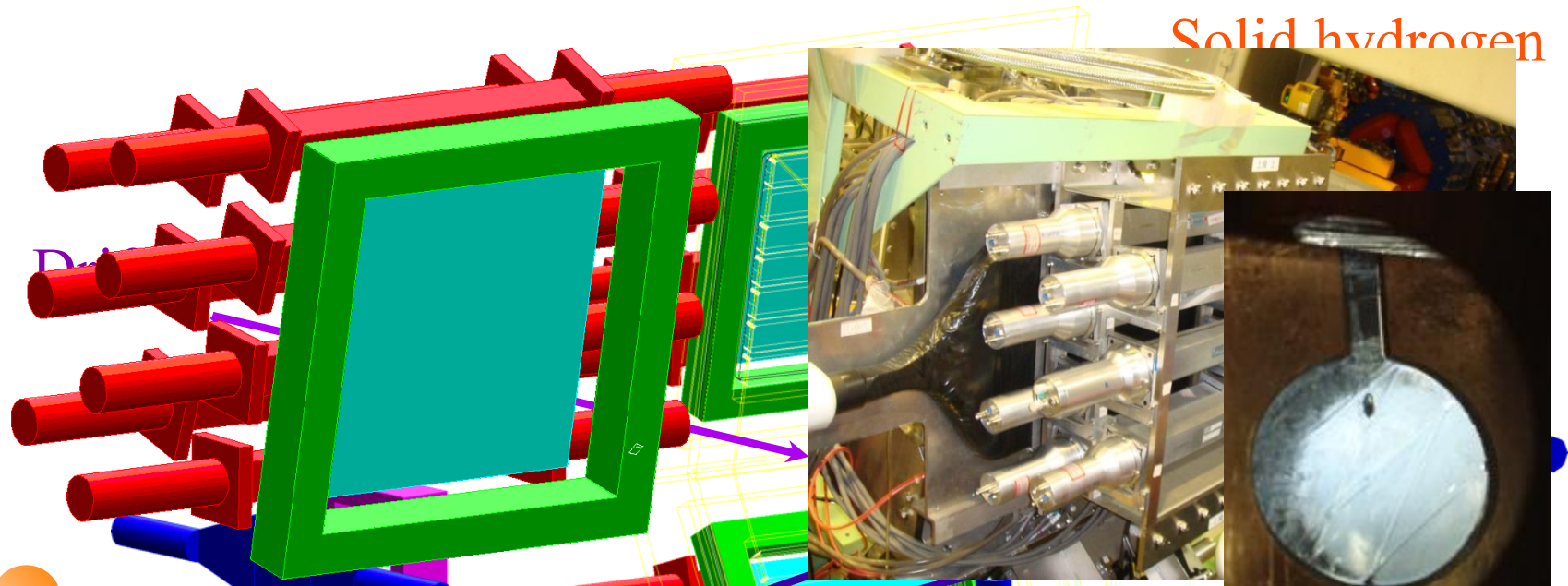
r_n	r_p	Δr_{np}
4.300(17)	4.210(20)	0.090(26)

(4.20 from $e^{-90}\text{Zr}$)

(all in fm)

Neutron density and skin study (2)

Unstable nuclei → **ESPRI at RIBF**



Solid hydrogen

$\theta_{lab} = 66^\circ - 80^\circ$, $E_p = 20-120$ MeV, $\Delta\Omega \sim 10$ msr/deg.
 $q = 1-2.2$ fm⁻¹, $\Delta E_x = 400-500$ keV

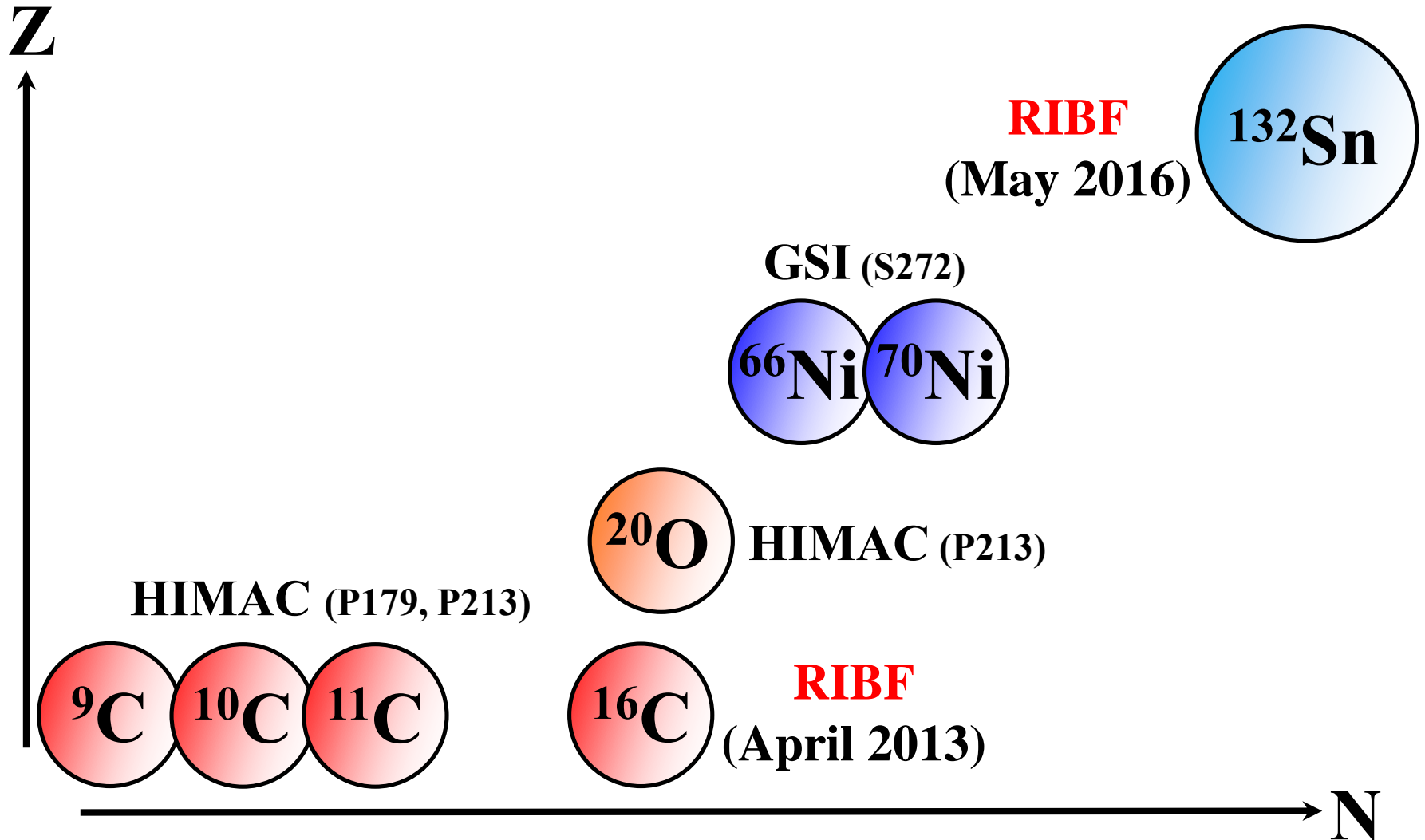
1 mm^t
 $\phi 30$ mm

Plastic scintillator

Recoil drift chamber	436x436 mm ² (x-y-x'-y'-x'-y)
Plastic scintillator	440x440 mm ² x 2 mm ^t

NaI(Tl) calorimeter	431.8x45.72 mm ² x 50.8 mm ^t
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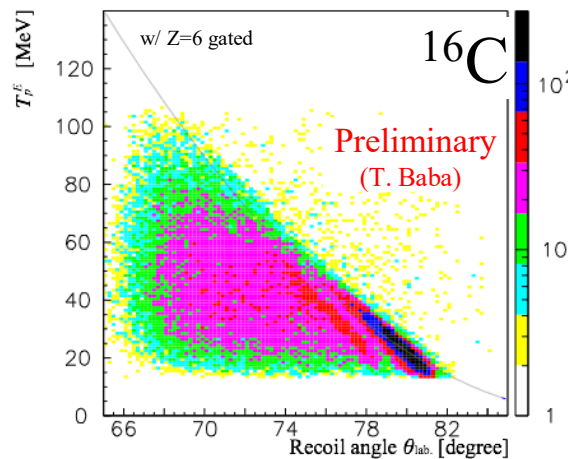
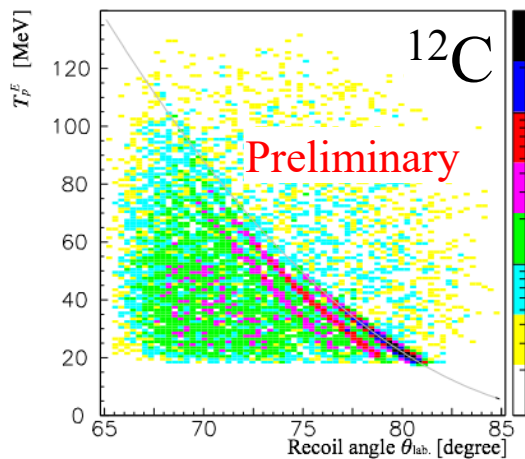
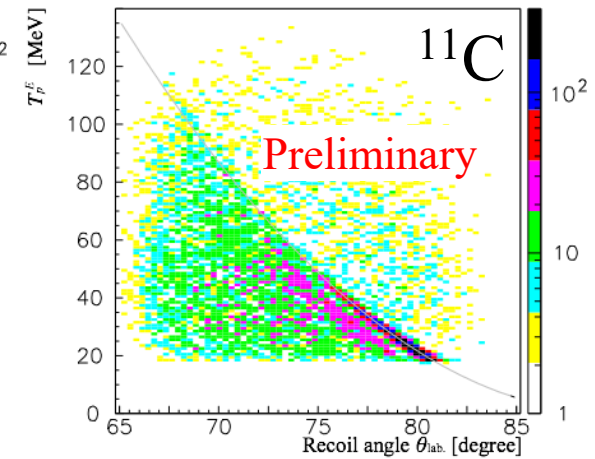
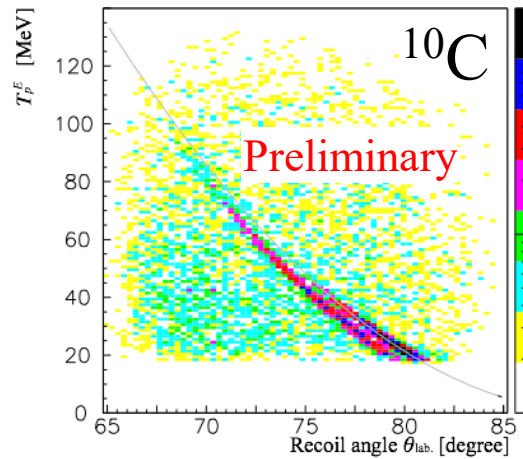
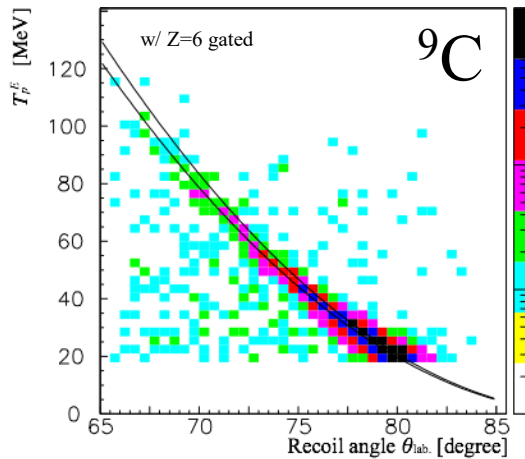
ESPRI Experiments



Light unstable nuclei : $^9\text{C}, ^{10}\text{C}, ^{11}\text{C}, ^{12}\text{C}, ^{16}\text{C}$

Kinematical correlation : T_p vs θ_p

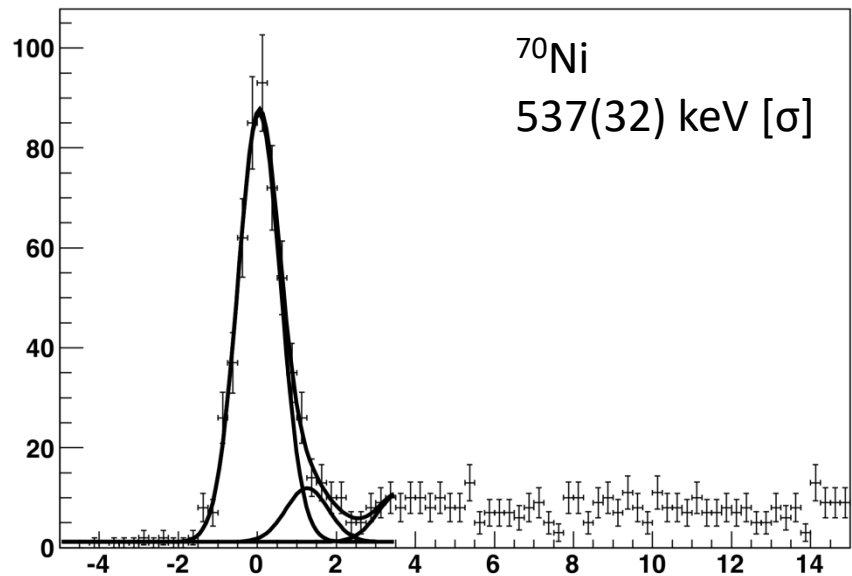
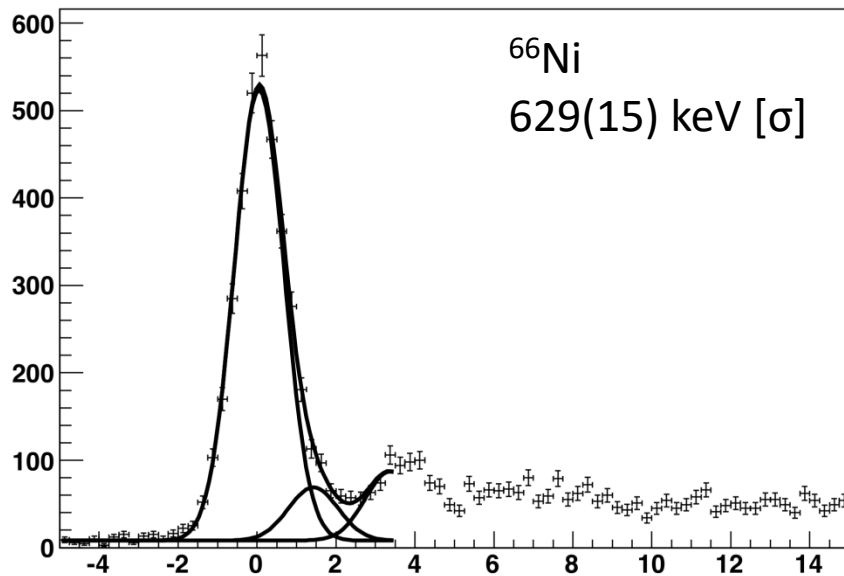
Recoil proton energy (MeV)



# of analyzed beams	
^9C	0.5×10^9
^{10}C	3×10^9
^{11}C	5×10^9
^{12}C	6×10^9
^{16}C	7×10^9

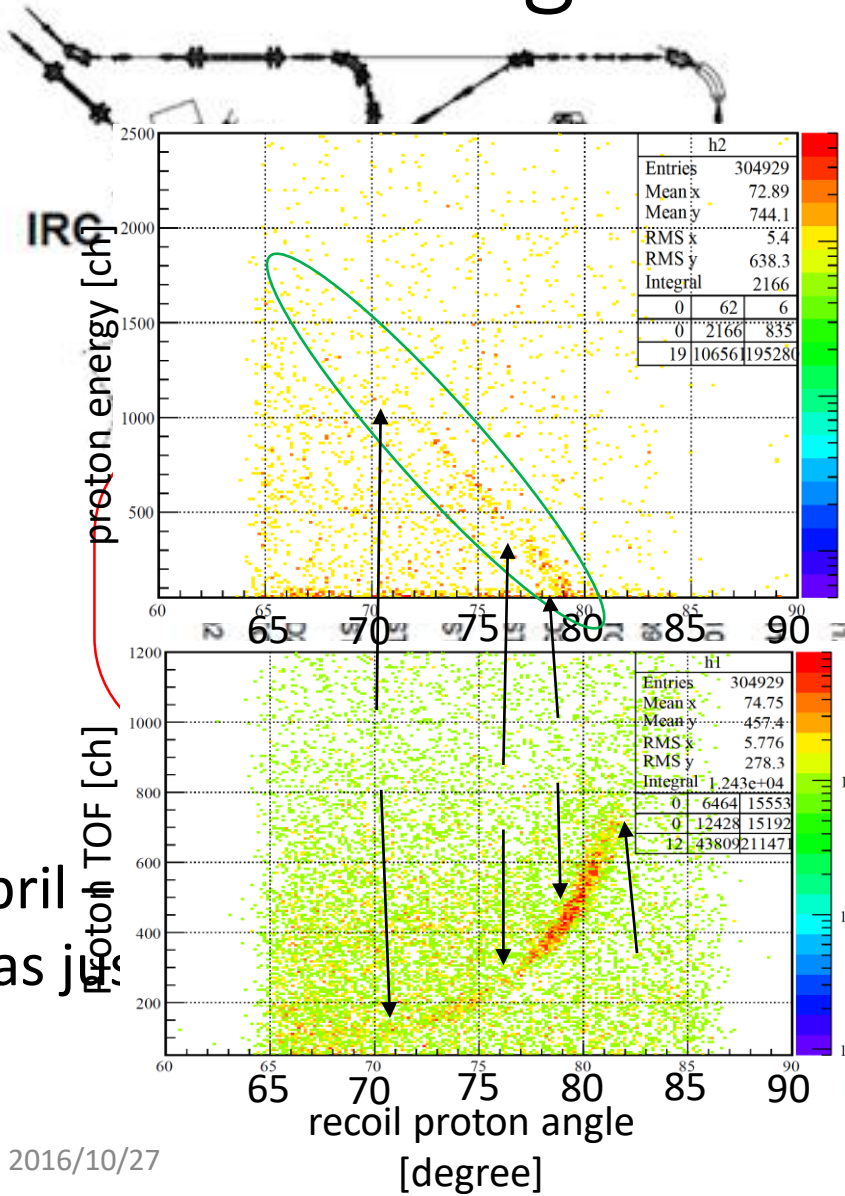
Medium-heavy unstable nuclei : $^{66,70}\text{Ni}$

Excitation energy spectra

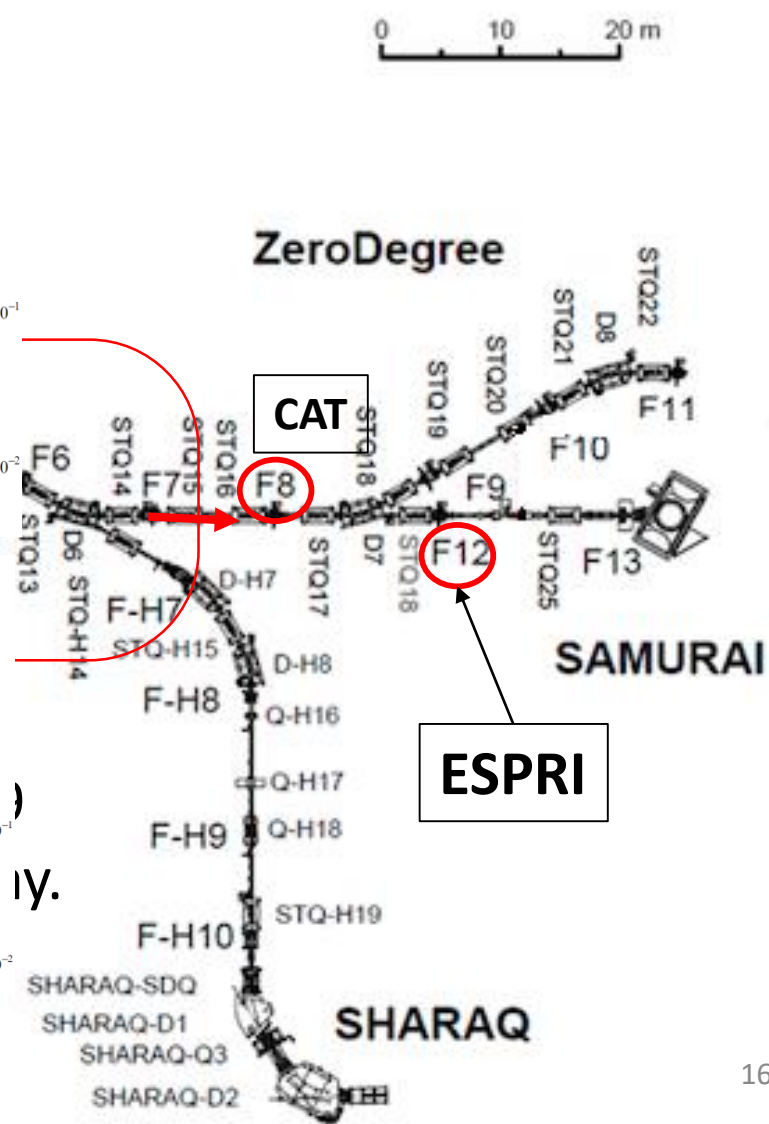


By S. Terashima

Double magic nucleus : ^{132}Sn



April was j...



Summary of ESPRI

- Neutron skins of double magic stable and unstable nuclei (flagship)
 - $40,48\text{Ca}$, 132Sn , 208Pb
- Next step : systematic survey of long isotope, isotone, isobar chains
 - $50,52\text{Ca}$, 50Ti , 52Cr
- Future : challenging experiment for 100Sn , 54Ca , 78Ni
 - New techniques are necessary.