B02:
Properties of neutron-rich nuclear matter with low-to-medium nuclear density
中性子過剰な中低密度核物質の物性

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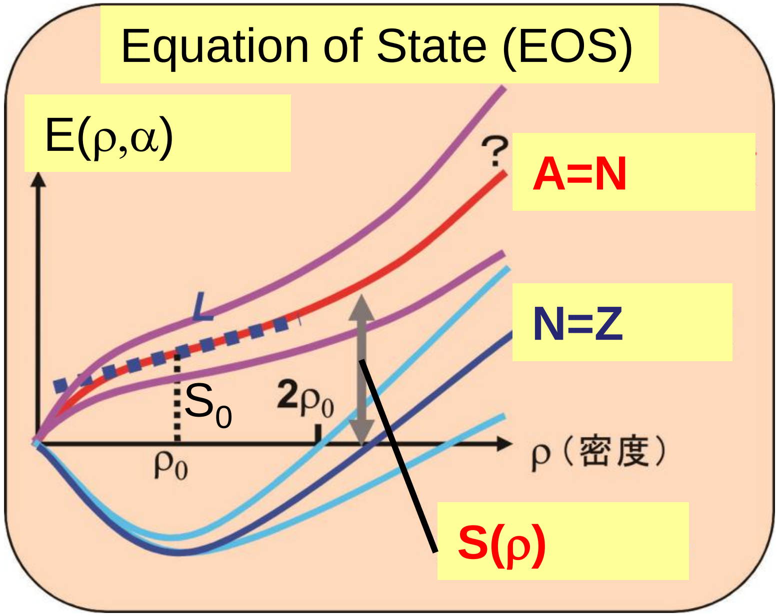
寺西高 九大

実験と観測で解き明かす中性子星の核物質 公募研究交流会
– Sep.12.13, 2013, @東北大

EOS of Nuclear Matter



Difference of n and p densities

$$E(\rho,\alpha) = E(\rho,0) + S\alpha^2 + \dots \qquad \alpha = \frac{\rho_n - \rho_p}{\rho_0} \approx \frac{N-Z}{A}$$

$$\underline{S(\rho)} = S_0 + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \dots$$

Symmetry Energy: $S(\rho)$

Neutron-rich Nuclei : Microscopic Laboratory for Neutron Star

- **Nuclear Force (NN,3N)**
- **Many-body Correlations** (Superfluidity(pairing), π condensation …)

at Extreme Conditions (not like normal N~Z nuclei)

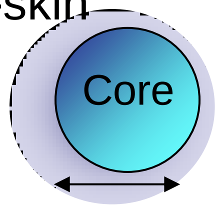
-- Wide range of **Density** $10^{-3}\rho_0$ --- $10\rho_0$ -- **Density Dependence**

-- **Asymmetric nuclear matter** N>>Z -- **Isospin Dependence**

How to determine the EOS?

---Projects of B02

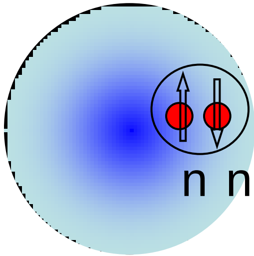
- S(ρ) : S_0, L(*pressure*), K_{sym}(*Incompressibility*)
  ← Collective Motion of Neutron-rich Nuclei



Pygmy Dipole Resonance (E1)

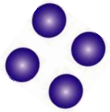
Breathing Mode (E0)

- Superfluidity ←Dineutron correlation in low-dense matter



2n Halo Nuclei

- S(ρ)←Nuclear force
  (density dependence, isospin dependence, 3N/4N force)
  ← tetra neutron, exotic nucleonic system

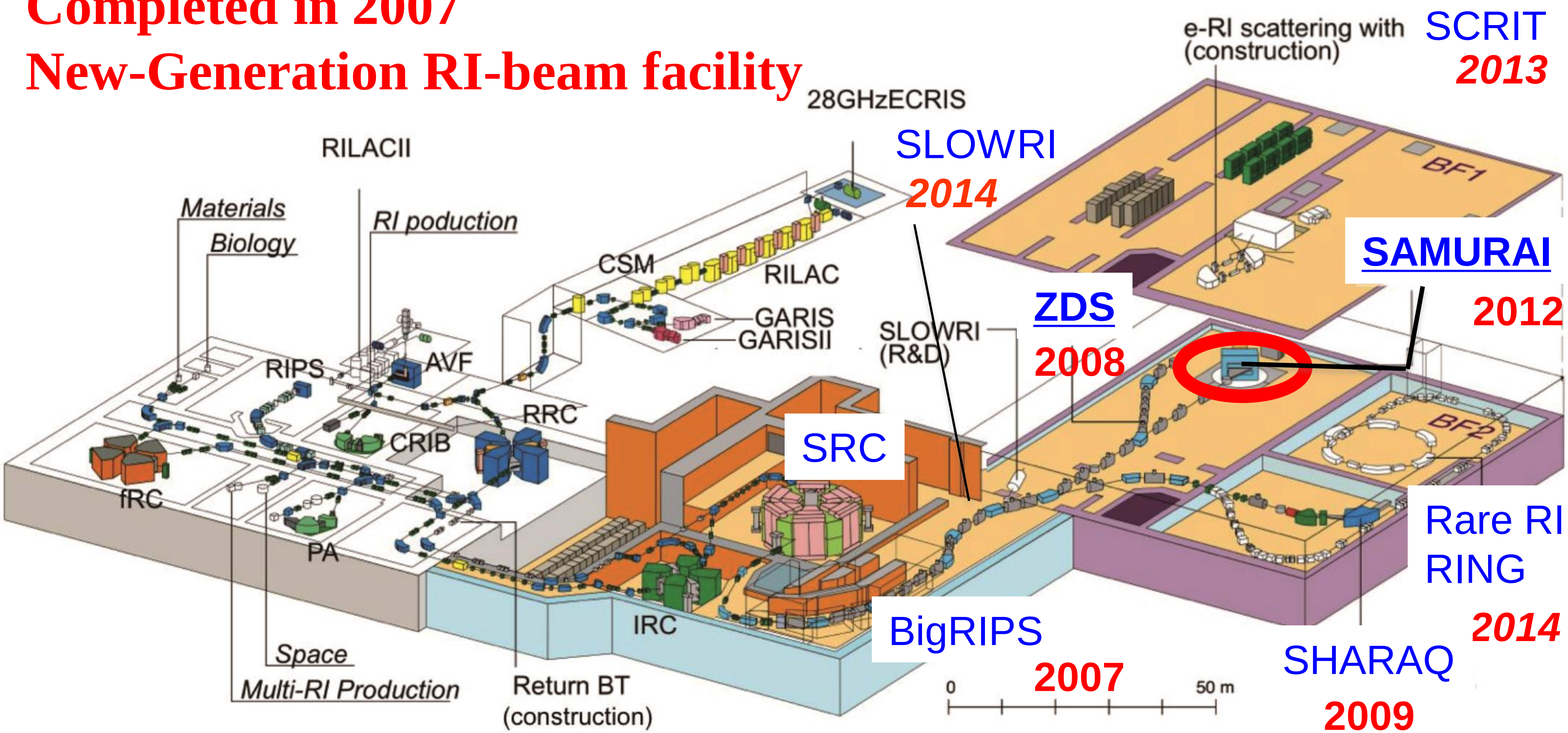
4n  26, ^{28}O

- S(ρ)←Bulk Property ← neutron skin thickness
  nuclear masses

RIKEN RI Beam Factory (RIBF)

Completed in 2007

New-Generation RI-beam facility



SRC: World Largest Cyclotron (K=2500 MeV)

Heavy Ion Beams up to ^{238}U at 345MeV/u (Light Ions up to 440MeV/u)

eg.

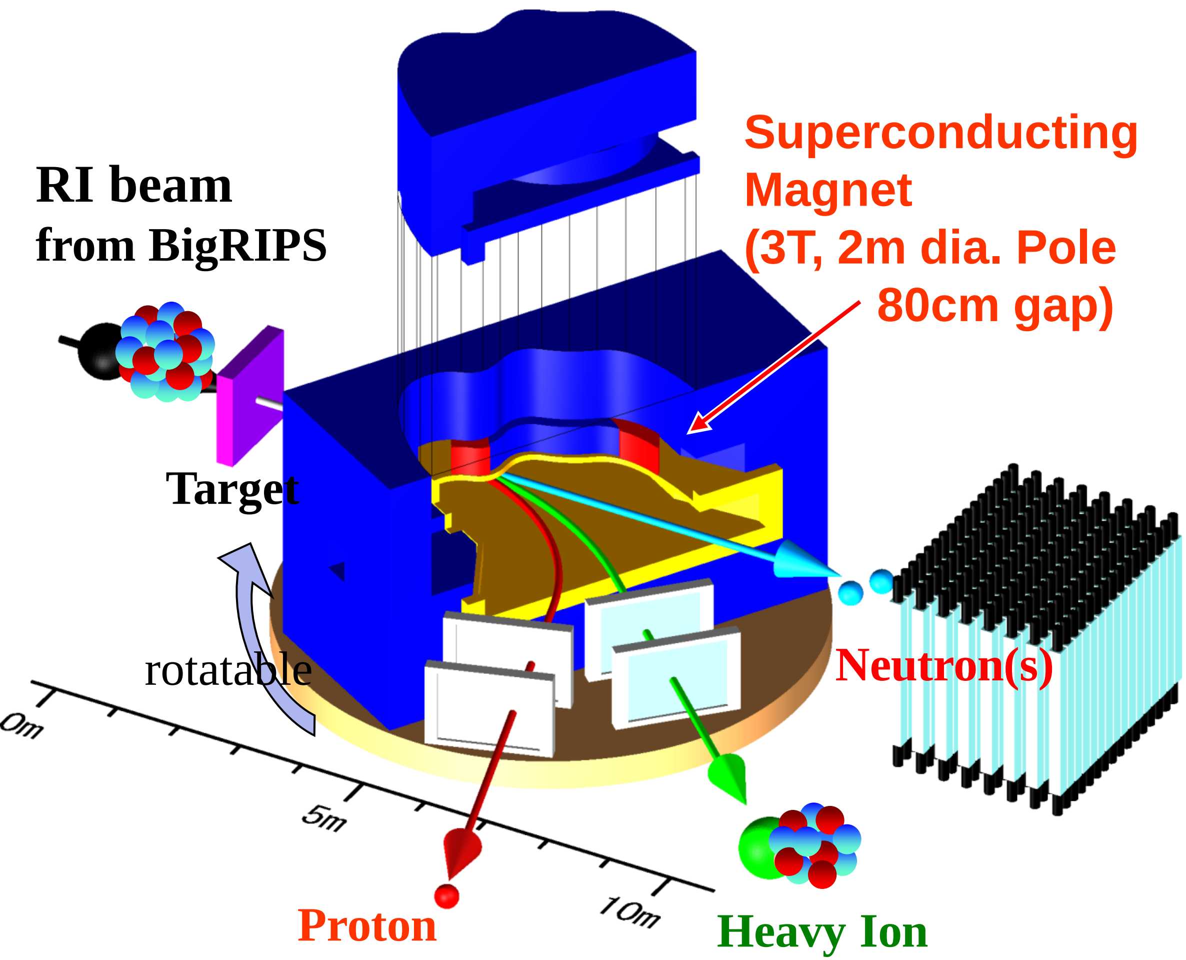
^{48}Ca beam (345 MeV/nucleon) ~200pnA (415 pnA max.)

^{238}U beam (345 MeV/nucleon) ~12pnA (15 pnA max.)

SAMURAI

Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam

Kinematically Complete measurements by detecting multiple particles in coincidence



Large momentum acceptance

$B\rho_{max} / B\rho_{min} \sim 2 - 3$

Good Momentum Resolution

$\Delta p/p \sim 1/700$ (designed value)

(5σ separation for A=100)

Large angular acceptance for *n*

20 deg (H) x 10 deg(V)

(~100% coverage < E_{rel} ~ 2MeV,

~ 30% coverage at E_{rel} ~ 10 MeV)

Stage: Rotatable (-5 -- 95 degrees)

Versatile Usage

Invariant mass for n+HI
Invariant mass for p+HI
(p,n),(p,p'),(p,pn)(p,pp) etc.
Heavy Ion Collision
polarized deuteron, etc.

SAMURAI

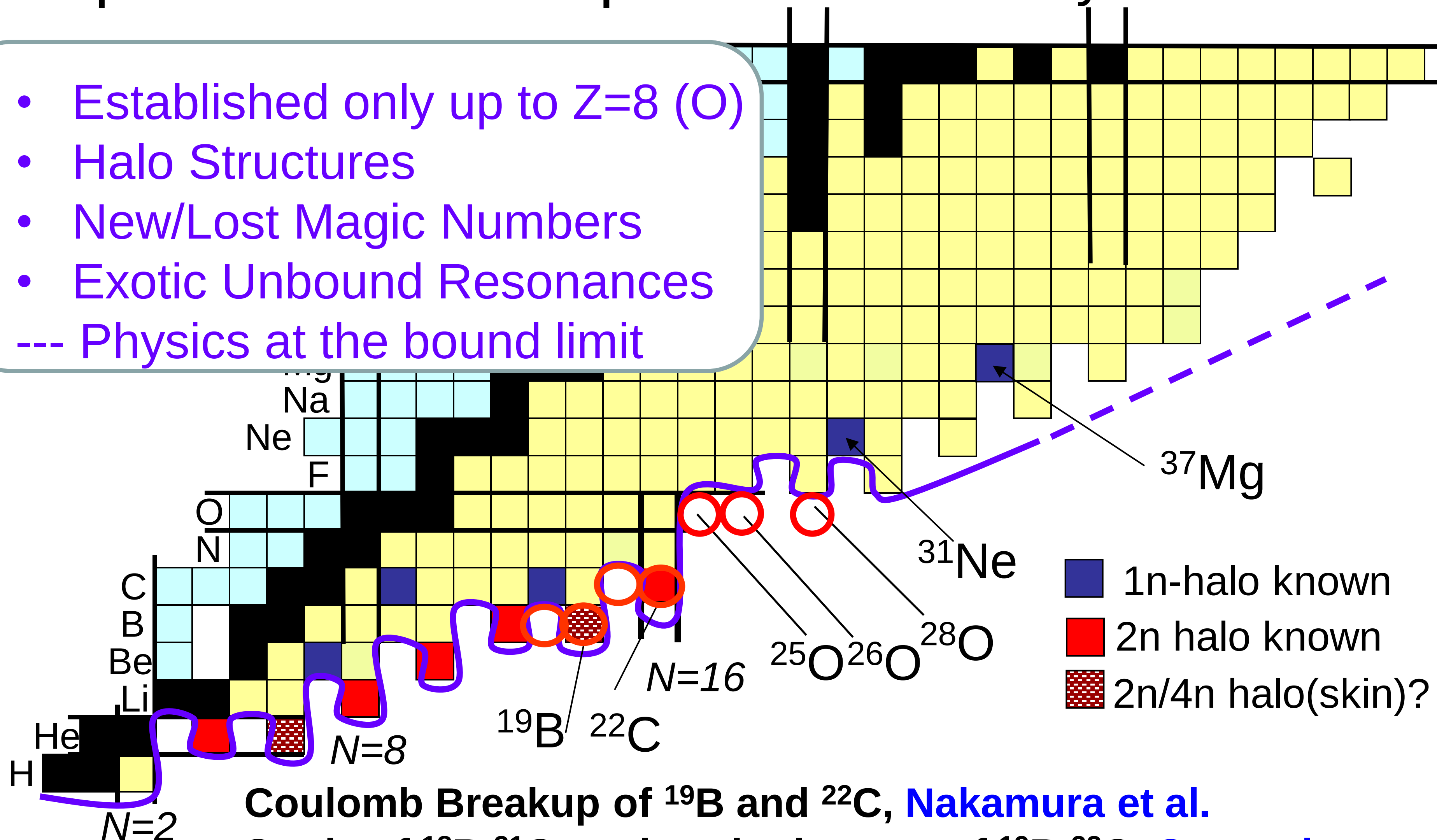
Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam

March 2012

Day-One Campaign Experiments at SAMURAI: Explore Neutron Drip Line --May/2012

- Established only up to Z=8 (O)
- Halo Structures
- New/Lost Magic Numbers
- Exotic Unbound Resonances

--- Physics at the bound limit



Coulomb Breakup of ^{19}B and ^{22}C, Nakamura et al.

Study of ^{18}B,^{21}C, and excited states of ^{19}B,^{22}C, Orr et al.

Structure of Unbound Oxygen Isotopes ^{25}O,^{26}O, Kondo et al.

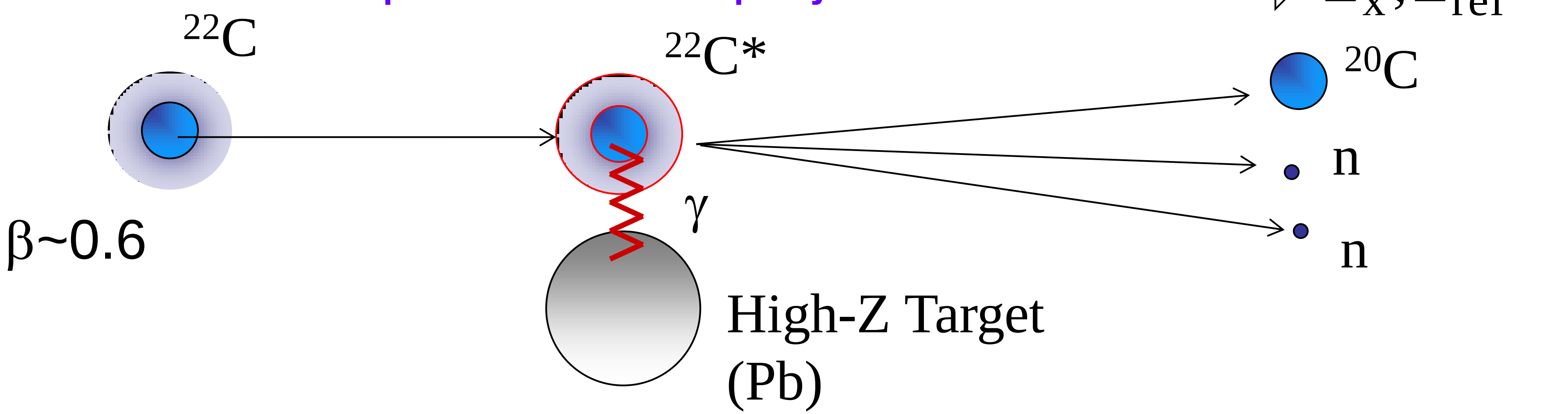
Coulomb Breakup

$\vec{P}(n), \vec{P}(n), \vec{P}(^{20}\mathrm{C})$

Invariant Mass

$\Rightarrow E_x, E_{rel}$

→Photon absorption of a fast projectile

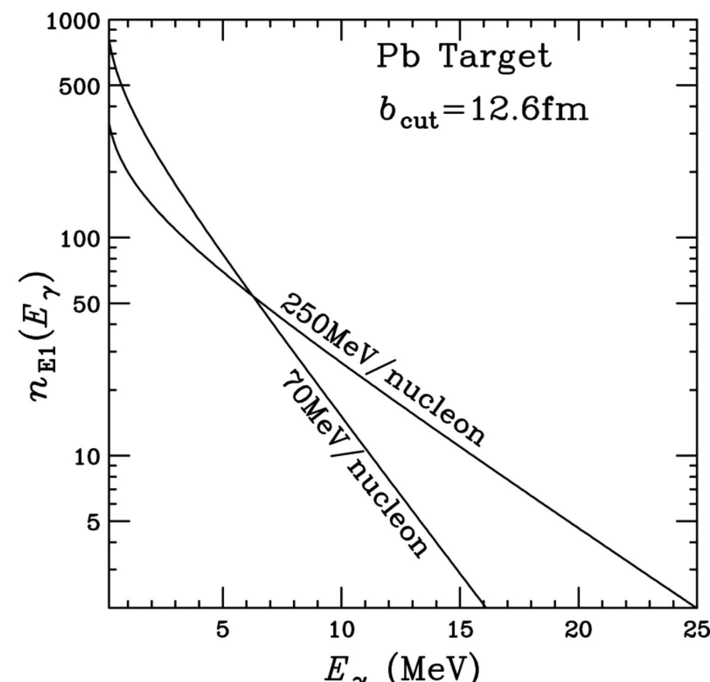


Equivalent Photon Method

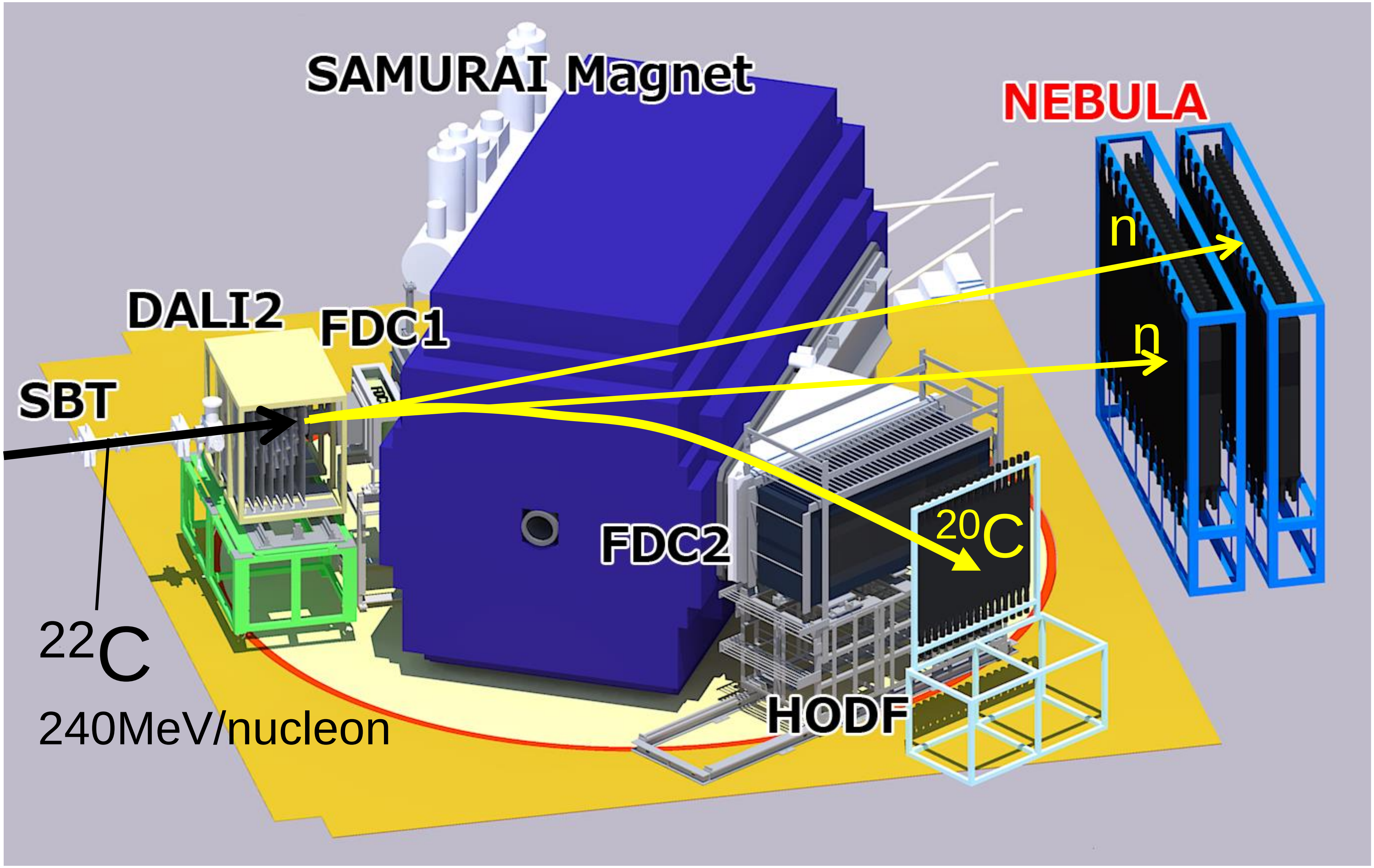
$$\frac{d\sigma_{CB}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x}$$

Cross section = (Photon Number)x(Transition Probability)

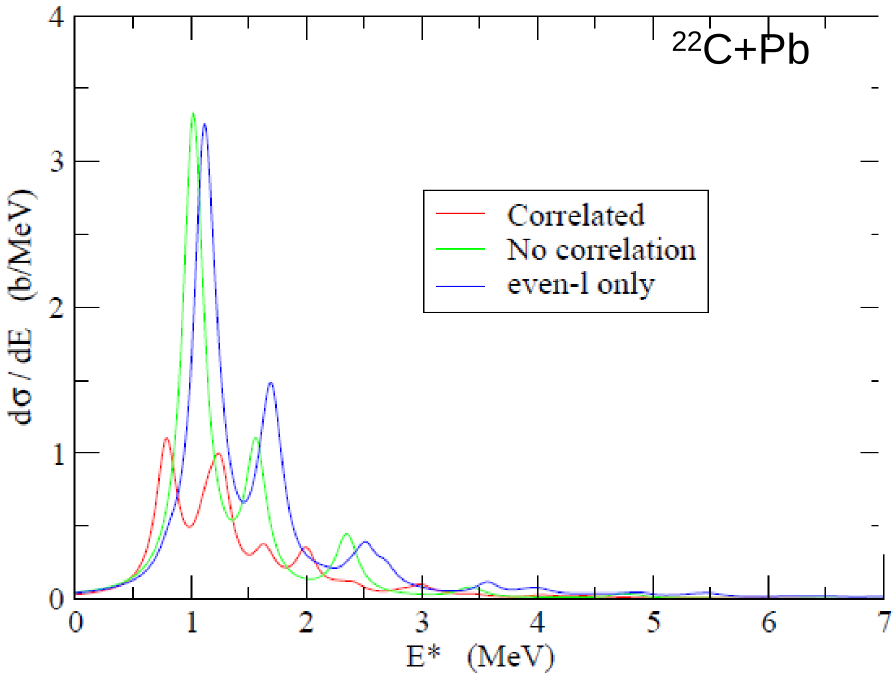
C.A. Bertulani, G. Baur, Phys. Rep. 163,299(1988).

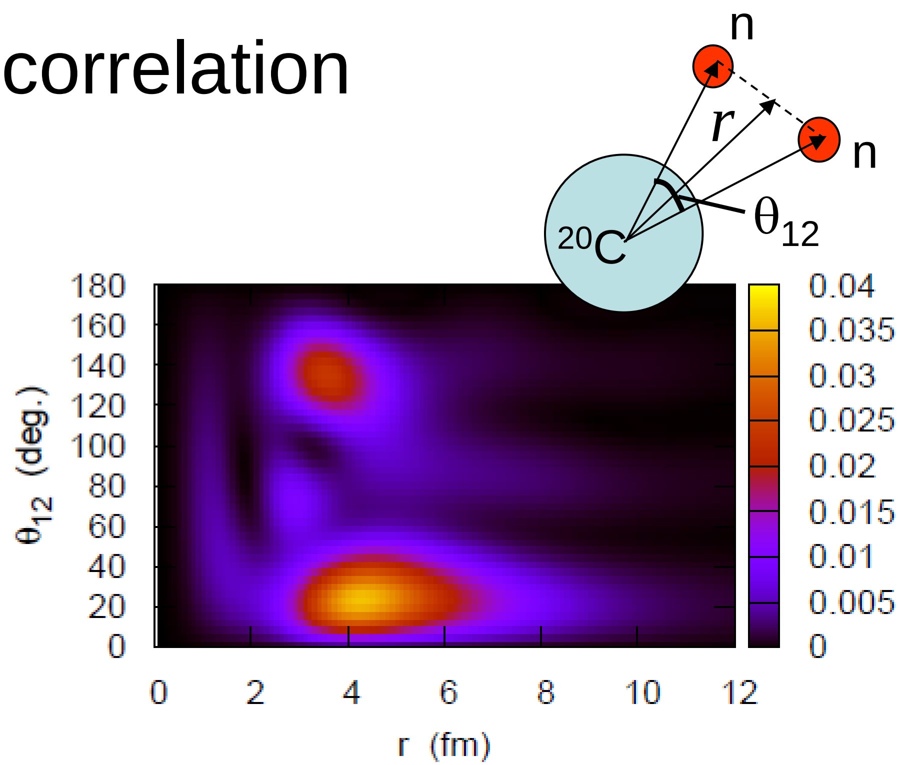


Experimental Setup



E1 response and dineutron correlation
: calculation *by K.Hagino*





S_{2n}=500keV

Correlated: $\alpha|(2s_{1/2})^2> +\beta\ |(1d_{3/2})^2> + \gamma|(2p_{3/2})^2> + \gamma|(1f_{7/2})^2>$ ….

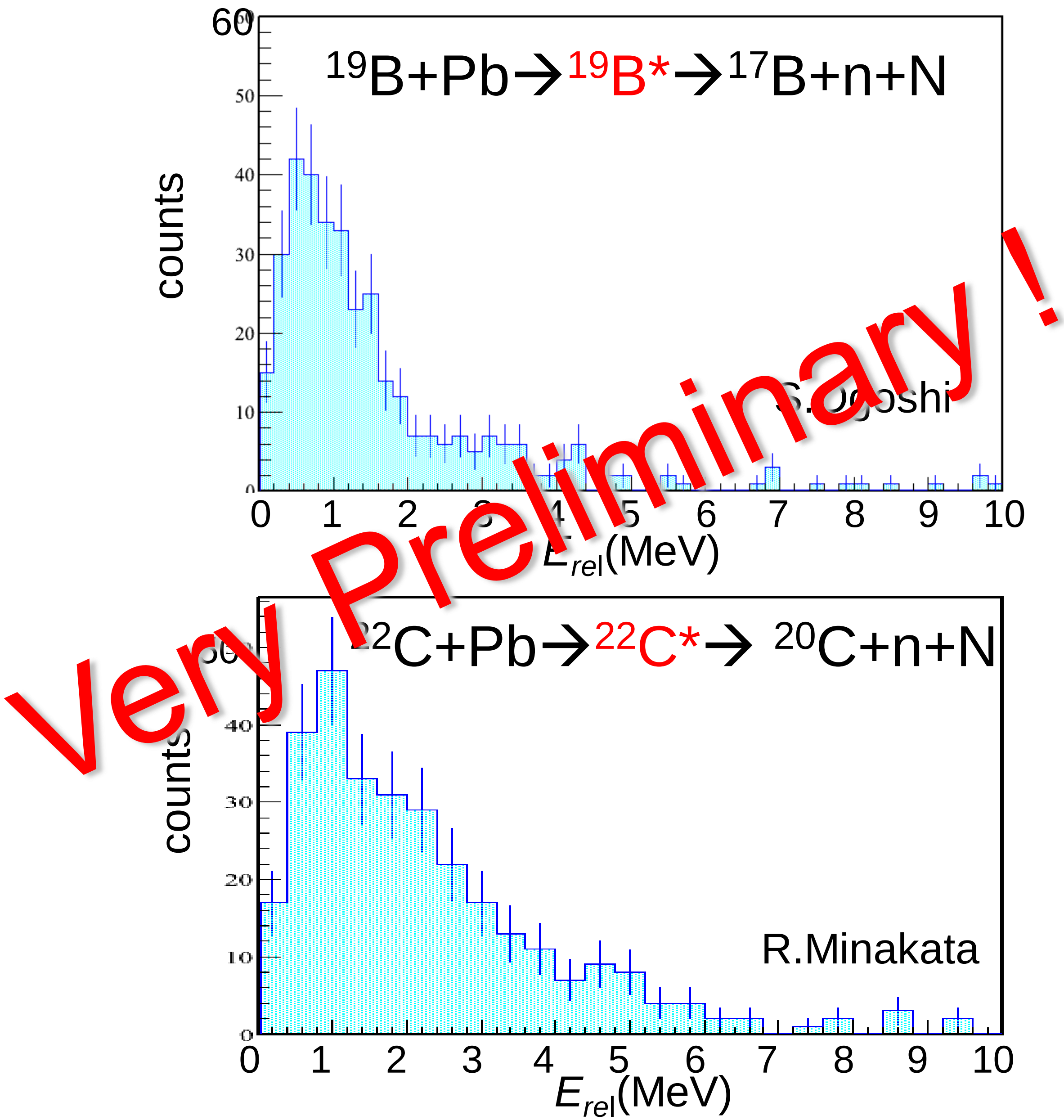
1.05b — 62.5% — 24.2% — 4.7% — 3.8%

Non-Correlated: $|(2s_{1/2})^2>$
(s only) 1.66b — 100%

→Kinematically Complete Measurement of Coulomb Breakup

Coulomb Breakup of 2n Halo Nuclei

Analysis by **R. Minakata**

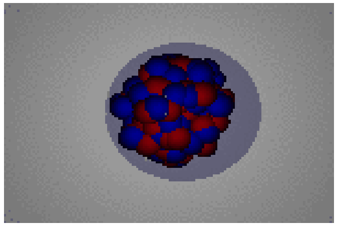


~40% statistics

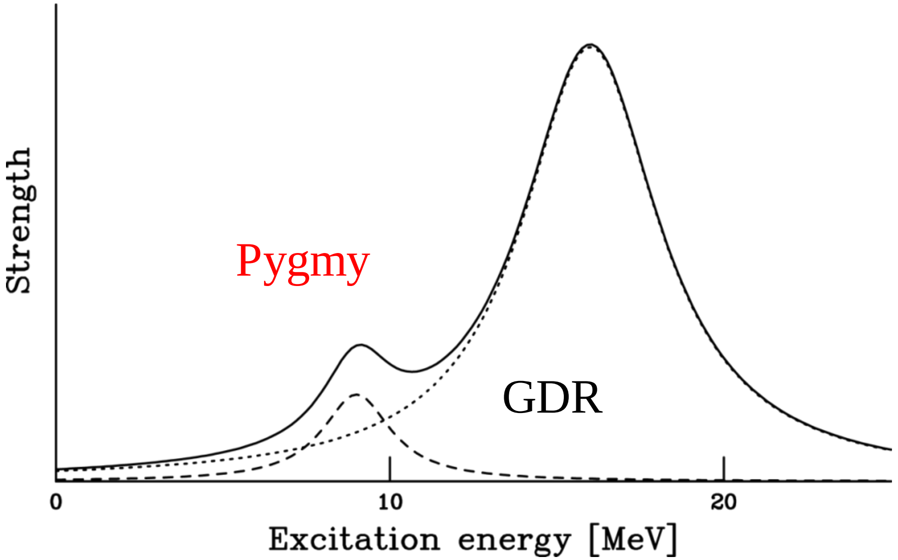
PDR(Pygmy Dipole Resonance)

Y.Togano et al. (Near future project)

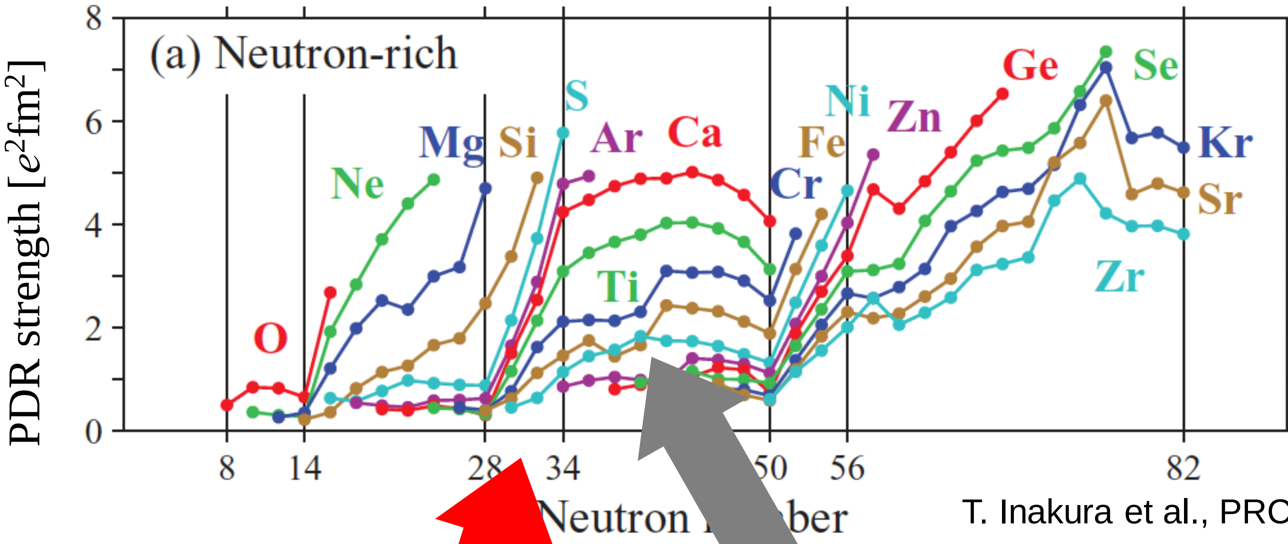
Pygmy Dipole Resonance



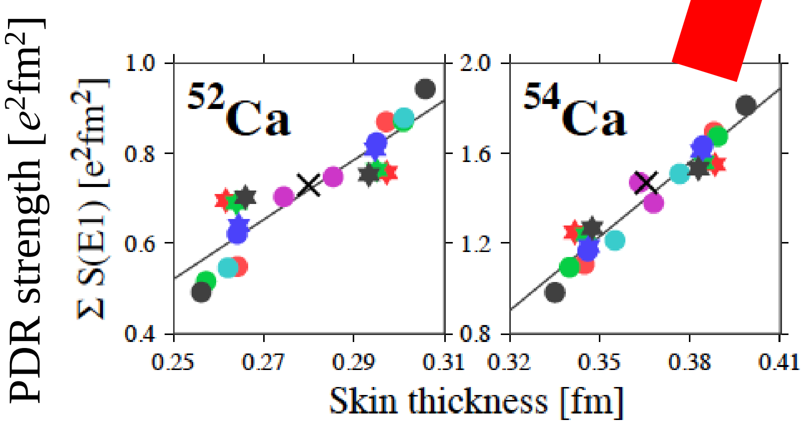
- New collective mode in n-rich nuclei
- Ex: 6~10 MeV, ~6% of TRK sum
  - Oscillation between core and excess neutrons
    - Y. Suzuki et al., Prog. Theor. Phys. 83, 180(1990). P. Van Isacker et al., PRC 45 R13 (1992).
  - Strength ⟷ neutron-skin thickness

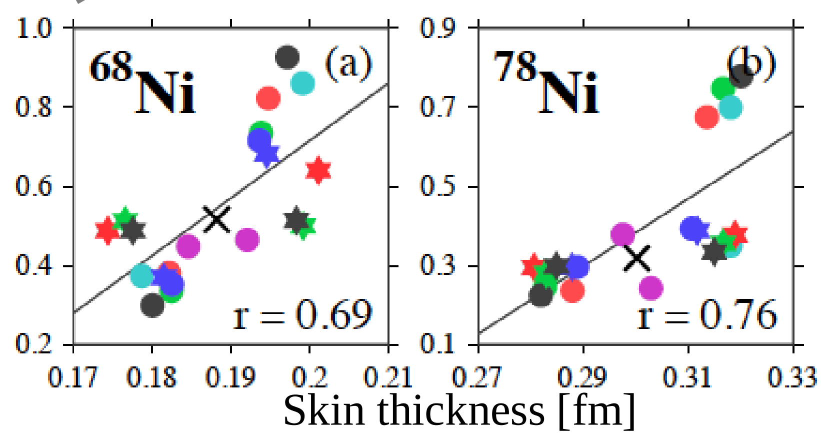


PDR and skin thickness



T. Inakura et al., PRC84, 021302 (2011)

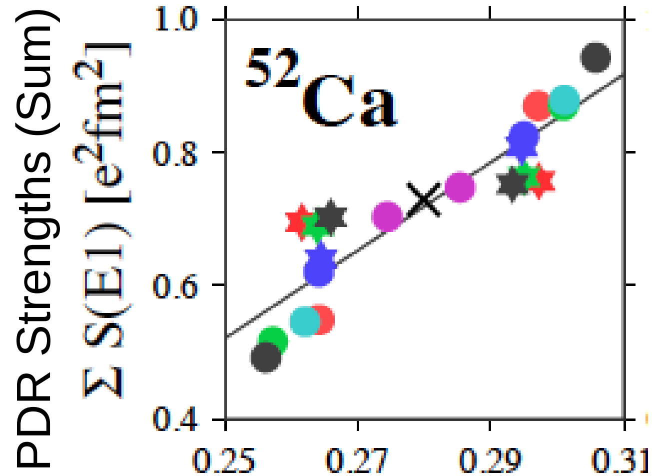


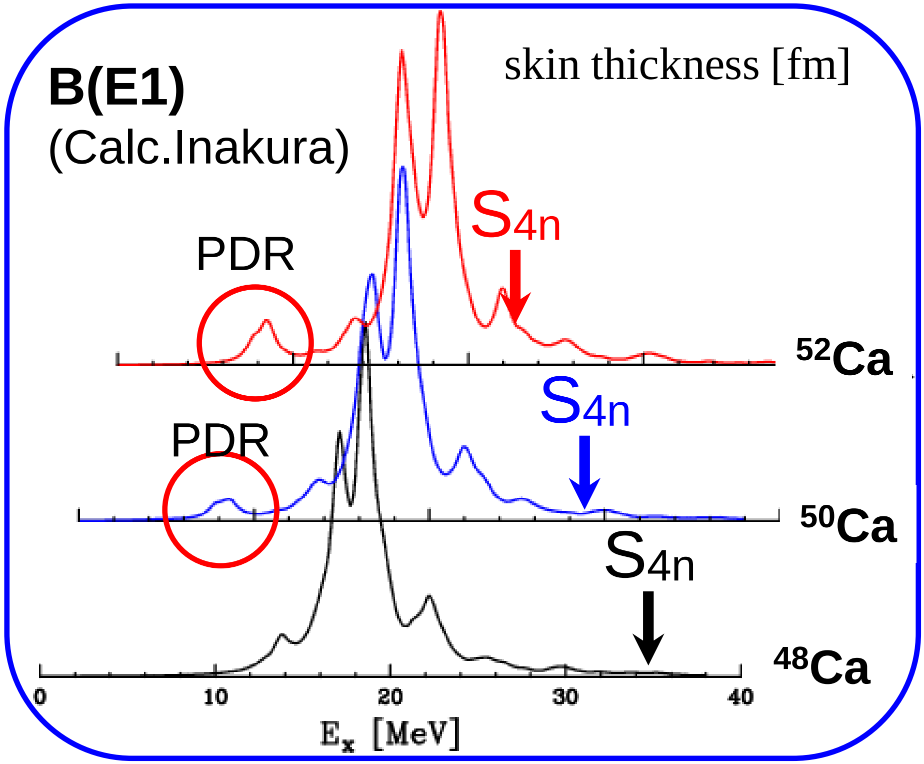


T. Inakura et al., arXiv:1306.3

E1 response of n-rich Ca isotopes (calculation)

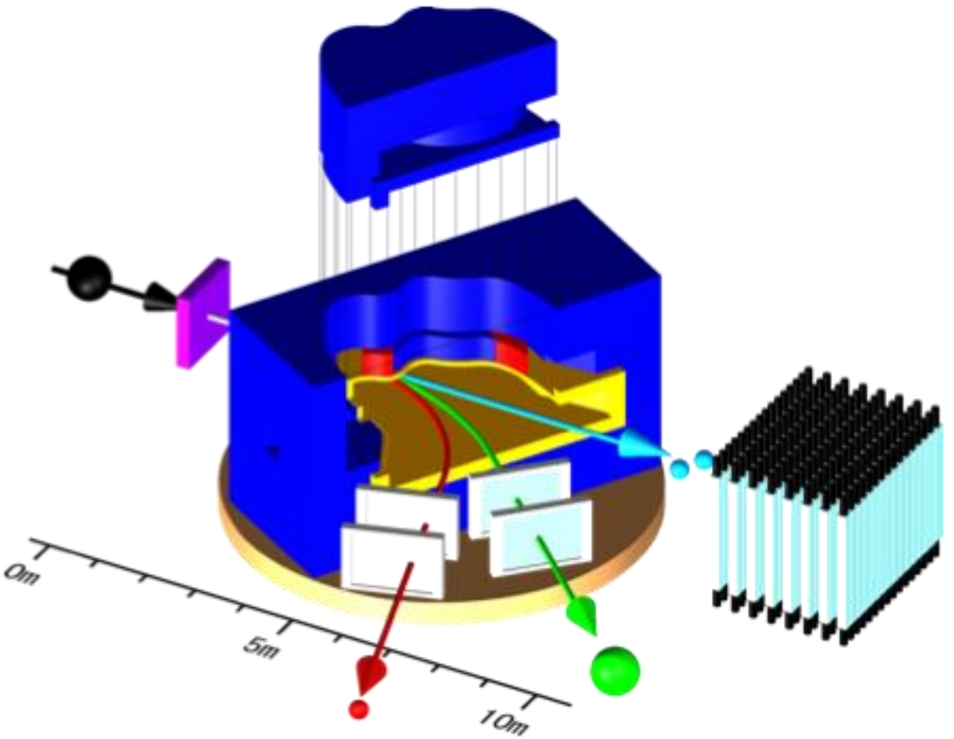
- ^{52}Ca
  - Enhanced PDR strength
  - Strong correlation: PDR ⟷ skin
  - α_D (dipole polarizability) could be measured
- ^{48,50}Ca (references)
  - Evolution of PDR & neutron skin thickness
  - ^{48}Ca: precise data at RCNP (Tamii et al.)

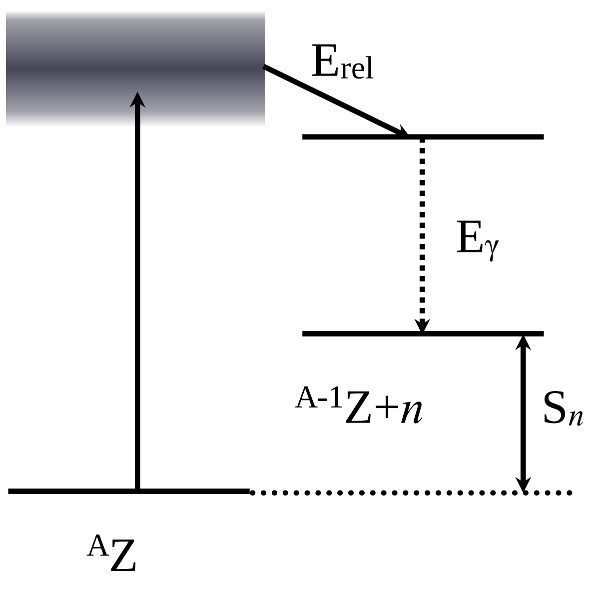




γ ray detector for SAMURAI

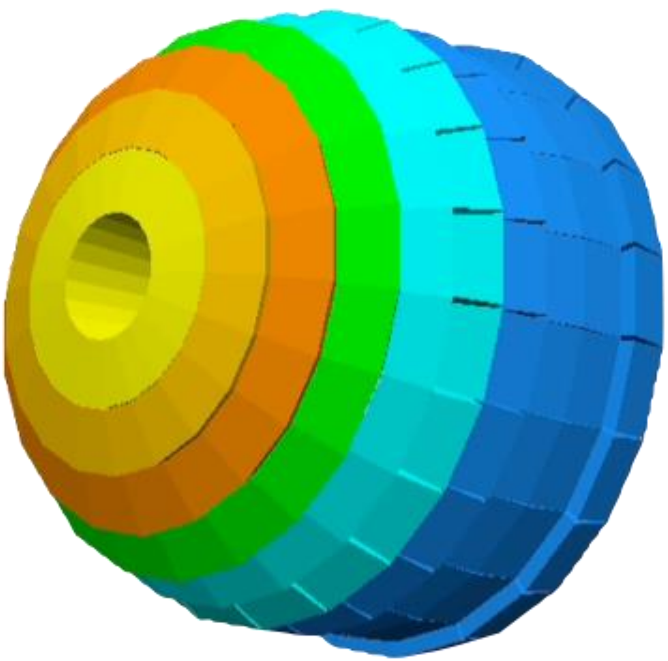
- SAMURAI: excellent tool for invariant mass spectroscopy
- higher unbound states: detection of γ ray is mandatory
  - Ex = E_{rel}(from invariant mass) + E_γ + Sn

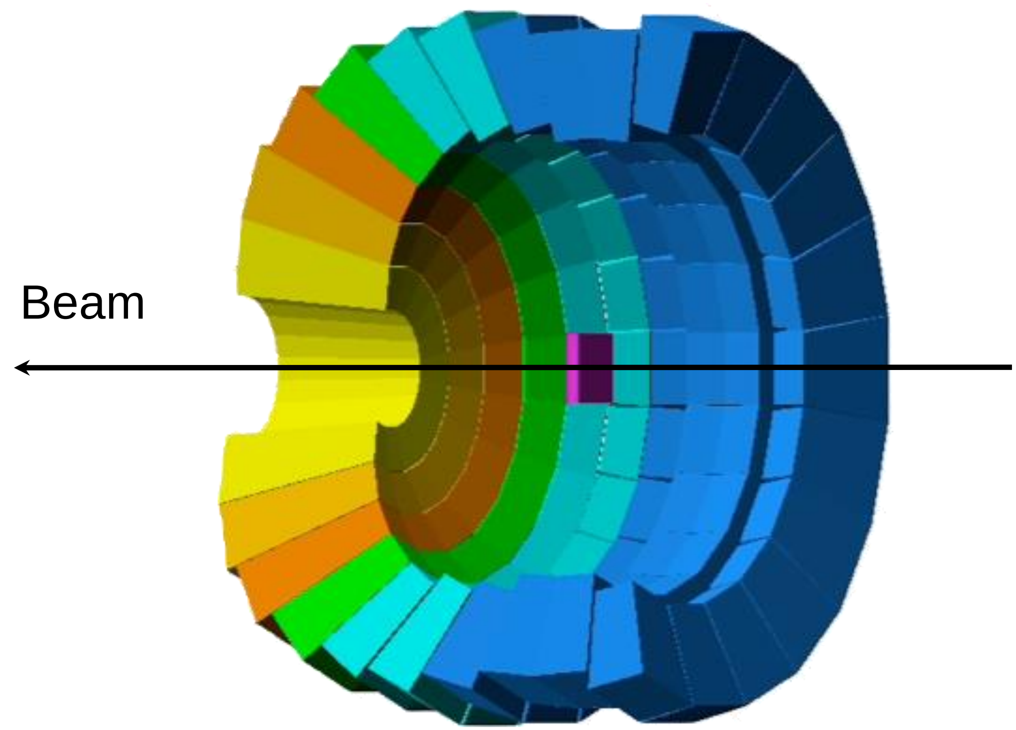




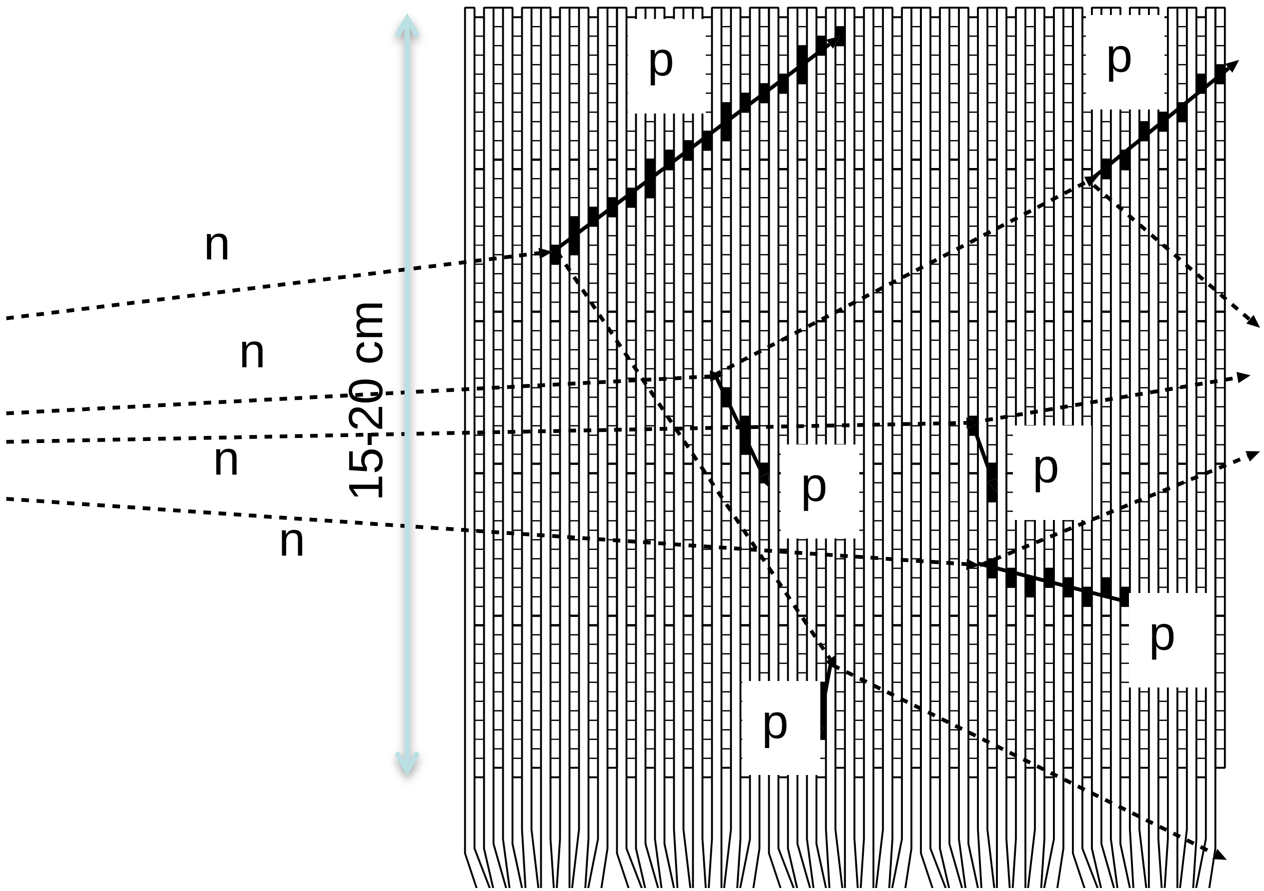
CATANA

- **CA**lorimetric de**T**ector for r**A**diations from exotic **N**uclear be**A**ms
- Crystals: CsI





Tetra Neutron Project
Are there “4n” resonance? -- 3N/4N force



Next Generation Neutron Detector -- Shimoura

Micro-Hodoscope: 2.5 × 5 mm^2
Cubic Module: (15~20cm)^3

Summary

Nuclear Structure using new-generation RI Beams

Exotic Nuclear Structure

Neutron Skin

Neutron Halo

Neutron Droplets

Pygmy Dipole Resonance
（民井、栂野）

Density-dependent
NN-correlation(中村)

Nuclear Force （関口、下浦、近藤）
(NNN, Isospin Dependence)

Nuclear Masses (山口）

Dynamics

Mean Field Calc.

EOS of Asymmetric Nuclear Matter

Neutron Star

Bulk Property (Radius, Mass)
Superfluidity
Glitch
Quark/Strangeness Phase

BUDGET:

B02: 1.62 億円 （計画研究）

CATANA(Gamma Calorimeter) ~9千万円
New-Generation Neutron Counter: ~3千万円
Human Resources : ~3千万円
Others ~1千万円

B02: Members:

計画研究
T. Nakamura: PI
Y.Togano, T.Nakamura, Y.Kondo → Gamma Calorimeter
S. Shimoura → New-generation Neutron Detectors
T. Teranishi → Collaboration in experiments

公募研究:
K.Sekiguchi→ 3N/4N force
A.Tamii→ Precise dipole strength measurement – Neutron skin → EOS
T.Yamaguchi→ Mass measurement of very neutron rich nuclei → EOS

SAMURAI Dayone Experiment (May 2012)

First experimental campaign for the 3 physics programs

1. Coulomb breakup of ^{22}C and ^{19}B (T. Nakamura)
2. Study of unbound states of ^{22}C, ^{21}C, ^{19}B, ^{18}B (N. A. Orr)
3. Study of unbound nuclei ^{25}O and ^{26}O (Y. Kondo)

Collaborators

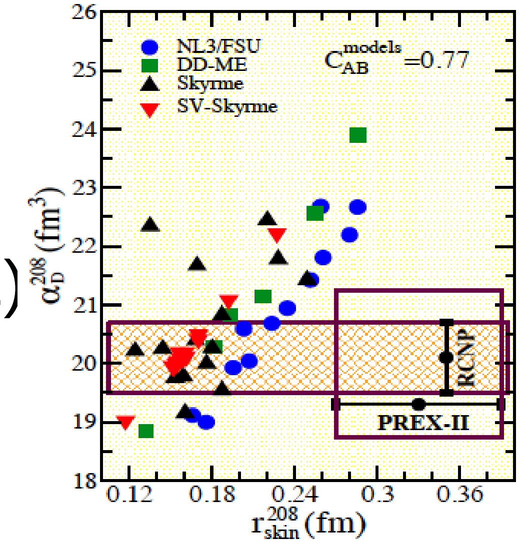
Tokyo Institute of Technology: **Y.Kondo, T.Nakamura**, N.Kobayashi, R.Tanaka, R.Minakata, S.Ogoshi, S.Nishi, D.Kanno, T.Nakashima
LPC CAEN: **N.A.Orr**, J.Gibelin, F.Delaunay, F.M.Marques, N.L.Achouri, S.Leblond
Tohoku University : T.Koabayshi, K.Takahashi, K.Muto
RIKEN: K.Yoneda, T.Motobayashi ,H.Otsu, T.Isobe, H.Baba,H.Sato, Y.Shimizu, J.Lee, P.Doornenbal, S.Takeuchi, N.Inabe, N.Fukuda, D.Kameda, H.Suzuki, H.Takeda, T.Kubo
Seoul National University: Y.Satou, S.Kim, J.W.Hwang
Kyoto University : T.Murakami, N.Nakatsuka
GSI : Y.Togano
Univ. of York: A.G.Tuff
GANIL: A.Navin
Technische Universit¨at Darmstadt: T.Aumann
Rikkyo Univeristy: D.Murai
Universit´e Paris-Sud, IN2P3-CNRS: M.Vandebrouck

backup

Dipole polarizability

- Inversely Energy weighted Sum Rule of B(E1)

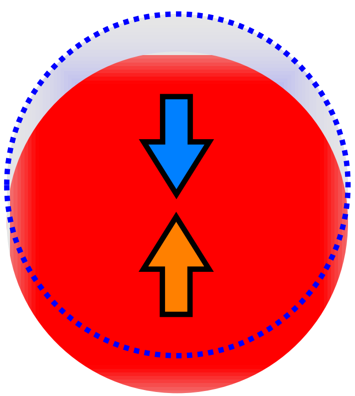
$$\alpha_D = \frac{\hbar c}{2\pi}\int \frac{\sigma_{abs}}{\omega^2} d\omega = \frac{8\pi}{9}\int \frac{dB(\mathrm{E1})}{\omega}$$



J. Piekarewicz, arXiv:1307.7746

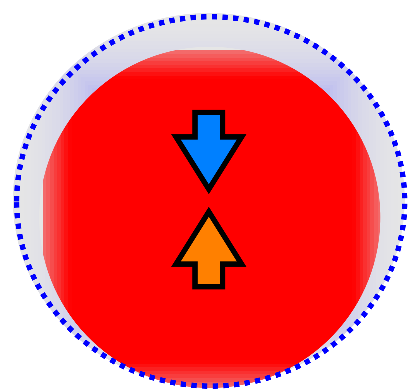
- Degree of polarization due to an external E1 field

without skin



larger restoring force
→ smaller α_D

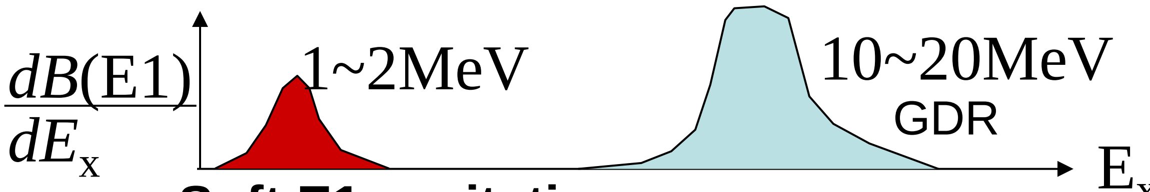
with skin



smaller restoring force
→ larger α_D

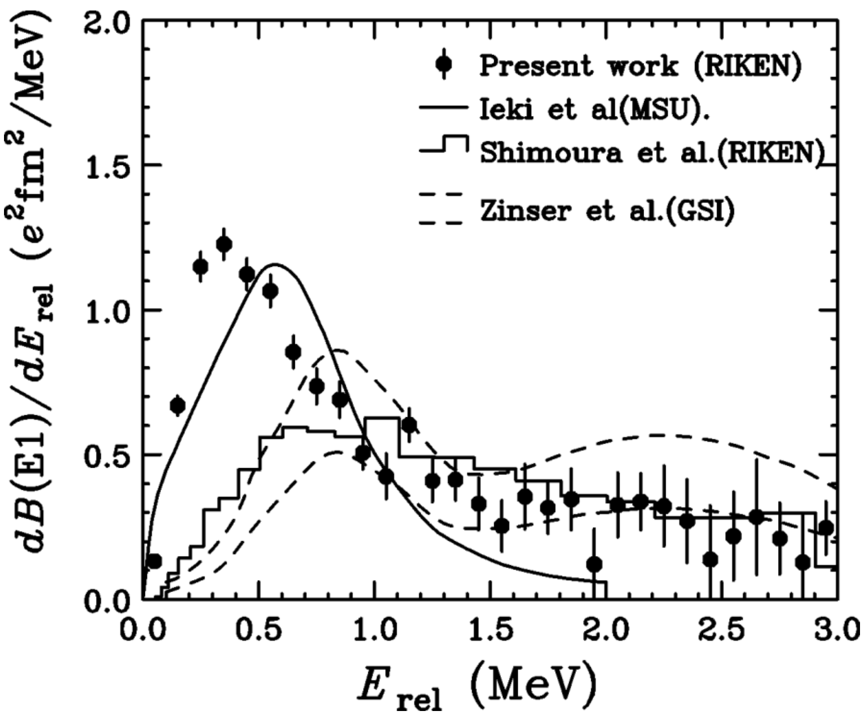
Dineutron Correlation

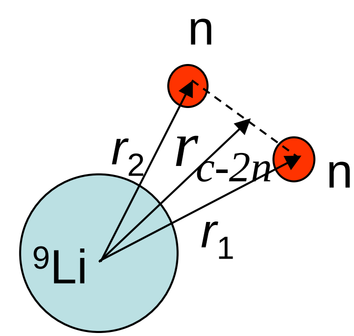
←Coulomb Breakup of 2n halo nucleus and Soft E1 Excitation



Soft E1 excitation

T.Nakamura et al. PRL96,252502(2006).





$$B(E1)=\int_{-\infty}^{\infty}\frac{dB(E1)}{dE_x}dE_x$$

$$=\frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2\left\langle r_1{}^2+r_2{}^2+2(\vec{r}_1\cdot\vec{r}_2)\right\rangle$$

$$B(E1)=1.42\pm0.18\,e^2\,fm^2\,(E_\mathrm{rel}\le 3\mathrm{MeV})$$

$$\rightarrow 1.78(22)\,e^2\,fm^2\rightarrow\langle\theta_{12}\rangle=48^{+14}_{-18}\,\mathrm{deg}.$$

Soft E1 Excitation of 2n-halo—dineutron-like correlation