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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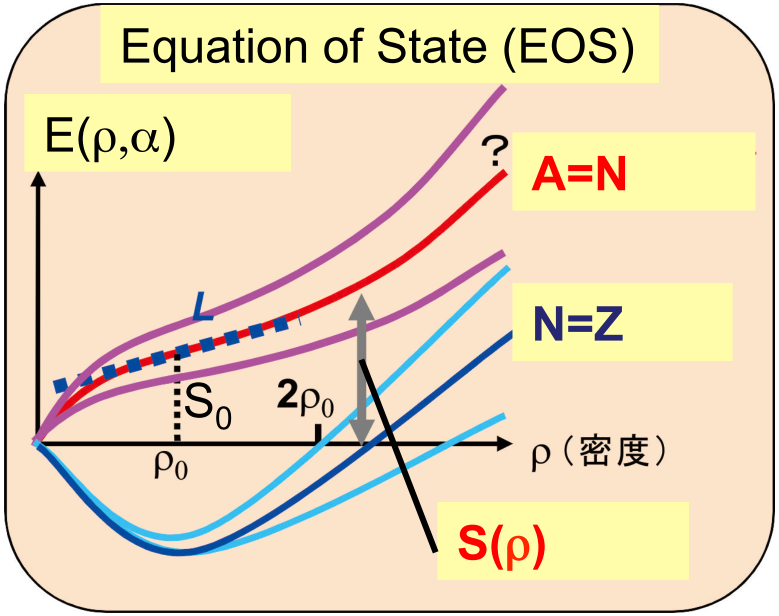
近藤洋介、栂野泰宏　東工大
寺西高　九大

実験と観測で解き明かす中性子星の核物質
– Dec.25-28, 2013, @RIKEN

公募研究　B02

- 関口　仁子(東北大･理)
  陽子･ヘリウム3散乱系における三体力発現機構の研究
- 山口　貴之(埼玉大･理工)
  二重魔法数エキゾチック核^{78}Niの質量精密測定
- 民井　淳　(阪大･RCNP)
  原子核の電気双極応答測定による対称エネルギーの研究

EOS of Nuclear Matter



Difference of n and p densities

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

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

Symmetry Energy: $S(\rho)$

Neutron-rich Nuclei :Microscopic Laboratory for Neutron Star

- **Nuclear Force (NN,3N)**
- **Many-body Correlations** (Superfluidity(pairing), halo, dineutron …) **at Extreme Conditions (not like normal N~Z nuclei)**

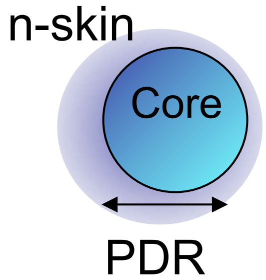
-- Wide range of **Density** $10^{-3}\rho_0$ --- $10\rho_0$ -- **Density Dependence**

-- **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

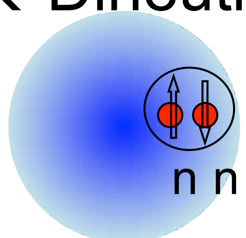


Pygmy Dipole Resonance (E1)

Breathing Mode (E0)

Y.Togano, M. Shikata, CATANA→ PDR of ^{52}Ca, Approved (Grade-A) by PAC in Dec.2013 !

□Superfluidity ←Dineutron correlation in low-dense matter



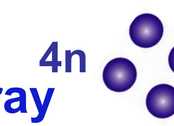
Coulomb Breakup of 2n Halo ^{22}C and ^{19}B

Done at SAMURAI, 2012.
Analysis: R.Minakata,S.Ogoshi,J.Tsubota

□S(ρ)←Nuclear force

(density dependence, isospin dependence, 3N/4N force)

← tetra neutron, exotic nucleonic system



^{26,28}O

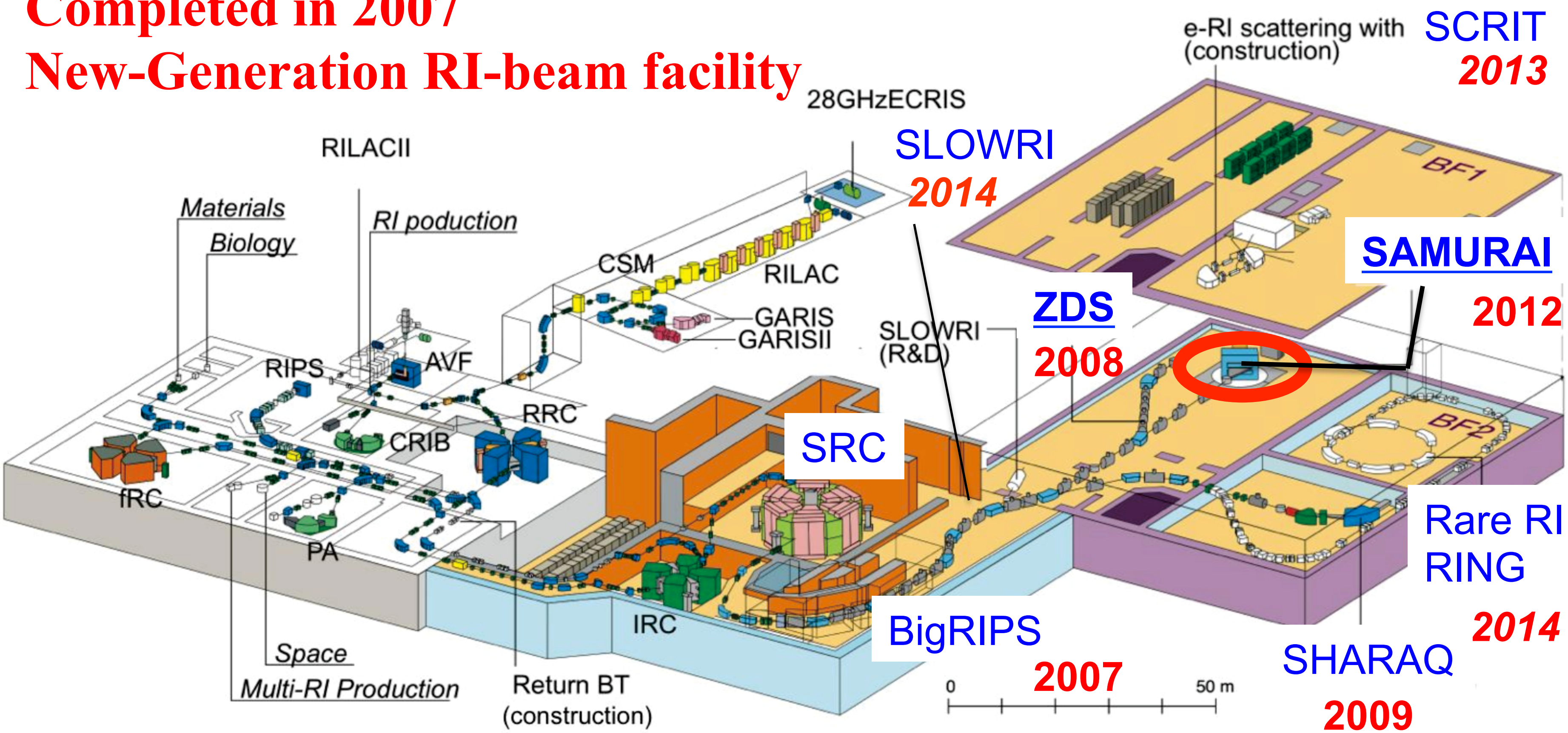
S.Shimoura 4n exp at SHARAQ Done, Next-generation N-array
Kondo: ^{26}O, Done at SAMURAI, 2012, ^{28}O exp Approved by PAC (Grade-S)
Sekiguchi 3N/4N force

□S(ρ)←Bulk Property

← neutron skin thickness(**Tamii,Togano**),masses (**Yamaguchi**)

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.

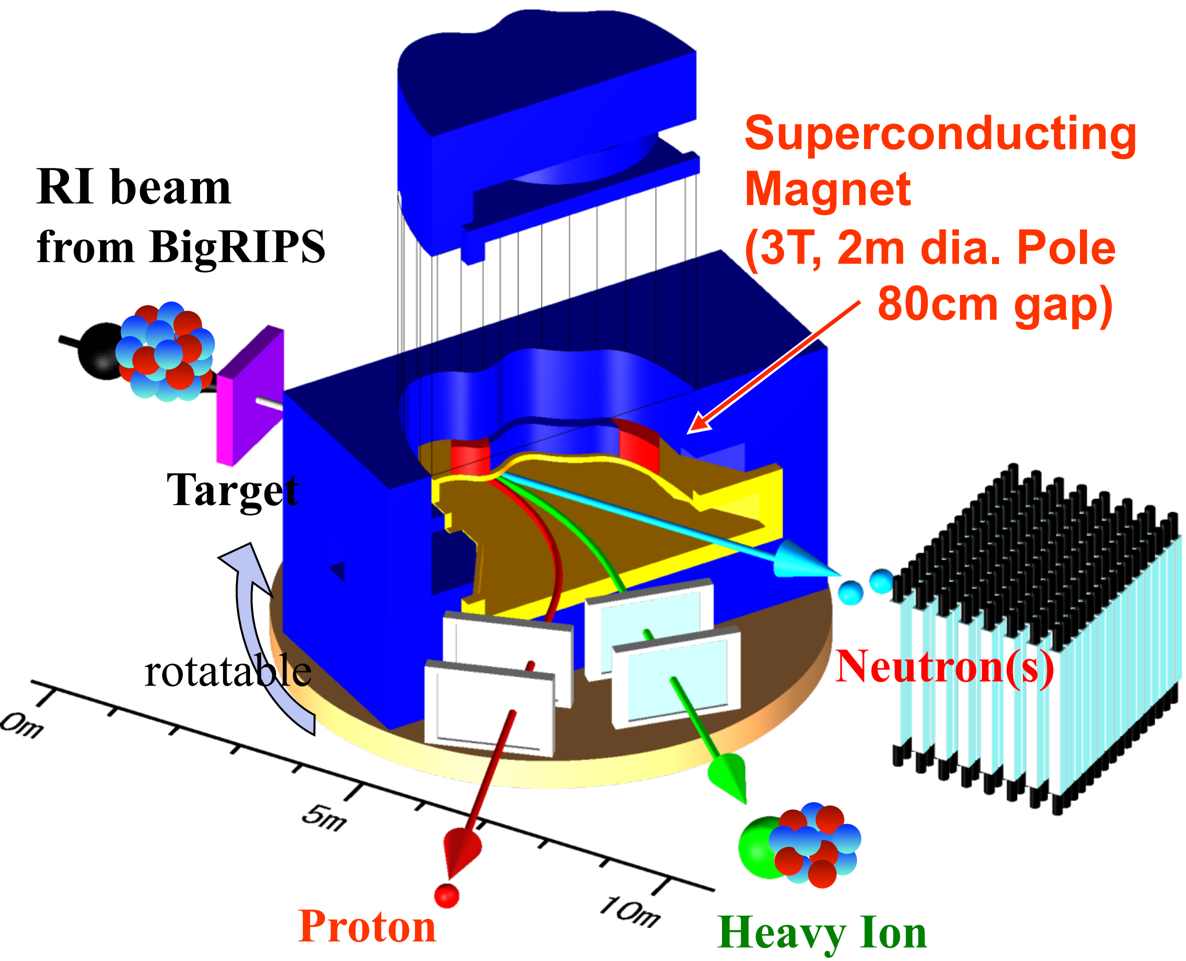
^{48}Ca beam (345 MeV/nucleon) ~200pnA (415 pnA max.)

^{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 $< E_{rel} \sim 2$MeV,

~ 30% coverage at $E_{rel} \sim 10$ 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

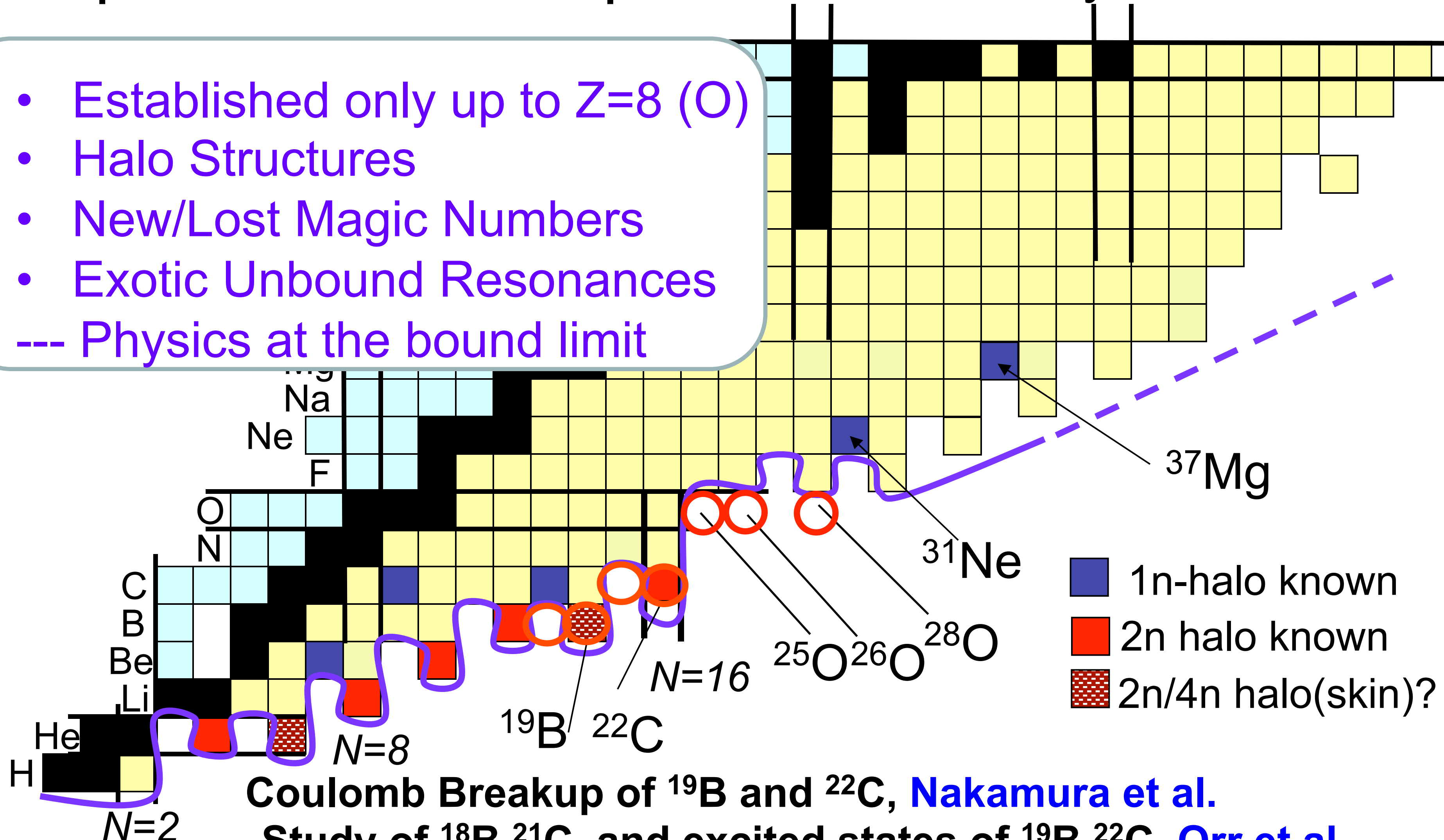
Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam

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.

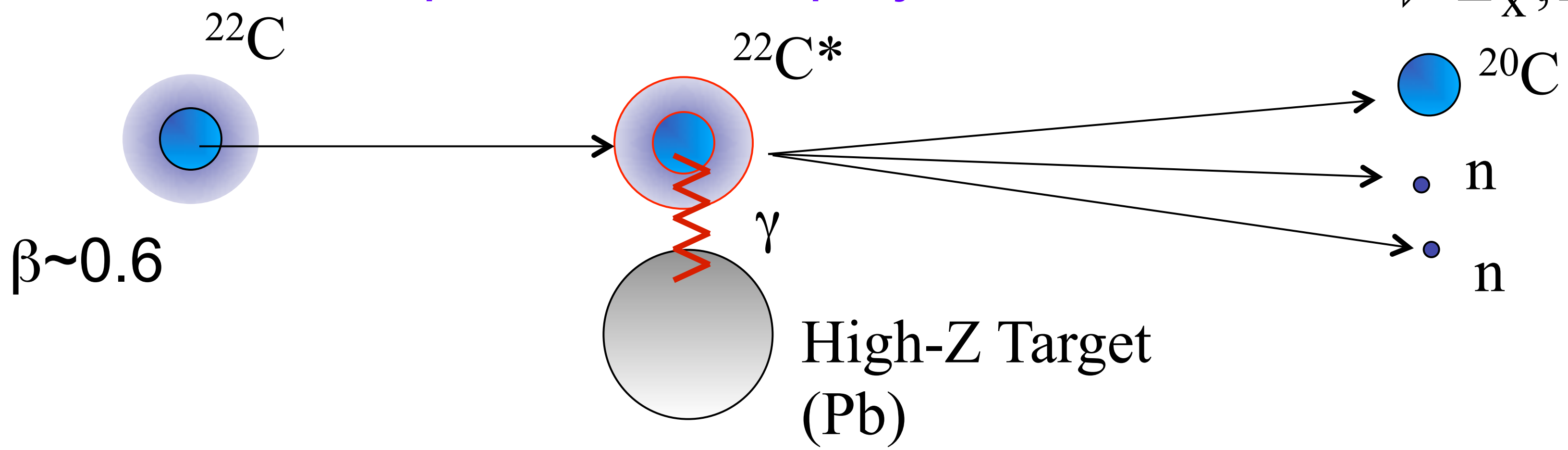
Coulomb Breakup

→Photon absorption of a fast projectile

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

Invariant Mass

⇒ E_x, E_{rel}

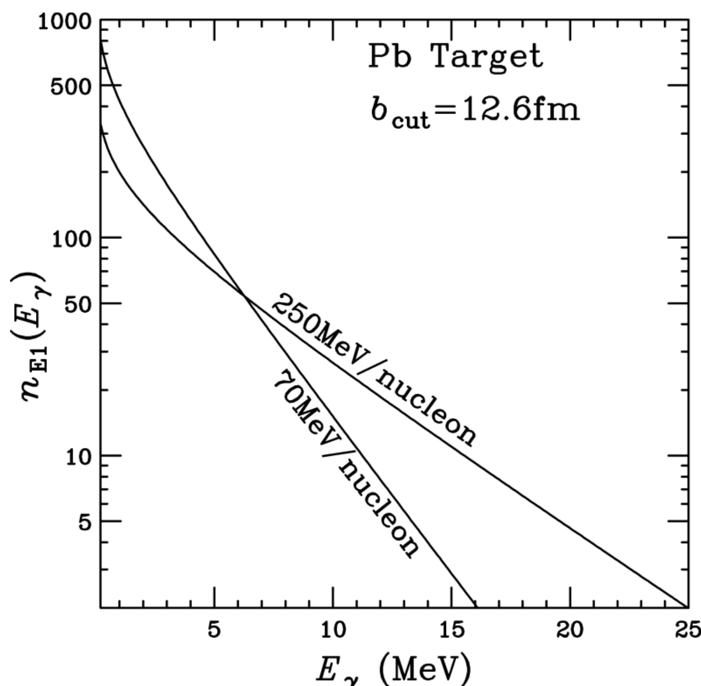


Equivalent Photon Method

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

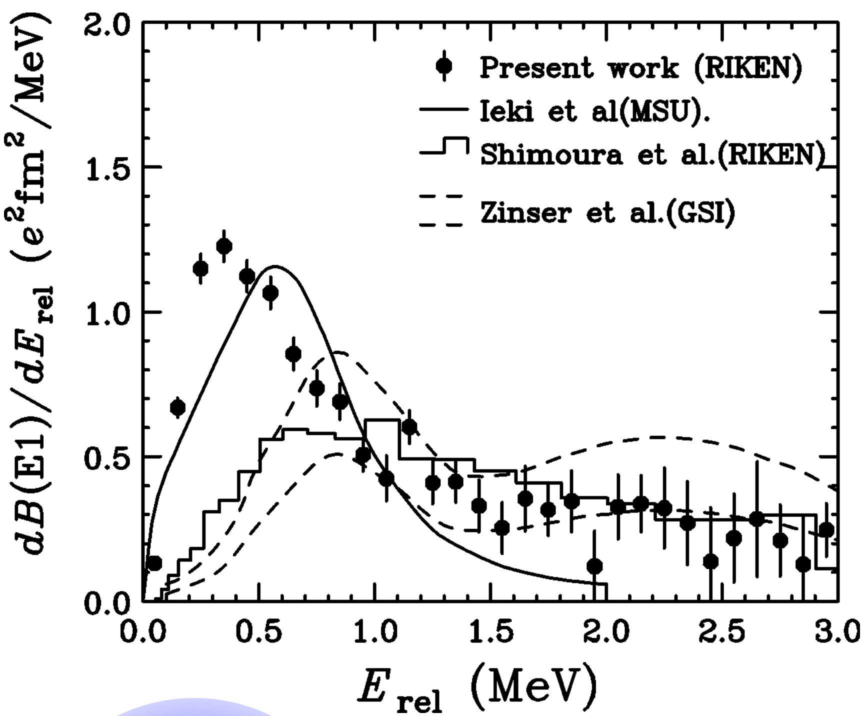
Cross section = (Photon Number)x(Transition Probability)

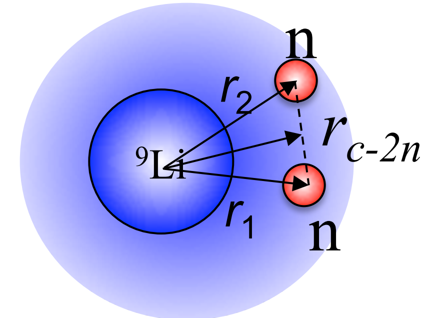
C.A. Bertulani, G. Baur, Phys. Rep. 163,299(1988).



Dineutron Correlation in ^{11}Li (Coulomb Breakup of 2n halo)

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



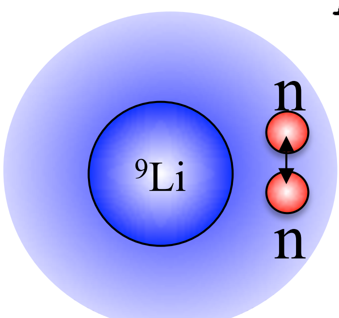


$$B(E1) = \int_{-\infty}^{\infty} \frac{dB(E1)}{dE_x} dE_x$$

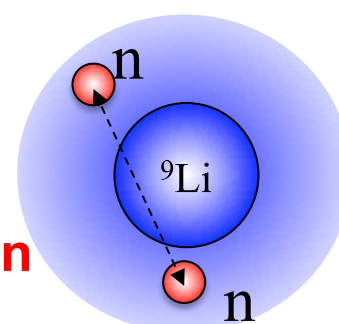
$$= \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_1^{\,2} + r_2^{\,2} + 2(\vec{r}_1 \cdot \vec{r}_2)\right\rangle$$

$$B(E1) = 1.42 \pm 0.18\ e^2 fm^2 (E_{\rm rel} \leq 3\mathrm{MeV})$$

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



Dineutron Correlation
→Strongly Polarized
→ Strong E1 Excitation

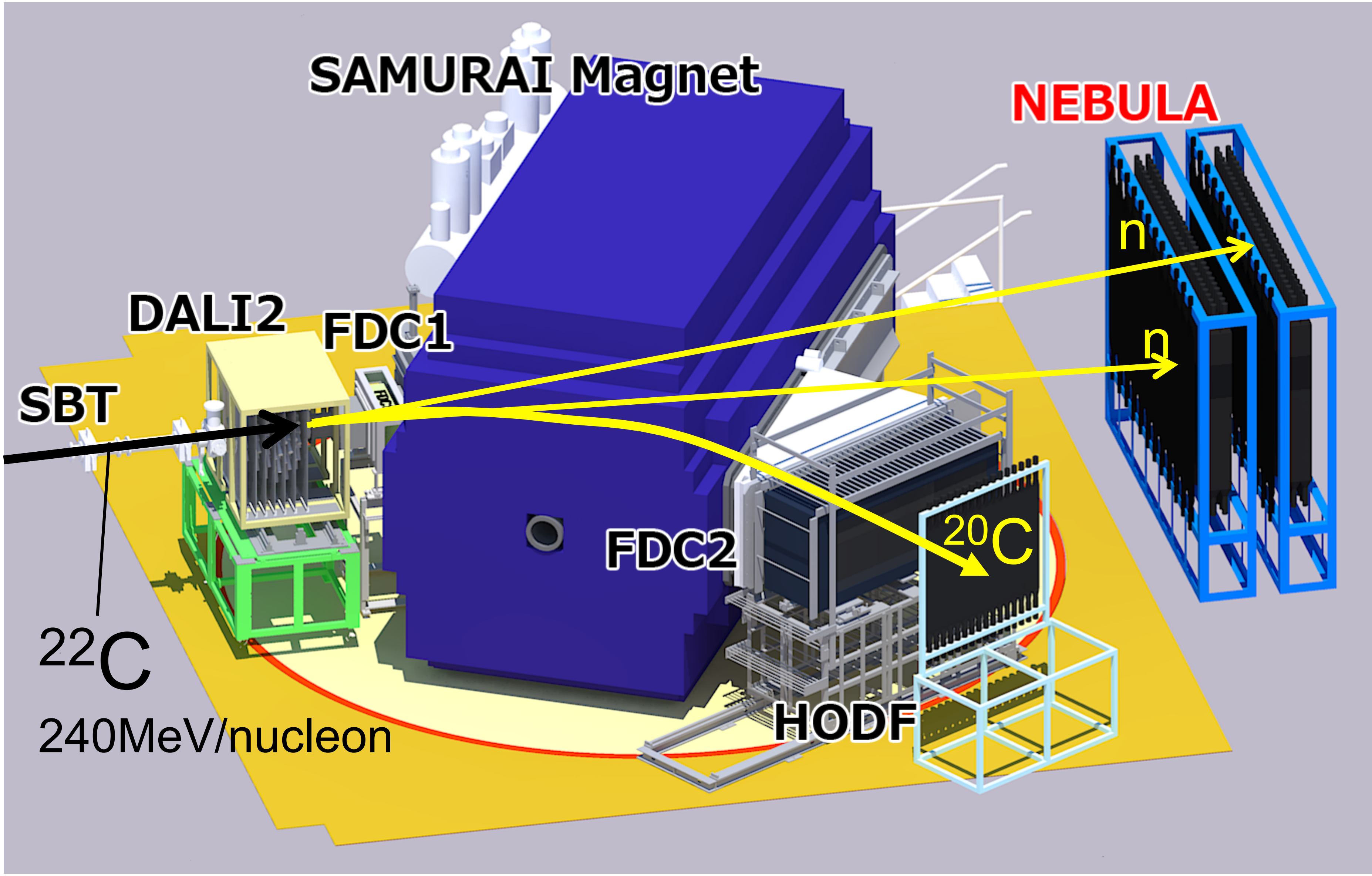


Weak 2n correlation
→Weakly Polarized
→Weak E1 Excitation

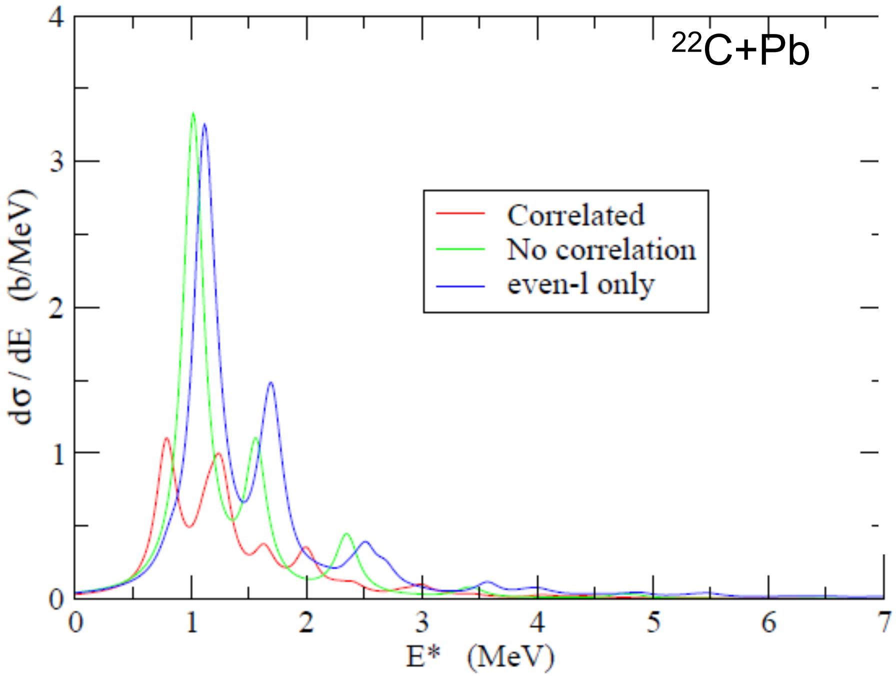
^{11}Li S_{2n}=0.37MeV

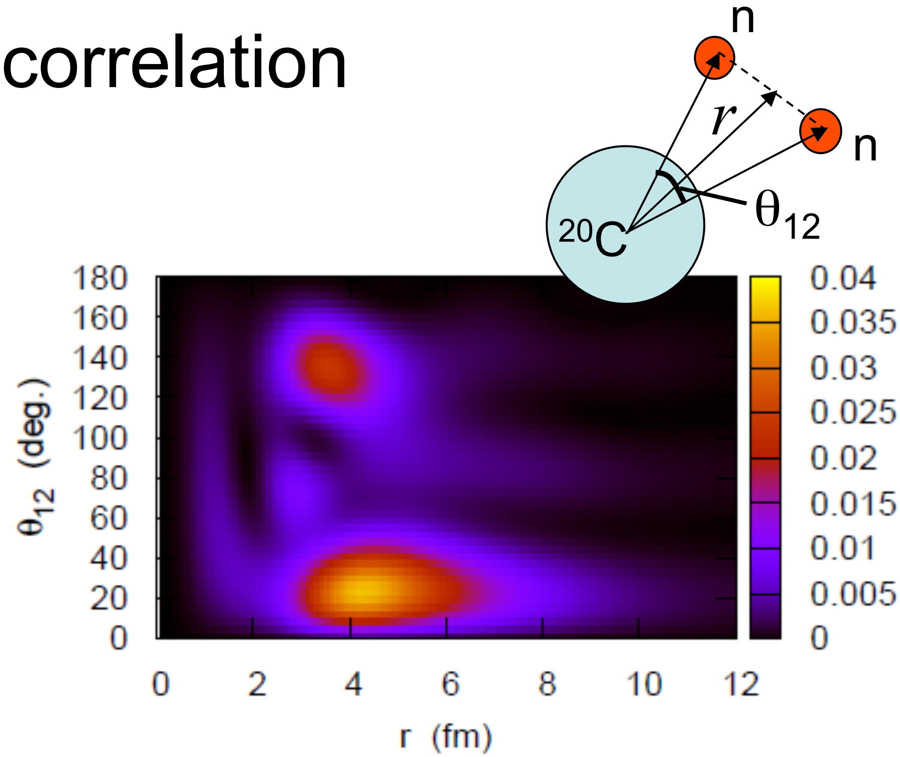
Soft E1 Excitation of 2n-halo—+dineutron-like correlation

Experimental Setup



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





S_{2n}=500keV

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

1.05b — 62.5%, 24.2%, 4.7%, 3.8%

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

→Kinematically Complete Measurement of Coulomb Breakup

Coulomb Breakup of 2n Halo Nuclei

Analysis by **R. Minakata**

60

$^{19}B+Pb \rightarrow$ $^{19}B^{*}$ $\rightarrow$ $^{17}B+n+N$

counts

S.Ogoshi

0 1 2 3 4 5 6 7 8 9 10

E_{rel}(MeV)

Very Preliminary !

50

$^{22}C+Pb \rightarrow$ $^{22}C^{*}$ $\rightarrow$ $^{20}C+n+N$

counts

R.Minakata

0 1 2 3 4 5 6 7 8 9 10

E_{rel}(MeV)

~40% statistics

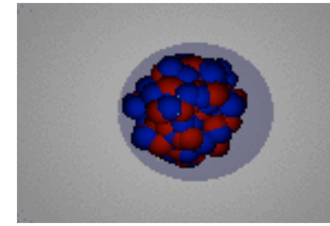
PDR(Pygmy Dipole Resonance)

Y.Togano, M.Shikata et al.

- ✓ Development and Construction of Gamma-ray Calorimeter (CATANA)
- ✓ Measurement of PDR and Dipole Polarizability of n-rich Calcium Isotopes

-- Approved as Grade A by RIBF PAC
(Possible run in 2015 or 2016)

Pygmy Dipole Resonance

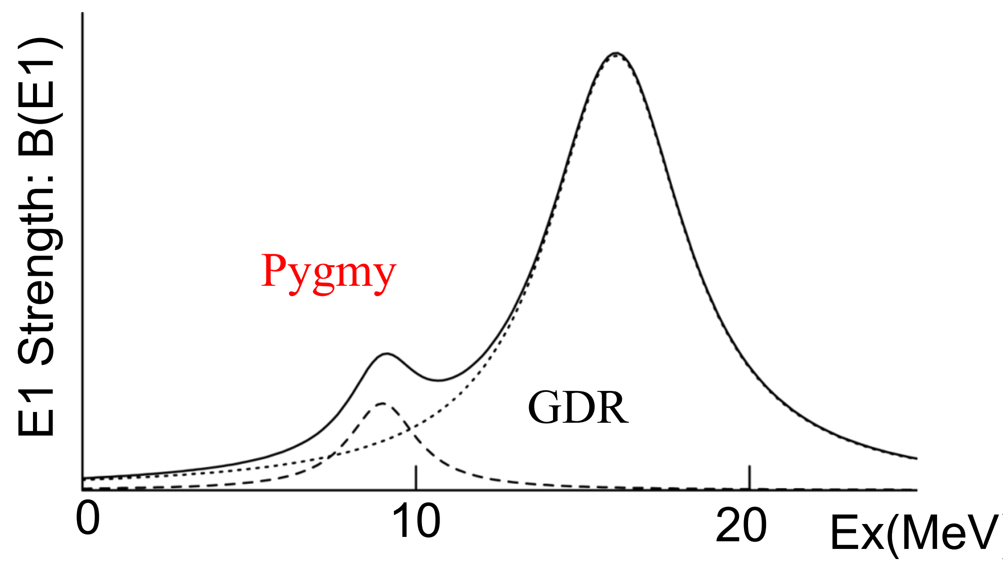


- New collective mode in n-rich nuclei
- Ex: 6~10 MeV, ~6% of TRK sum
  - Oscillation between core and excess neutrons
    - Y. Suzuki et al., Prog. Theor. Phys. 83, 180(1990). P. Van Isacker et al., PRC 45 R13 (1992).
  - Strength ⟷ neutron-skin thickness

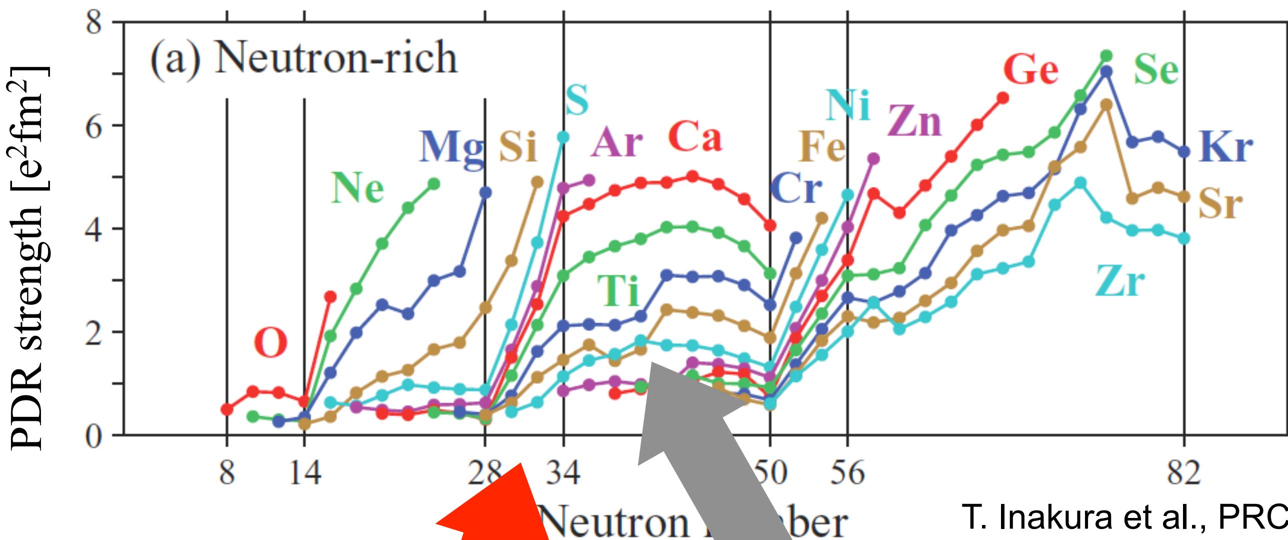
Dipole Polarizability

- Dipole polarizability

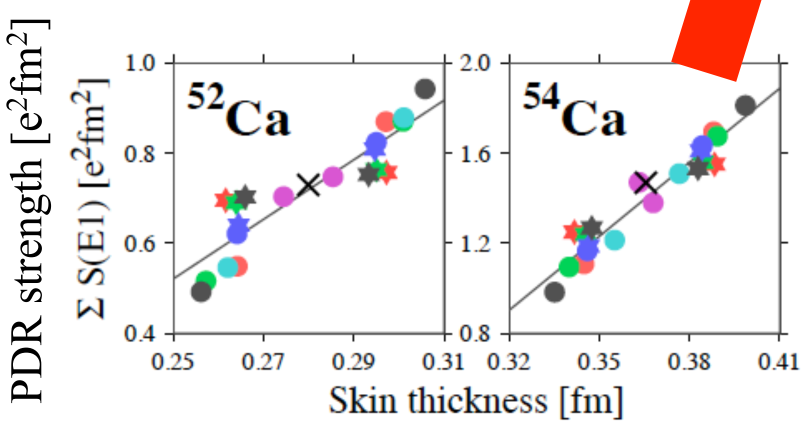
$$\alpha_D = \frac{8\pi}{9}\int \frac{dB(E1)}{\omega}$$

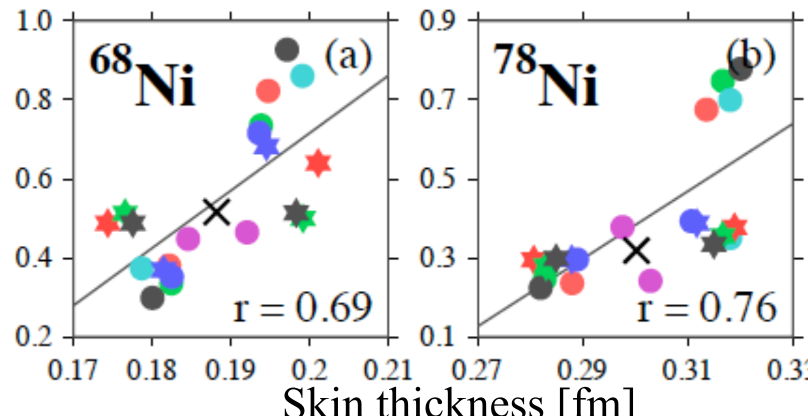


PDR and skin thickness



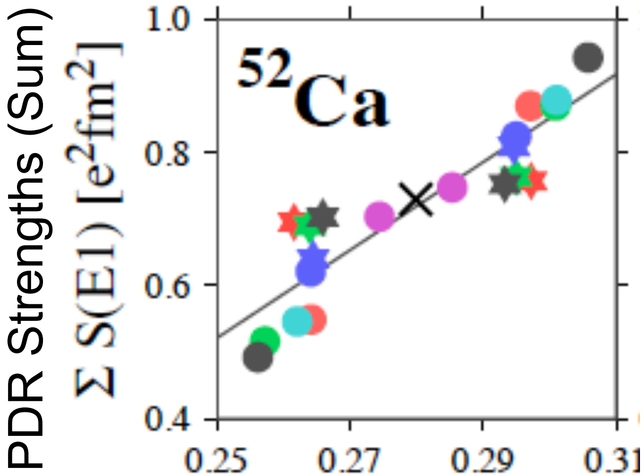
T. Inakura et al., PRC84, 021302 (2011)



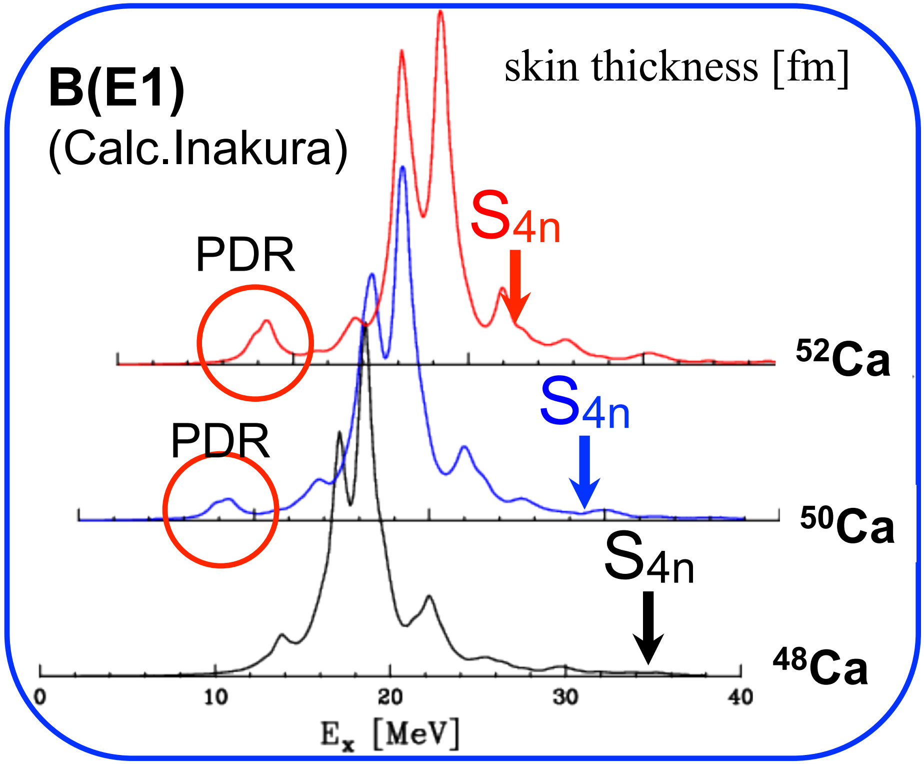


T. Inakura et al., arXiv:1306.3089

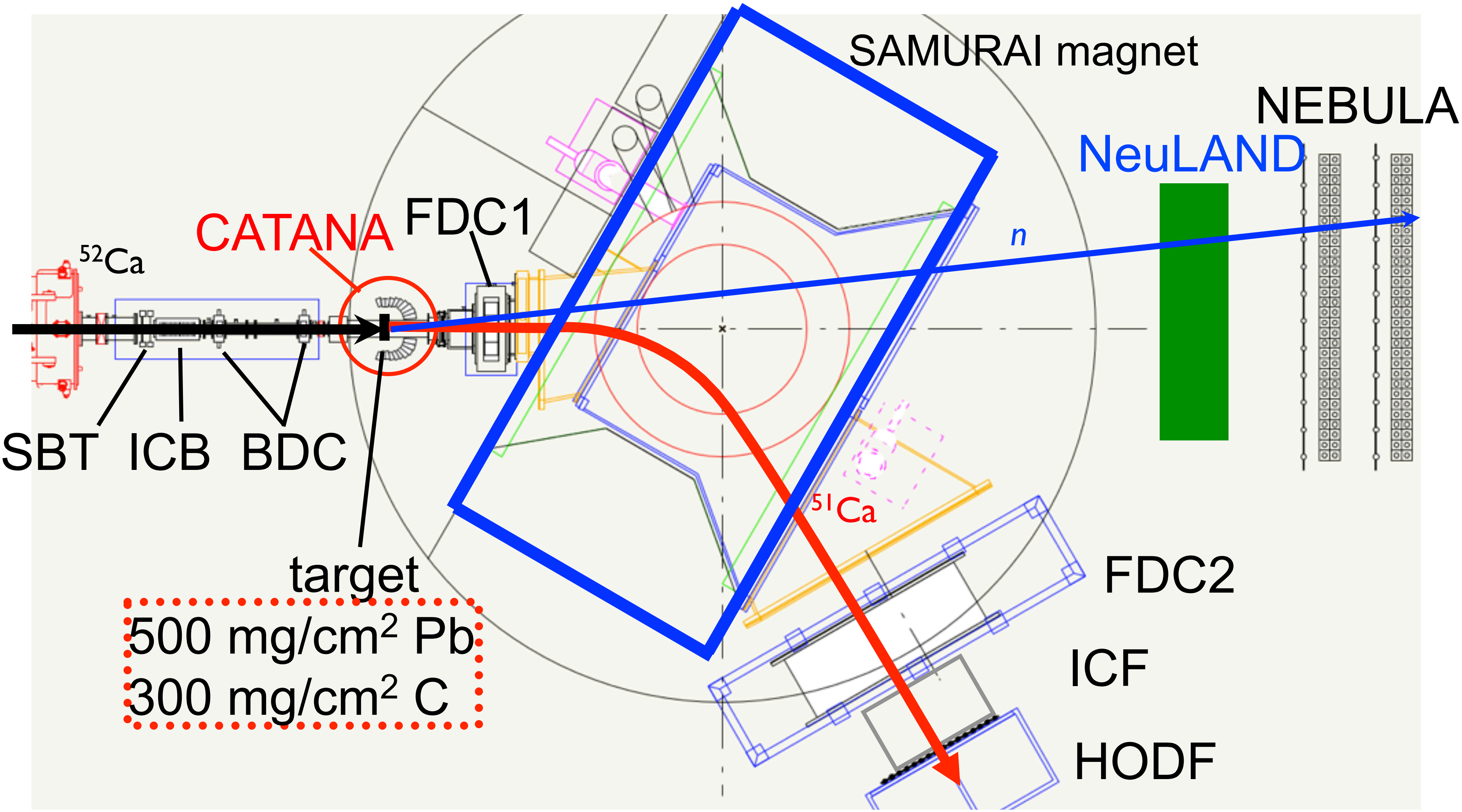
E1 response of n-rich Ca isotopes (calculation)



- ^{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.)

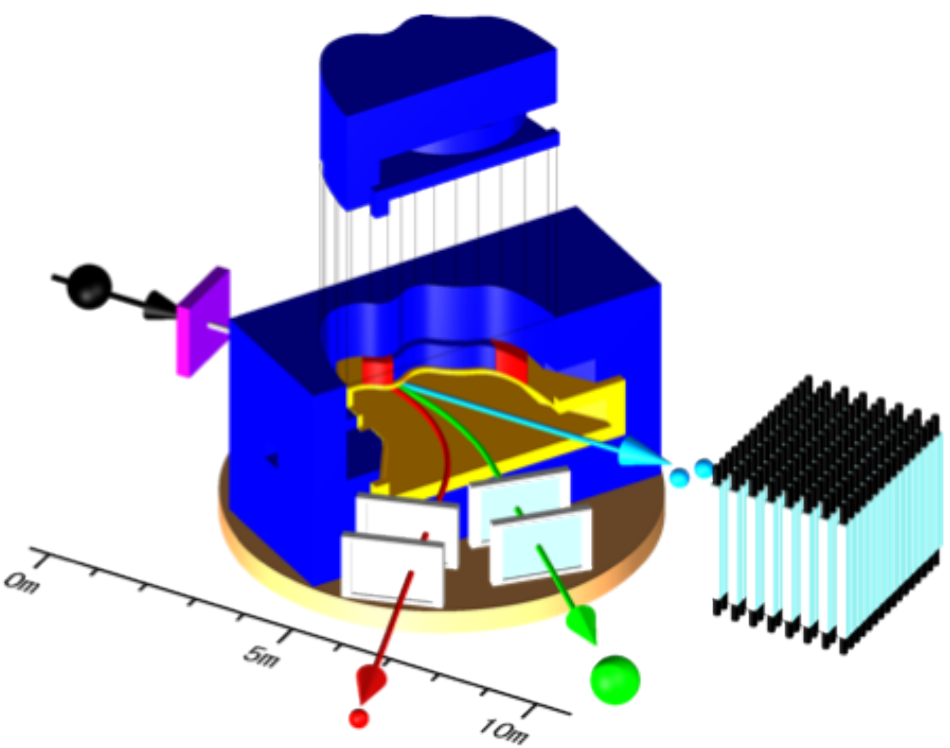


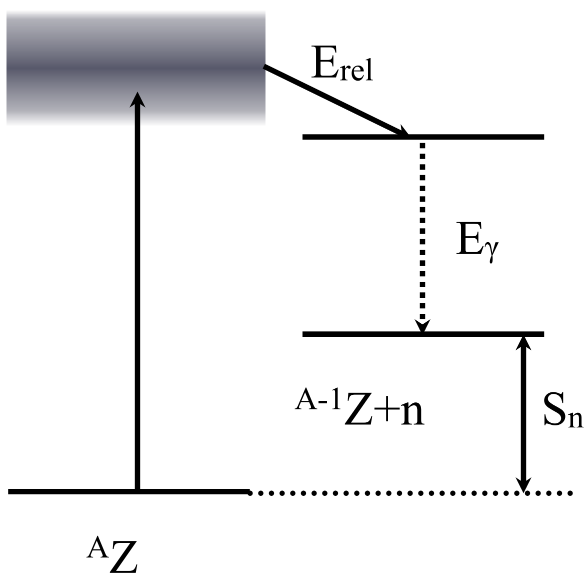
Experimental setup



γ ray detector for SAMURAI

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

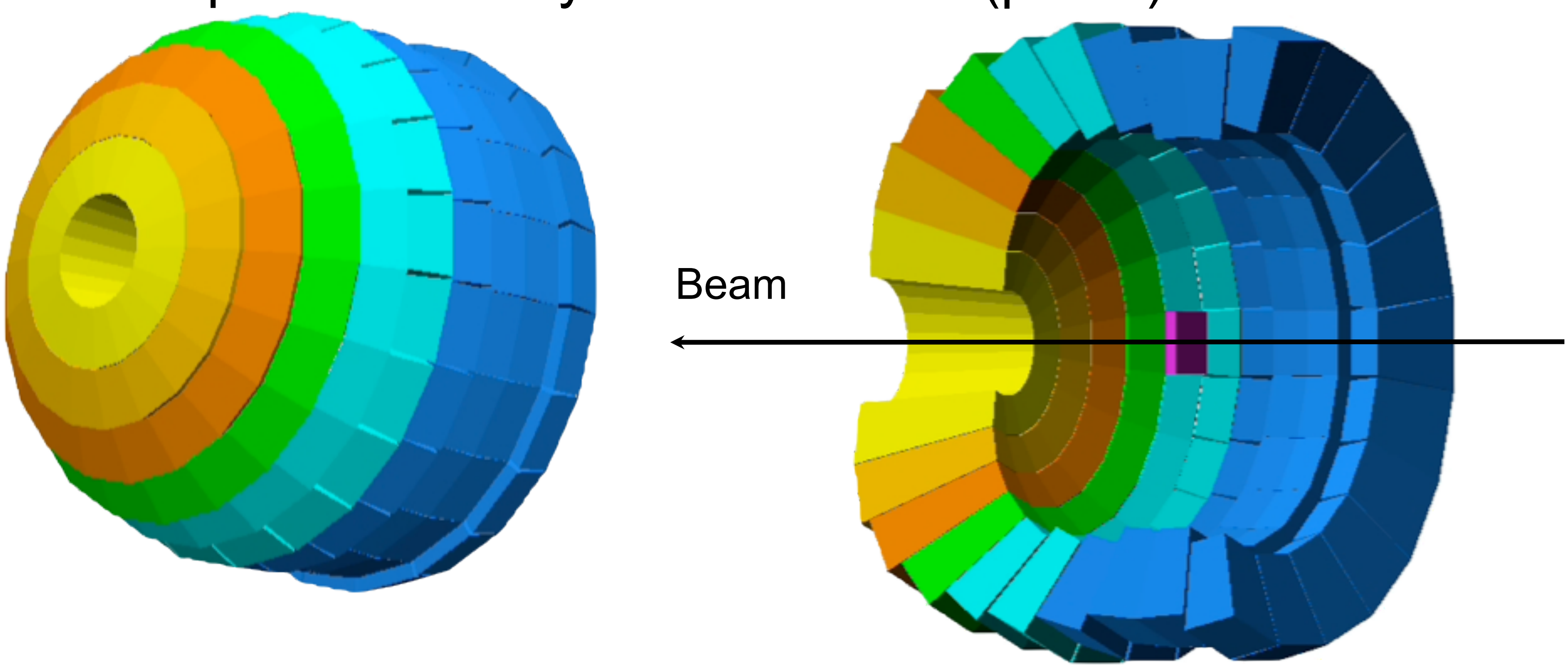




CATANA

CAlorimetric de**T**ector for r**A**diations from exotic **N**uclear be**A**ms

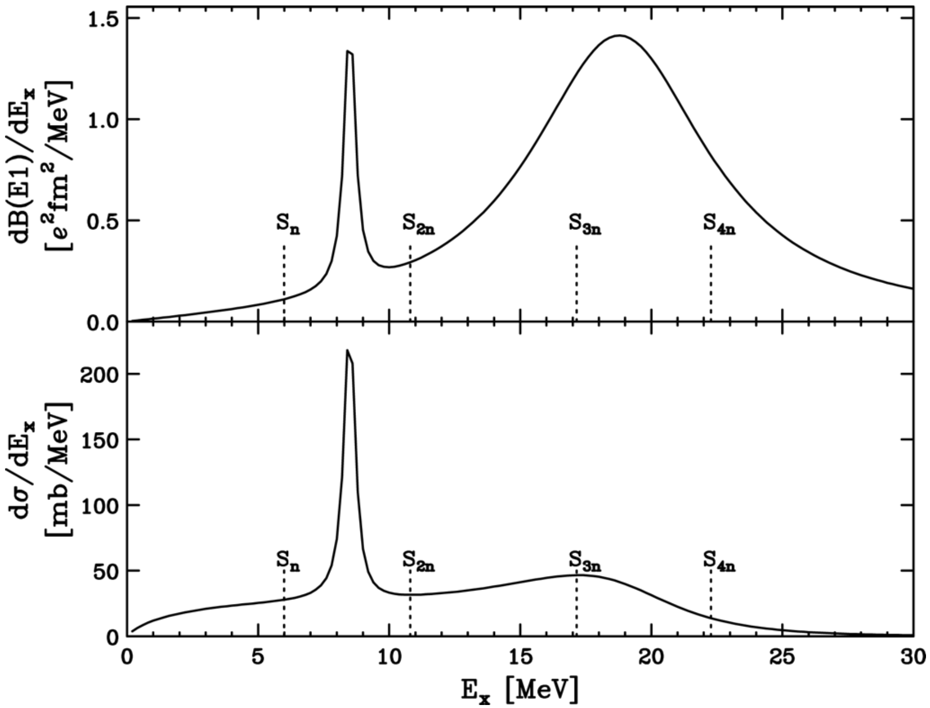
- 200 Crystals: CsI(Tl) or CsI(Na)
- Thickness: 9.5—15cm
- Photo peak efficiency 56% for 1MeV (β=0.6)

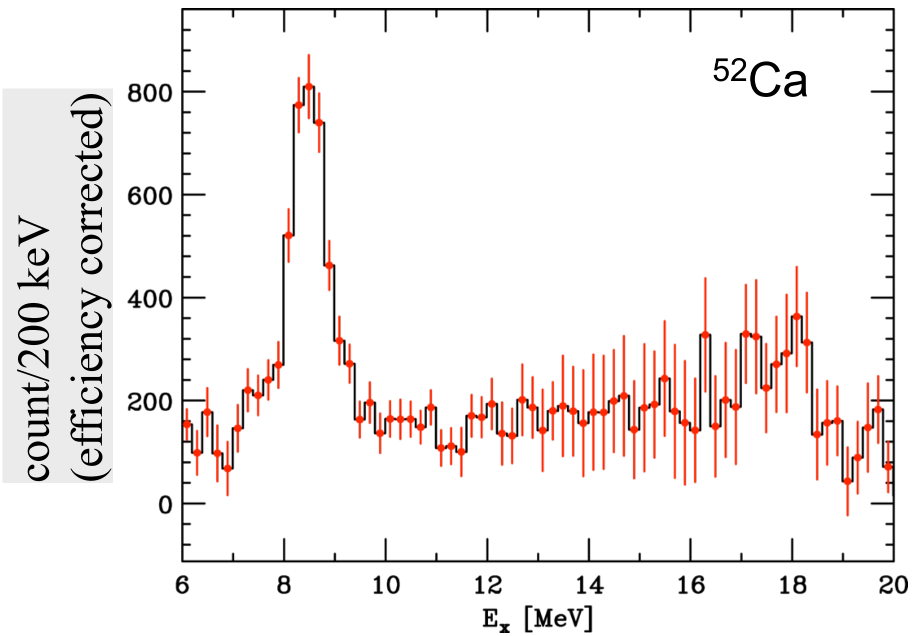


Expected Spectrum (Simulation)

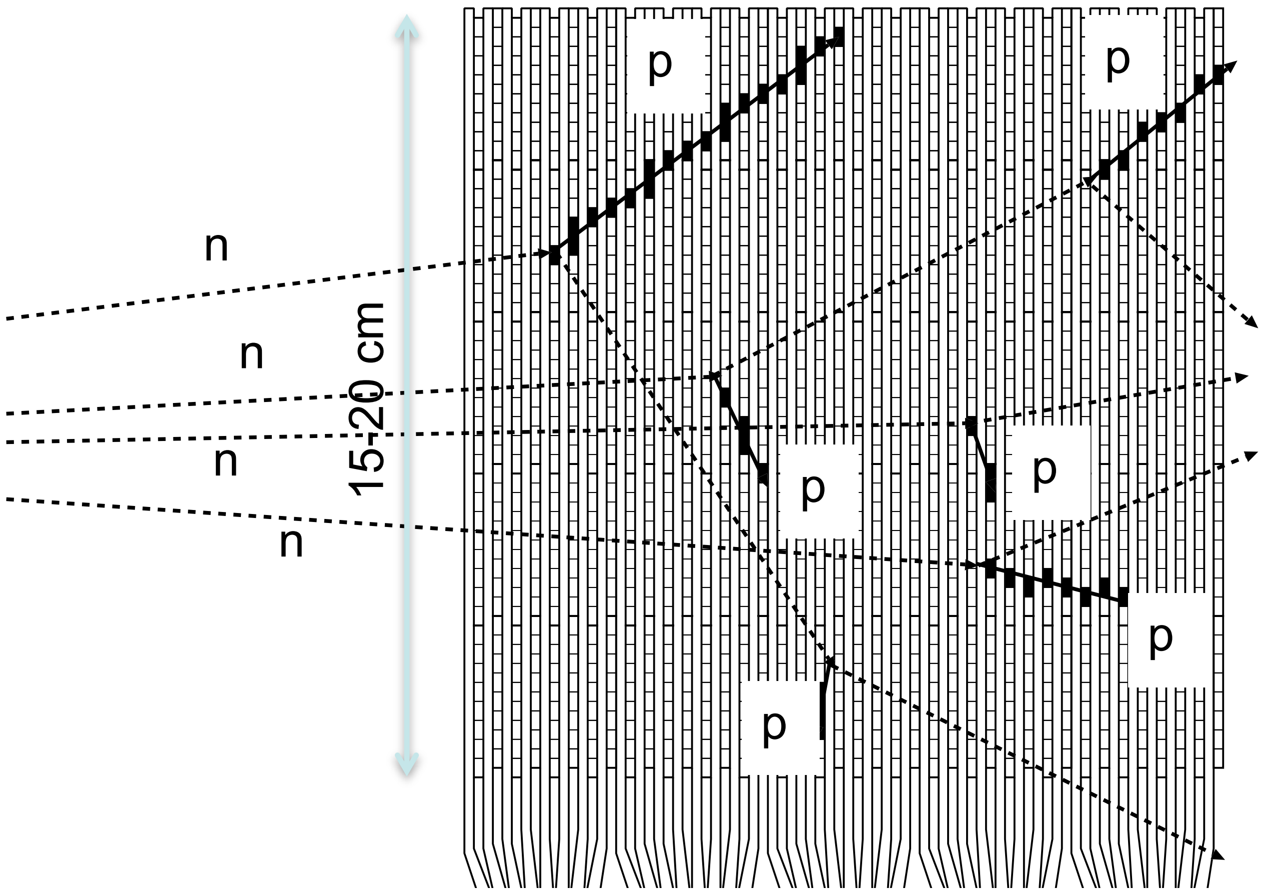
- Primary beam: ^{70}Zn
  - 345 AMeV, 75 pnA
- LISE++: EPAX3.01/measured CS
- B(E1) distribution: PDR + GDR(^{48}Ca parameter)

Approved by PAC, Dec. 2013 (Grade A)





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

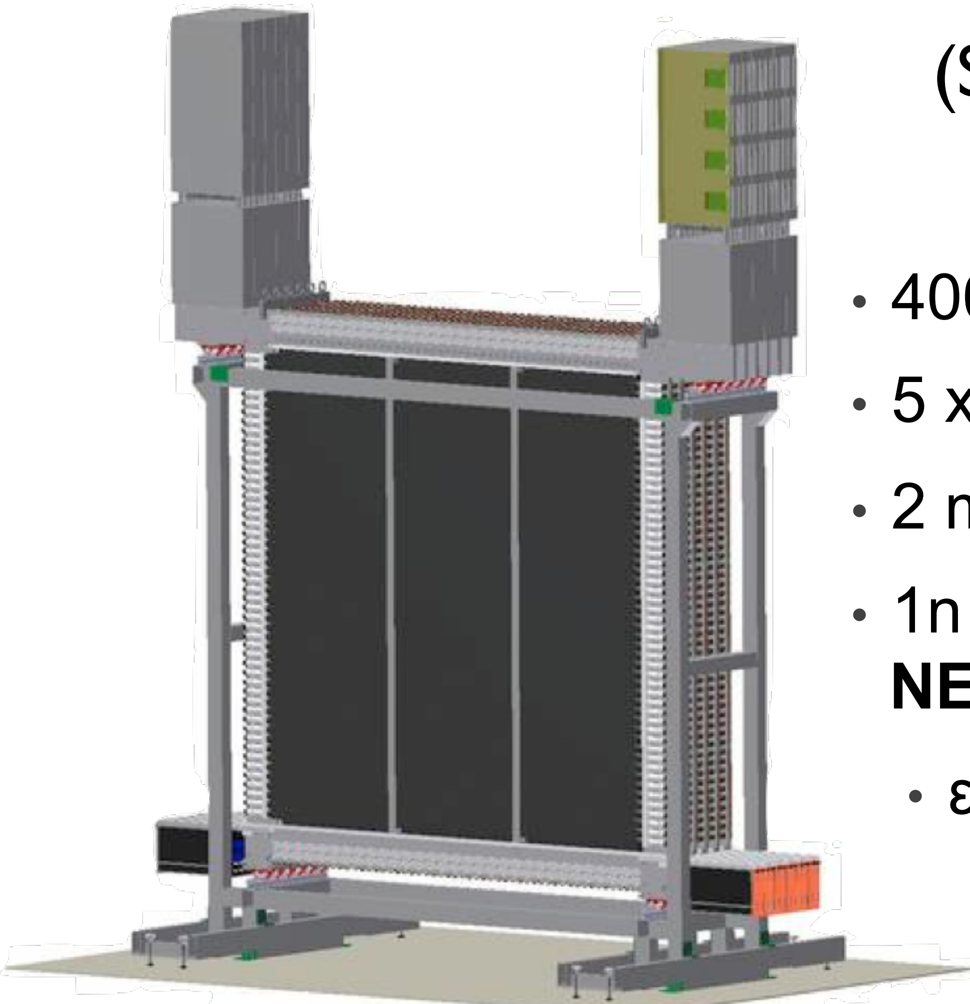
PDR of ^{52}Ca
Approved by PAC
(Grade A)

^{28}O production
Approved by PAC
(Grade S)

NEULAND
Neutron-Array
At GSI
Will be Brought
To RIKEN
In Late 2014.

Addition of Neutron Detectors

NEULAND
--**New L**arge **N**eutron **D**etector from GSI (Scheduled End of 2014--)



- 400 plastic scintillator bar
- 5 x 5 x 250 cm^3 (40cm thick)
- 2 m upstream of NEBULA
- 1n detection efficiency with **NEBULA(48cm)+NEULAND**
  - ε_{1n} = 56%

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

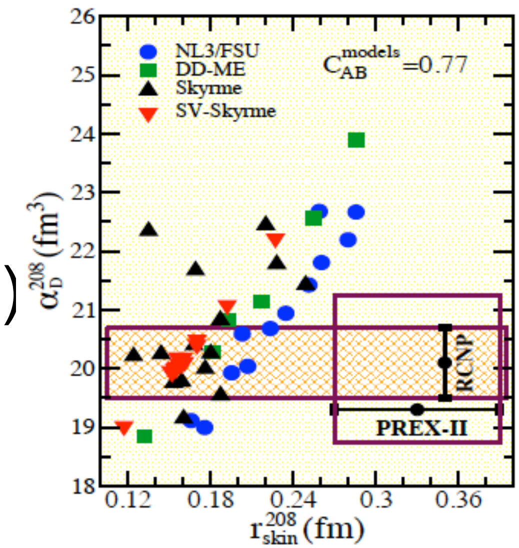
Technische Universit¨at Darmstadt: T.Aumann

Rikkyo Univeristy: D.Murai

Universit´e Paris-Sud, IN2P3-CNRS: M.Vandebrouck

backup

Dipole polarizability



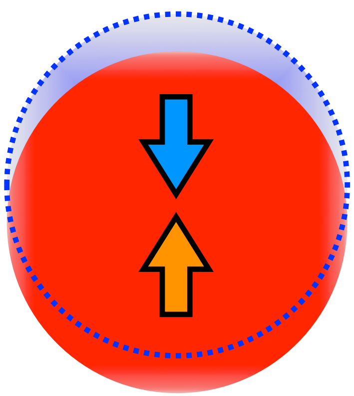
J. Piekarewicz, arXiv:1307.7746

- Inversely Energy weighted Sum Rule of B(E1)

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

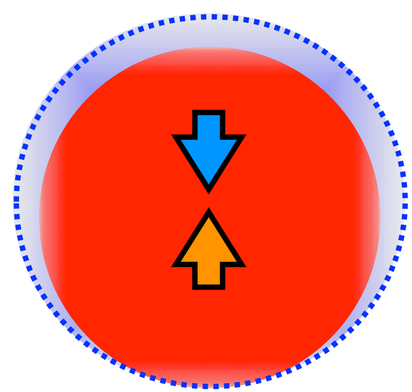
- Degree of polarization due to an external E1 field

without skin



larger restoring force
→ smaller α_D

with skin



smaller restoring force
→ larger α_D