Breakup reactions of neutron-rich nuclei for application to stellar reactions

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RIKEN NiSHiNA CENTER

革新的研究開発推進プログラム ImPACT Impulsing Paradigm Change through Disruptive Technologies Program

Indirect Methods in Nuclear Astrophysics, 5-9,Nov. 2018 @ECT, Trento, Italy*

Contents

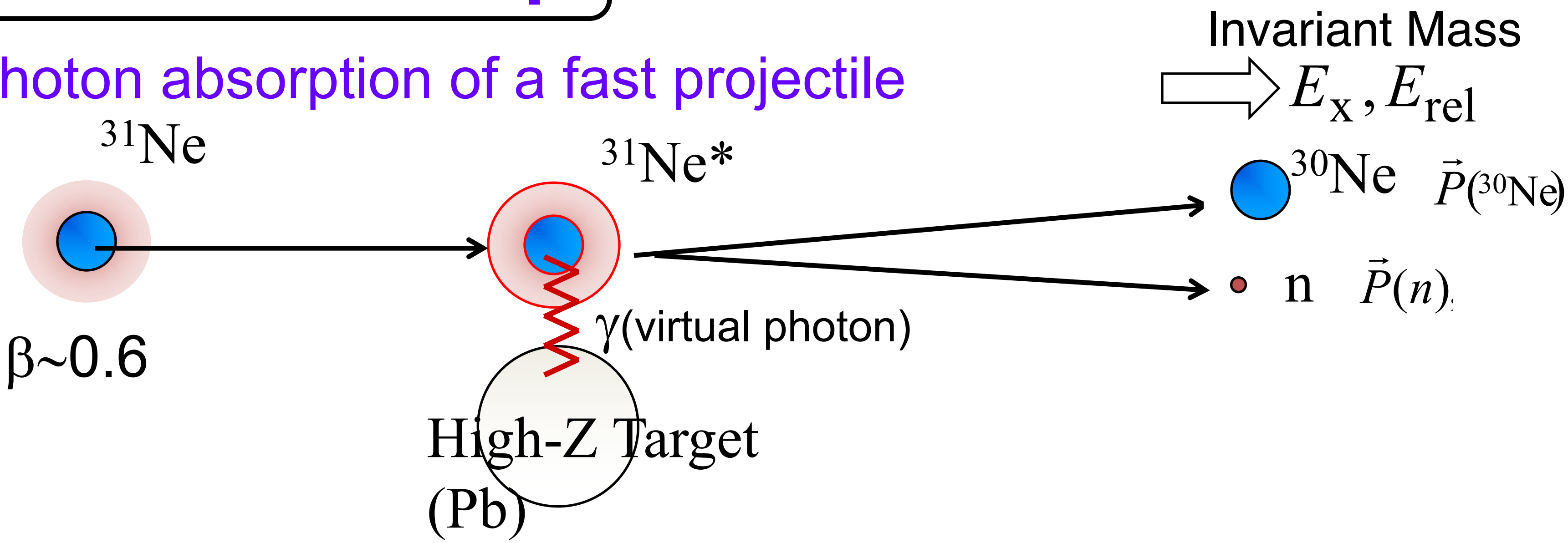
- Coulomb breakup for evaluating neutron capture reaction rate
- Coulomb breakup of ^{15}C – Simple example
- Coulomb breakup of island-of-ineversion nucleus ^{31}Ne
- Coulomb breakup of LLFP (Long-lived Fission Products) and neighboring nuclei for evaluating the (n,γ) reaction rates
- Coulomb breakup of 2n halo
- Summary and Outlook

A part of this research was funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

- Coulomb breakup for evaluating neutron capture reaction rate

Coulomb Breakup

→Photon absorption of a fast projectile

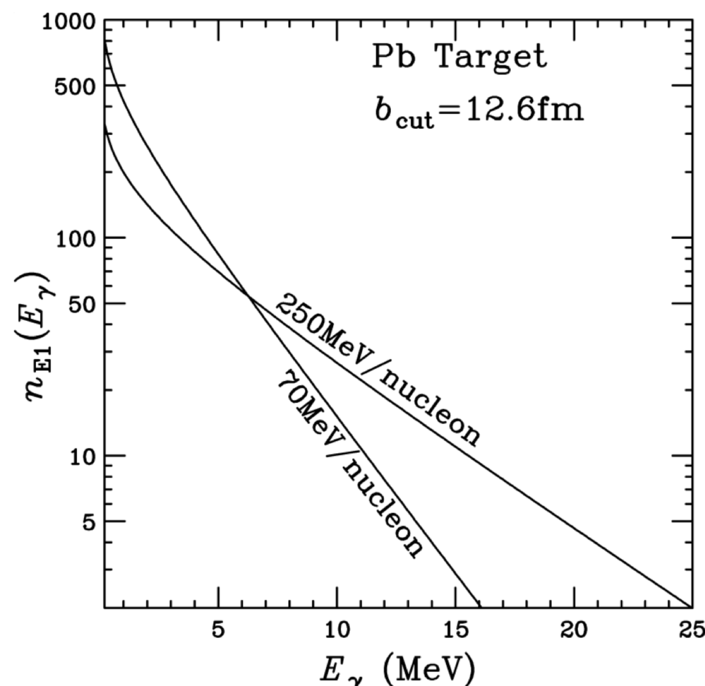


Equivalent Photon Method

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

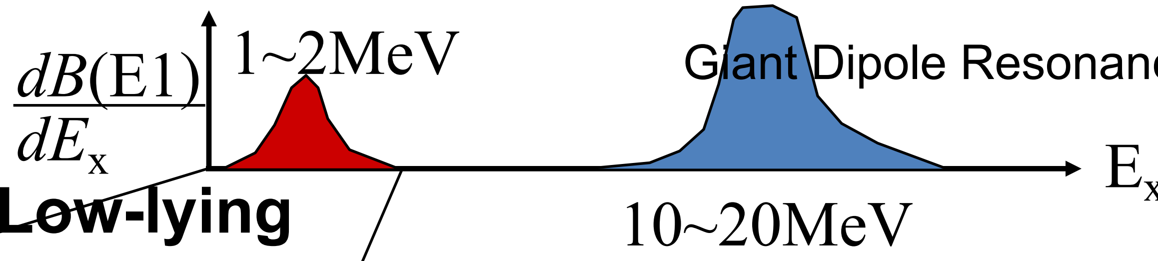
$$= N_{E1}(E_x) \frac{\sigma_{\gamma,n}(E_x)}{E_x}$$

(Photon Number)x(Photoabsorption cross section)

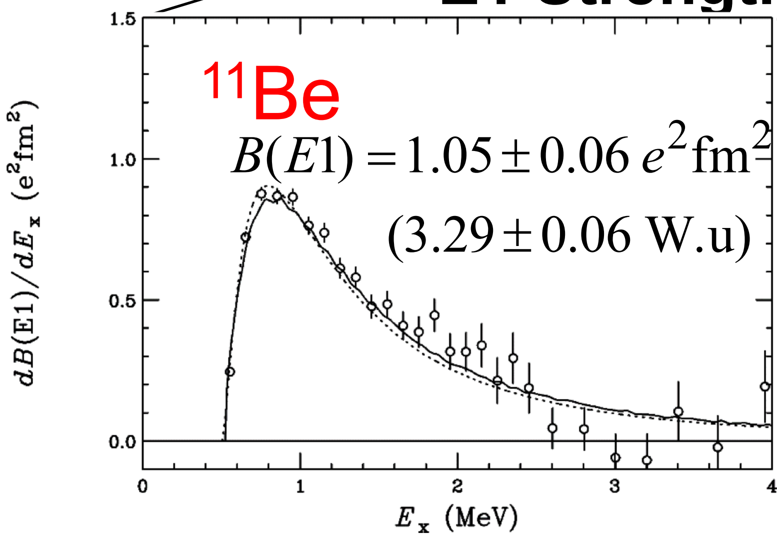


C.A. Bertulani, G. Baur, Phys. Rep. **163**, 299(1988).
T. Aumann, T. Nakamura, Phys. Scr. T**152**, 014142(2013).

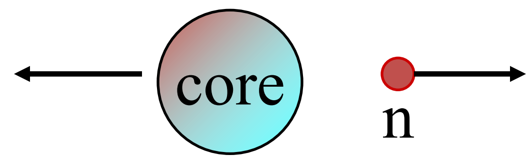
Coulomb Breakup and E1 Response--Case of 1n Halo



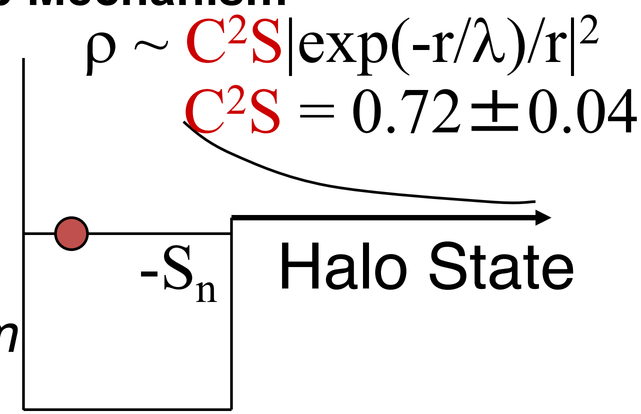
Low-lying E1 Strength (Soft E1 excitation)



N.Fukuda *et al.*, PRC**70**, 054606 (2004).
T.Nakamura *et al.*,PLB **331**,296(1994).
Palit *et al.*, PRC**68**, 034318(2003).
T.Aumann, T.Nakamura, Phys. Scr. T152 (2013) 014012.



Direct Breakup Mechanism



E1 Strength

$$\frac{dB(E1)}{dE_x} \propto |\langle \exp(i\boldsymbol{qr})|\frac{Z}{A}rY^1{}_m|\Phi_{gs}\rangle|^2$$
$$\propto C^2S|\langle \exp(i\boldsymbol{qr})|\frac{Z}{A}rY^1{}_m|s_{1/2}\rangle|^2$$

Fourier Transform

Soft E1 Excitation of 1n halo—Sensitive to S_n, l, C^2S

Neutron Capture Reaction Rate from Coulomb Breakup

Principle of Detailed Balance

$^{14}C(n,\gamma)^{15}C$ $^{15}C(\gamma,n)^{14}C$

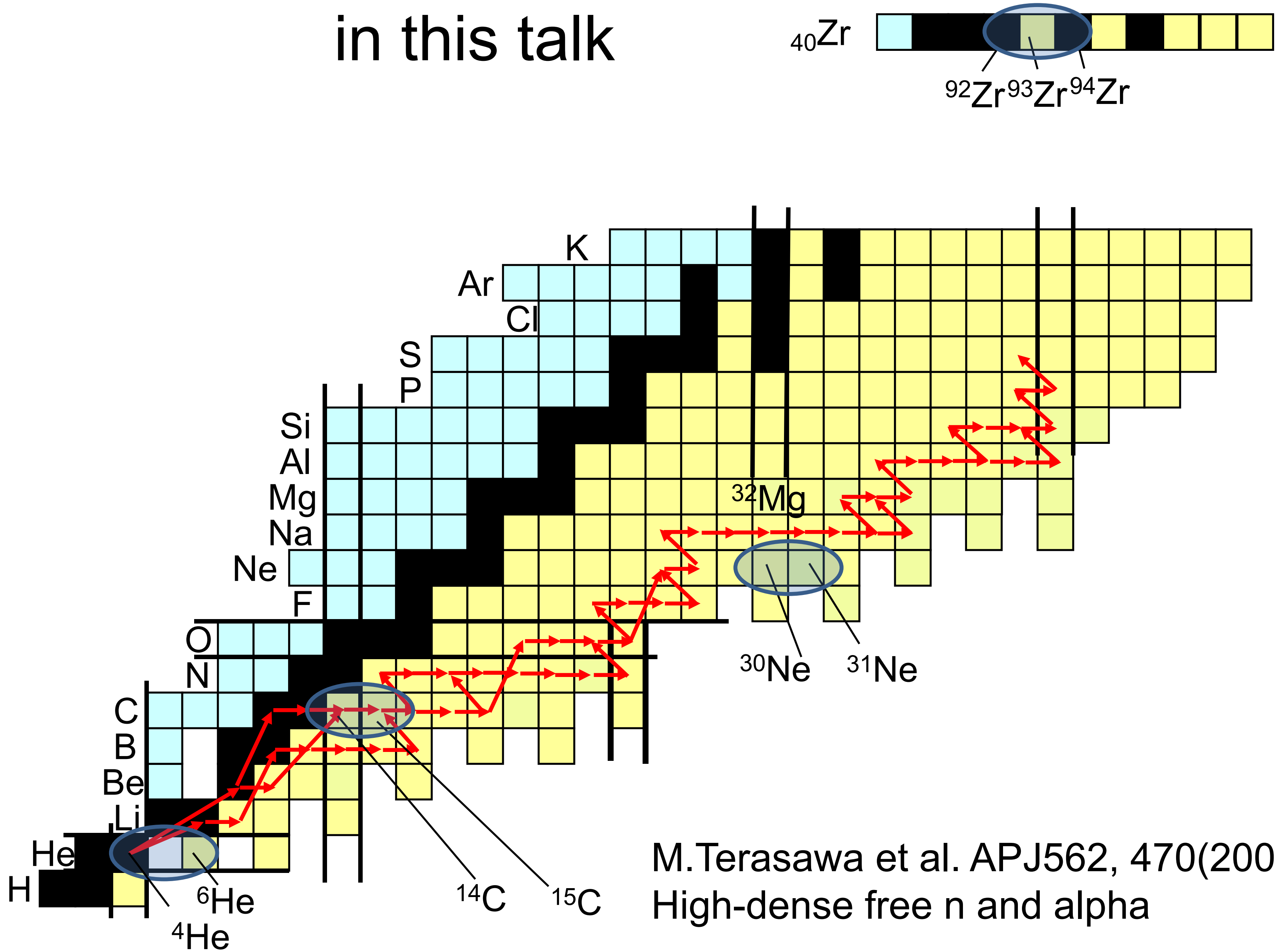
Neutron Capture ⬌ Coulomb Breakup

$$\sigma_{n,\gamma}(E_{rel}) = \frac{(2I_A+1)}{(2I_{A-1}+1)}\frac{E_\gamma^{\ 2}}{2\mu c^2 E_{rel}}\sigma_{\gamma,n}(E_\gamma)$$

Advantages of Coulomb Breakup

Phase Factor ~100
Photon Number ~500
Thick Target
Kinematical Focusing

Coulomb breakup and neutron captures in this talk



M.Terasawa et al. APJ562, 470(2001)
High-dense free n and alpha

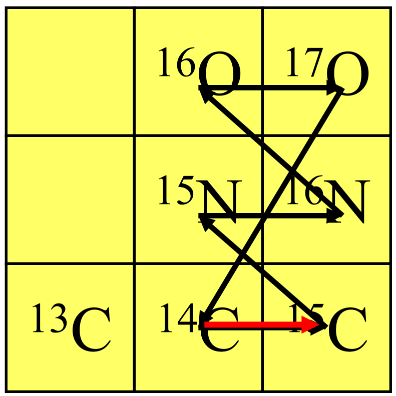
Coulomb breakup of ^{15}C
-- Simple example

TN et al., Phys.Rev.C 79, 035805 (2009).

Why ^{15}C ? $^{14}C(n,\gamma)^{15}C$

Astrophysical Interests

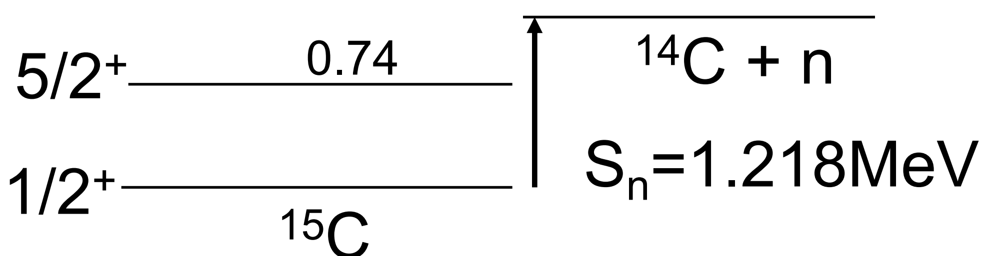
- Burning zone in Low mass Asymptotic Giant Branch(AGB) stars
  Neutrons from $^{13}C(\alpha,n)$ reactions
  $^{14}C(n,\gamma)^{15}C(\beta^-)^{15}N(n,\gamma)^{16}N(\beta^-)^{16}O(n,\gamma)^{17}O(n,\alpha)^{14}C$ *M.Wiescher et al.,* ApJ, 363,340

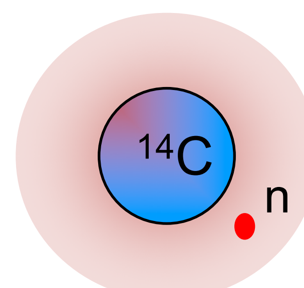


Neutron induced CNO cycle
$(4n \rightarrow {}^4He + 2e^- + 2\overline{\nu})$

- Inhomogeneous Big Bang Model
- r-process model Terasawa,Sumiyoshi,Kajino, ApJ562,470(2001).

Moderate Halo





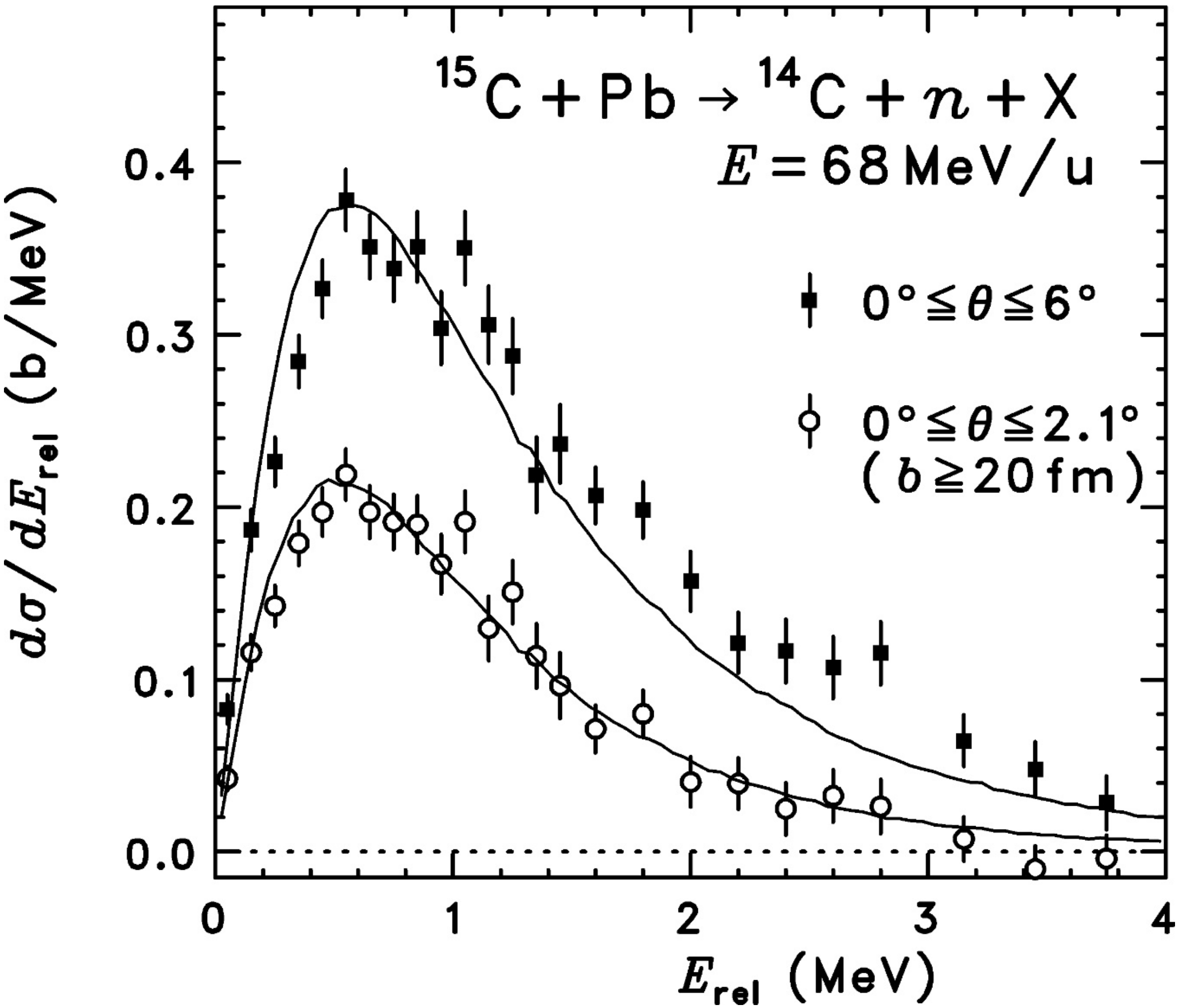
$\alpha^2=0.88$

$$^{15}C(g.s) = \alpha|\,^{14}C(0^+)\otimes 2s_{1/2}\rangle + \beta|\,^{14}C(2^+)\otimes 1d_{5/2}\rangle$$

Results: Coulomb Breakup of ^{15}C

^{15}C: moderate neutron-halo $1/2^+$ gs, S_n=1.27MeV

$$^{15}C(g.s) = \alpha|\,^{14}C(0^+)\otimes 2s_{1/2}\rangle + \beta|\,^{14}C(2^+)\otimes 1d_{5/2}\rangle$$



^{15}C+Pb@68MeV/u

α^2=0.91(6)

r_0=1.223 fm

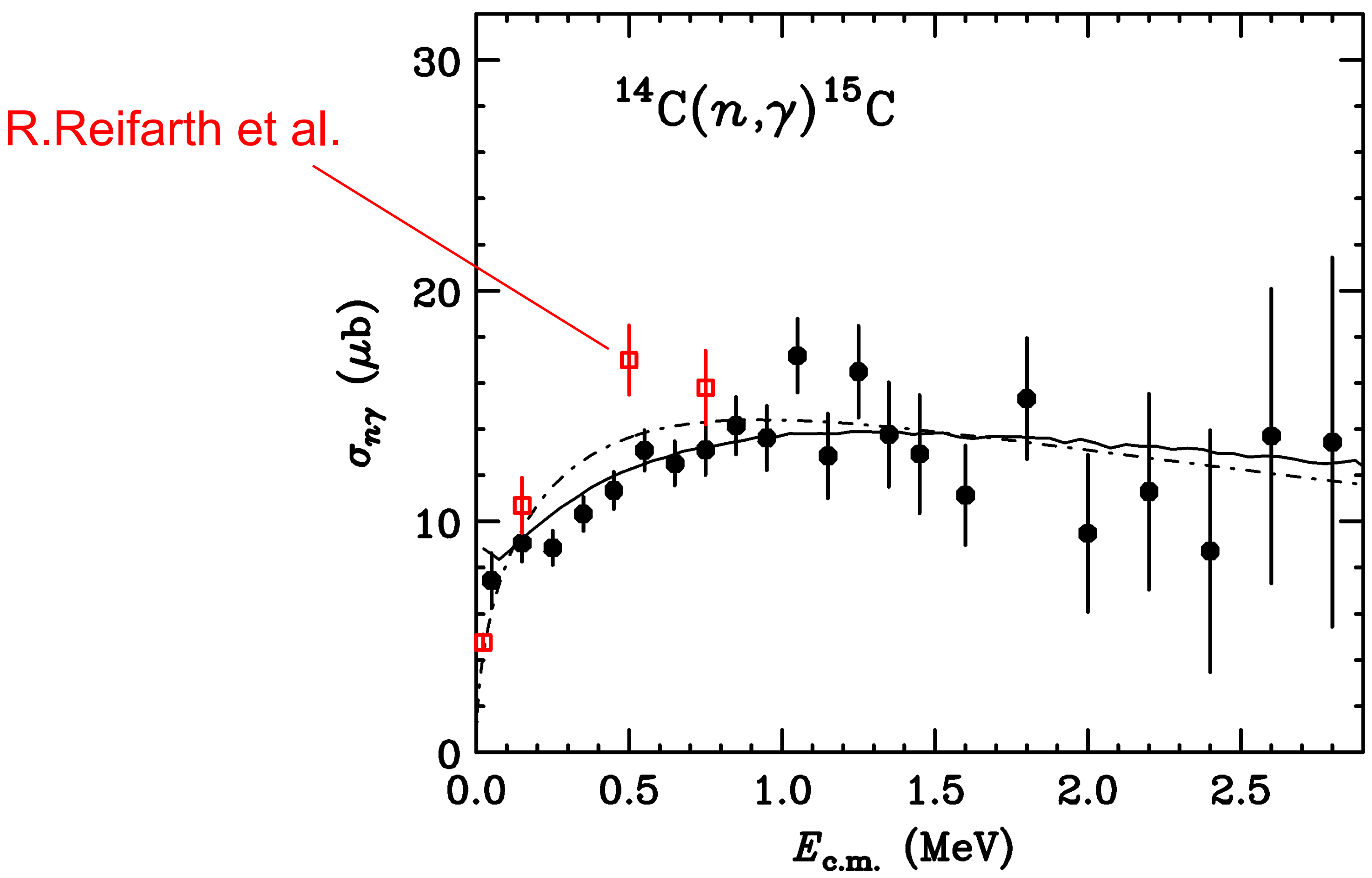
a=0.5 fm

T.Nakamura et al. PRC79,035805(2009).

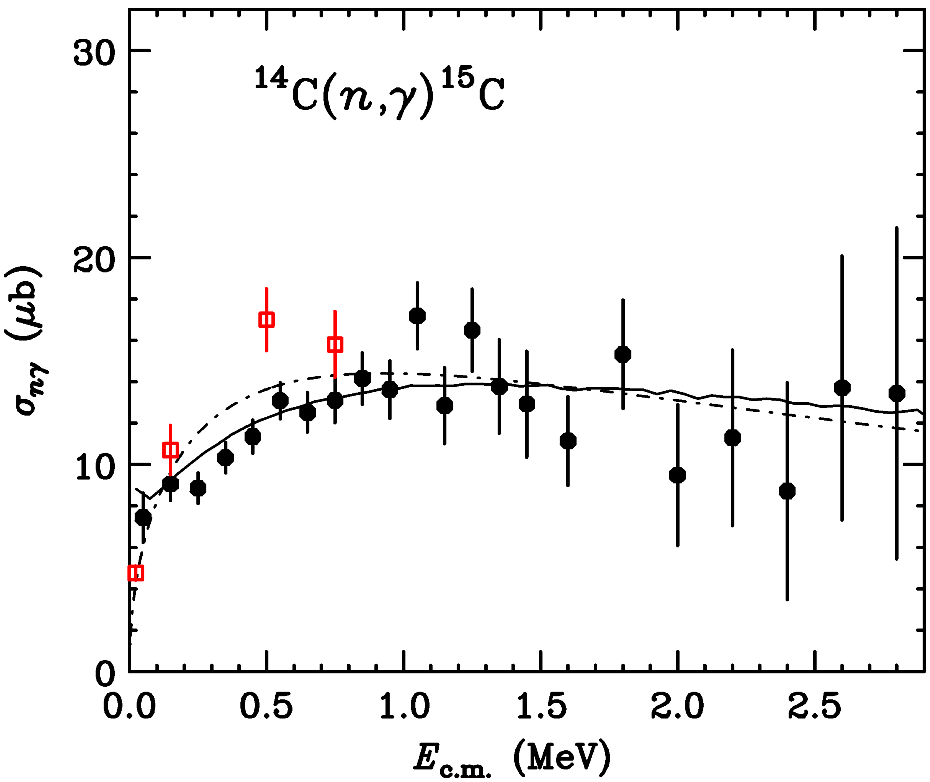
Consistent with GSI U.D.Pramanik et al PLB551,63(2003).

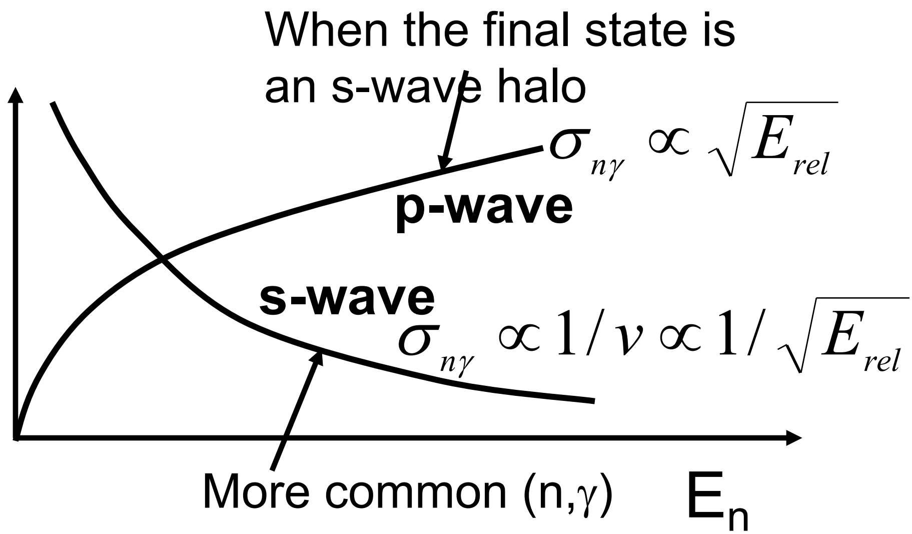
Neutron Capture Cross Section

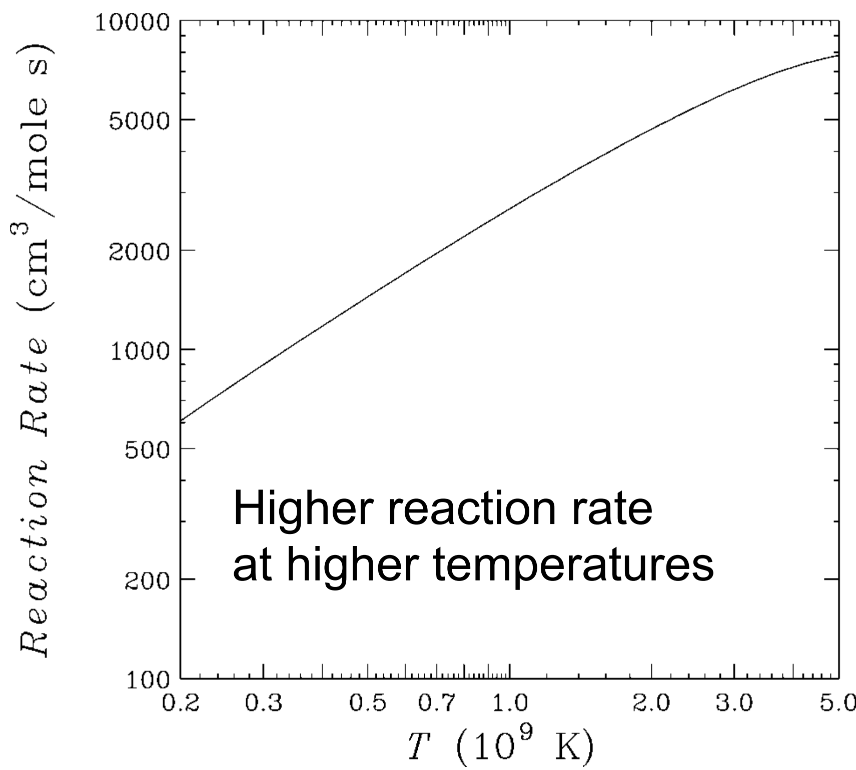
From the data with b>20fm



Consistent with Direct Capture Measurement $^{14}C(n,\gamma)^{15}C$
By R.Reifarth et al., PRC77,015804(2008)







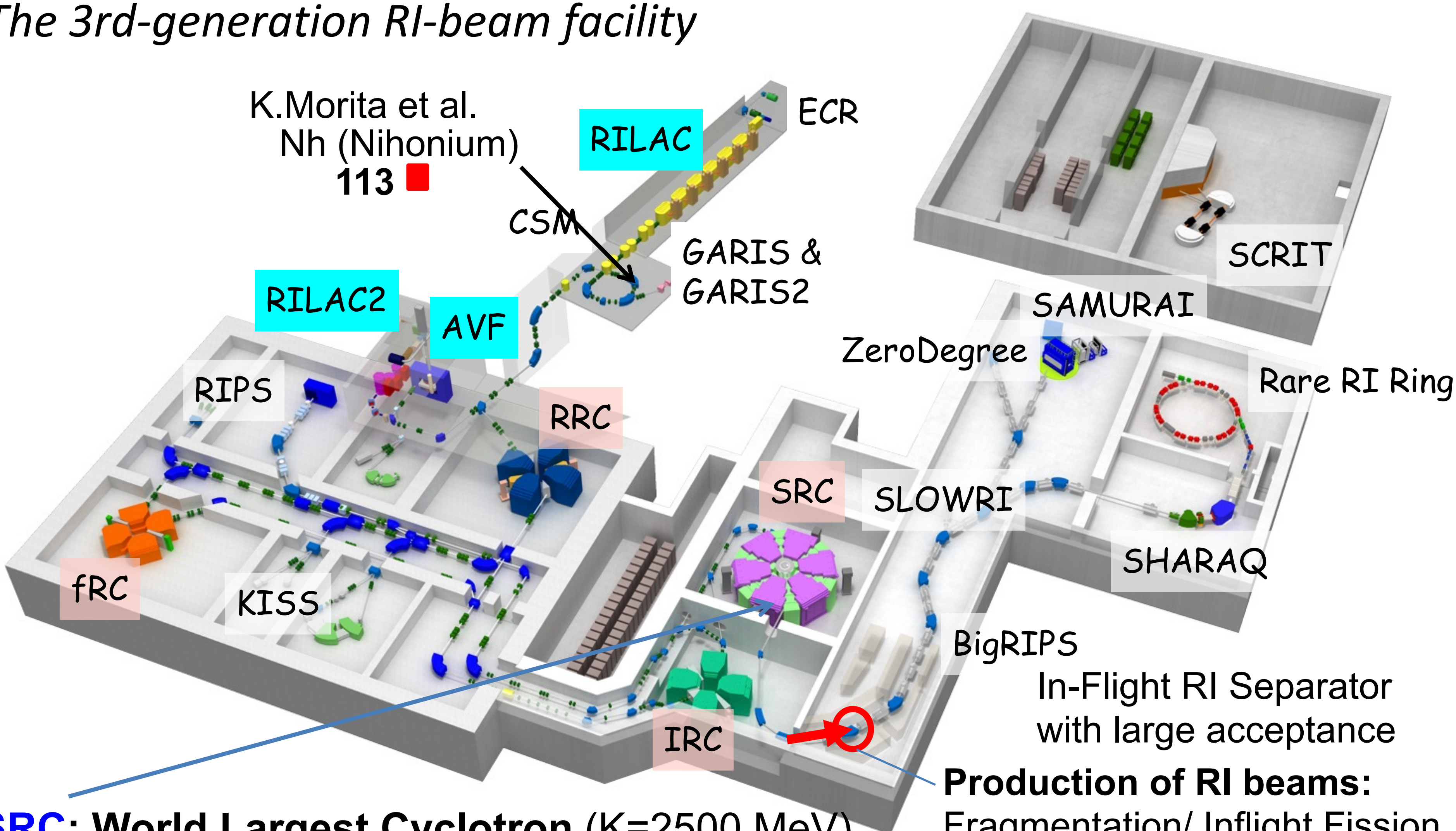
$$R_{n\gamma}(T) = N_A\langle\sigma v\rangle = N_A\left[\frac{8}{\pi\mu(kT)^3}\right]^{1/2}\int\sigma_{n\gamma}(E)E\exp\left(-\frac{E}{kT}\right)dE$$

Coulomb breakup of island-of-inversion nucleus ^{31}Ne

T. Tomai,
N. Kobayashi
Y. Kondo,
T. Nakamura
et al.

RI Beam Factory (RIBF) at RIKEN 2007~

The 3rd-generation RI-beam facility



Production of RI beams:
Fragmentation/ Inflight Fission

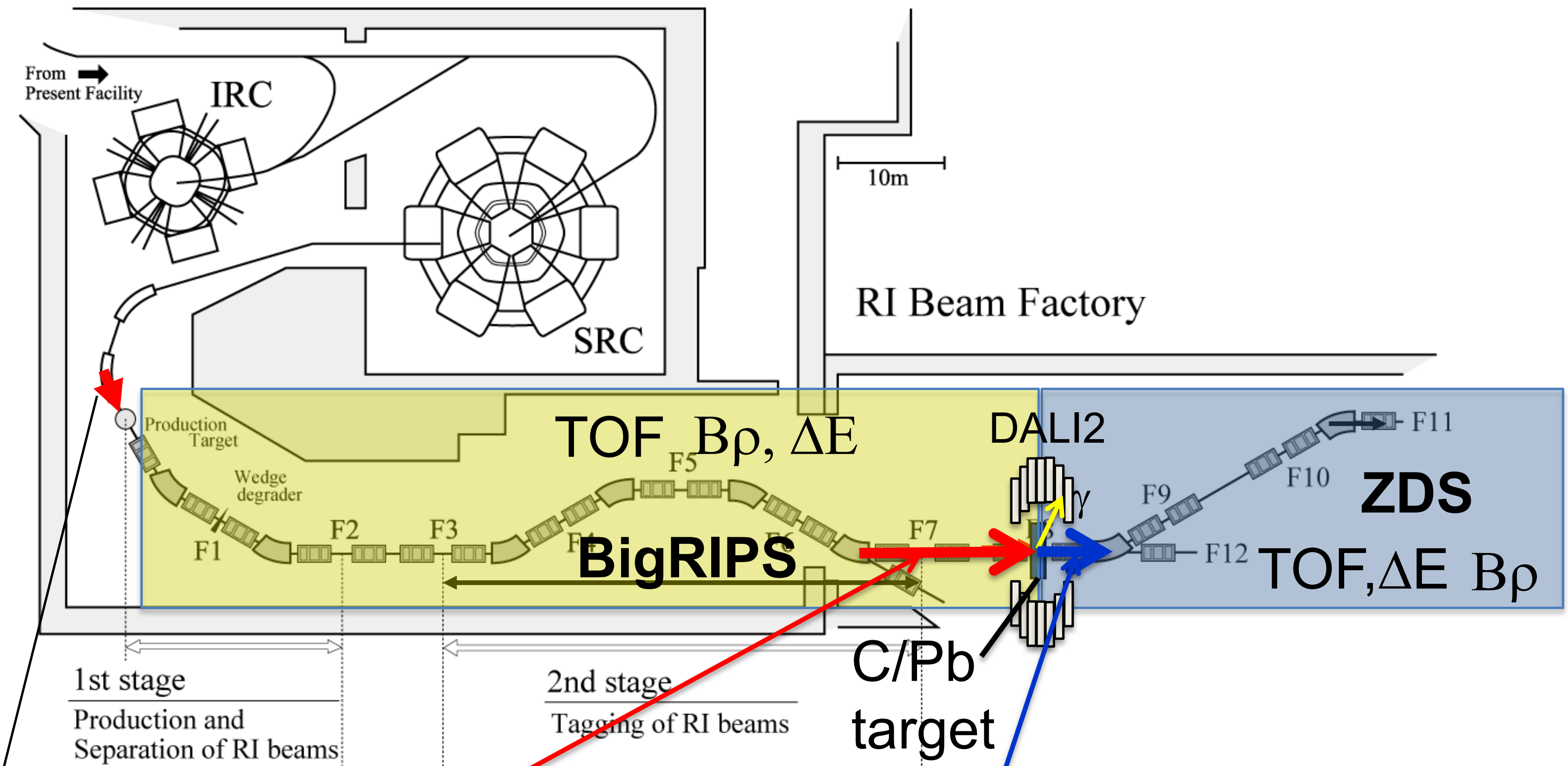
SRC: World Largest Cyclotron (K=2500 MeV)

High-Intense Heavy Ion Beams up to ^{238}U at 345MeV/u

eg. ^{48}Ca: ~700pnA (~4x10^{12}pps) *~10 times compared to 2008*

^{238}U: ~70pnA (~4x10^{11} pps) *~10^3 times compared to 2007*

Inclusive nuclear/Coulomb Breakup at BigRIPS & ZDS at RIBF



^{48}Ca 345MeV/u

^{31}Ne (230 MeV/u)+C/Pb→^{30}Ne+(γ)+X

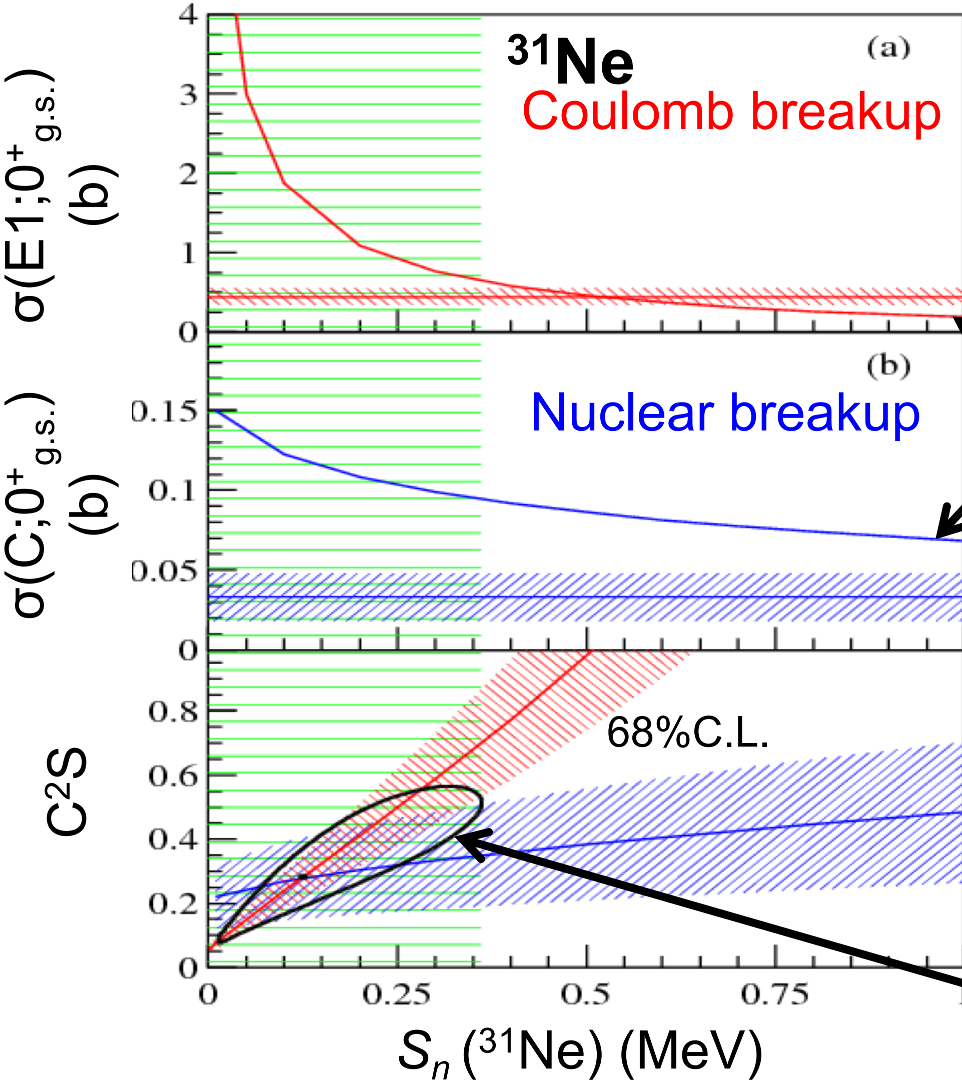
^{37}Mg (240 MeV/u)+C/Pb→^{36}Mg+(γ)+X

^{29}Ne (240 MeV/u)+C/Pb→^{28}Ne+(γ)+X

$\sigma_{-1n}(E1; 0_{gs}^{+})$

$\sigma_{-1n}(C; 0_{gs}^{+})$

Deformation Driven p-wave Halo --- ^{31}Ne, ^{37}Mg, ^{29}Ne



S_n (^{31}Ne)=-0.06(0.42) MeV
L.Gaudefroy et al., PRL(2012)

$|^{31}Ne_{g.s.}\rangle$: 3/2$^-$
$|^{30}Ne(0^+_{g.s.}) \otimes p_{3/2}\rangle$ component

Exp. $\sigma_{-1n}(E1;0^+_{g.s.})$ = 448(108) mb

Theoretical calc. for
$|^{31}Ne_{g.s.}\rangle = |^{30}Ne(0^+_{g.s.}) \otimes p_{3/2}\rangle$
(C^2S = 1)

Exp. $\sigma_{-1n}(C;0^+_{g.s.})$ = 33(15) mb

^{31}Ne: **3/2$^-$** **p**-wave
Deformed in spite of **N=21**

$$C^2S = 0.32^{+0.21}_{-0.17}$$

[321 3/2]
β~0.5

$$S_n = 0.15^{+0.16}_{-0.10}\ \text{MeV}$$

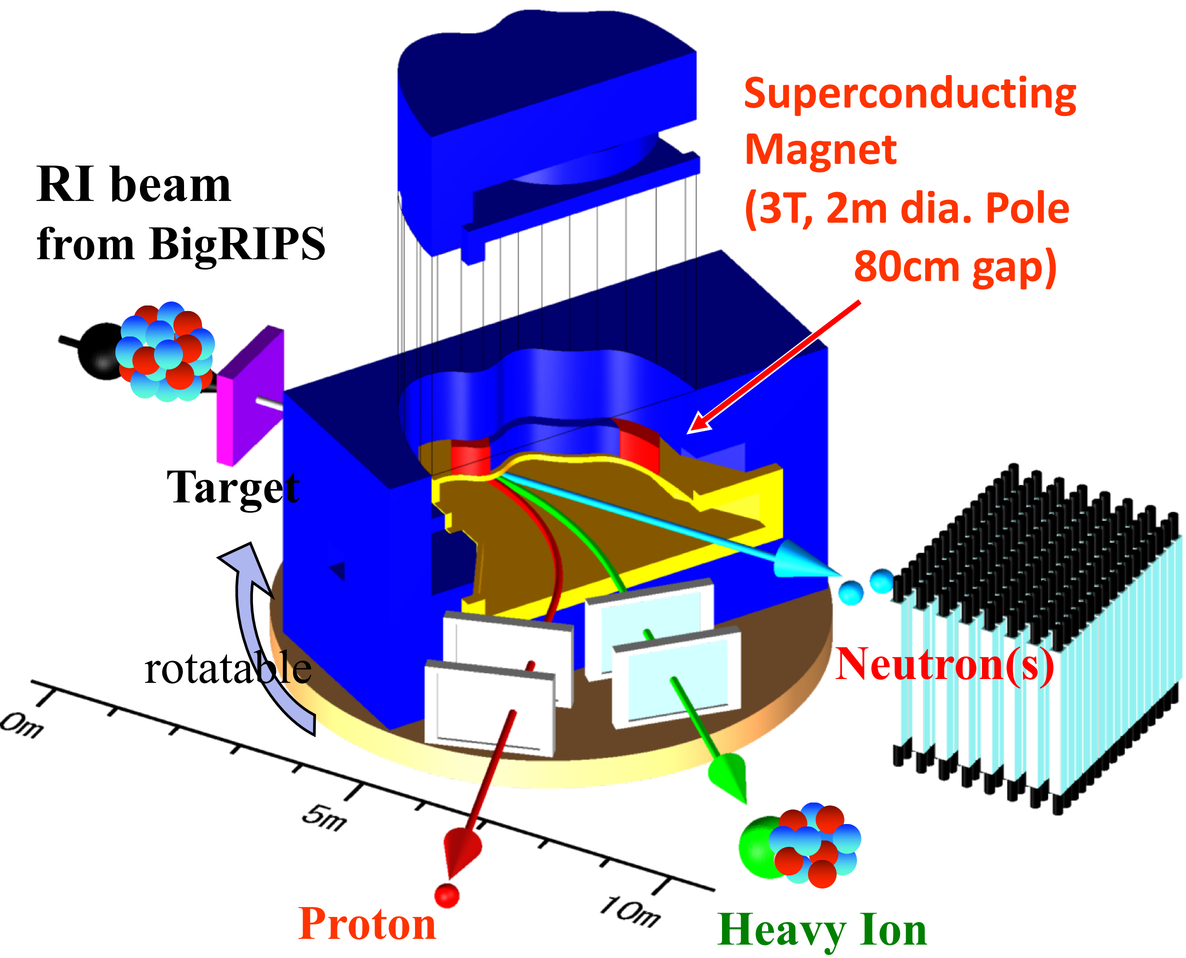
^{31}Ne: TN, N.Kobayashi et al., PRL **112**, 142501 (2014). 3/2$^-$ S_n=150(16)keV
^{37}Mg: N.Kobayashi, TN et al., PRL **112**, 242501 (2014). 3/2$^-$/1/2$^-$ S_n=220(12)keV
^{29}Ne: N.Kobayashi, TN et al., PRC **93**, 014613 (2016). 3/2$^-$ S_n=960(140) keV

Inclusive at BigRIPS/ZDS
→ Exclusive at SAMURAI

SAMURAI

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

Kinematically Complete measurements by detecting multiple particles in coincidence→ Powerful tool for nuclei near and beyond the driplines.



Large momentum acceptance

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

Good Momentum Resolution

$\Delta p/p \sim 1/1000$

→$A/\Delta A>100$ (>5σ)

Large Bending Angle (~60deg)

+4 Tracking Detectors

T.Kobayashi NIMB **317**, 294 (2013)

Large angular acceptance for *n*

+-8.8 deg (H) x +-4.4 deg(V)

(~50% coverage < E_{rel} ~ 5MeV)

TN, Y.Kondo, NIMB **376**, 156 (2016).

Moderate Erel Resolution

ΔE = 200 keV (σ) at E_{rel}=1MeV

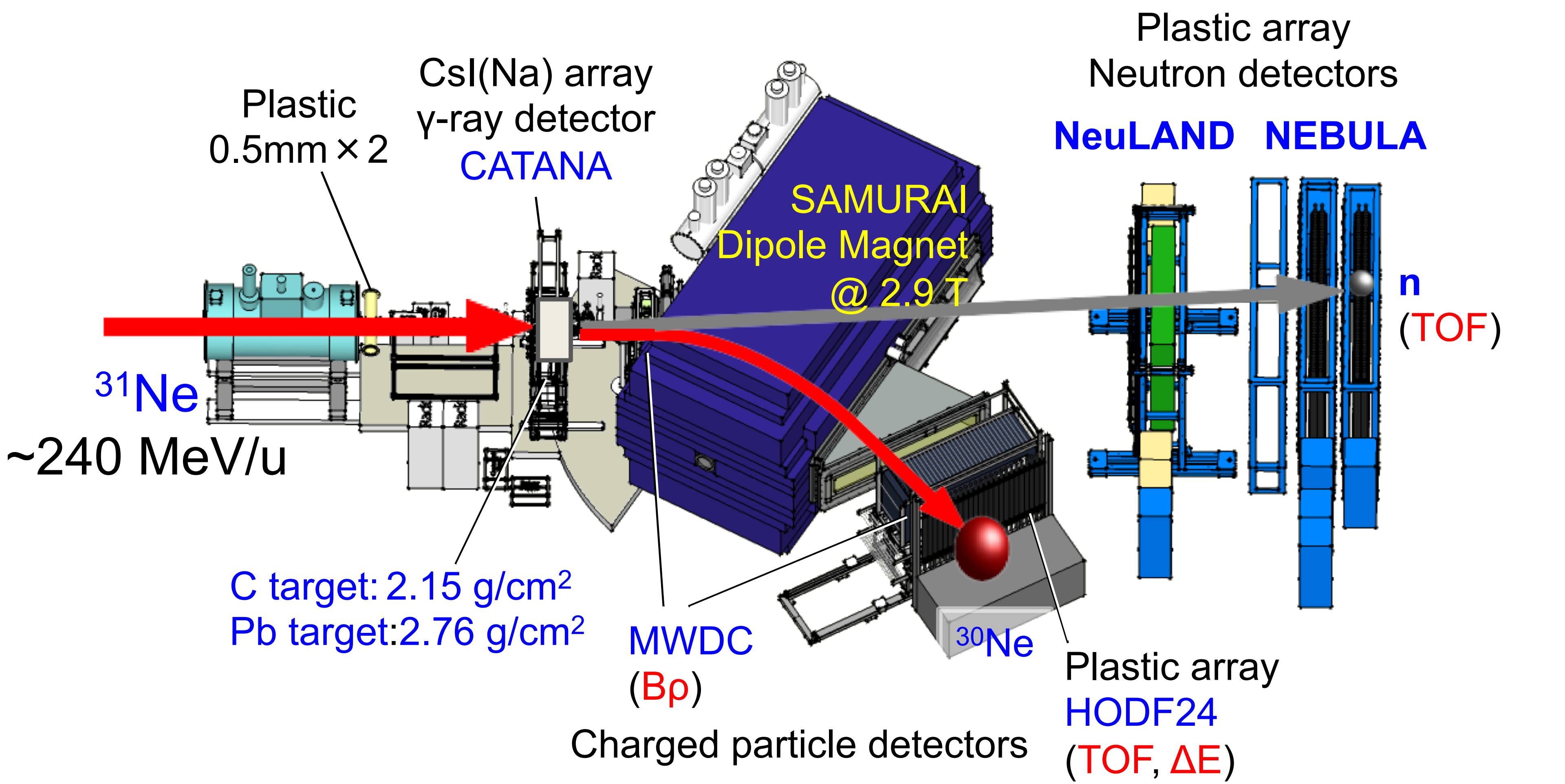
Stage: Rotatable (-5 -- 95 degrees)

→Variety of Physics Opportunities

SAMURAI Experiment

Full Exclusive Coulomb Breakup Measurement of ^{31}Ne T.Tomai et al.

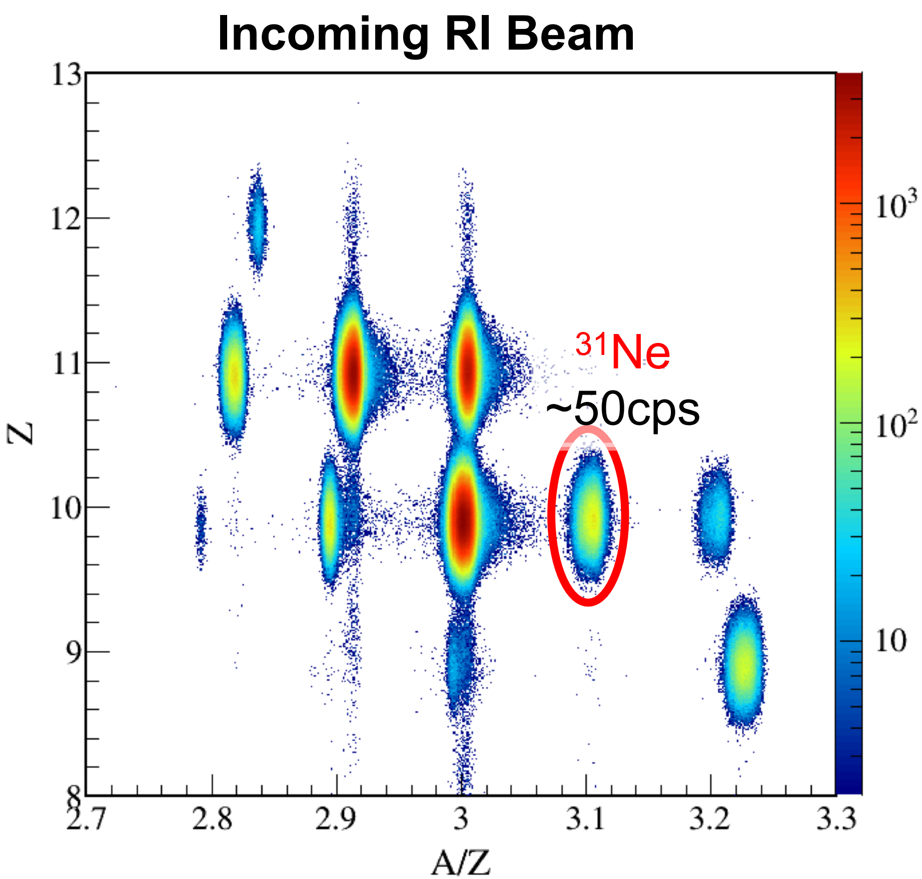
-Autumn,2015

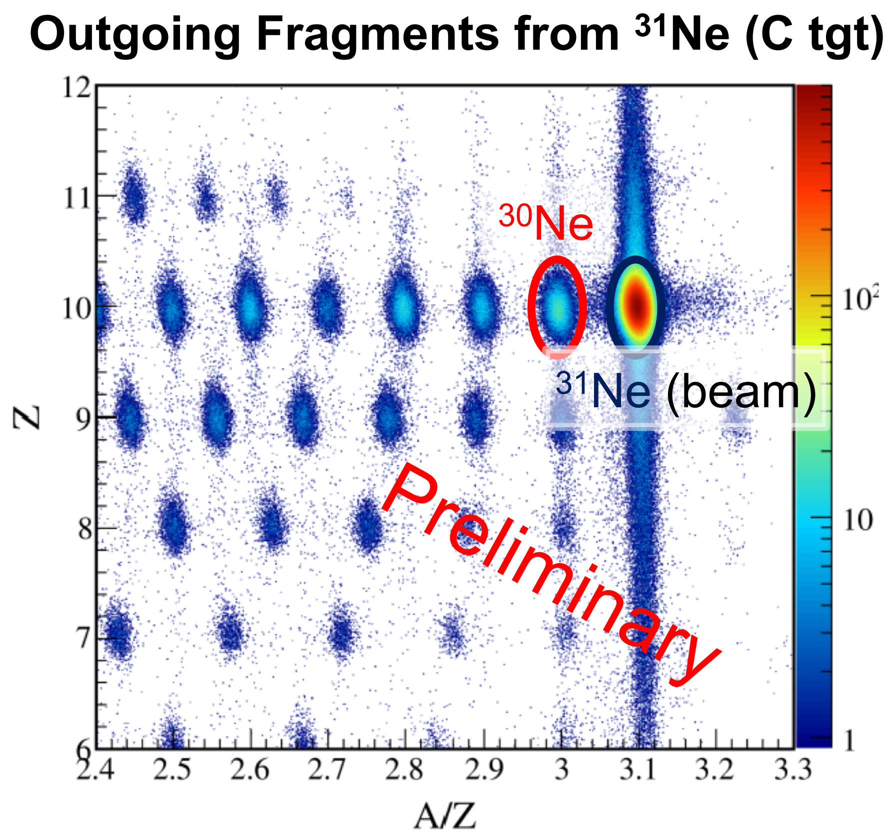


Slide by T.Tomai

PID Spectra

T.Tomai et al.



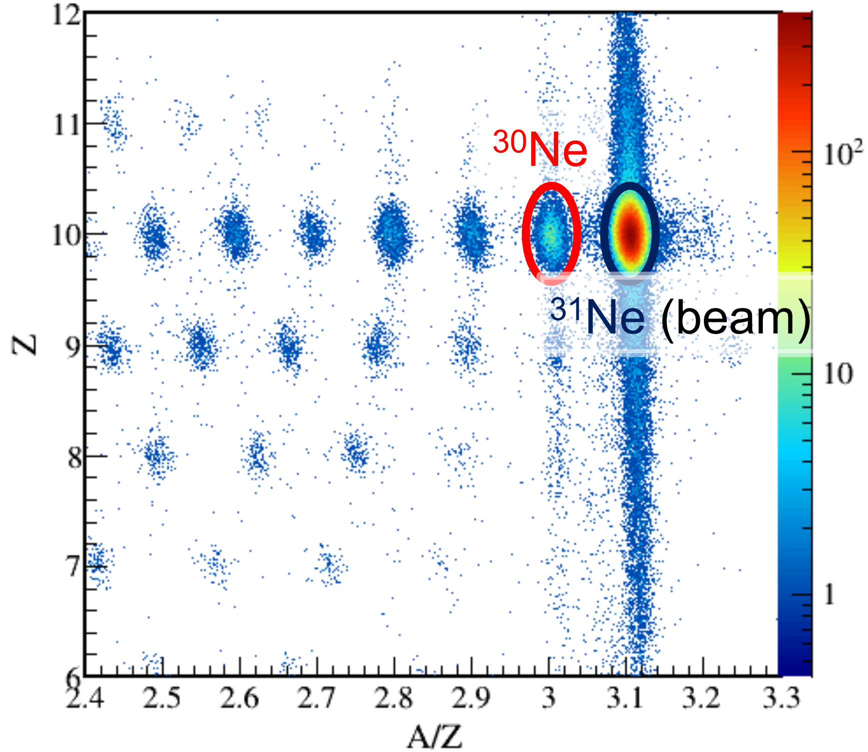


Intensity: 10 times higher
than previous RIBF experiment in 2008

Slide by Tomai

Inclusive cross sections $^{31}Ne+Pb/C \rightarrow ^{30}Ne+X$

- PID of reacted particles (^{31}Ne gated in upstream)



	C target (mb)	Pb target (mb)
This work	89(3)	674(28)
Previous work	N.A	N.A.

Consistent with previous work

[3] T. Nakamura, N. Kobayashi et al. Phys. Rev. Lett. 112, 142501 (2014)

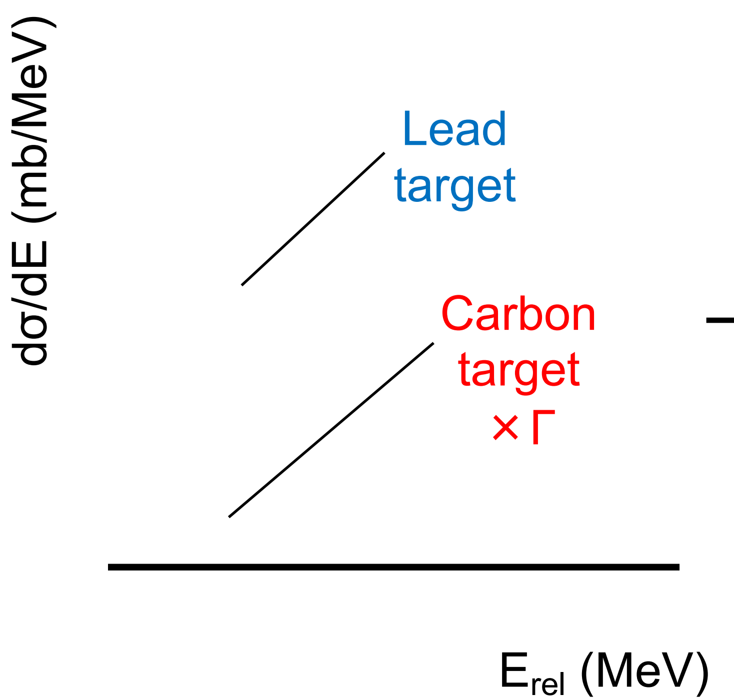
Exclusive differential cross section of Coulomb breakup reaction

- Pb(^{31}Ne,^{30}Ne+n) → Coulomb breakup spectrum

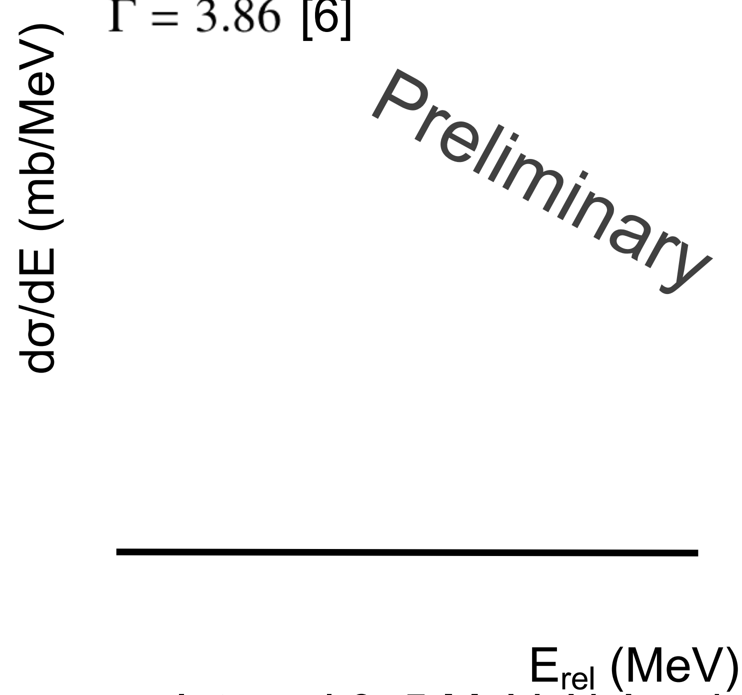
$$\frac{\mathrm{d}\sigma(\mathrm{Coul})}{\mathrm{d}E} = \frac{\mathrm{d}\sigma(\mathrm{Pb})}{\mathrm{d}E} - \Gamma\frac{\mathrm{d}\sigma(\mathrm{C})}{\mathrm{d}E}$$

Nuclear breakup component

$\Gamma = 3.86$ [6]



Integral 0–5 MeV: N.A. mb
For Lead target



Integral 0–5 MeV: N.A. mb
For Coulomb breakup

[6] K. Yoshida et al., Prog. Theo. Exp. Phys. 2014, 5, 053D03

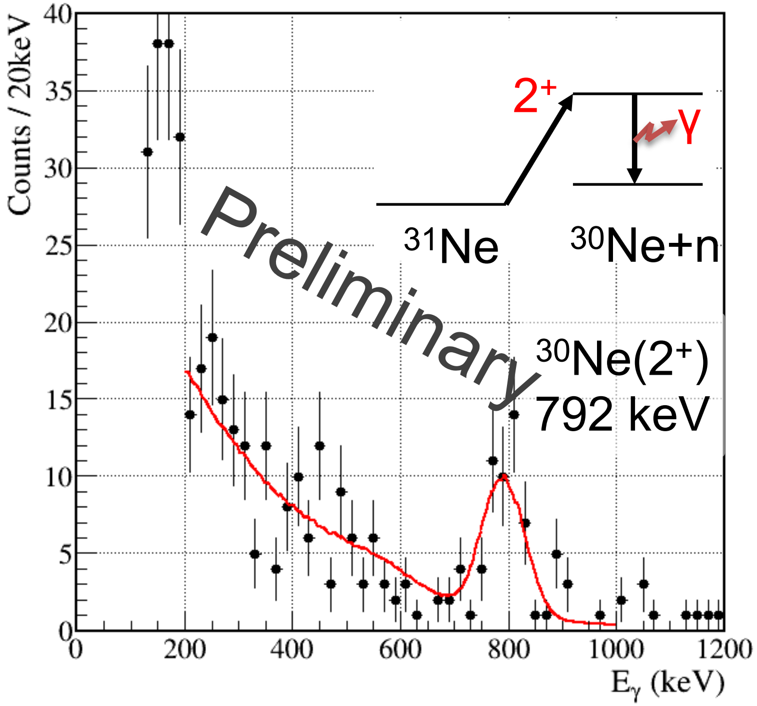
Excited state component of Coulomb breakup reaction

- ^{30}Ne(2^+) component:

$$|^{31}\mathrm{Ne}(3/2^-)\rangle = \alpha\,|^{30}\mathrm{Ne}(0^+)\otimes 2p_{3/2}\rangle + \beta\,|^{30}\mathrm{Ne}(2^+)\otimes 2p_{3/2}\rangle + \gamma|^{30}\mathrm{Ne}(2^+)\otimes 1f_{7/2}\rangle$$

Coulomb contribution

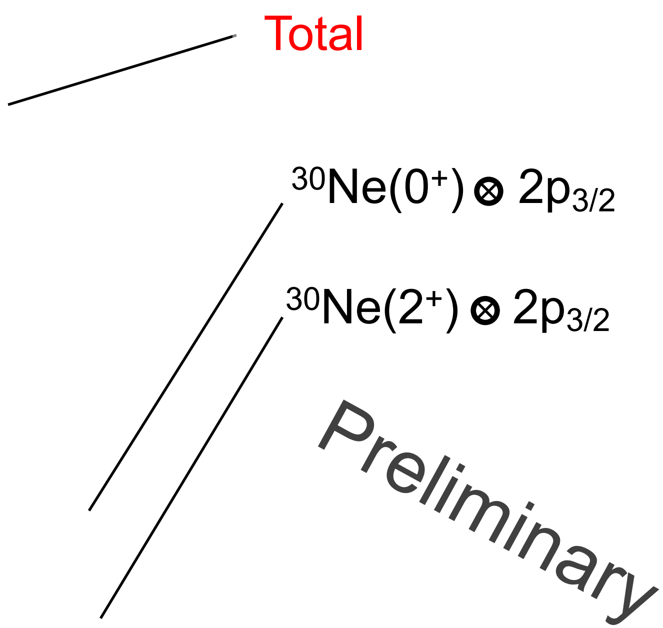
^{31}Ne + Pb → ^{30}Ne + γ + n



Lead target	Exclusive cross section (mb) (require n) Integral for E_{rel}=0-5MeV
^{31}Ne→^{30}Ne(total)	N.A.
^{31}Ne→^{30}Ne(2^+)	N.A.
^{31}Ne→^{30}Ne(0^+)	N.A.
Ratio(0^+ : 2^+)	N.A.

Coulomb breakup of ^{31}Ne: **Energy Spectrum**

Tomai et al.



(preliminary, statistical error only)

	S_n (MeV)	C^2S $^{30}Ne(0^+);3/2^-$	C^2S $^{30}Ne(2^+);3/2^-$
This work	N.A.	N.A.	N.A.
Prev. work[3]	$0.15^{+0.16}_{-0.10}$	$0.32^{+0.21}_{-0.17}$	---
SDPF-M[3]		0.21	0.34

Consistent with previous work

*TN, N. Kobayashi et al., PRL**112**, 142501 (2014)

- Fitted with 2 components

$$\alpha | ^{30}Ne(0^+) \otimes 2p_{3/2} > + \beta | ^{30}Ne(2^+) \otimes 2p_{3/2} >$$

← Fixed from γ-ray data

Main Halo Component Sub-Halo Component → **Doubly-component Halo**

$|^{30}Ne(0^+) \otimes 2p_{3/2}> : |^{30}Ne(2^+) \otimes 2p_{3/2}>$

→Correspondence with Nilsson/Particle-Rotor Model →Deformation Parameter?

c.f. Y.Urata, K.Hagino, H.Sagawa, PRC83, 041303(R) (2011).

Coulomb breakup of LLFP(Long-lived Fission Products) and neighboring nuclei for evaluating the (n,γ) reaction rates

^{93}Zr ($t_{1/2}$=1.61My)

S. Takeuchi,
TN et al.

Method: Applicable to r-process nuclei

革新的研究開発推進プログラム ImPACT
Impulsing Paradigm Change through Disruptive Technologies Program

This work research was funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

ImPACT Program by Cabinet office (2014 – 2018)   PM: R.Fujita

Reduction/Recycle of High-level Radioactive Wastes with Nuclear Transmutation

Goal : To propose a concept for the "separation and recovery" of LLFP from high level radioactive wastes with nuclear transmutation → "recycling" process.

Obtain Nuclear reaction data with new nuclear-reaction controlled methods

- Reaction Measurements at RIBF with fast secondary beams (E ~ 200*A* MeV)
  - (n,xn) neutron knockout reaction (Otsu et al.: RIKEN)
  - Fragmentation reaction (Watanabe et al., Kyushu U.)
  - **Coulomb Breakup (T. Nakamura, S. Takeuchi et al., Tokyo Tech)**
- OEDO (S. Shimoura, N. Imai, CNS)
  + Low Energy beam line (Yoshida, RIKEN)
- Muon (Matsuzaki, RIKEN)

Photo-absorption cross sections: σ_γ for ^{79,80}Se, ^{93,94}Zr

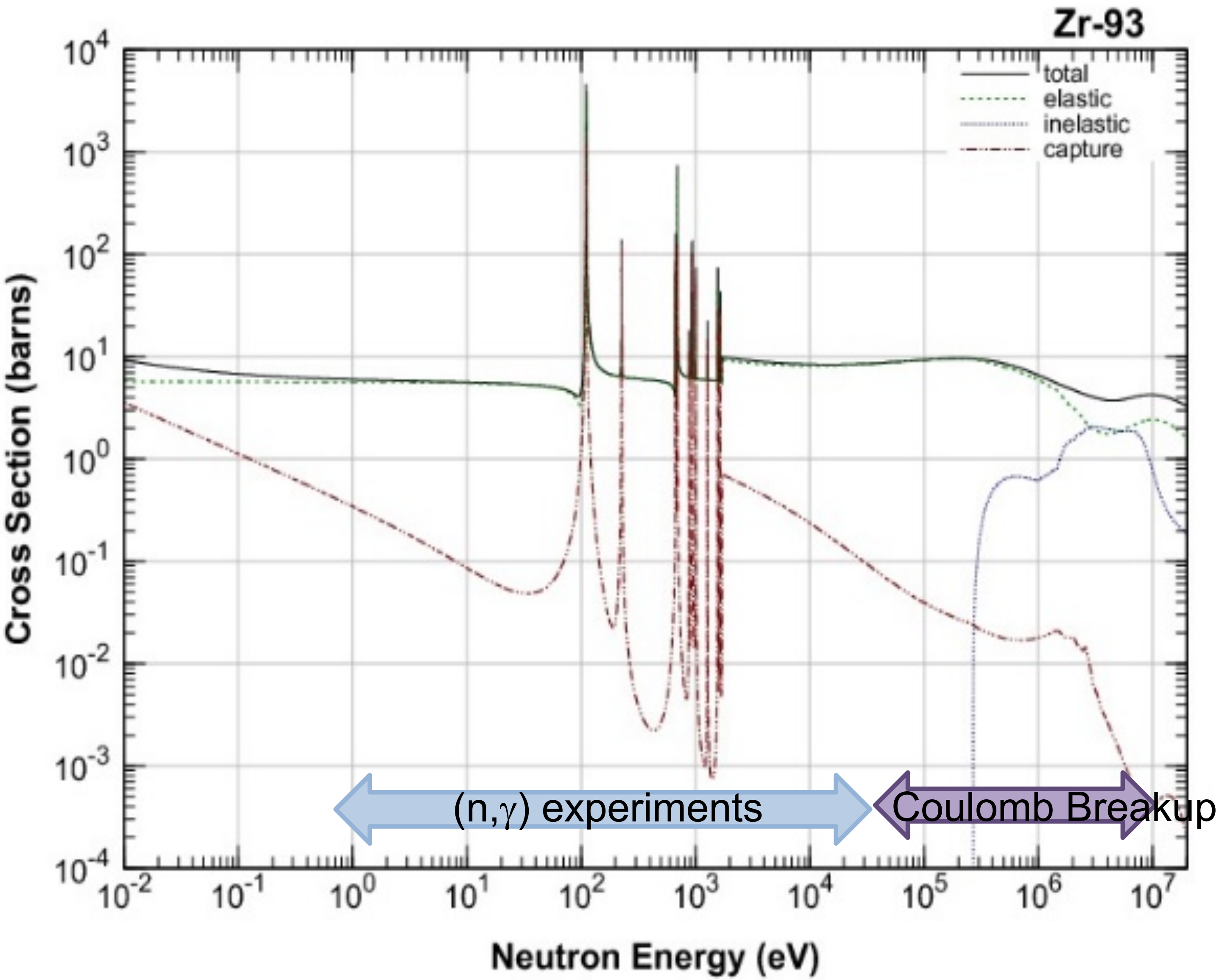
via (γ,n),(γ,xn) measurements in inverse kinematics

σ_γ + (Detailed balance) + Brink Axel hypothesis

→Neutron capture cross section $\boldsymbol{\sigma_{n\gamma}}$

Advantages:

- Applicable to Rare Isotopes
- Cross section can be extracted for each individual isotope
- Sensitive to low excitation energies owing to virtual photon spectrum.



Database JENDL4: Evaluation based on calculation

Extraction of (n,γ) cross section from $\sigma_{\gamma n}$

Hauser-Feshbach model

$$\sigma_{n\gamma} = \frac{\pi}{k_n^2} \sum_{J,\pi} g_J \frac{T_\gamma(E,J,\pi) T_n(E,J,\pi)}{T_{\text{tot}}},$$

$$T_\gamma(E,J,\pi) = \sum_{\nu,X,\lambda} T^{\nu}_{X\lambda}(\epsilon_\gamma) + \sum_{X,\lambda} \int T_{X\lambda}(\epsilon_\gamma)\rho(E-\epsilon_\gamma)d\epsilon_\gamma.$$

$$T_{X\lambda}(\epsilon) = 2\pi\epsilon_\gamma^{(2\lambda+1)} f_{X\lambda}(\epsilon_\gamma)\downarrow$$

Transmission Coefficient — γ strength function

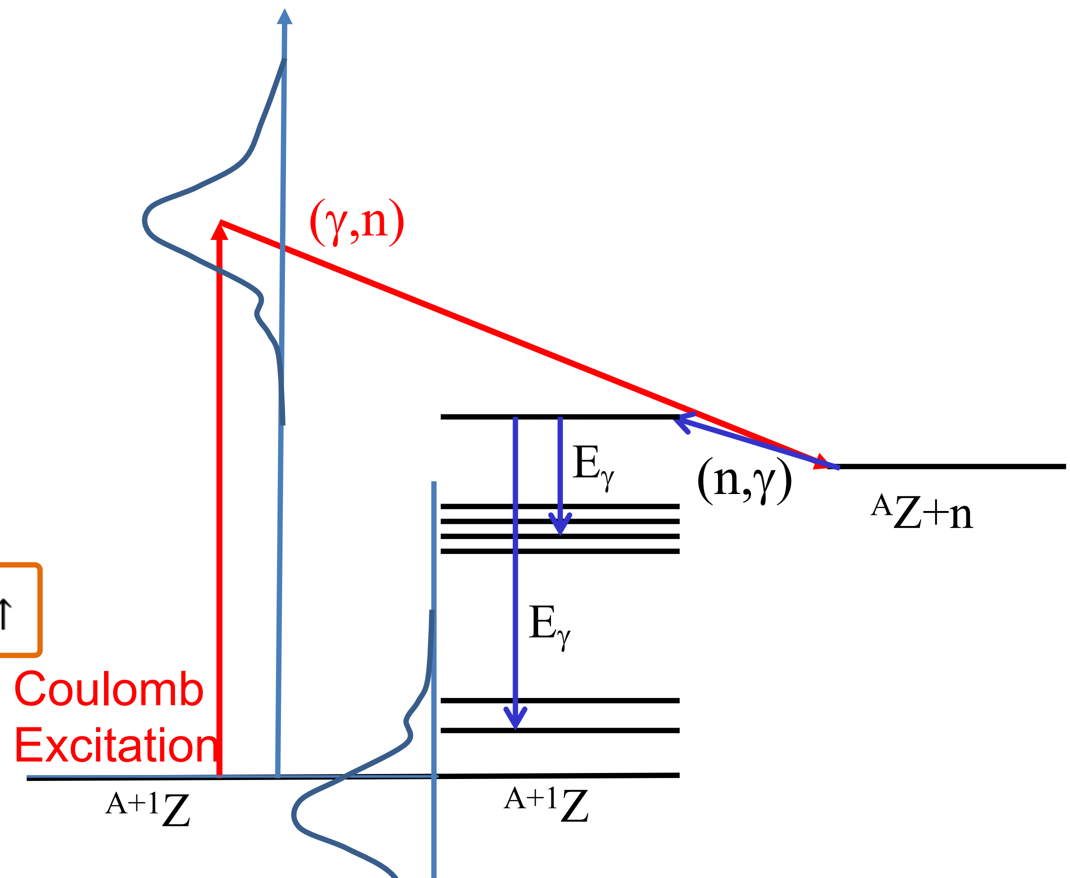
Brink Hypothesis

$$f_{X\lambda}(\epsilon_\gamma)\downarrow = f_{X\lambda}(\epsilon_\gamma)\uparrow$$

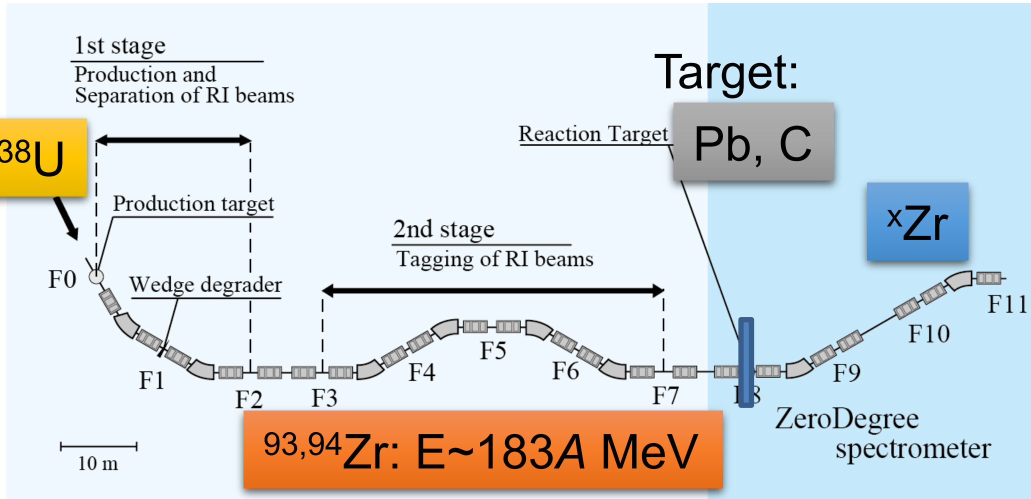
$$\sigma^{abs}_{X\lambda} = (\pi\hbar c)^2(2\lambda+1)\epsilon_\gamma^{2\lambda-1} f_{X\lambda}(\epsilon_\gamma)\uparrow$$

($\sigma_{\gamma n}$)

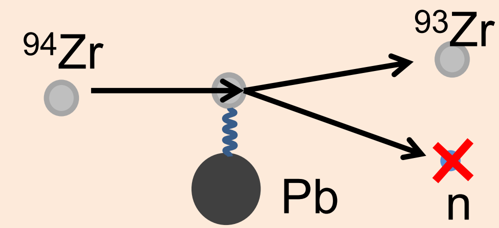
c.f.
H. Utsunomiya et al., PRC**82**, 064610 (2010).
T.K. Ericksen et al., PRC**90**, 044311 (2014).



Inclusive measurements of $^{93,94}Zr$

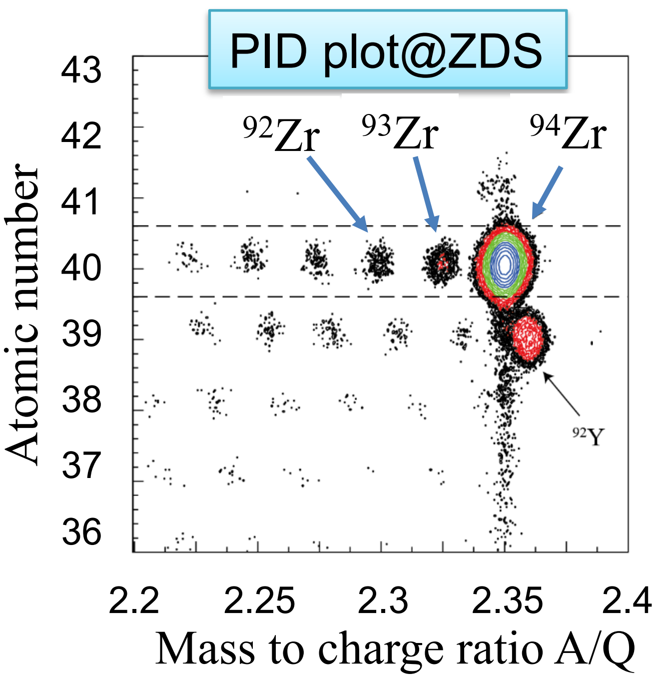


Inclusive measurement



Yield measurement of ^{93}Zr

→ **Integral cross section**



Integral Coulomb breakup cross sections

	-1n [mb]	-2n [mb]	Sum [mb]
^{93}Zr	N.A.	N.A.	N.A.
^{94}Zr	N.A.	N.A.	N.A.

Estimated cross section for ^{94}Zr

$$\sigma_{CB} = \int \frac{N_{E1}(E_x)}{E_x} \sigma_{\gamma}^{E1}(E_x) dE_x$$

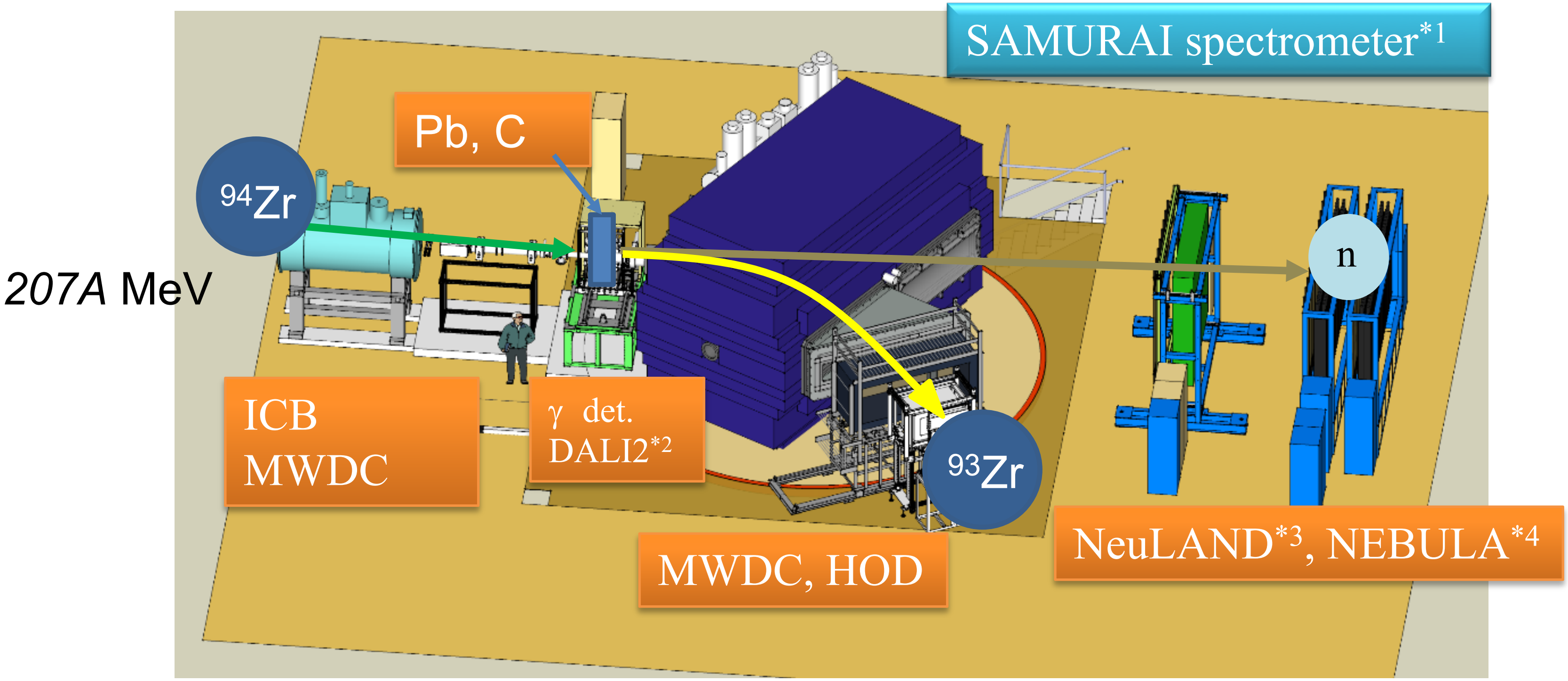
RIPL3*1 388 [mb]
Berman*2 317 [mb]

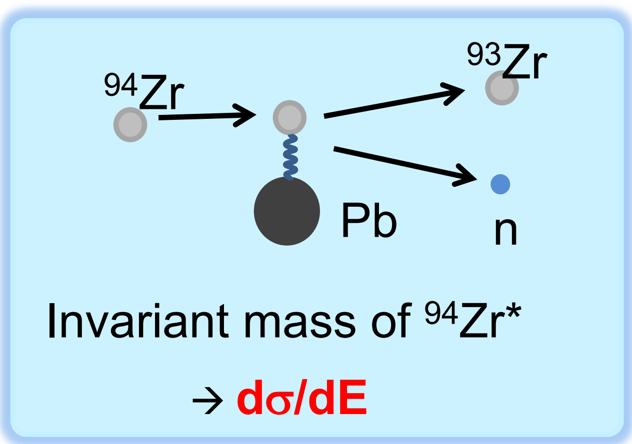
- Confirmation of method by comparing with known data
- Small enhancement of cross section → PDR/GQR

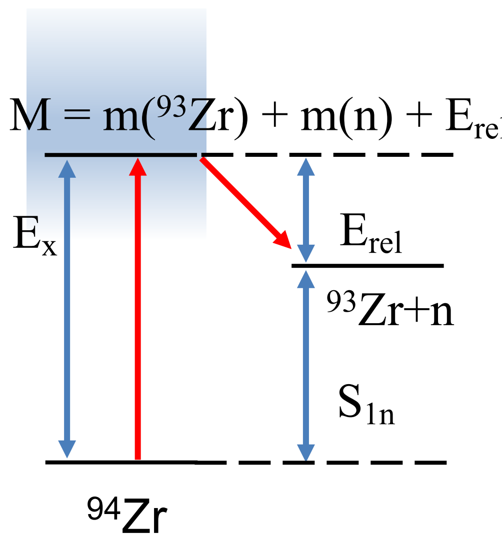
Submitted to PTEP (S.Takeuchi et al.)

*1 R. Capote et al., Nucl. Data Sheets 110, 3107 (2009) (evaluation) *2 Berman et al., Phys. Rev. 162,1098(1967)(exp.)

Coulomb Breakup of ^{79,80}Se and ^{93,94}Zr (Exclusive)







Coincidence measurements

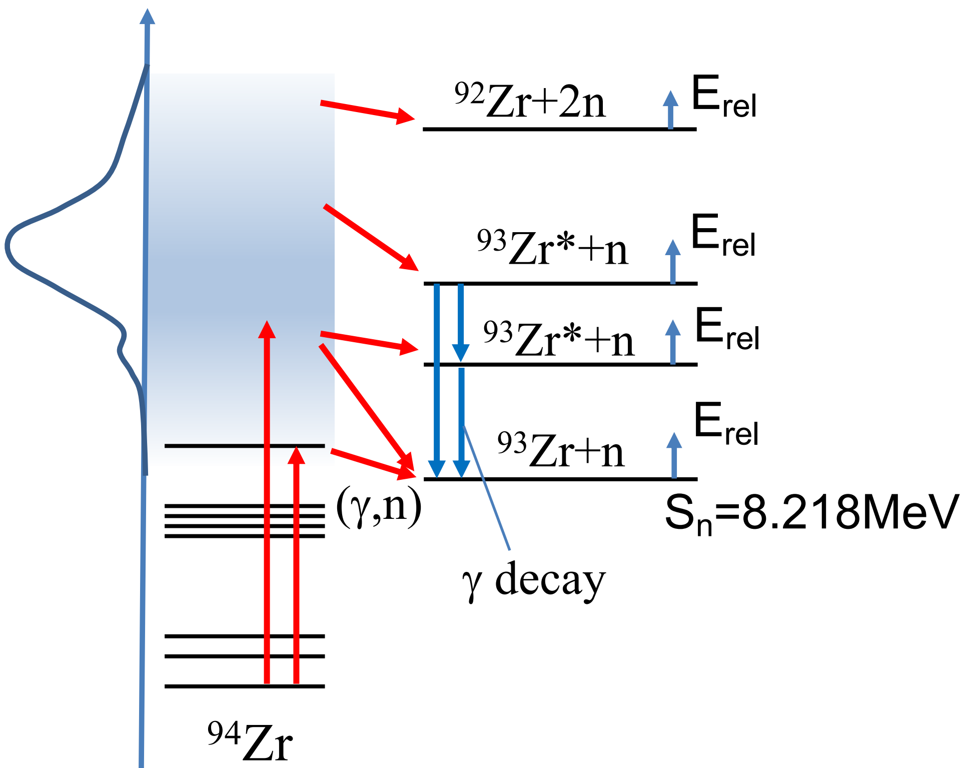
- beam PID
- momentum: $\boldsymbol{p}(^{93}\mathrm{Zr})$, $\boldsymbol{p}(\mathrm{n})$
- γ rays

@SAMURAI spectrometer

→Invariant mass M (or E_{rel}).

Results of Coulomb breakup of ^{94}Zr (exclusive)

Coincidence measurements of momentum vectors and de-excitation γ rays
→ Relative energy spectrum and γ-ray energy spectrum



Relative energy

Preliminary

E_{rel}(^{93}Zr + n) [MeV]

γ-ray energy

Events decaying from high excited states and its de-excitation γ-rays were observed.
→ Statistical decay

Preliminary

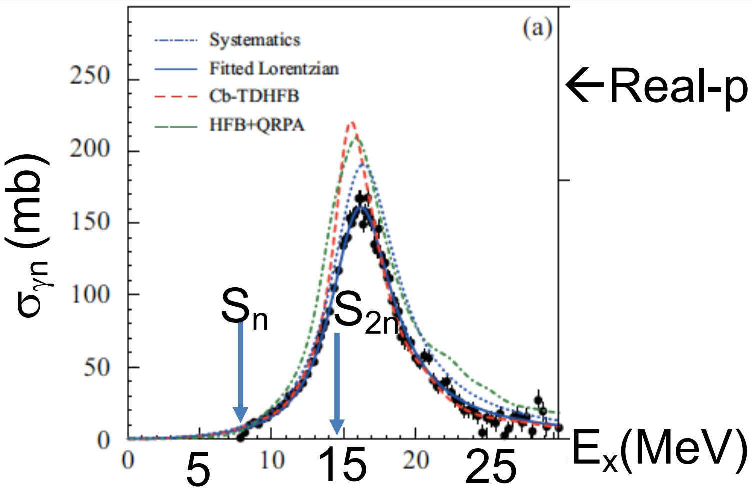
Analyze spectra with statistical decay model (TALYS http://www.talys.eu/home/)

E_γ [keV]

Response function and photo-absorption cross section of ^{94}Zr

Photo-absorption cross section of ^{94}Zr: Known.
*1. B.L.Berman et al., Phys. Rev. 162, 1098 (1967)

Proof-of-principle



Response function by Talys + GEANT4

Input-1: Level density

Back-shifted Fermi Gas model

Input-2: Photo-absorption cross section

Standard Lorentzian model (SLO)*1

^{94}Zr: GDR parameters from real-photon data*1

*1. R. Capote et al., Nucl. Data Sheets **110**, 3107 (2009).

→ *$d\sigma/dE_{rel}$*: Fit with Response functions

CB cross section: σ_{CB} = 412.1(98) mb

c.f. σ_{CB} (Berman's)= 356.7 mb

→ **Enhancement Observed**

Present Work

total
statistical
direct

Preliminary

Erel(^{93}Zr + n) [MeV]

total
de-excitation γ
atomic b.g.
target ex.

Preliminary

E_γ [keV]

Todo

➢Extract $d\sigma/dE_{rel}$ for $2n+{}^{92}Zr$ channel

➢Examine PDR/GQR response
c.f. W.Horiuchi et al., PRC 96, 024605 (2017).

➢Analysis of $d\sigma/dE_{rel}$ by response functions with statistical decay (TALYS)

→Extraction of $\sigma_{n,\gamma}$
using Brink Axel Hypothesis

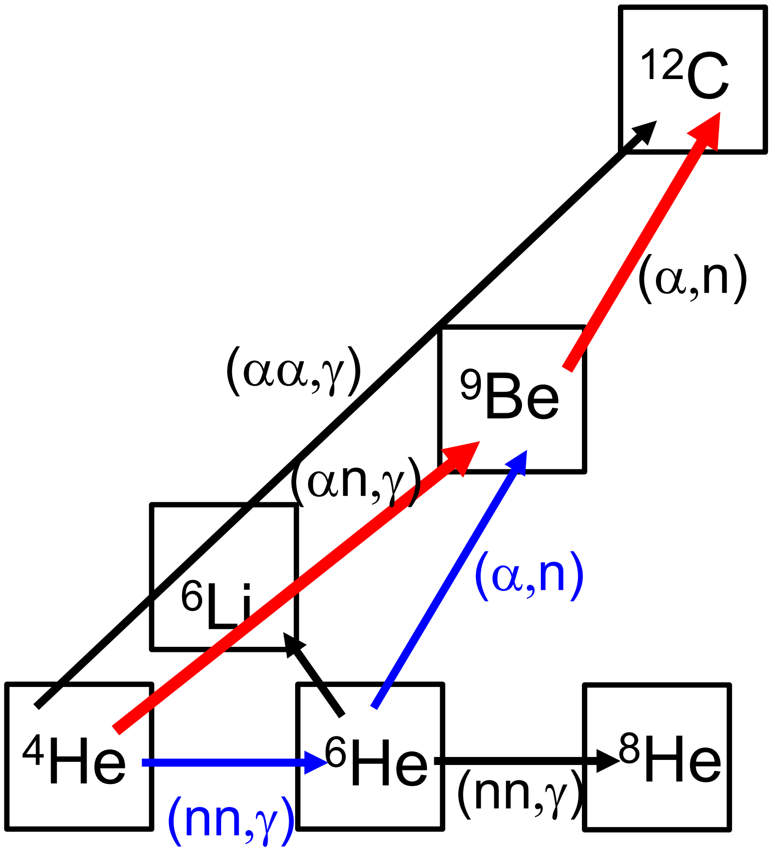
Issues

- $\sigma_{\gamma,n}$: Cascade of γ-rays from daughter nuclei
  → Use of Statistical Model (TALYS)
- Brink Axel Hypothesis
- Estimation of Nuclear Level Densities (NLD)

- Coulomb breakup of 2n halo nuclei

Direct "dineutron" capture?

$^{4}He+2n \rightarrow {}^{6}He+\gamma$



N-rich environment
(n-star/supernova):

$^{4}He(\alpha n,\gamma)^{9}Be(\alpha,n)^{12}C$

$\gg {}^{4}He(nn,\gamma)^{6}He(\alpha,n)^{9}Be(\alpha,n)^{12}C$

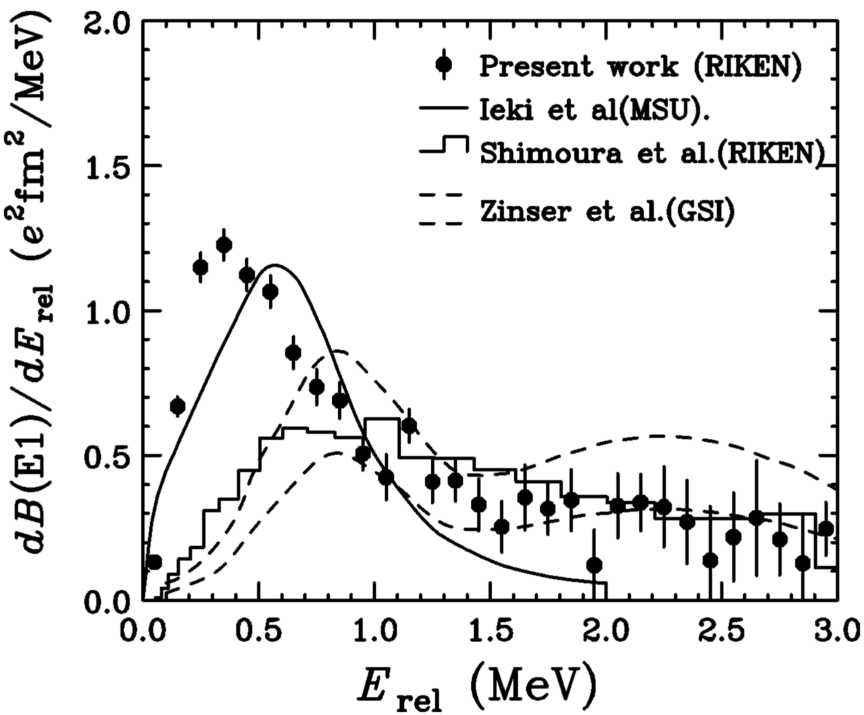
$^{4}He(n,\gamma)^{5}He(3/2^{-})(n,\gamma(E1))^{6}He$: Enhanced ($\sim 10^{3}$)
But still negligible compared to $^{4}He(\alpha n,\gamma)^{9}Be$…
V.D.Efros et al., Z.Phys.A355,101(1996).

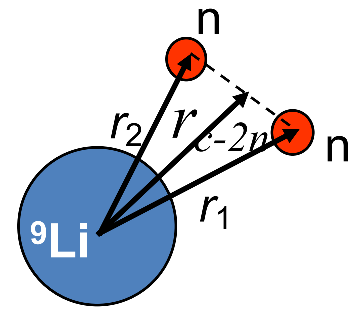
Can we revisit this issue with revised data and theories?

→ Coulomb Breakup of ^{6}He

Coulomb Breakup of 2n Halo
→ Probe of Dineutron Correlation

^{11}Li T.Nakamura et al. PRL96,252502(2006).





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

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

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

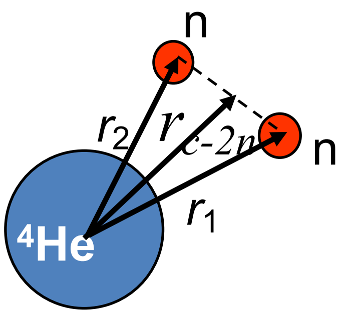
$$\rightarrow 1.78(22)\, e^2 fm^2 \rightarrow \langle \theta_{12} \rangle = 48^{+14}_{-18}\ \mathrm{deg}.$$

Correlation in the Ground State of ^{11}Li

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

^{6}He Sun Yelei, TN et al. in preparation

69 MeV/nucleon
RIPS @RIKEN



Preliminary

T.Aumann et al., PRC59, 1252 (1999).

CSLS: Y.Kikuchi et al., PRC81, 044308 (2010)

HHX1.25: B.Danilin, I. Thompson, J.Vaagen, M.Zhukov NPA632, 383 (1998).

Detailed theoretical analysis with Matsumoto/Ogata is in progress.

Summary and Outlook

- Coulomb breakup for evaluating neutron capture reaction rate
  - ✓ Useful Method to Evaluate (n,γ) reaction rates
- **Coulom breakup of ^{15}C –Simple example**
  - ✓ Simple case → Negligible contribution from ^{15}C excited states for the inverse (n,γ) reaction
  - →Succeeded in extracting (n,γ) cross sections.
- **Coulomb Breakup of Island-of-inversion nucleus ^{31}Ne**
  - ✓ Simple case: Coulomb Breakup of p-wave halo
  - → Could be used to evaluate ^{30}Ne(n,γ)
- **Coulomb Breakup of LLFP and neighboring nuclei for evaluating the (n,γ) reaction rates**
  - ✓ Experiments: Successful→ E_{rel}(n+HI), γ spectra obtained
  - ➢ Analysis of 2n+fragment channel
  - ➢ Evaluation of (n,γ) using Axcel Brink Hypothesis.
- **Coulomb Breakup of 2n Halo nuclei** 2n capture?

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