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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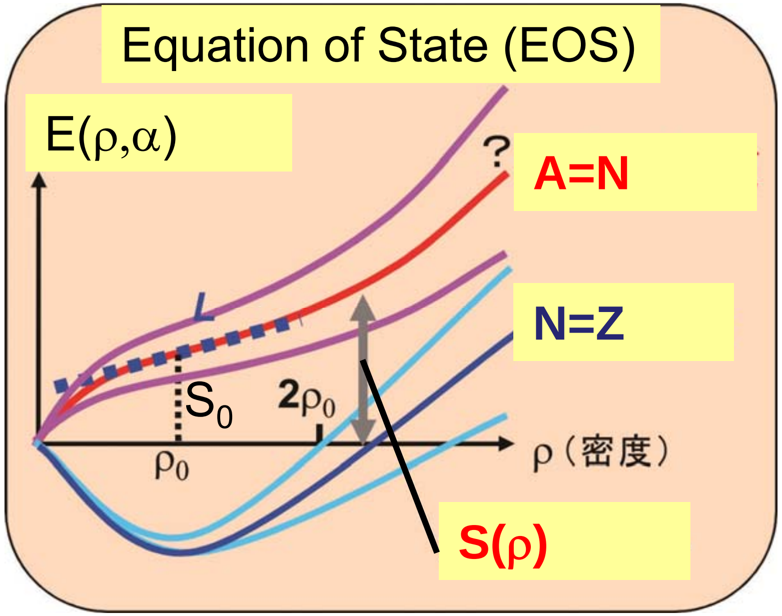
寺西高　九大

実験と観測で解き明かす中性子星の核物質
23-25 Sep., 2014, @Atagawa

EOS of Nuclear Matter



Difference of n and p densities

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

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

Symmetry Energy: S(ρ)

Neutron-rich Nuclei :Microscopic Laboratory for Neutron Star

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

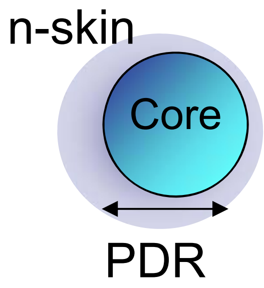
at Extreme Conditions (not like normal N~Z nuclei)

-- 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

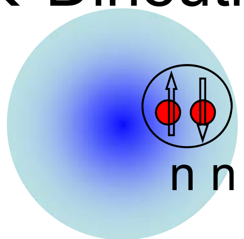


Pygmy Dipole Resonance (E1)

Breathing Mode (E0)

Y.Togano, 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

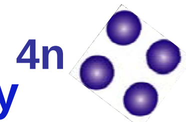
Done at SAMURAI, 2012.
Analysis is in progress

Study of Deformed Driven Halos: ^{31}Ne, ^{37}Mg

□ S(ρ)←Nuclear force

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

← tetra neutron, exotic nucleonic system



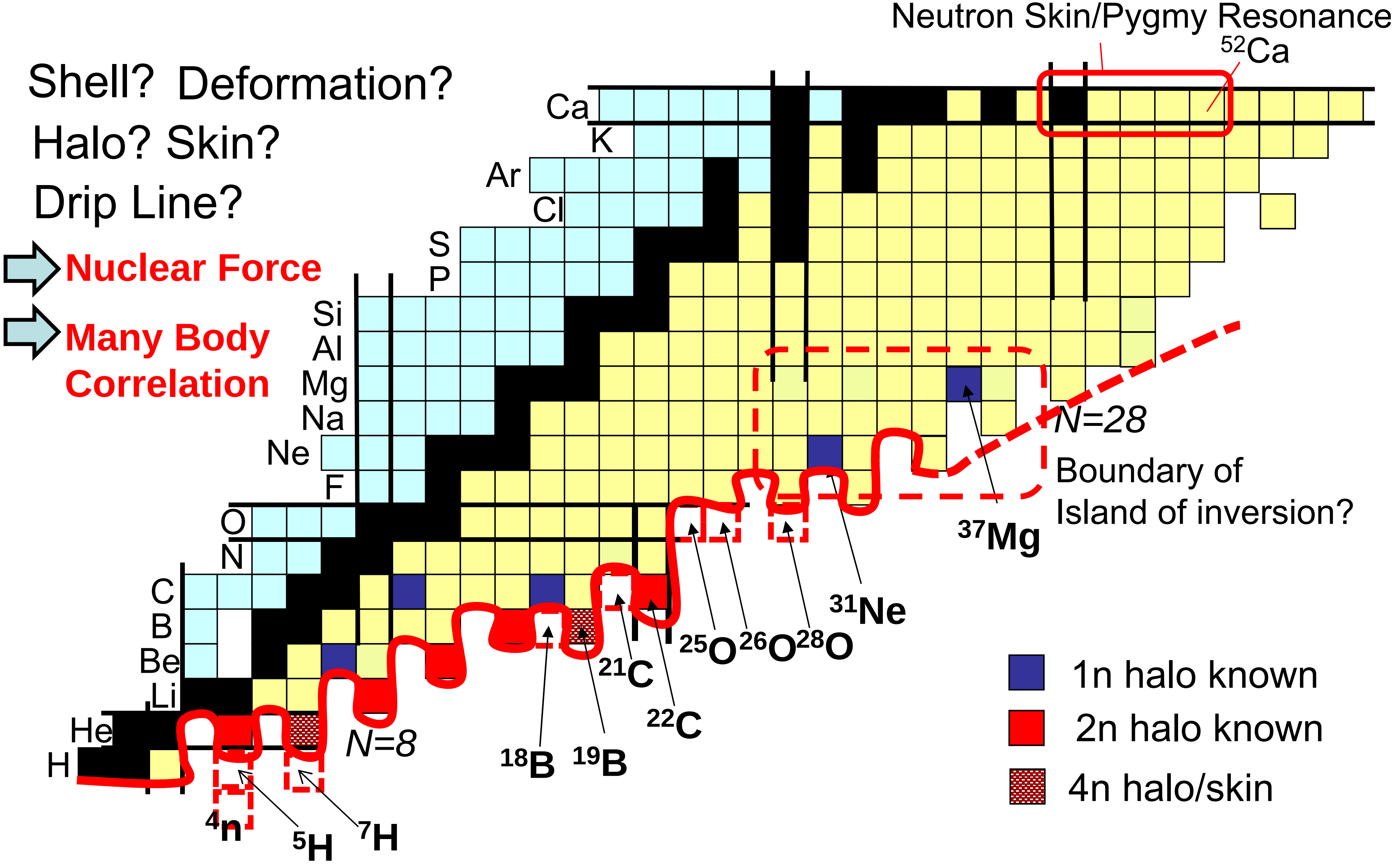
26, 28O

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

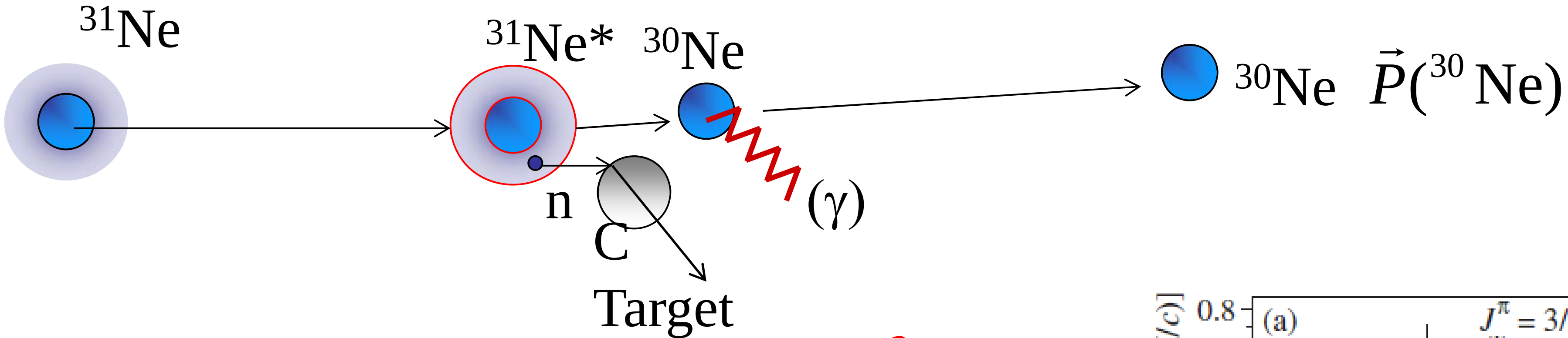
← neutron skin thickness(**Tamii,Togano**),masses (**Yamaguchi**)

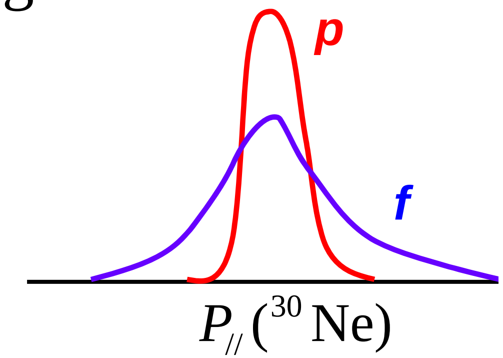
Evolution Towards the Stability Limit

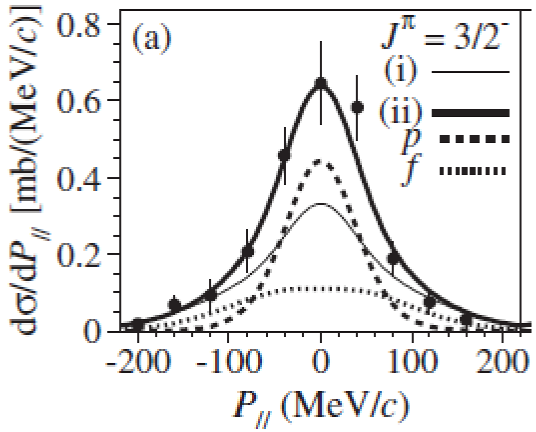


Probe-1: Nuclear Breakup

→e.g. 1n knockout reaction of ^{31}Ne (TN et al. , PRL**112**,142501 (2014).)





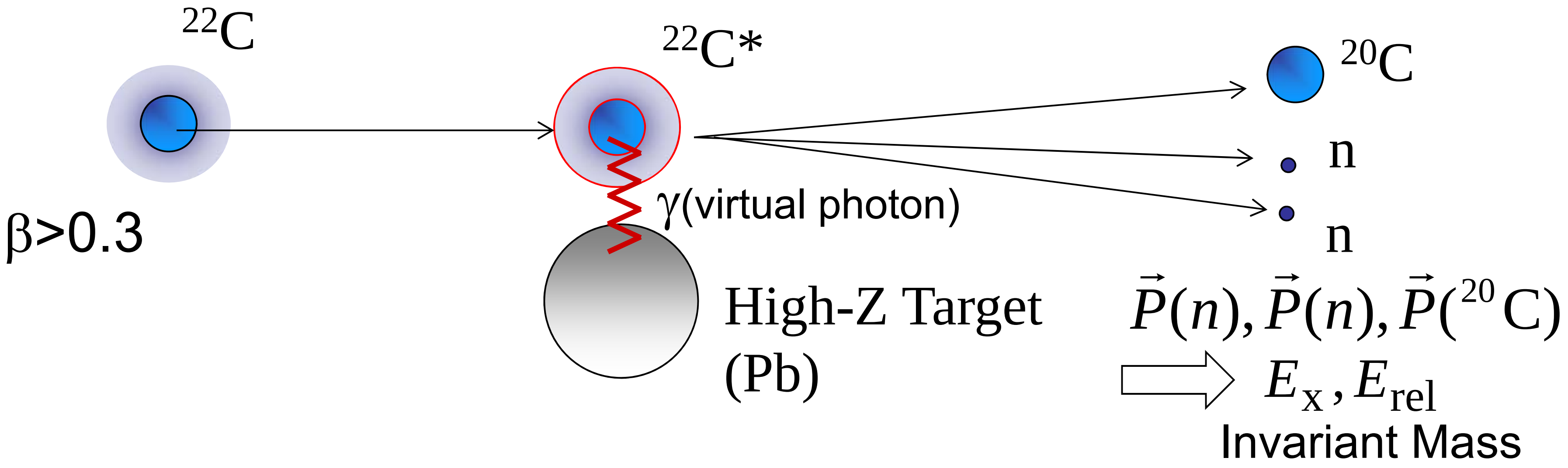


- γ ray in coincidence → ^{30}Ne(2^+) / ^{30}Ne(0^+) Contribution
- σ_{-1n} and $P_{//}$ distribution → ℓ of valence n, configuration

Theory: Eikonal Approximation

Probe-2: **Coulomb Breakup**

→ E1(Electric Diplole) Rresponse→**Soft E1**(Halo),**Pygmy Dipole**(Skin)

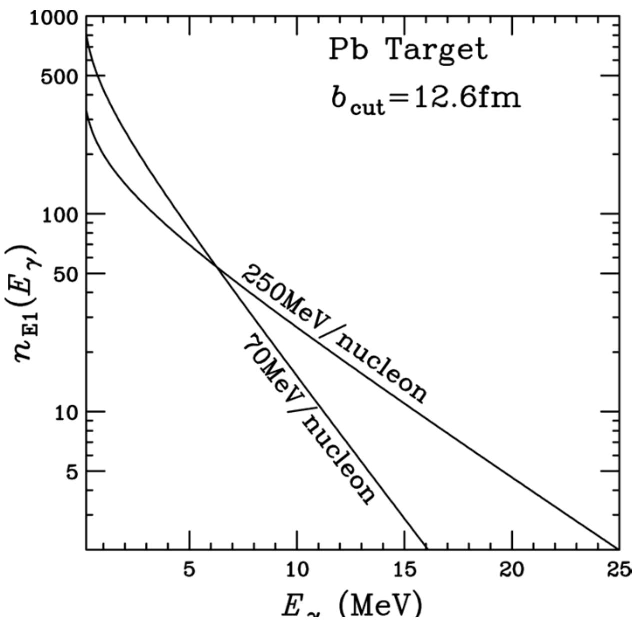


Equivalent Photon Method

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

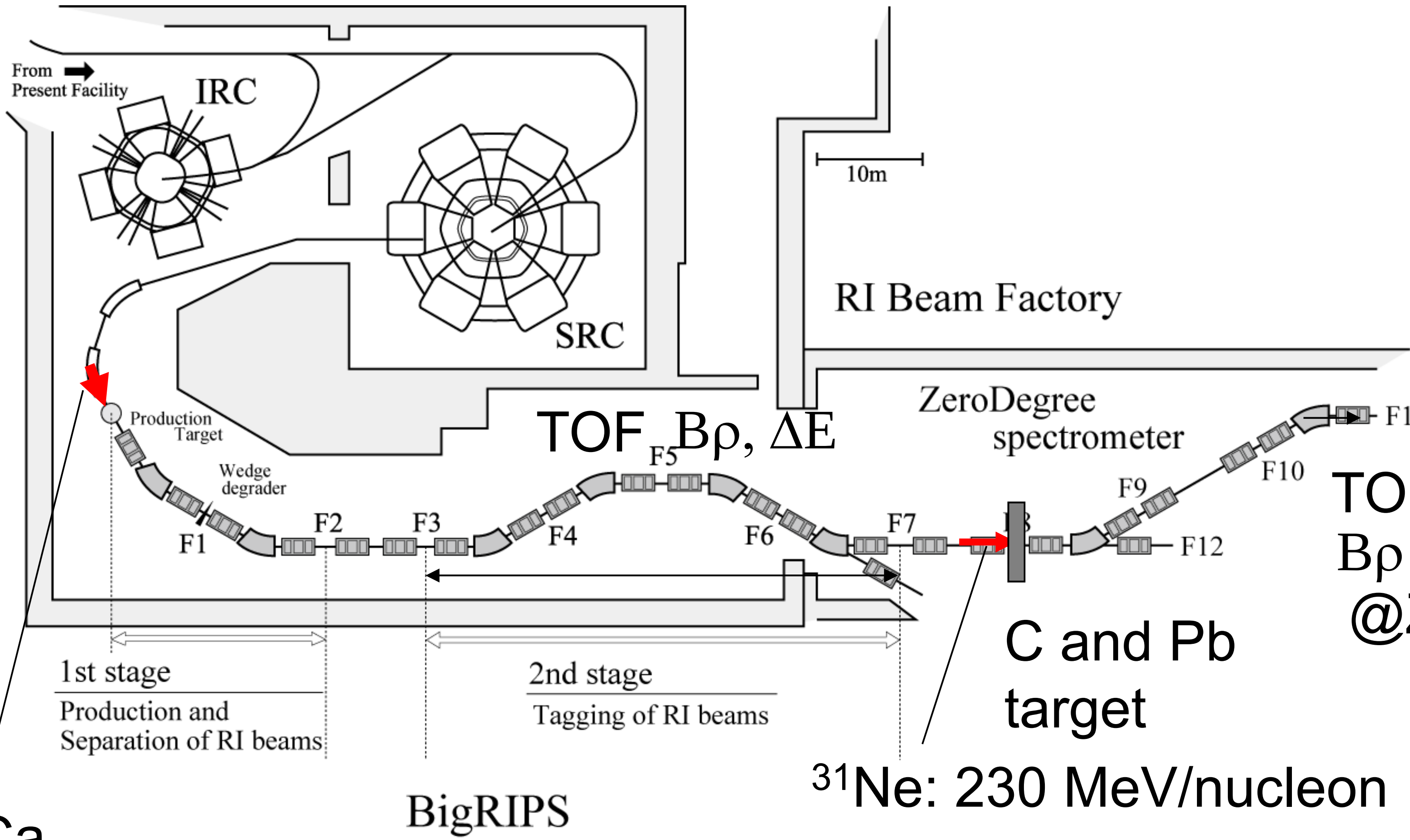
Cross section = (Photon Number)x(Transition Probability)

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



Inclusive Coulomb/Nuclear Breakup of ^{31}Ne/^{37}Mg

N.Kobayashi, TN et al.



TOF,ΔE
Bρ
@ZDS

C and Pb target

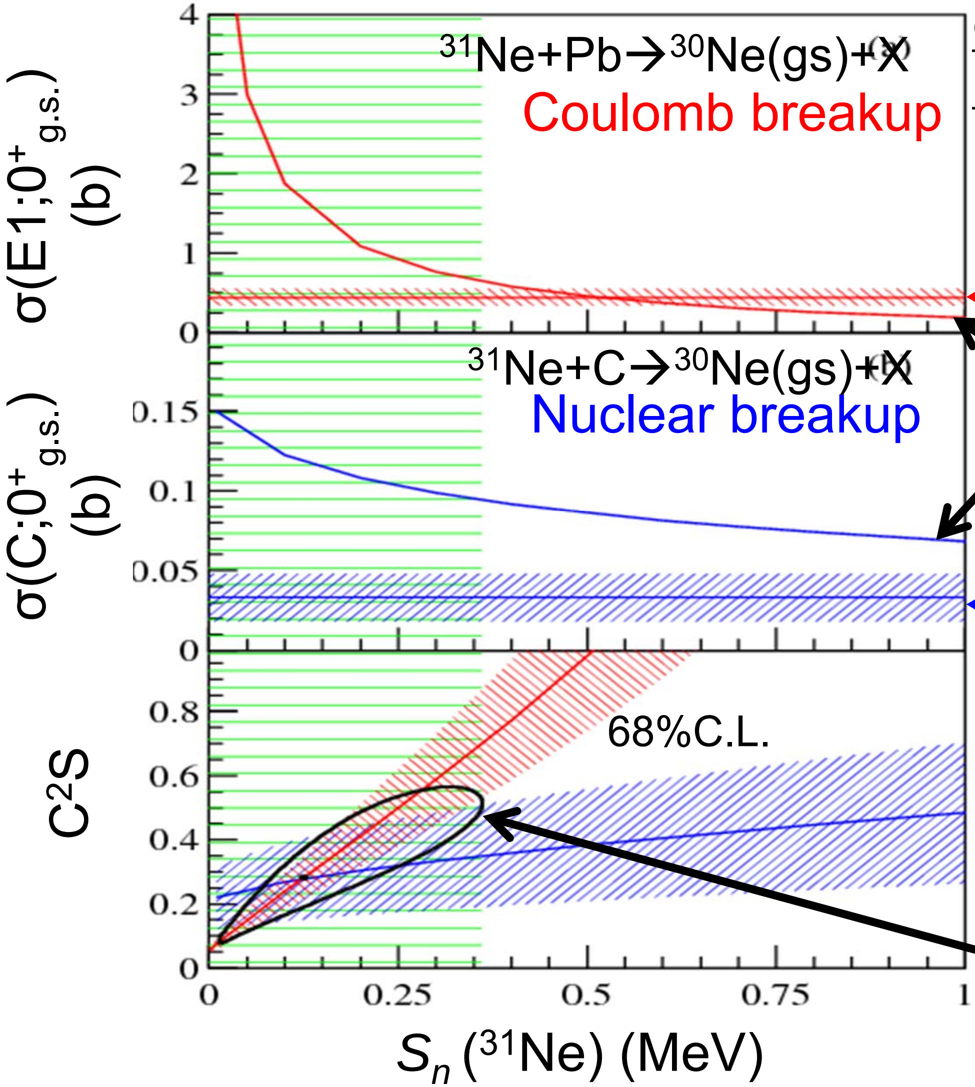
^{48}Ca 345MeV/nucleon

^{31}Ne: 230 MeV/nucleon

^{37}Mg: 240 MeV/nucleon

Spectroscopic factor (C^2S) & Separation energy (S_n) of ^{31}Ne

^{31}Ne($3/2^-$) : ^{30}Ne(0_1^+) $\otimes 1p_{3/2}$



Only one configuration can couple with 0^+
→ isolate C^2S and S_n

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

Theoretical calculations for
$|^{31}\mathrm{Ne}_{g.s.}\rangle = |^{30}\mathrm{Ne}(0^+_{g.s.}) \otimes p_{3/2}\rangle$

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

S_n (^{31}Ne)=-0.06(0.42) MeV
L.Gaudefroy et al.,
PRL109,202503(2012)

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

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

Results on 1n Halo:

PRL **112,** 142501 (2014) PHYSICAL REVIEW LETTERS week ending 11 APRIL 2014

Deformation-Driven *p*-Wave Halos at the Drip Line: ^{31}Ne

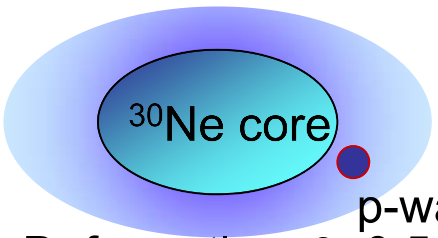
T. Nakamura,[1] N. Kobayashi,[1] Y. Kondo,[1] Y. Satou,[1,2] J. A. Tostevin,[3] Y. Utsuno,[4] N. Aoi,[5] H. Baba,[5] N. Fukuda,[5] J. Gibelin,[6] N. Inabe,[5] M. Ishihara,[5] D. Kameda,[5] T. Kubo,[5] T. Motobayashi,[5] T. Ohnishi,[5] N. A. Orr,[6] H. Otsu,[5] T. Otsuka,[7] H. Sakurai,[5] T. Sumikama,[8] H. Takeda,[5] E. Takeshita,[5] M. Takechi,[5] S. Takeuchi,[5] Y. Togano,[1,5] and K. Yoneda[5]

PRL **112,** 242501 (2014) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2014

Observation of a *p*-Wave One-Neutron Halo Configuration in ^{37}Mg

N. Kobayashi,[1,*] T. Nakamura,[1] Y. Kondo,[1] J. A. Tostevin,[2,1] Y. Utsuno,[3] N. Aoi,[4,†] H. Baba,[4] R. Barthelemy,[5] M. A. Famiano,[5] N. Fukuda,[4] N. Inabe,[4] M. Ishihara,[4] R. Kanungo,[6] S. Kim,[7] T. Kubo,[4] G. S. Lee,[1] H. S. Lee,[7] M. Matsushita,[4,‡] T. Motobayashi,[4] T. Ohnishi,[4] N. A. Orr,[8] H. Otsu,[4] T. Otsuka,[9] T. Sako,[1] H. Sakurai,[4] Y. Satou,[7] T. Sumikama,[10,§] H. Takeda,[4] S. Takeuchi,[4] R. Tanaka,[1] Y. Togano,[4,¶] and K. Yoneda[4]

^{31}Ne



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

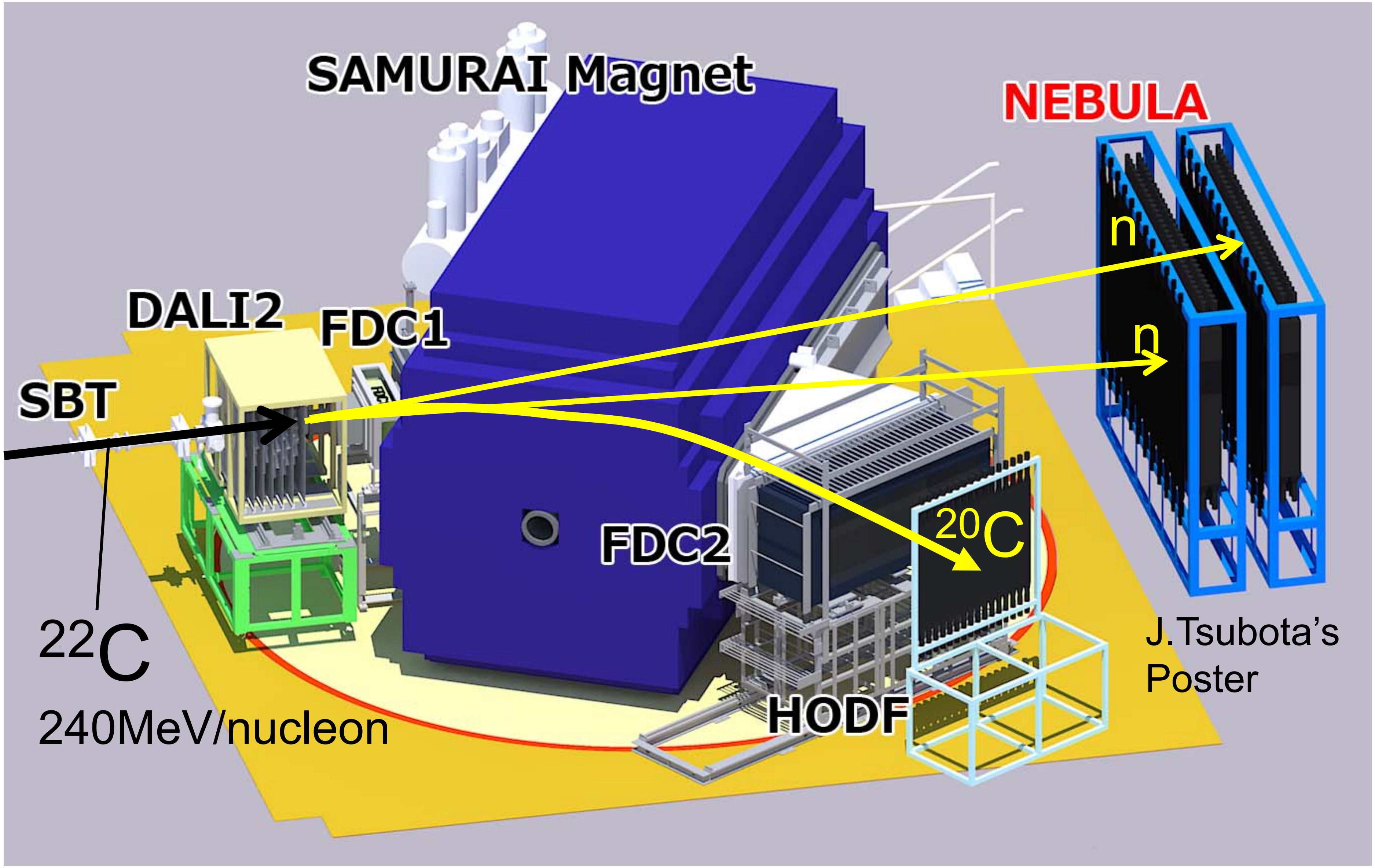
p-wave halo neutron

Deformation β~0.5 (~ 3:2)

Coulomb/nuclear breakup cross sections→p-wave 30%→Deformed and Halo

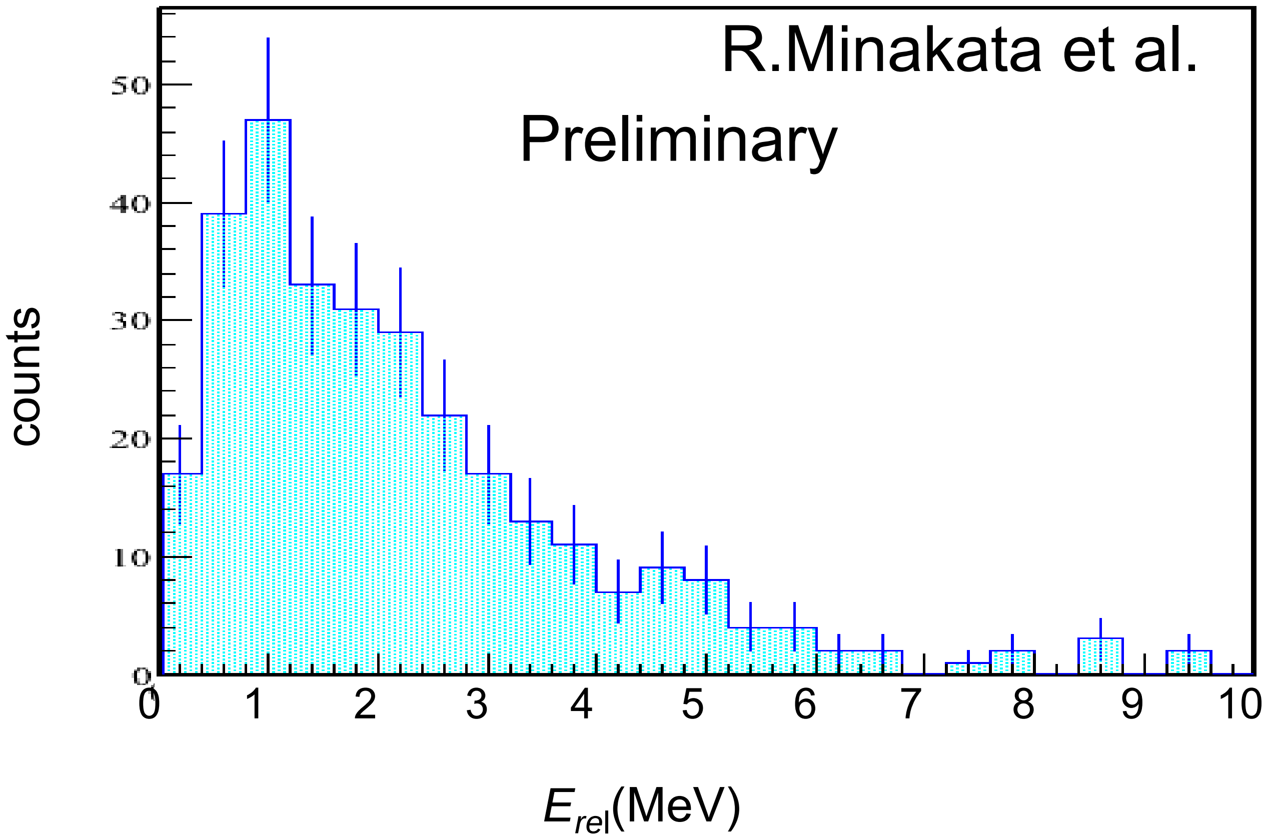
Strongly deformed although it is N=21 (20+1)

Exclusive Coulomb Breakup of ^{22}C, ^{19}B



Coulomb Breakup of ^{22}C

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



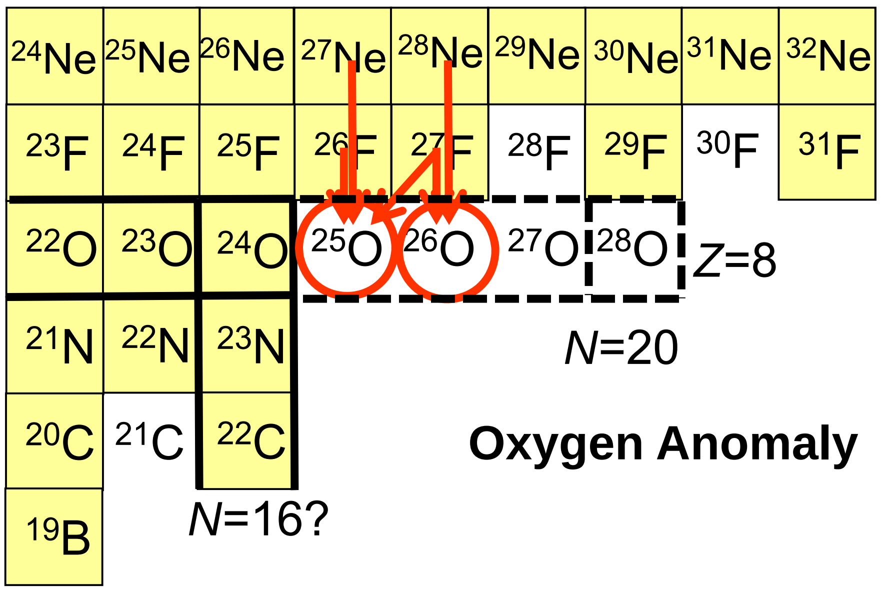
Strong Soft E1 → Halo

(Preliminary value: ~0.9b) Dineutron Correlation?

Study of unbound nuclei ^{25}O and ^{26}O

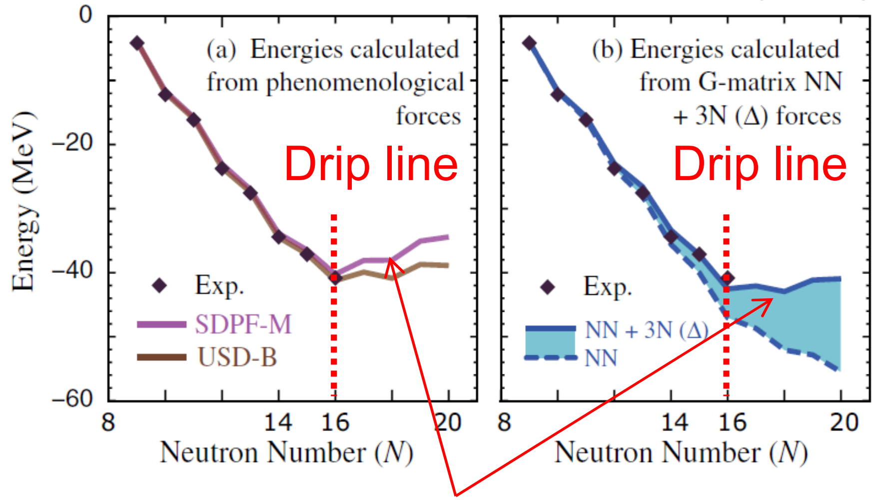
Spokesperson Yosuke Kondo

Experimental study of *unbound* oxygen isotopes towards the possible *double magic nucleus* ^{28}O



Oxygen Anomaly

T. Otsuka et al., PRL105, 032501 (2010)

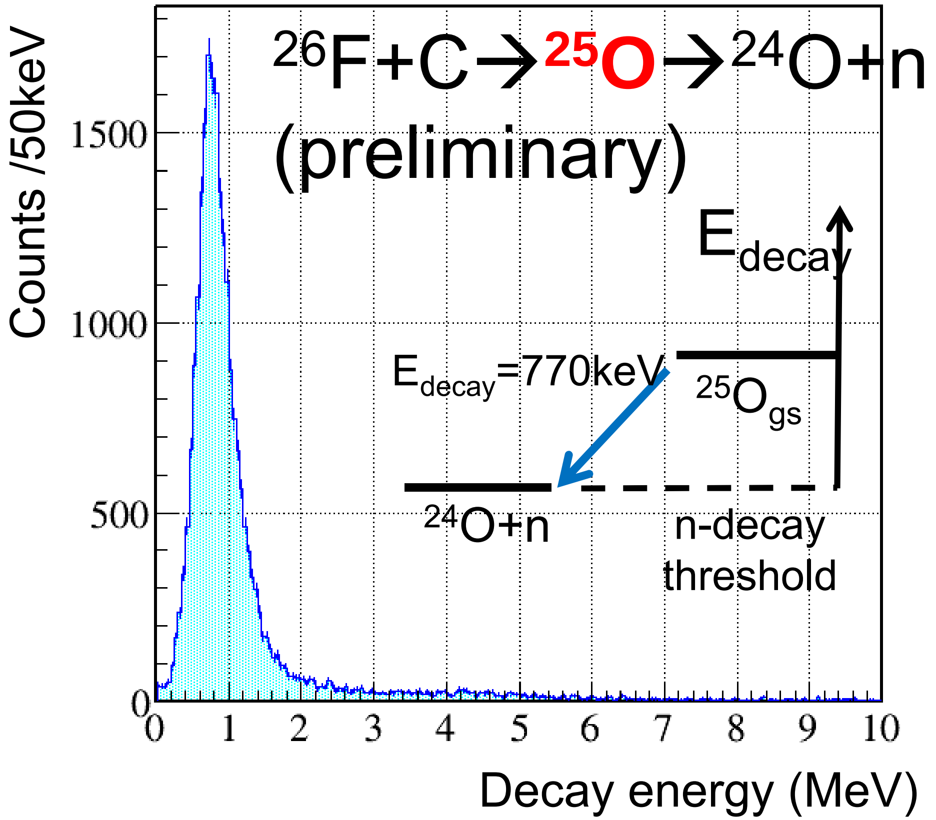


The effect is large at N>16

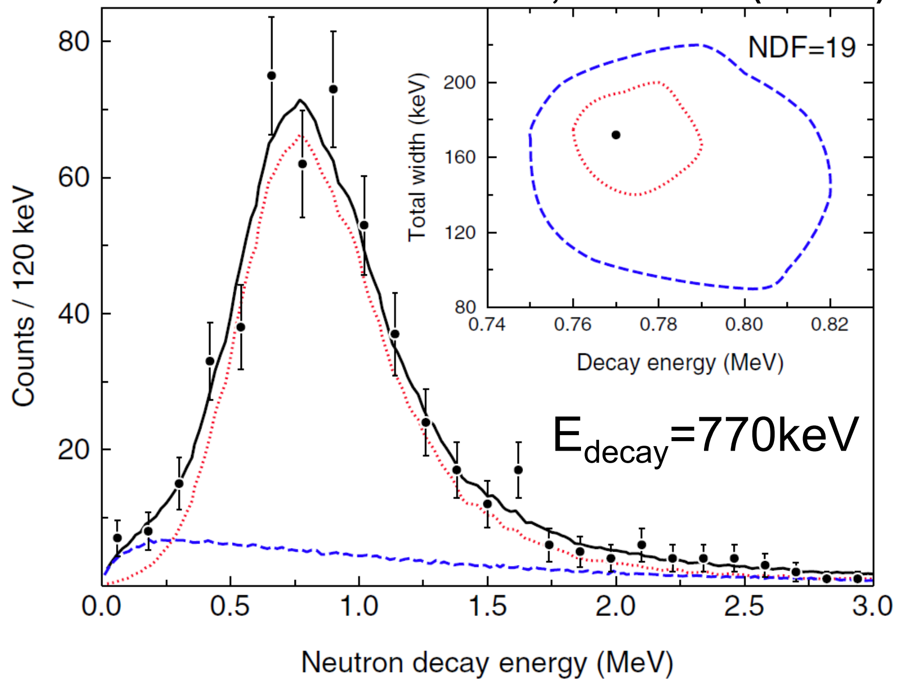
G. Hagen et al., PRL108, 242501(2012).
H. Hergert et al.,, PRL110, 242501(2013).

Slide by Kondo

Decay energy spectrum ($^{26}F+C \rightarrow {}^{25}O \rightarrow {}^{24}O+n$)



C.R.Hoffman et al., PRL100, 152502 (2008)



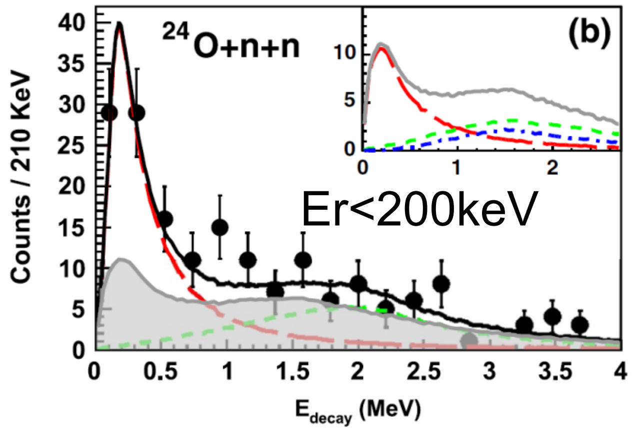
<u>50 times higher statistics!</u>

Different decay channel ($^{25}O \rightarrow {}^{23}O+2n$) can be studied

Decay energy spectrum ($^{27}F+C \rightarrow ^{26}O \rightarrow ^{24}O+2n$)

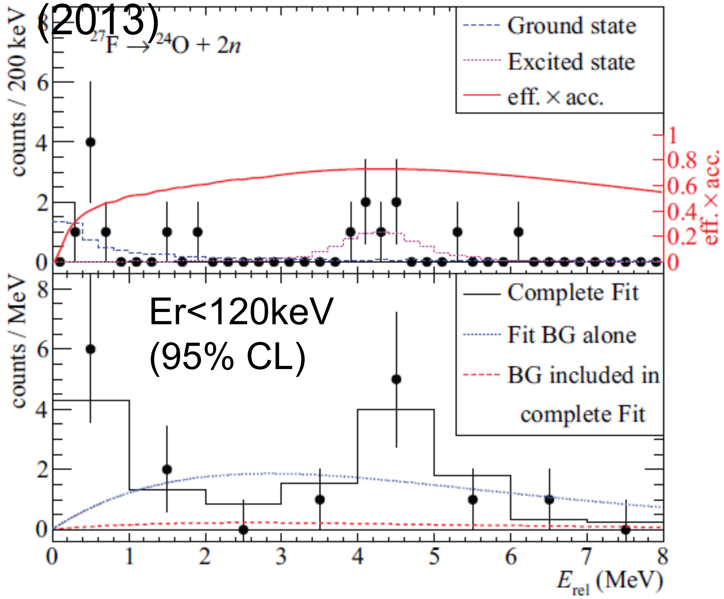
E. Lunderberg et al.PRL108, 142503 (2012)

Y.Kondo et al.



Preliminary data

C. Caesar et al.PRC88, 034313 (2013)



Ground state

- 5 times higher statistics
- →better determination of energy

Excited state at ~1.3MeV

- First observation, Most probably 2^+
- No peak at ~4.2MeV

Summary

- Inclusive Coulomb/Nuclear Breakup

→ Deformed driven Halo in ^{31}Ne, ^{37}Mg (N.Kobayashi et al.)

PRL112,142501(2014), PRL112,242501(2014).

- Exclusive Coulomb breakup of ^{22}C/^{19}B

→ 2n correlation -- Analysis in Progress

- Production of unbound nuclei ^{25}O,^{26}O

→Observation of 1st excited state of ^{26}O →3N force

- ^{28}O (Doubly magic? ^{24}O+4n) – Planned in 2015

With NeuLAND (n-detector, GSI) and MINOS (H-target, SACLAY)

- Tetra neutron → S.Shimoura's talk, Pygmy→Togano's talk, Inakura's talk

E. Lunderberg et al.PRL108, 142503 (2012)

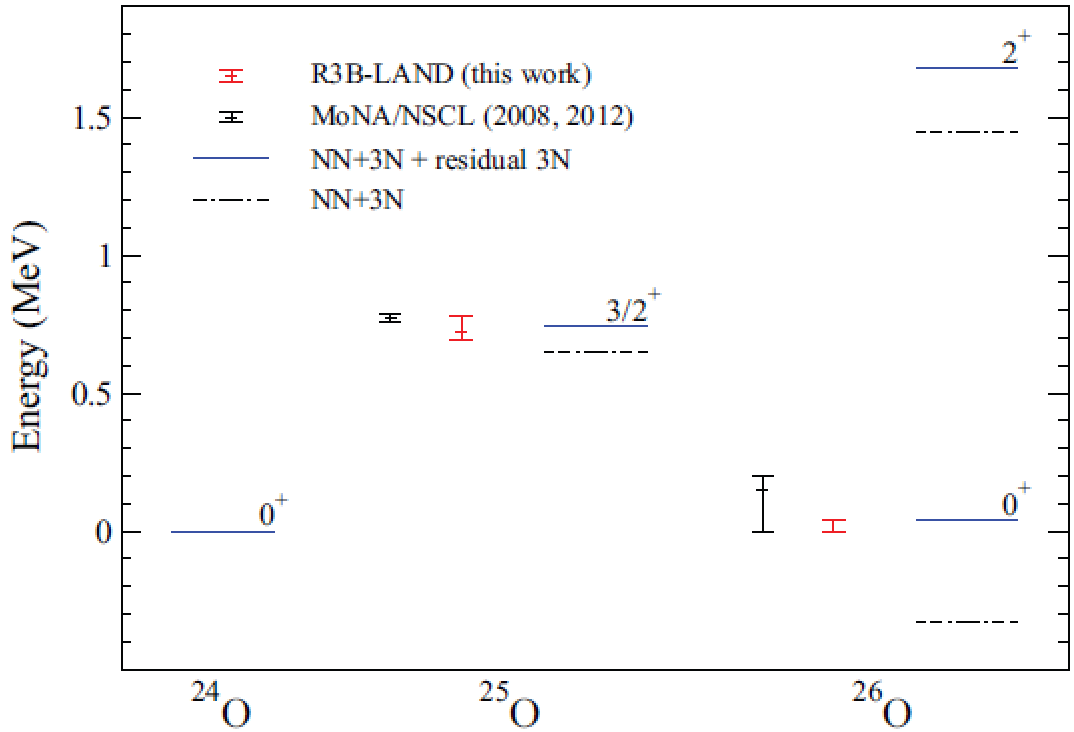


FIG. 8. (Color online) Comparison of the experimental ^{25}O and ^{26}O energies with theoretical shell-model calculations based on chiral NN and $3N$ forces ($NN + 3N$) and including residual $3N$ forces. Note that the contribution from residual $3N$ forces is 0.1 MeV in ^{24}O. The data labeled as MoNA/NSCL are from Refs. [6,13].

→ Constraint on Theories on 3-body Force