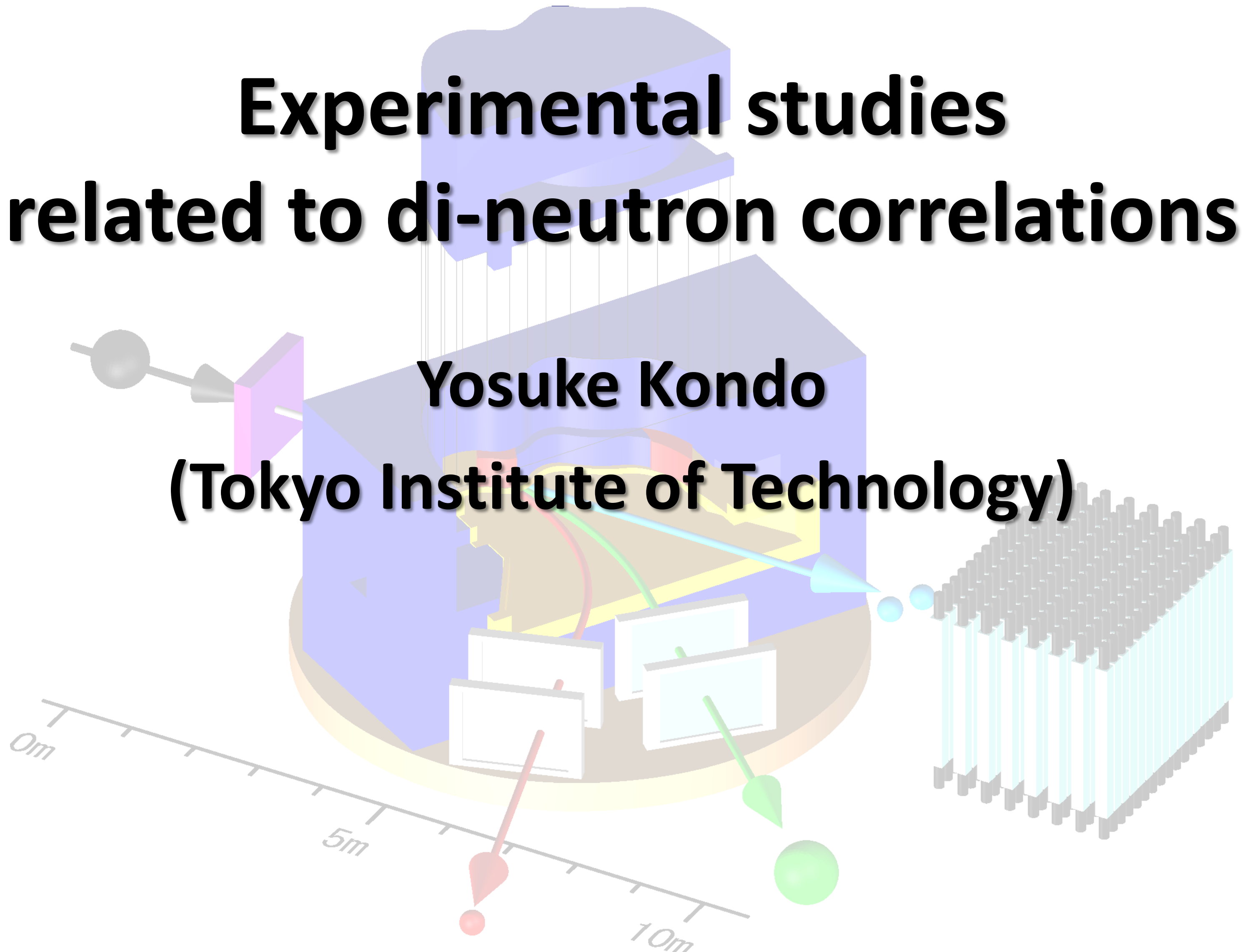
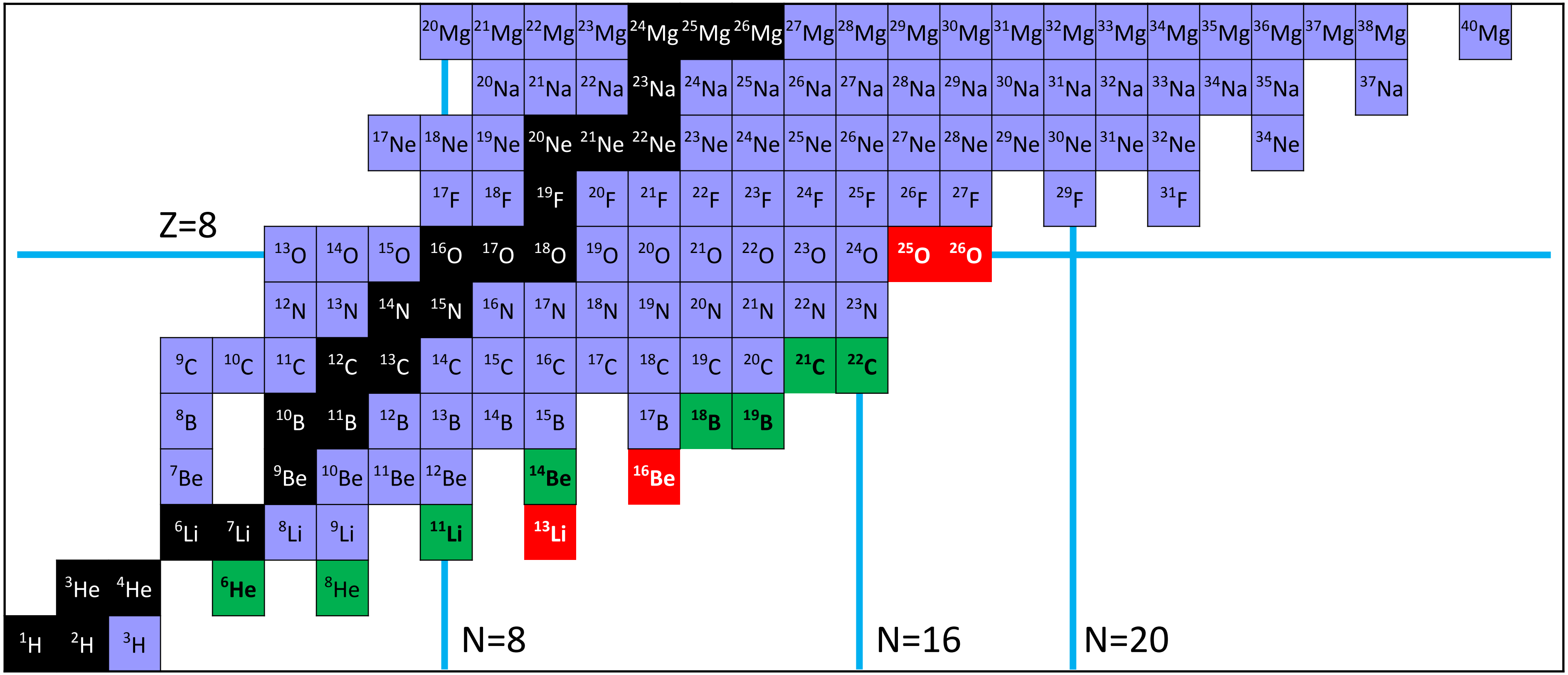
Experimental studies related to di-neutron correlations

Yosuke Kondo

(Tokyo Institute of Technology)



Contents



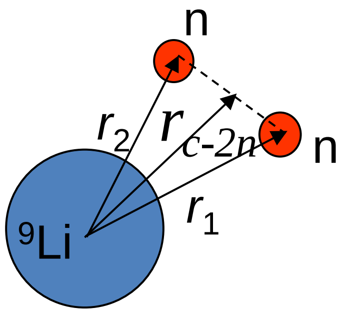
1. Coulomb breakup measurement
2. 2n correlation in 3-body decay

B(E1) : Probe of di-neutron correlation

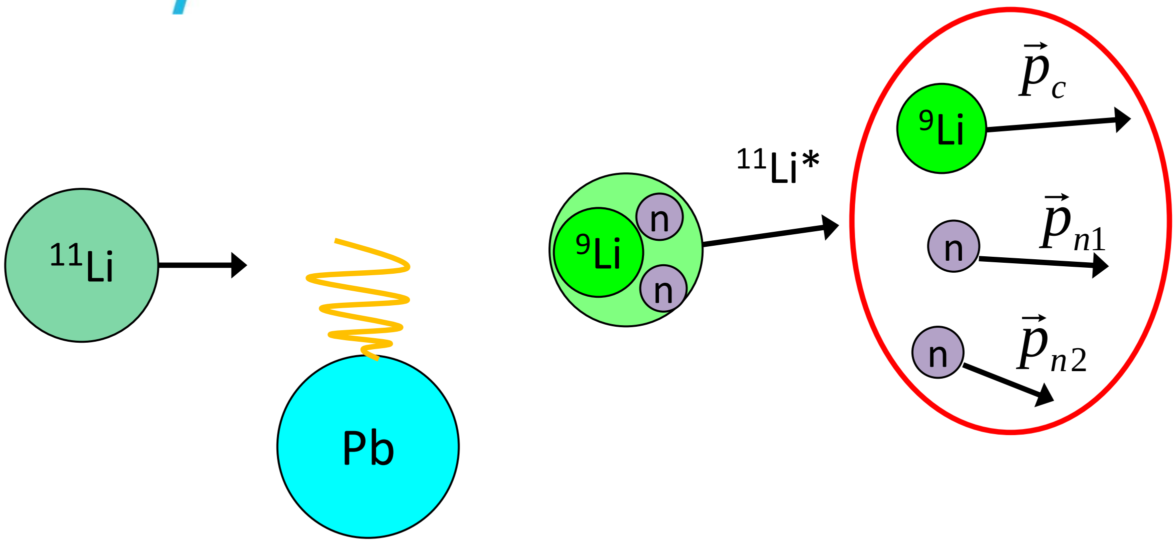
Cluster sum rule
H. Esbensen et G.F. Bertsch, NPA542, 310 (1992)

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

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

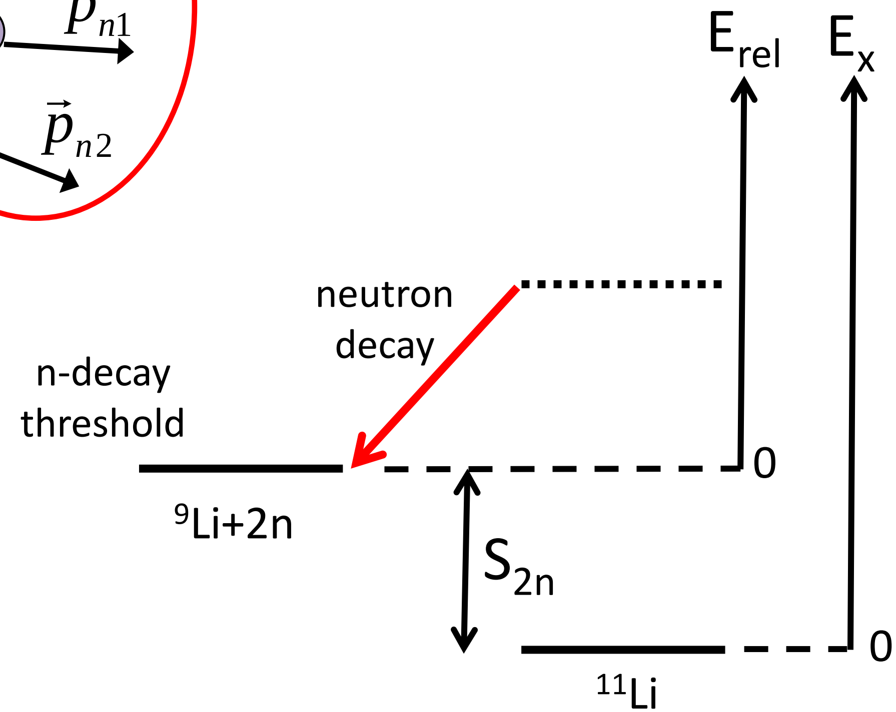


Coulomb breakup



Relative energy (Decay energy)

$$E_{rel} = \underbrace{\sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}}_{\text{Invariant mass}} - \sum M_i$$

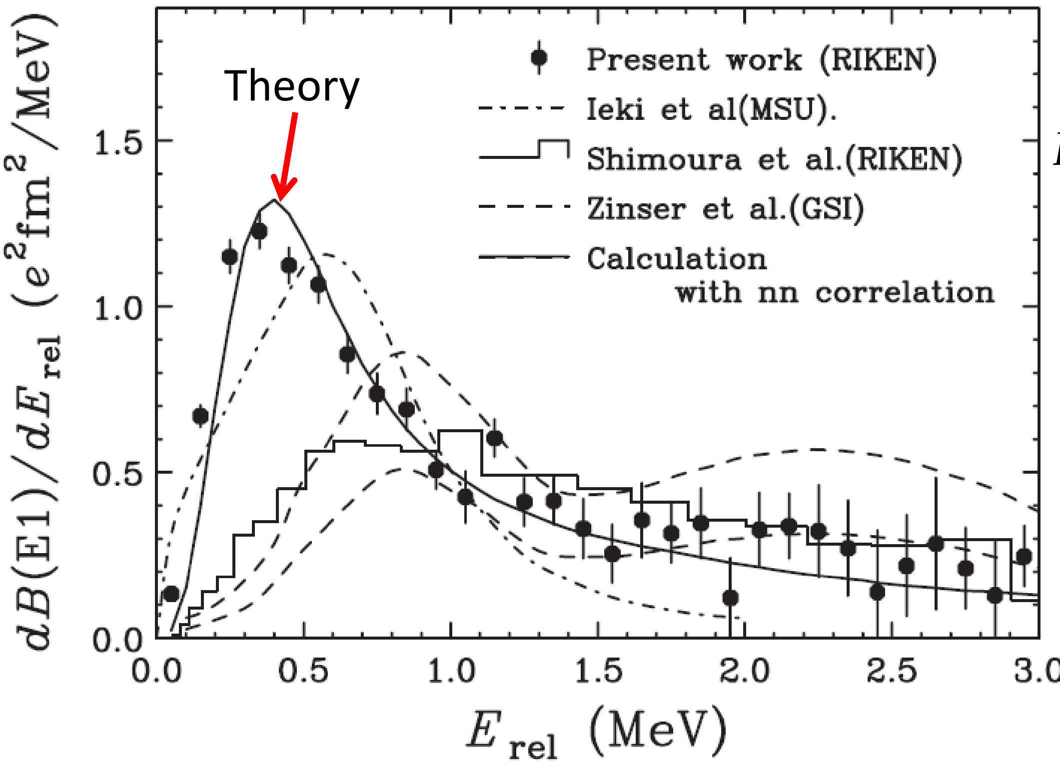


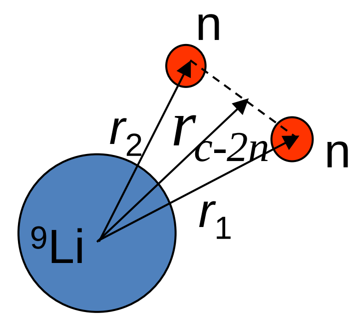
$$\frac{d\sigma(E1)}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x}$$

Example of B(E1) measurement

^{11}Li

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





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

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

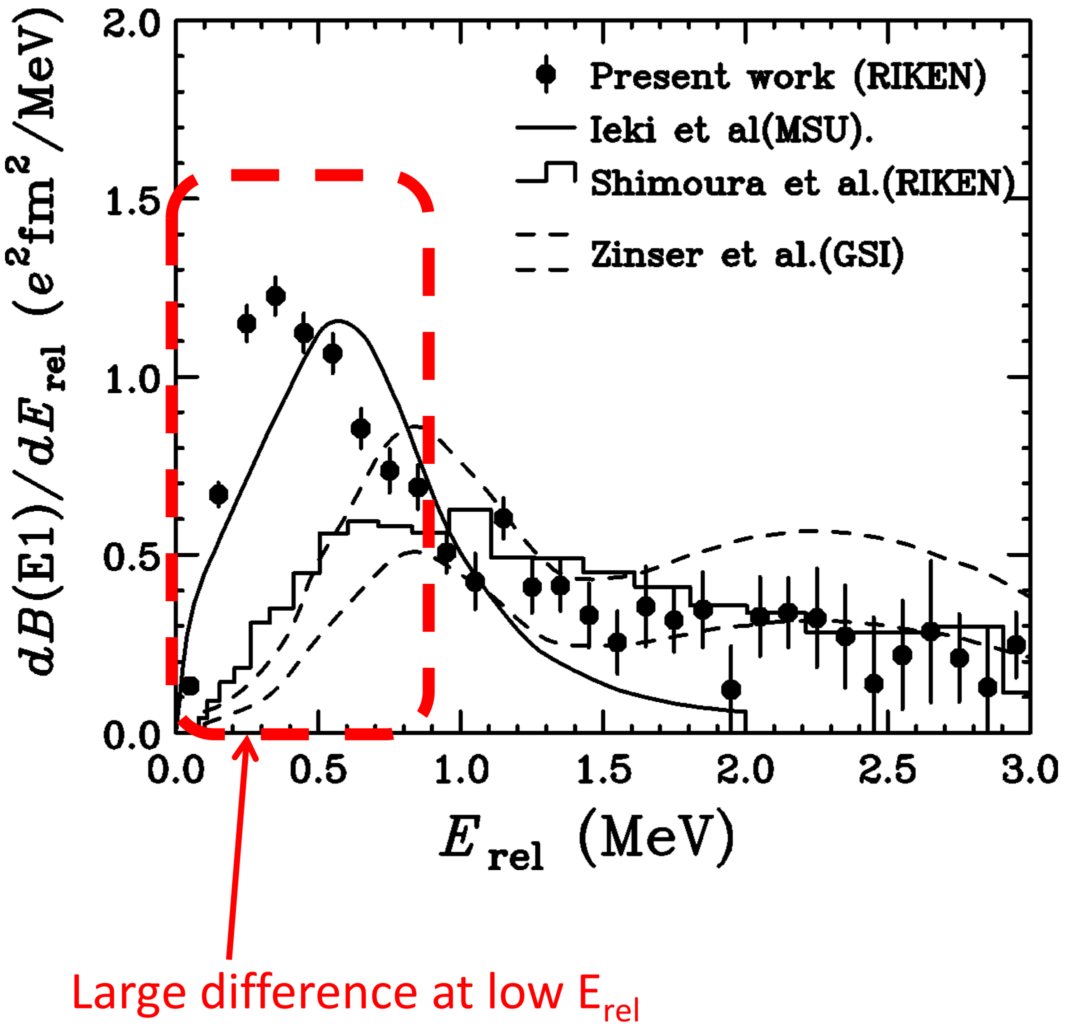
$$B(E1) = 1.42 \pm 0.18\, e^2\, fm^2 (E_{rel} \leq 3\text{MeV})$$

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

(No correlation: 90deg.)

Low energy E1 excitation of 2n-halo
→ dineutron-like correlation

Discrepancy between measurements

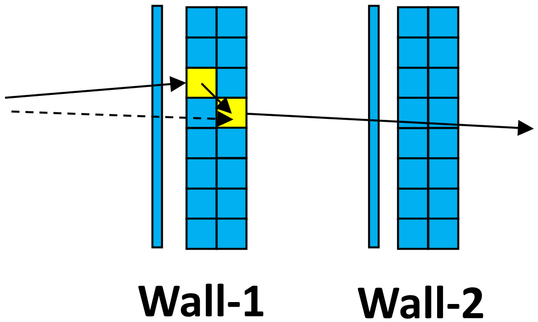


Due to difficulty of 2n detection

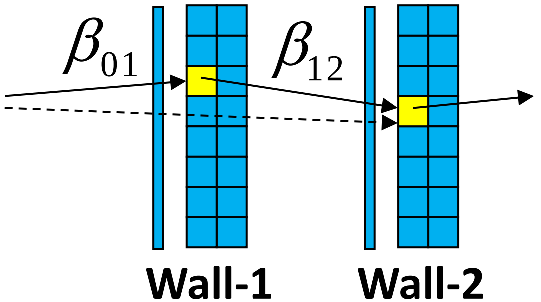
Neutron crosstalk

- Crosstalk … multiple hits caused by 1n
  - should be eliminated
  - Same wall event → position information
    - 2 hits are regarded as 1n if positions are close
    - lose efficiency for small E_{rel}
  - Different wall event → velocity information
    - event is regarded as crosstalk if $\beta_{01} > \beta_{12}$
      - because crosstalk neutron must be slow
    - can measure up to E_{rel}~0

Same Wall event



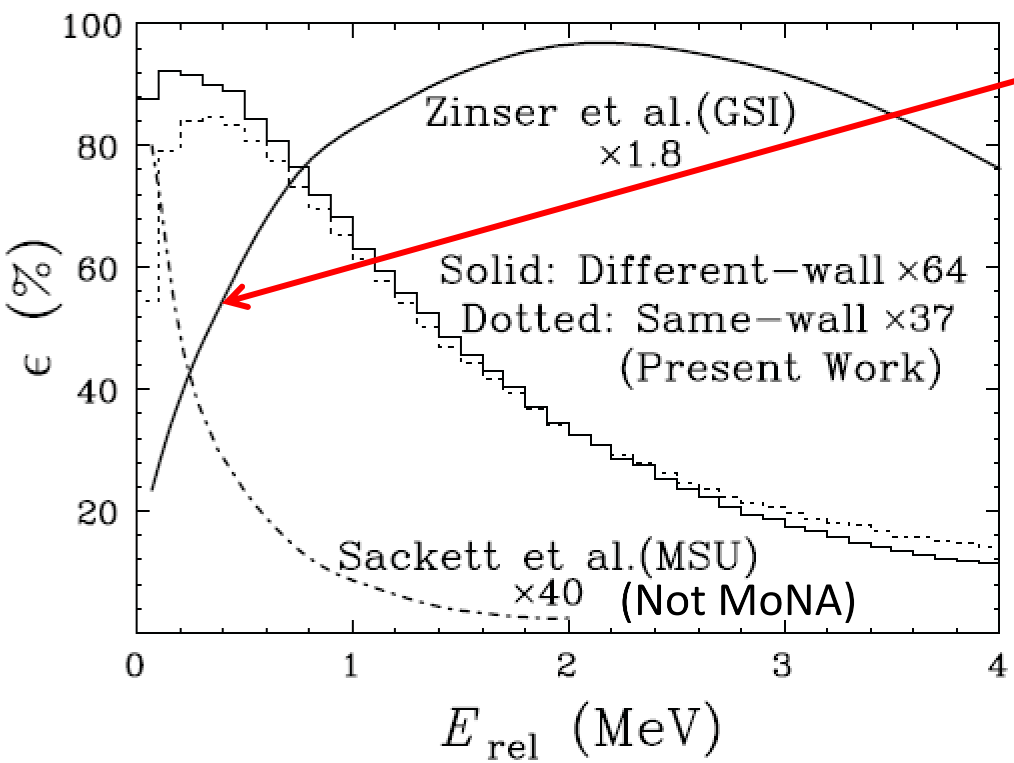
Different Wall event



hit detector

Difficulty of 2n detection

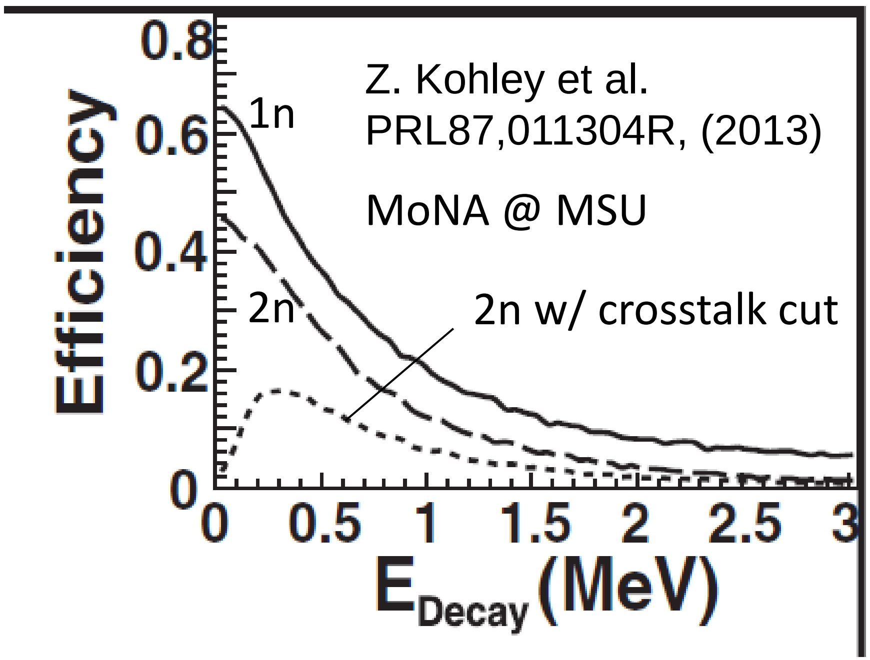
T.Nakamura, Y. Kondo et al.
PRL96,252502(2006)



Rapid drop at E_{rel}~0

Almost zero sensitivity of LAND below ~0.2MeV

Yu. Aksyutina et al.,
PRL111, 242501 (2013)



- I think…
  - Independent experimental study is preferable

Experiment needs theory

$$\frac{d\sigma_C}{dE_{rel}} \Rightarrow \frac{dB(E1)}{dE_x} \Rightarrow \text{Di-neutron correlation}$$

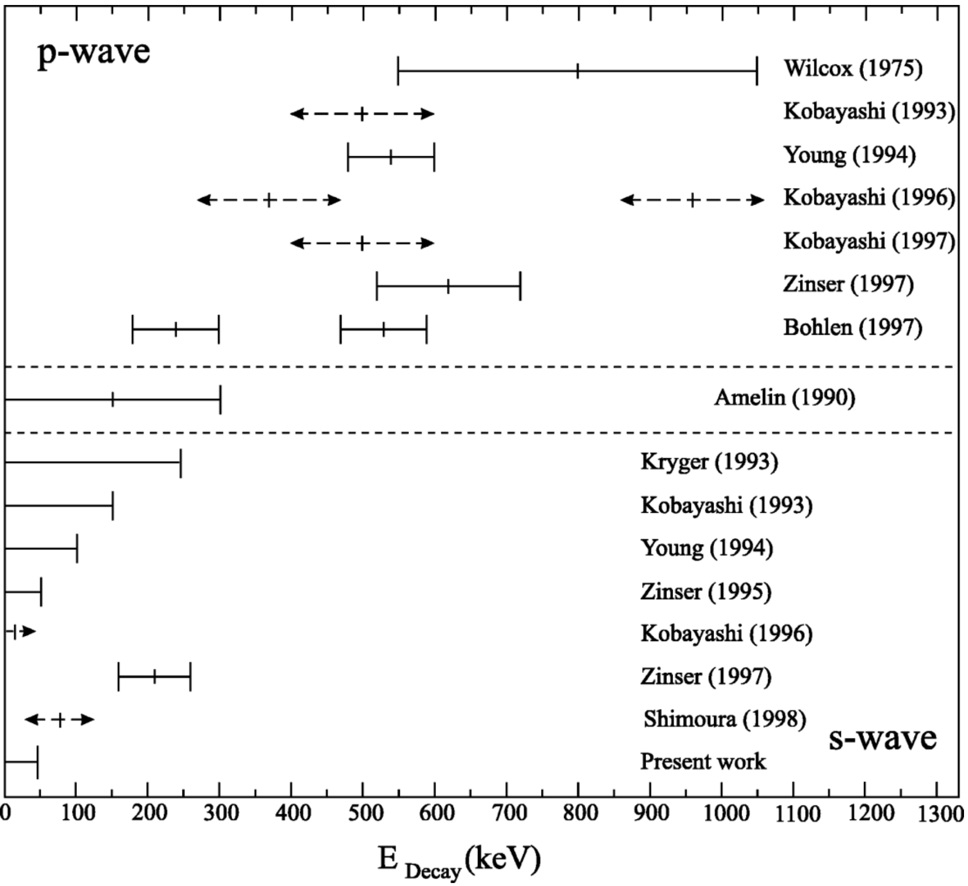
S_{2n}

Theory
- Core + n
- S_{2n}

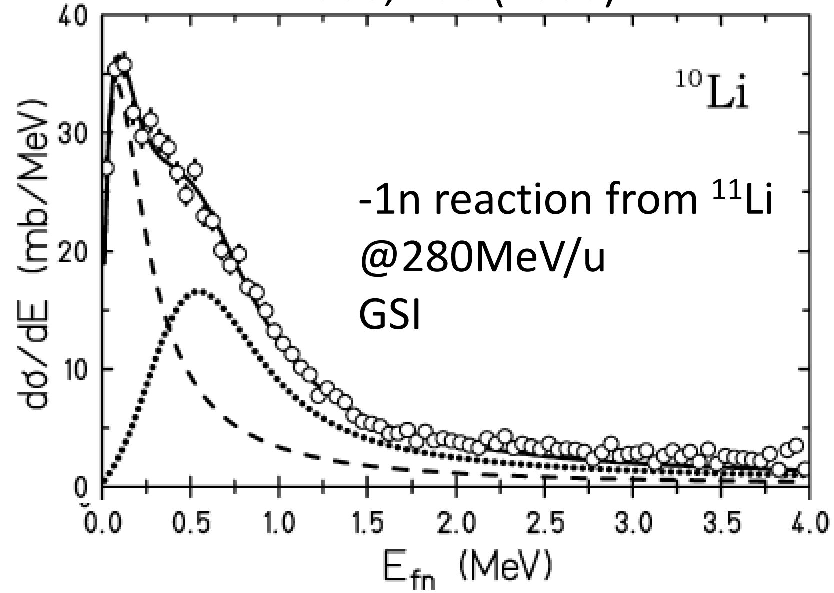
<u>Knowledge of Core + n system is important</u>

^{10}Li structure is still unclear

M. Thoennessen et al., PRC59, 111 (1999)



Yu. Aksyutna et al.
PLB666, 430 (2008)



-1n reaction from ^{11}Li
@280MeV/u
GSI

- ^{9}Li(3/2-) + $\nu p_{1/2}$ → 1+ and 2+
- ^{9}Li(3/2-) + $\nu s_{1/2}$ → 1- and 2-

<u>Doublets should be there…</u>

Question to theorist:

Is it important to clarify the missing state?

Summary of Borromean studies

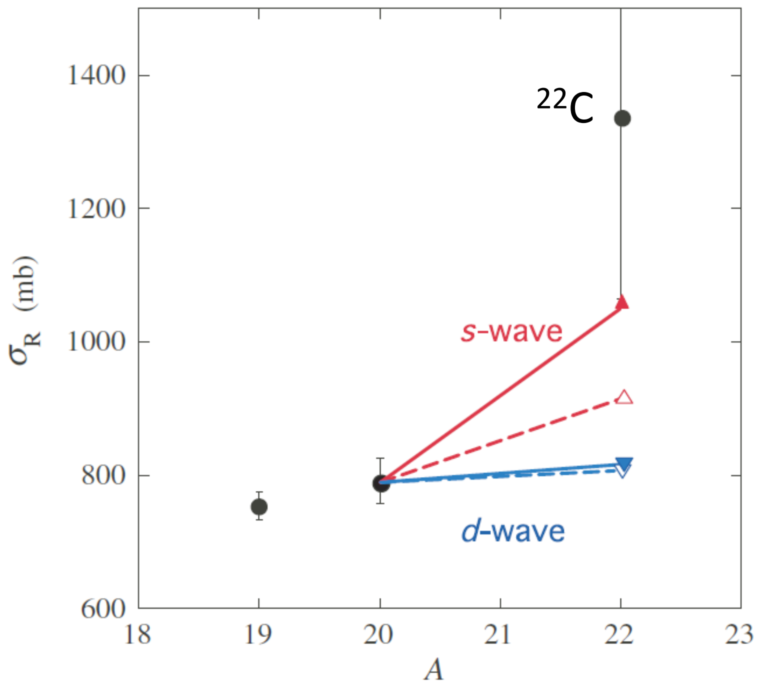
	S_{2n} (accuracy)	B(E1)	Core-n	σ_R	Other points
^{6}He	○ 0.975MeV	△ • 1 old data from GSI • 1 data from RIPS-RIKEN (analysis is not completed…)	○ ^{5}He	○	Rc, core is a,
^{8}He	○ 2.125MeV	×	○ ^{7}He	○	Rc
^{11}Li	○ 0.369MeV	○	△ ^{10}Li	○	
^{14}Be	△ 1.27(13)MeV	△ • 1 old data from GANIL • 1 data from SAMURA-IRIBF (analysis is not completed…)	× ^{13}Be	○	^{12}Be (core) is complicated
^{19}B	× 0.14(39)MeV	× (1 inclusive, not published)	△ ^{18}B	○	
^{22}C	× -0.14(46)MeV	× (1 inclusive, not published)	△ ^{21}C	△ (error is large)	

New experiment by SAMURAI at RIBF

No B(E1) data is available for Borromean nuclei with Z>4

Available data for ^{22}C (reaction cross section)

K.Tanaka et al., PRL 104, 062701(2010).

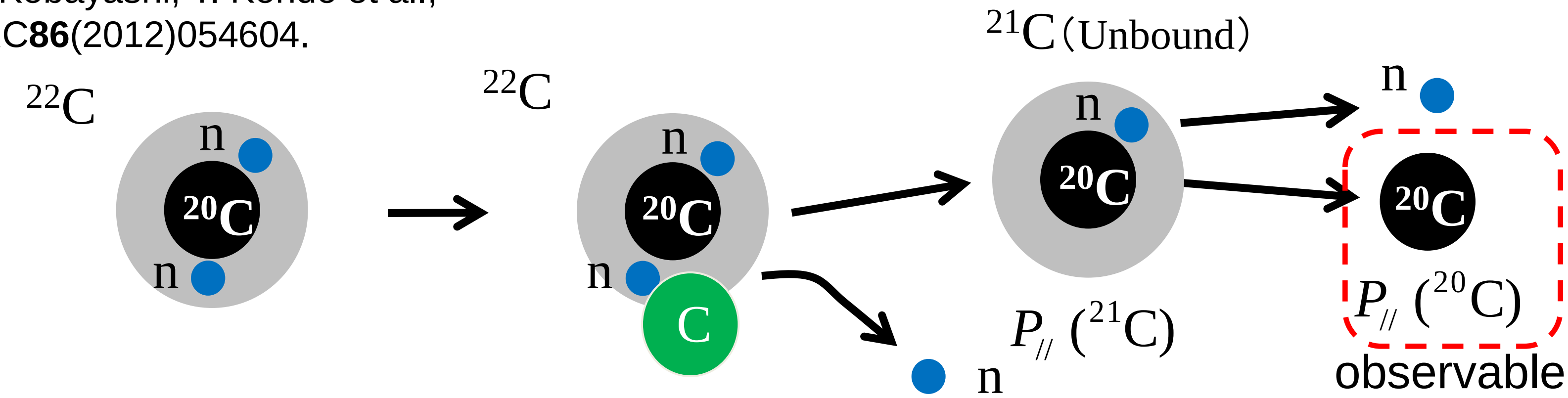


E=40AMeV
Proton target (liquid hydrogen)

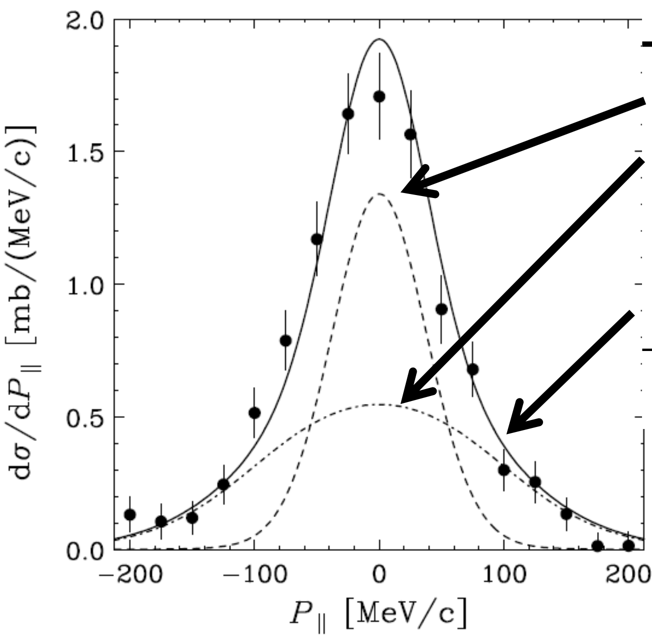
- Large reaction cross section
  - s-wave configuration is important
  - development of neutron halo
- Large experimental error…

Available data for ^{22}C (momentum dist. In -1n reaction)

N. Kobayashi, Y. Kondo et al., PRC**86**(2012)054604.



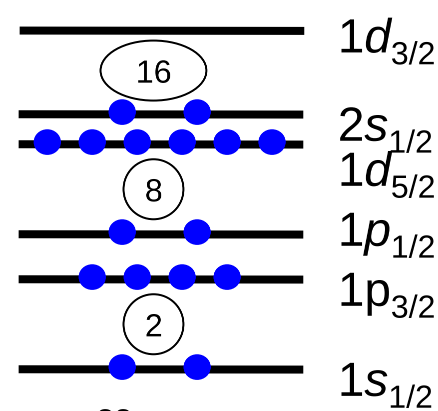
sum



Resolution(σ) = 27 MeV/c

State	C^2S	σ(mb)
$\vert^{21}C\otimes 2s_{1/2}\rangle$	1.403	137.55
$\vert^{21}C\otimes 1d_{5/2}\rangle$	4.212	135.87
$\vert^{21}C\otimes 1d_{3/2}\rangle$	0.342	9.55
Total		283.0
Exp. value		266(19)

Eikonal calculation
C^2S : Shell Model (WBP)
psd model space
Normalized to 266mb



$^{22}C_{g.s.}$ configuration (neutron)

SAMURAI Dayone Experiment (May 2012)

First experimental campaign for the 3 physics programs

1. Study of unbound nuclei ^{25}O and ^{26}O (SAMURAI02, Y. Kondo)
2. Coulomb breakup of ^{22}C and ^{19}B (SAMURAI03, T. Nakamura)
3. Study of unbound states of ^{22}C, ^{21}C, ^{19}B, ^{18}B (SAMURAI04, N. A. Orr/J. Gibelin)

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

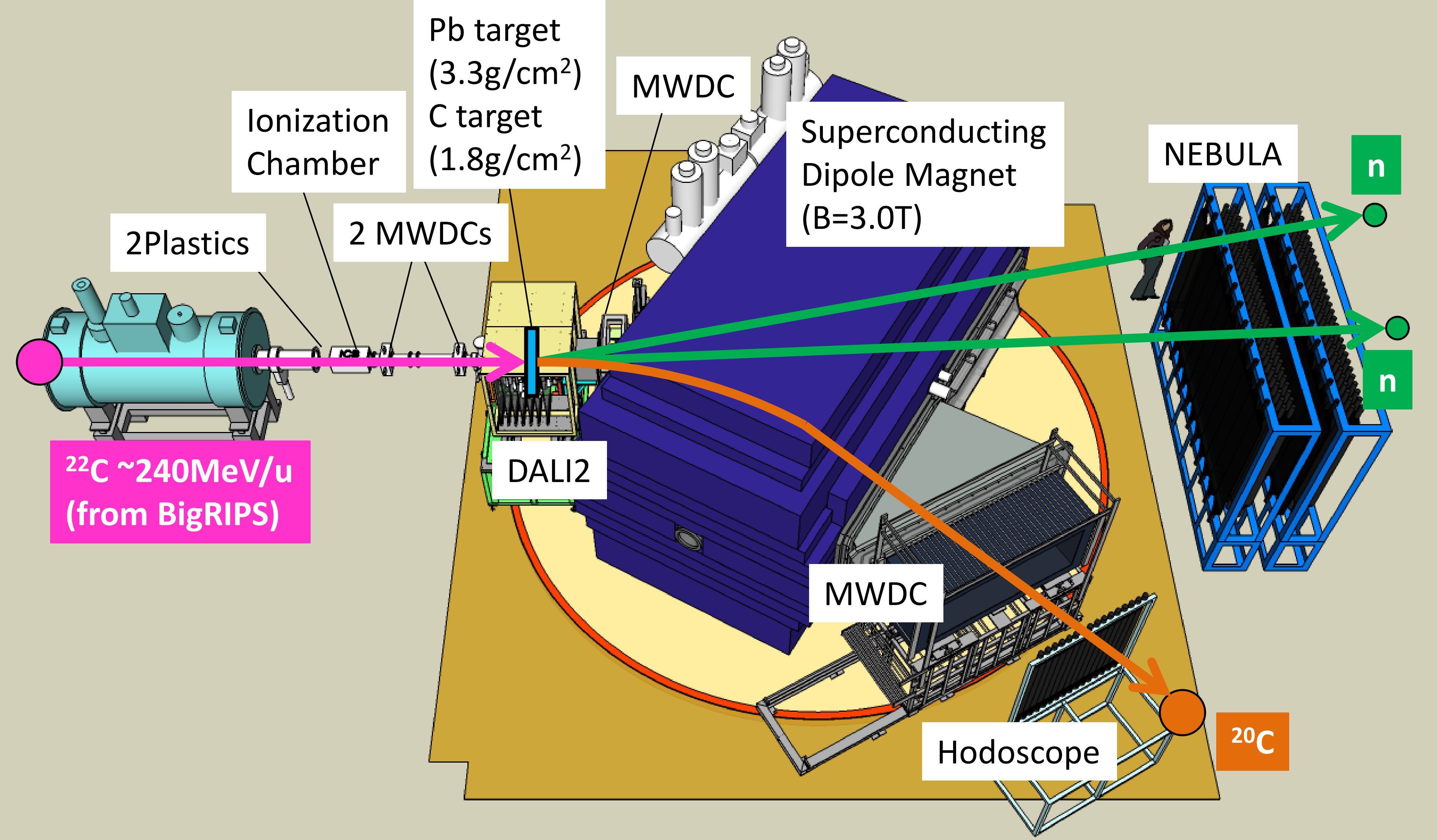
GANIL: A.Navin

Technische Universit¨at Darmstadt: T.Aumann

Rikkyo Univeristy: D.Murai

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

Experimental setup



Coulomb Breakup of 2n halo nuclei (Spokesperson: T. Nakamura)

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

S.Ogoshi

Preliminary

50

E_{rel}(MeV)

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

R.Minakata

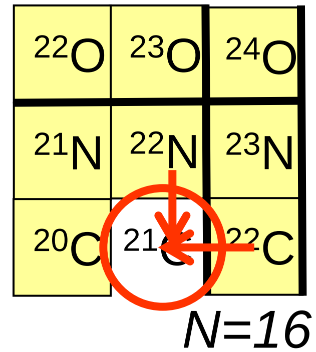
Preliminary

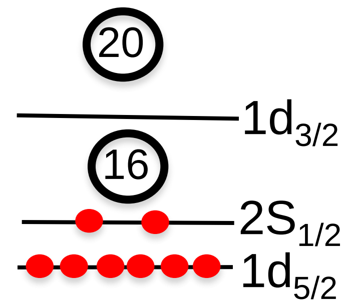
counts

0 1 2 3 4 5 6 7 8 9 10

E_{rel}(MeV)

Study of the unbound nucleus ^{21}C (Spokesperson: N.A. Orr/J. Gibelin)





s? d? *New!*

$^{22}C \rightarrow {}^{21}C \rightarrow {}^{20}C+n$

Preliminary

S.Leblond

s?

$^{22}N \rightarrow {}^{21}C \rightarrow {}^{20}C+n$

Preliminary

S.Leblond

Study of the unbound nucleus ^{18}B (Spokesperson: N.A. Orr/J. Gibelin)

-1n reaction

$^{19}B \rightarrow$ **^{18}B** $\rightarrow {}^{18}B+n$

New!

Preliminary

S.Leblond

-1p reaction

$^{19}C \rightarrow$ **^{18}B** $\rightarrow {}^{17}B+n$

Preliminary

S.Leblond

Short summary

- **B(E1) is a probe of di-neutron correlation**
  - Knowledge of core + n system
    → ^{6}He and ^{11}Li are available now

- **New data for ^{22}C and ^{19}B by SAMURAI experiment**
  - B(E1) distribution
  - ^{21}C and ^{18}B can also be studied by -1n and -1p reactions
  - Cannot determine S_{2n}
    → Reaction cross section can be determined
      - (σ_R result of ^{22}C will be given by Y. Togano at Hawaii2014)

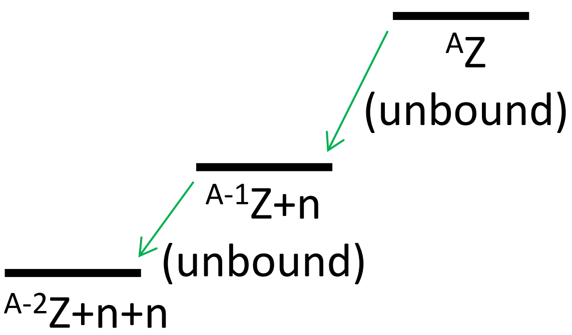
→ <u>sufficient for understanding Borromean system</u>

2n correlation in 3-body decay

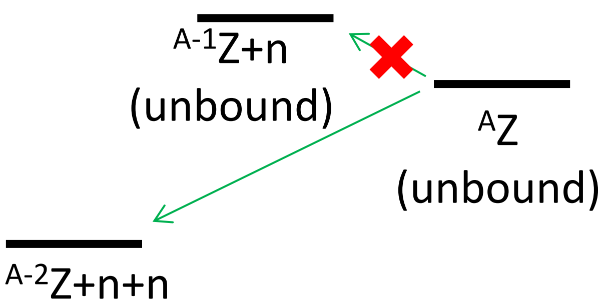
Correlation in 3-body decay

- Decay of 3-body unbound system
  - **Sequential** decay via core + n resonance
  - Direct 3-body decay
    - **Democratic** decay (phase space decay)
    - **Di-neutron** decay
    - **Back-to-back** decay

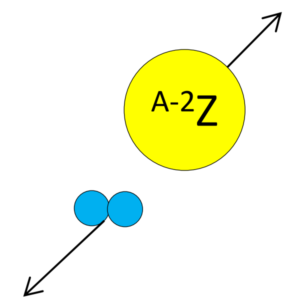
Sequential



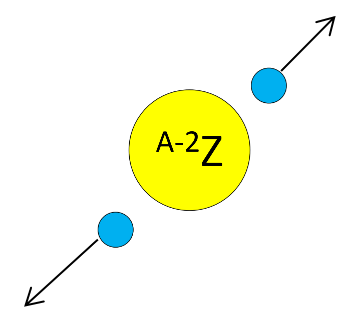
Direct 3-body



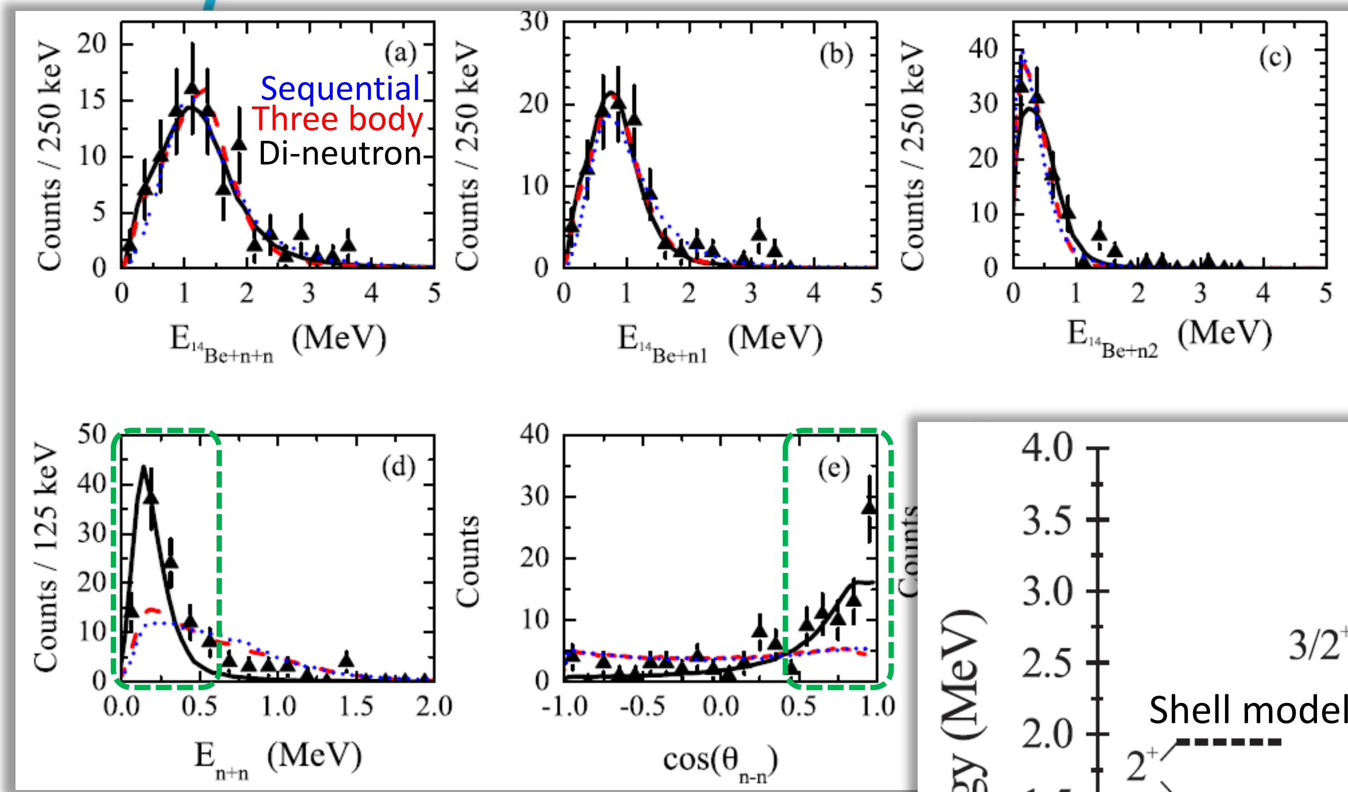
Di-neutron



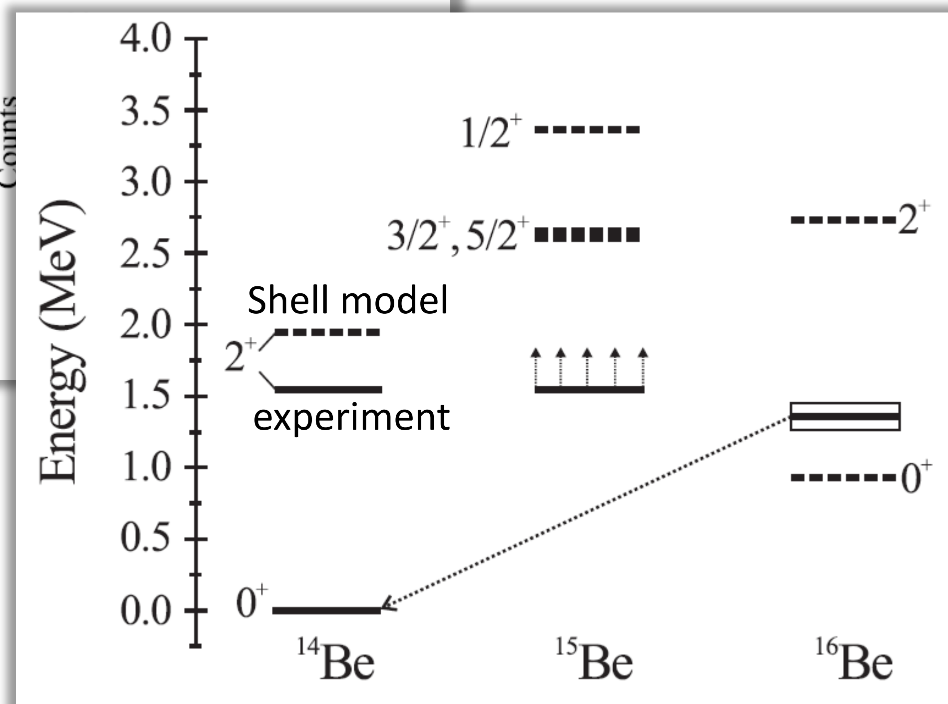
Back-to-back



Di-neutron decay of ^{16}Be



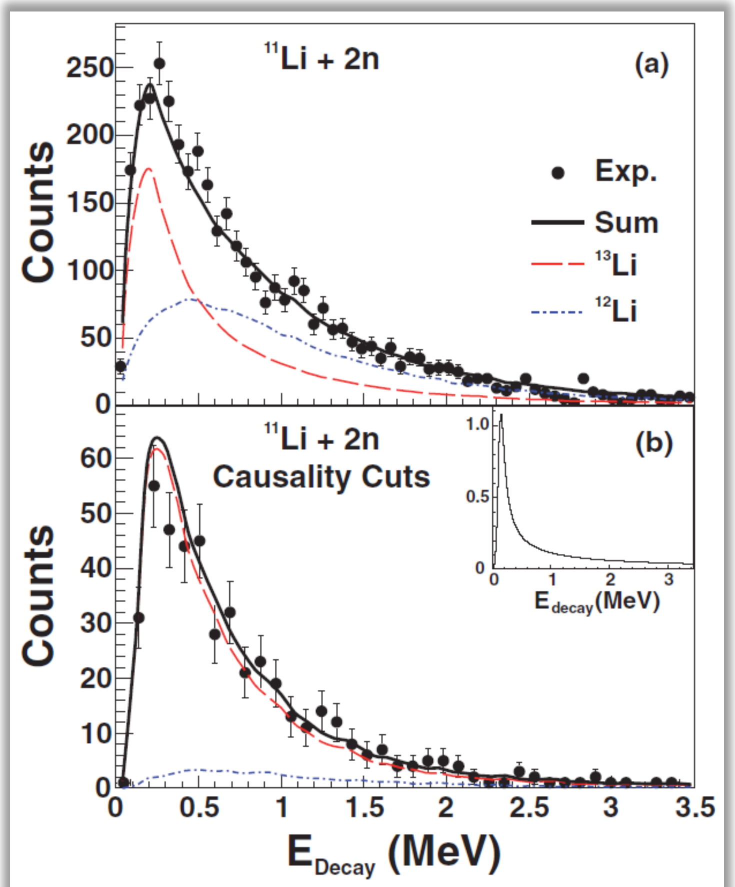
A. Spyrou et al.,
PRL108, 102501 (2012)
-1p reaction from ^{17}B
@ 53MeV/u

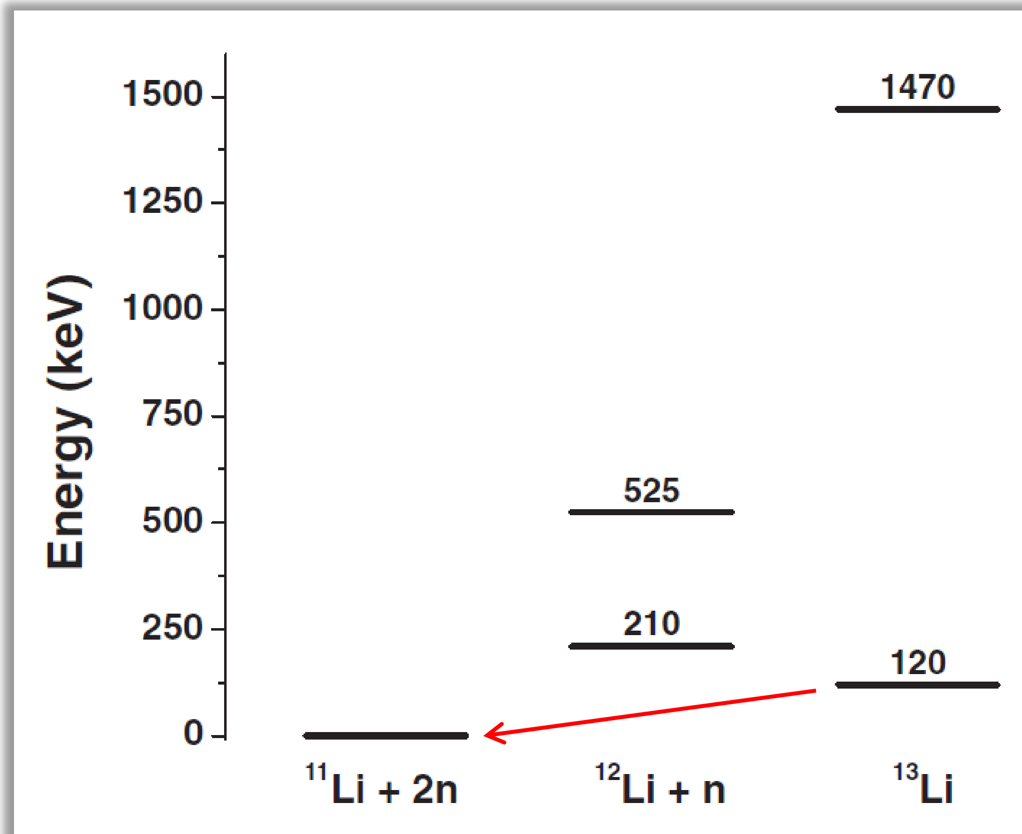


- ^{16}Be state at 1.35(10)MeV
- Enhancement of low E_{n+n} and θ_{nn}~0
  → di-neutron decay

^{13}Li

Z. Kohley et al., PRC87, 011304 (2013)
-1p reaction from ^{14}Be @ 53.6MeV/u

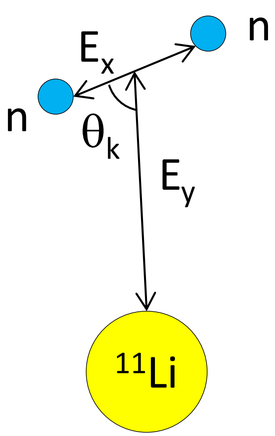




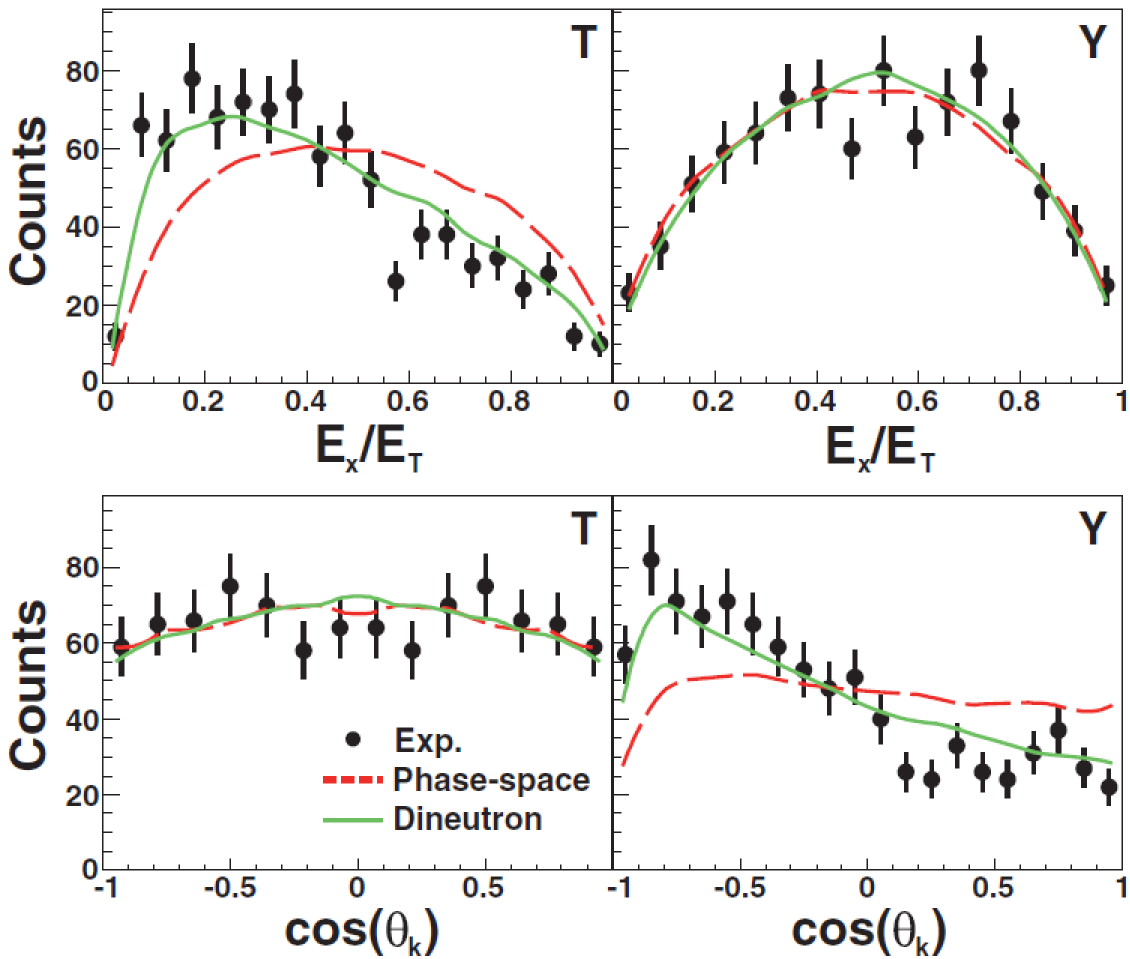
- Sequential decay via ^{12}Li is not open

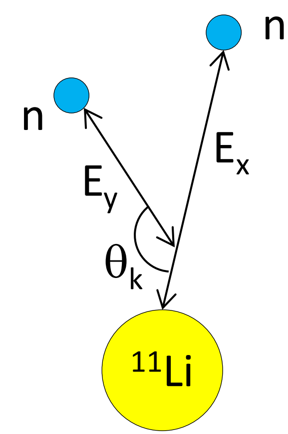
Di-neutron correlation in decay of ^{13}Li?

Z. Kohley et al., PRC87, 011304 (2013)



T coordinate



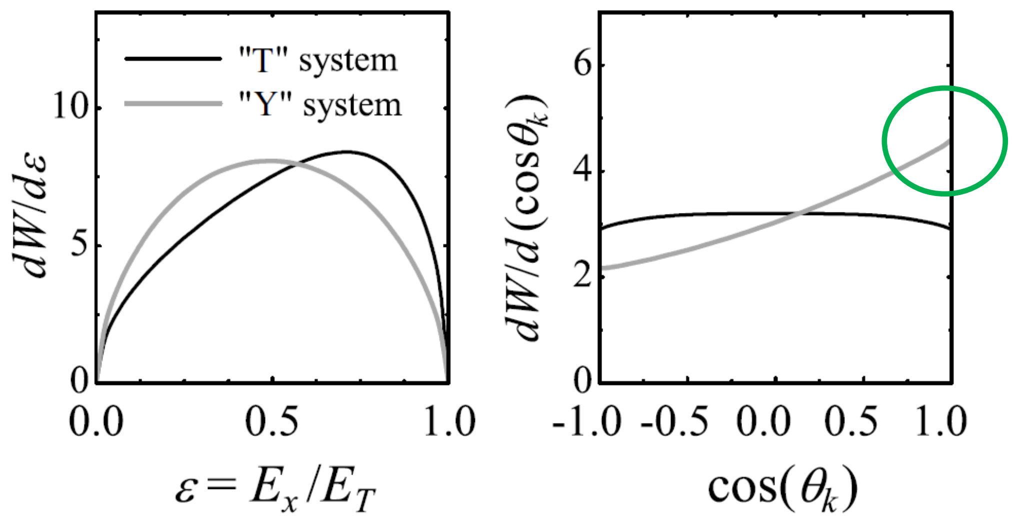


Y coordinate

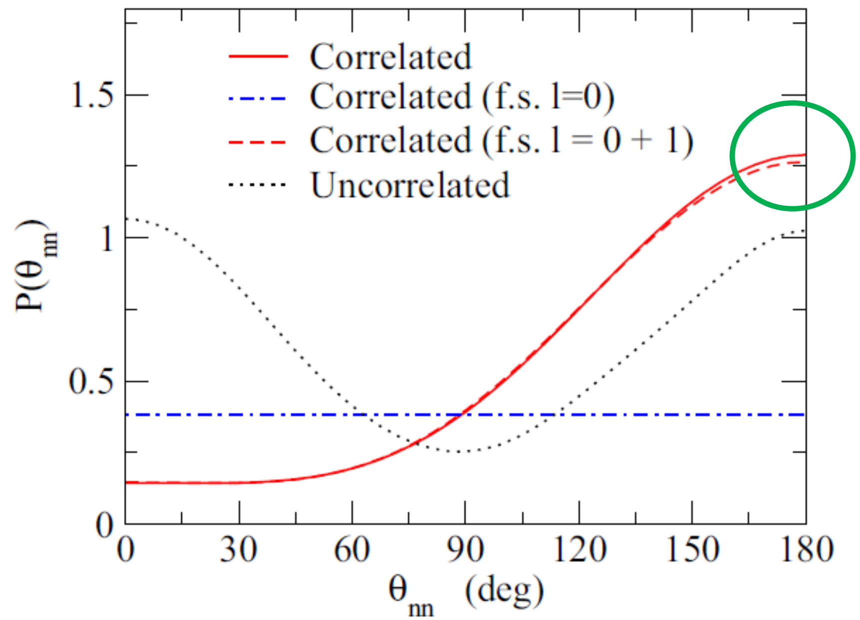
Di-neutron character in the decay of ^{13}Li ground state

Correlation in ^{26}O decay?

L. V. Grigorenko et al
PRL111, 042501 (2013)



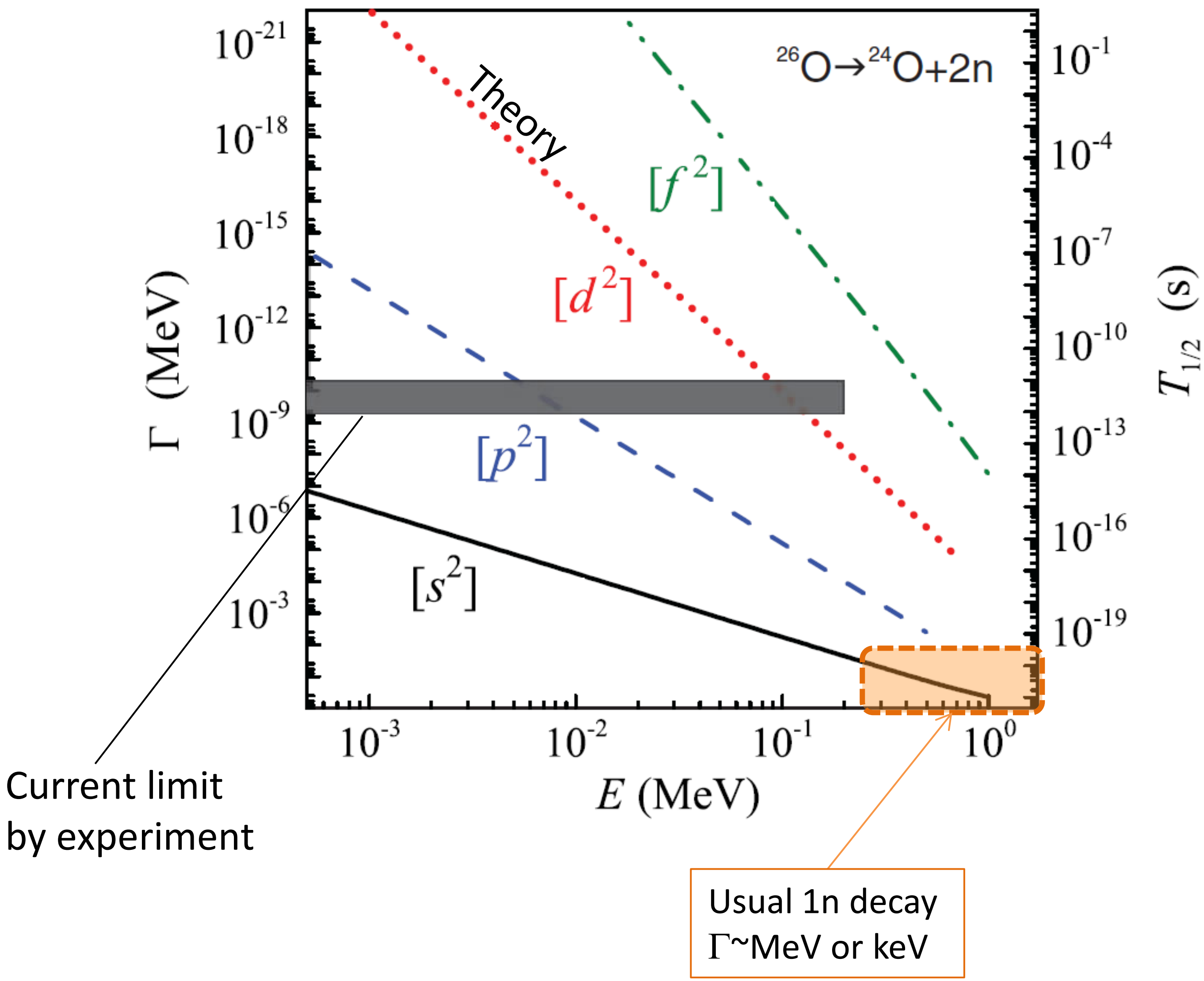
K. Hagino and H. Sagawa
PRC89, 014331, (2014)



Enhancement of back-to-back decay

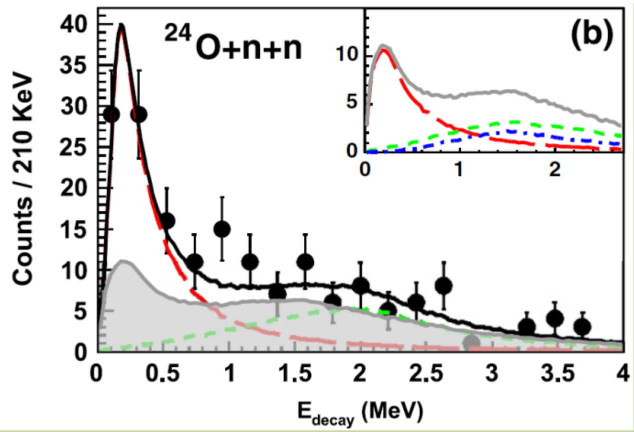
2n radioactivity of ^{26}O?

L.V. Grigorenko et al. PRC 84, 021303 (2011)



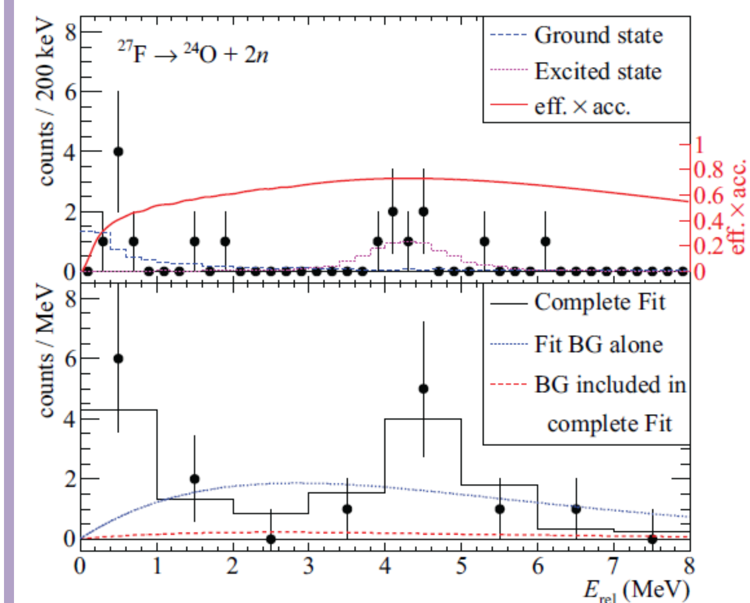
2n radioactivity of ^{26}O?

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



Er < 200keV

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

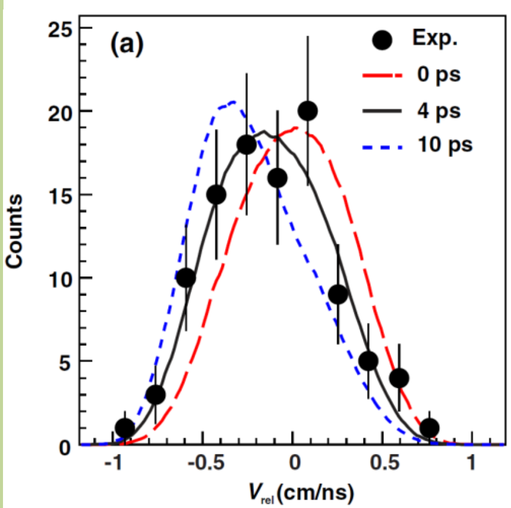


Er < 120keV (95% CL)

τ < 5.7ns

Excite state at 4.2MeV?

Z. Kohley et al,PRL110,152501 (2013)



$T_{1/2}=4.5^{+1.1}_{-1.5}$ps

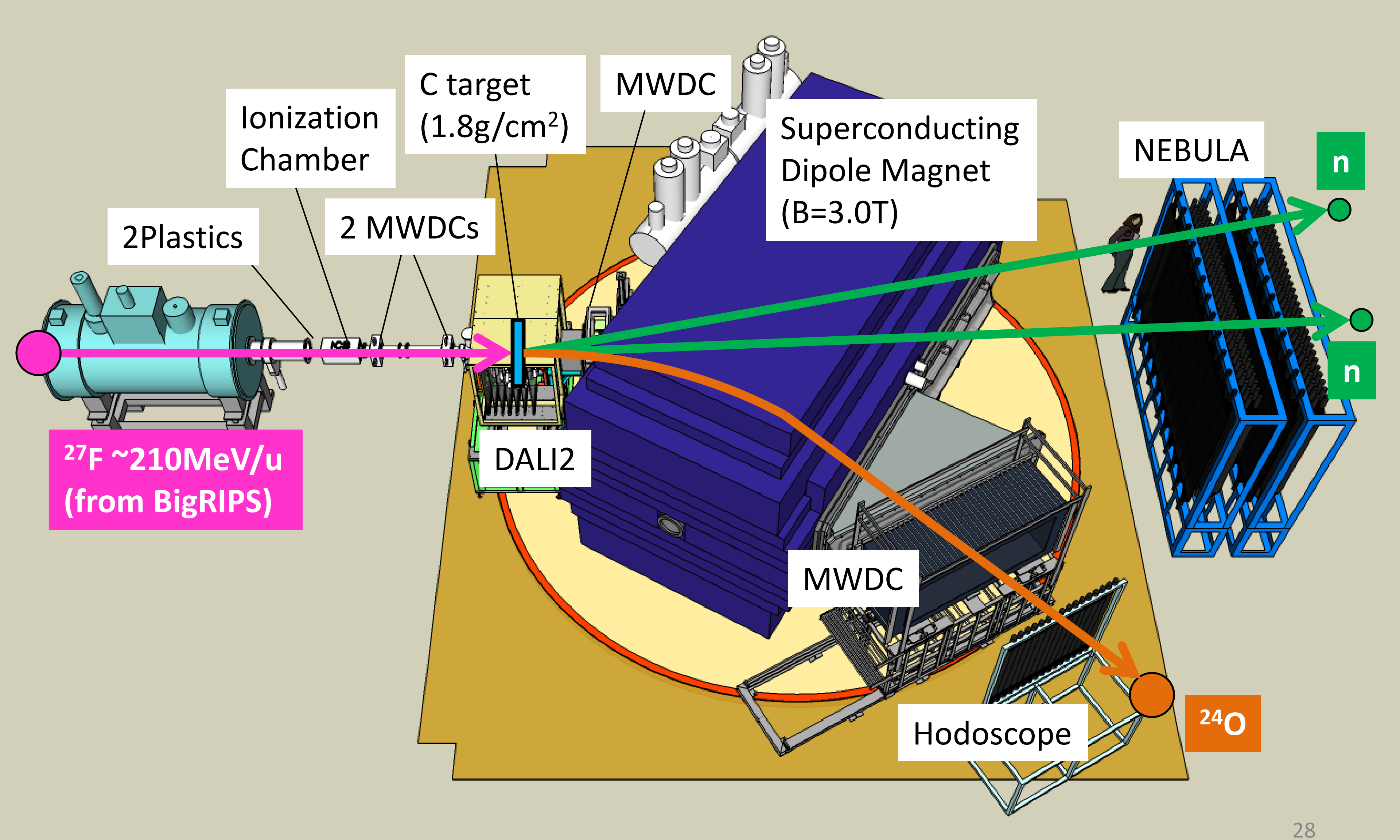
(3ps systematic error)

→2n radioactivity?

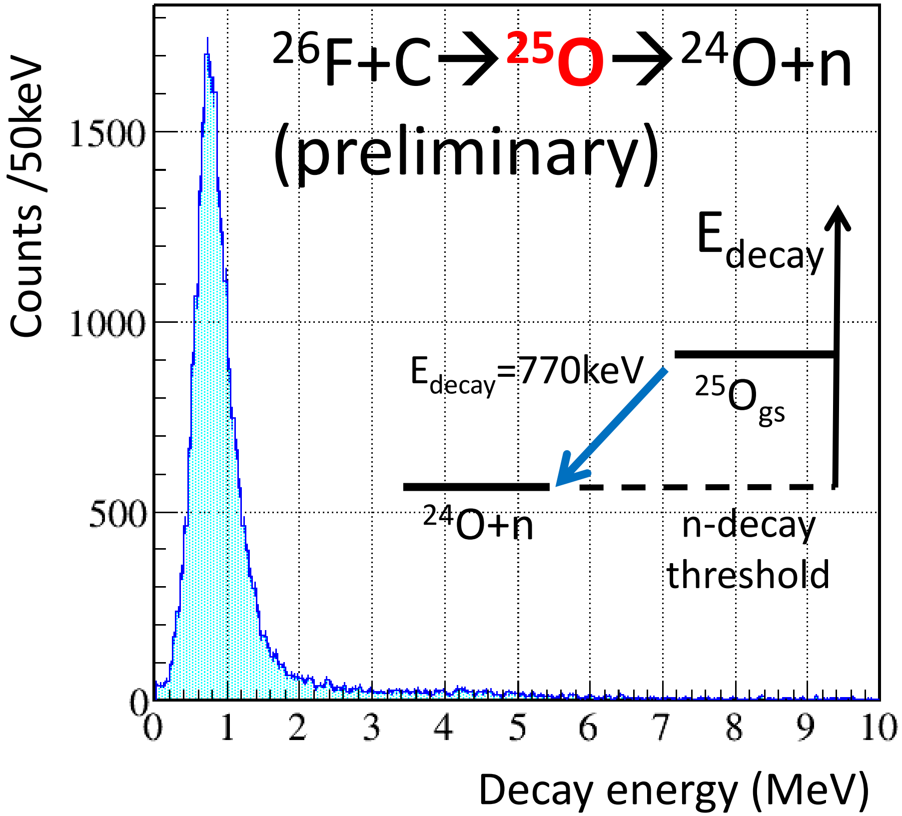
Large uncertainty of experimental study

- Only upper limit is given for the ground state energy
- Large systematic error in the lifetime measurement

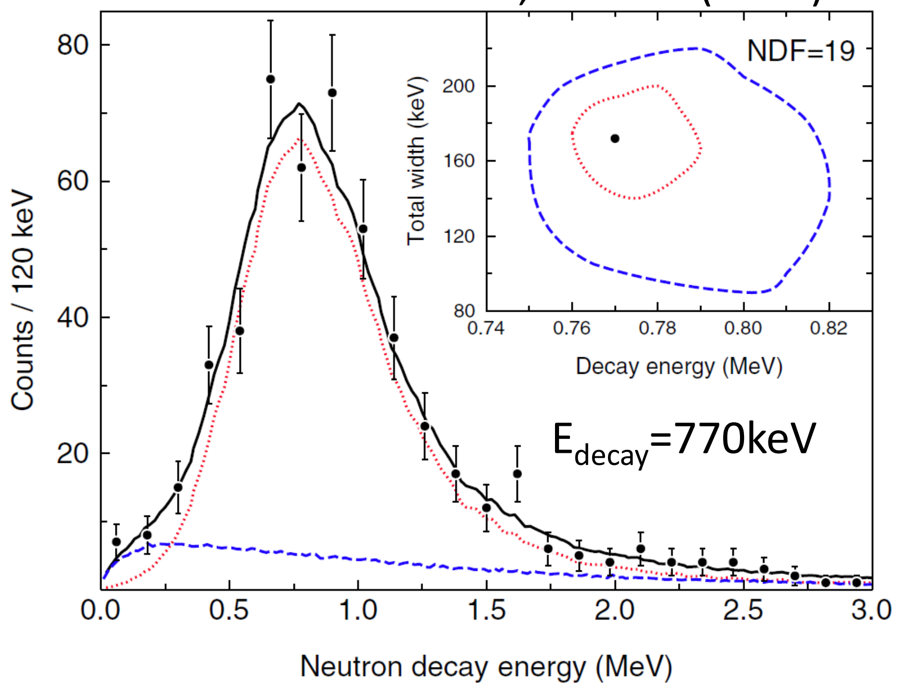
New measurement at RIBF



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



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



50 times higher statistics!

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

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

Ground state

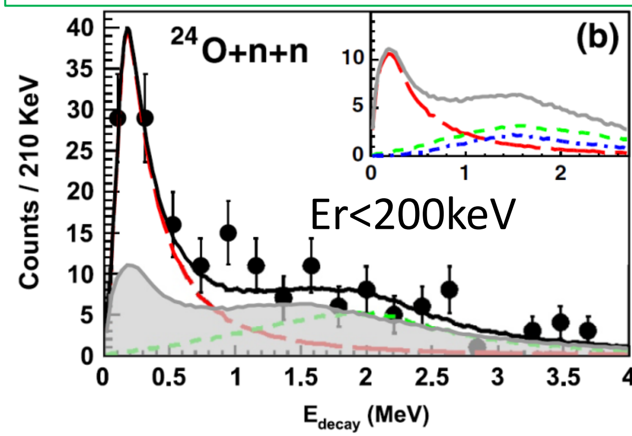
$^{27}F+C \rightarrow$ **^{26}O** $\rightarrow {}^{24}O+2n$
(preliminary)

Excited state (new)

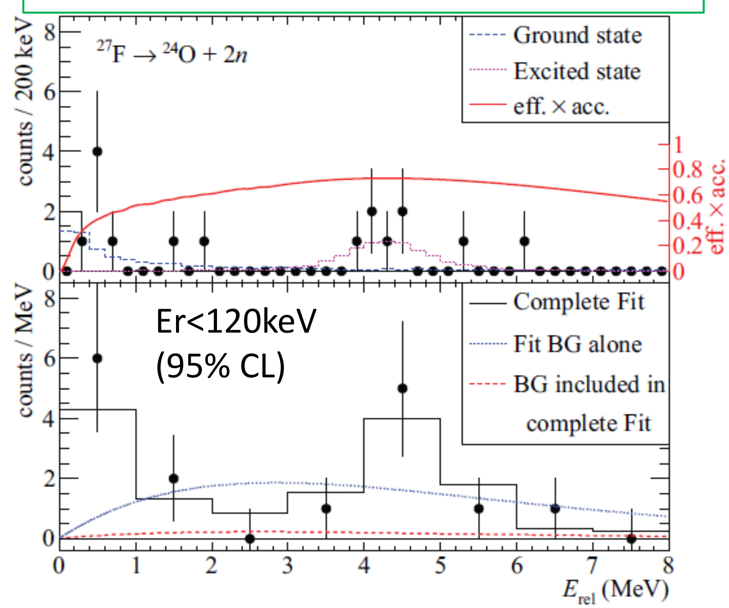
Counts /100keV

Decay energy (MeV)

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



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



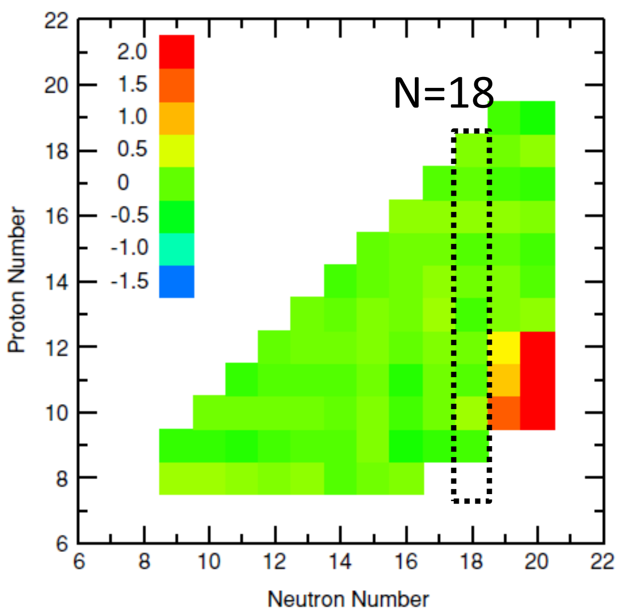
Ground state
- 5 times higher statistics
- →better determination of energy

Excited state at ~1.3MeV
- First observation
- Most probably 2^+

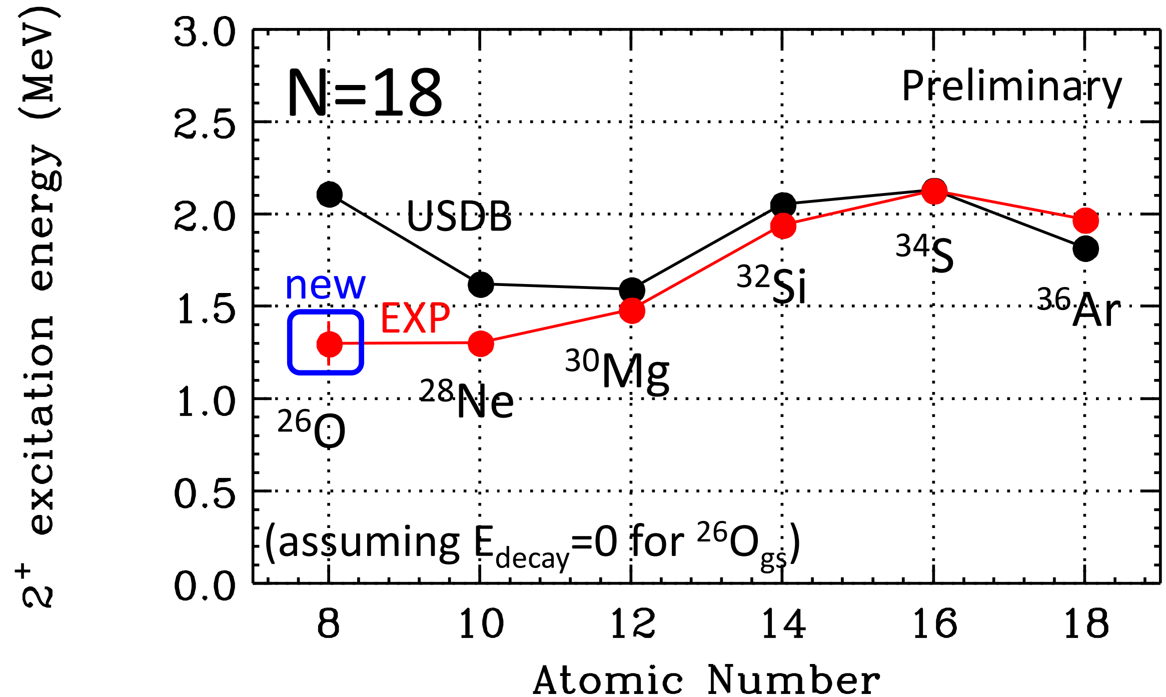
No peak at ~4.2MeV

Comparison with USDB calculation

B.A. Brown, W.A. Richter
PRC74, 034315 (2006)



Difference between ground state energies of EXP and USDB calculation



Ground state

– USDB predicts S_{2n}= - 0.35MeV for ^{26}O ground state
(Almost consistent with experiment)

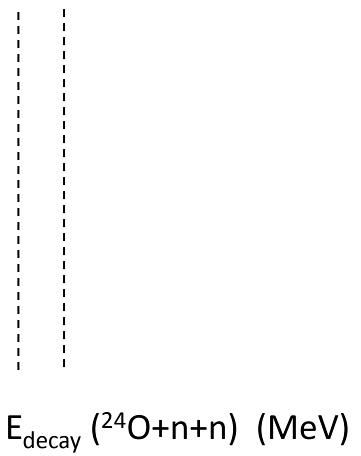
2+ state

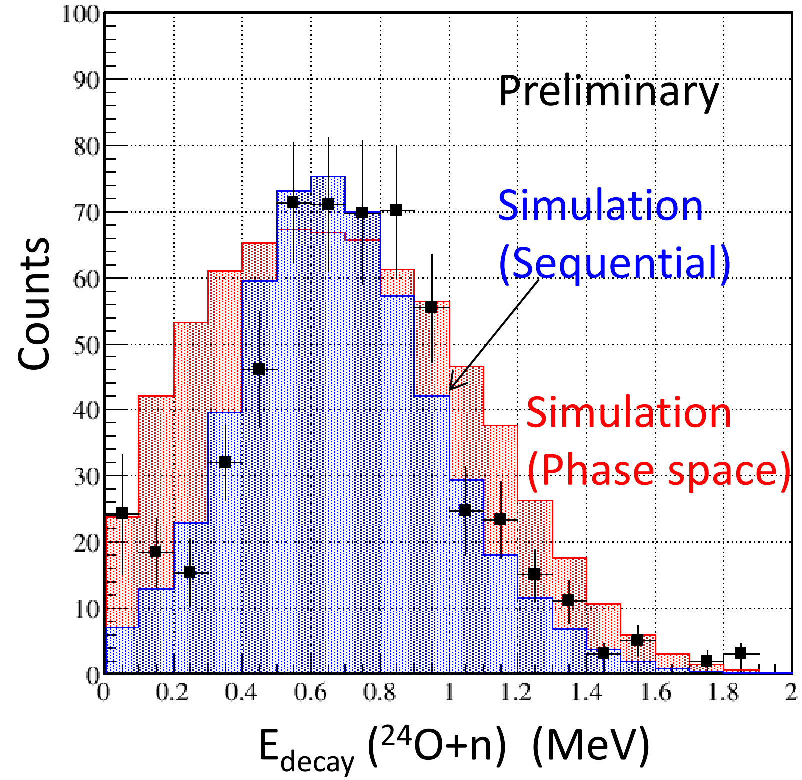
– Calculation overestimates at low Z
→effect of pf-shell? or continuum effect?

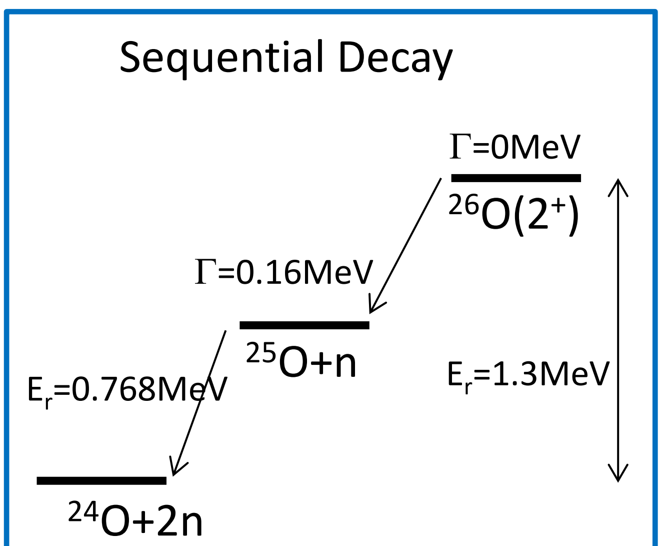
– E.g. Continuum shell model predicts 1.8MeV
A. Volya, V. Zelevinsky, PRC74, 064314 (2006)

Sequential decay of $^{26}O(2^+)$

Gated by 3-body decay energy
$0.8\,MeV < E_{decay}(^{24}O+n+n) < 2\,MeV$







<u>2^+ state decays sequentially</u>

^{24}O excited state

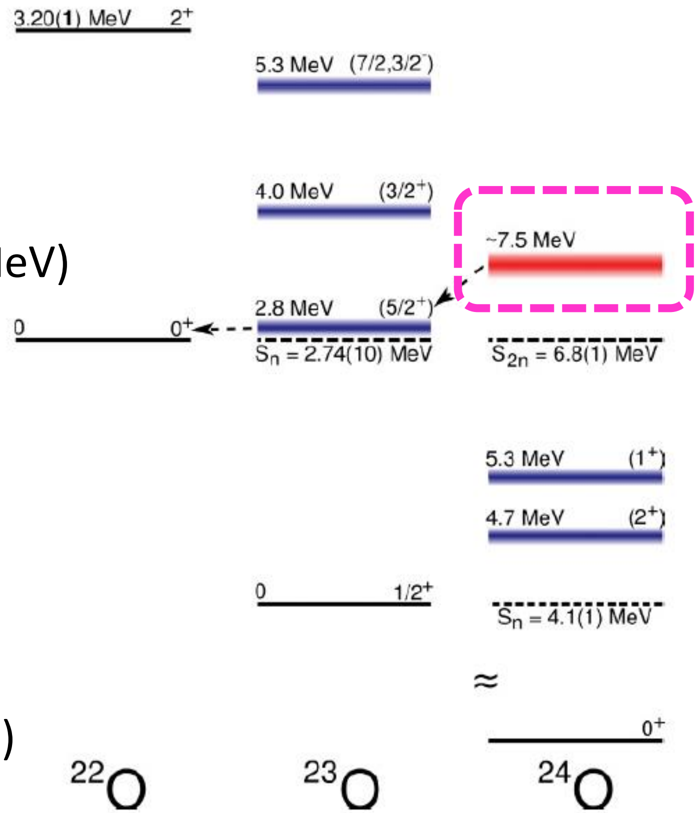
^{26}F+C→^{24}**O***

→^{22}O+2n

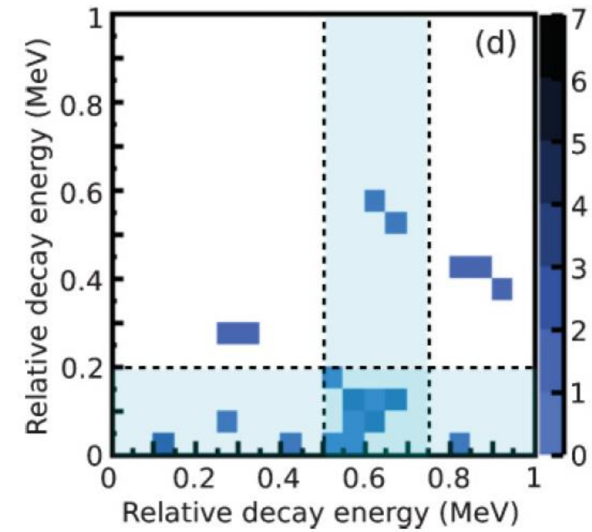
(preliminary)

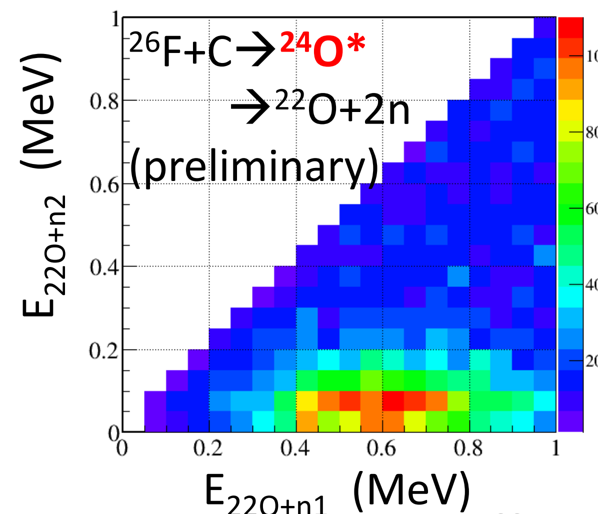
counts/50keV

Decay energy (MeV)



C.R. Hoffman et al, PRC83, 031303 (2011)





<u>Sequential decay of ^{24}O excited state is confirmed</u>

Summary

- B(E1) measurement by Coulomb breakup
  - Di-neutron correlation in Borromean nucleus
  - New data for ^{22}C and ^{19}B
    - Core + n systems (^{21}C and ^{18}B)
    - Reaction cross section of ^{22}C

- Study of 3-body decay
  - Correlation of decaying two-neutrons
  - New experimental data for ^{26}O
    - 2+ state is newly observed
    - Sequential decay of 2+ state via ^{25}O ground state is confirmed
    - Sequential decay of ^{24}O excited state is confirmed