

Lifetime measurements with GRETINA at NSCL

- magnetic responses of halo nuclei -



Hiro IWASAKI (NSCL/MSU)

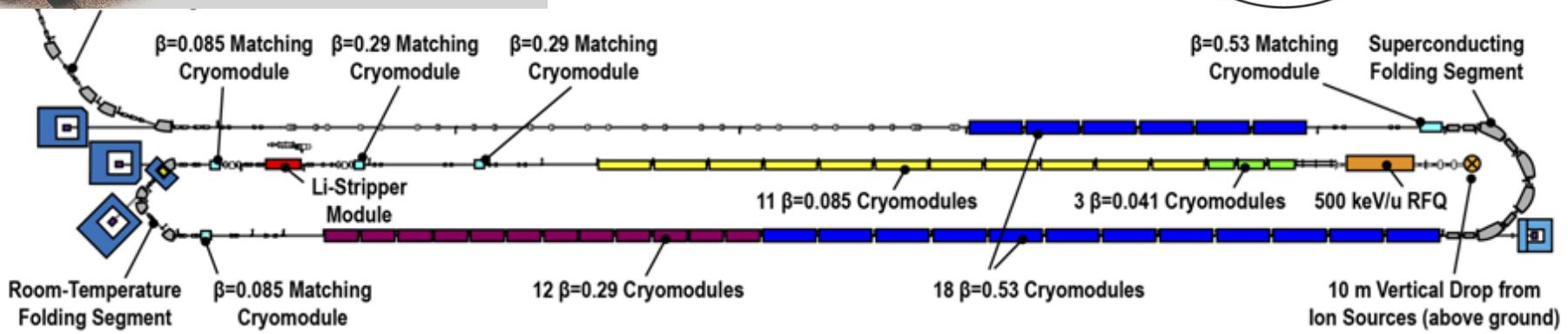
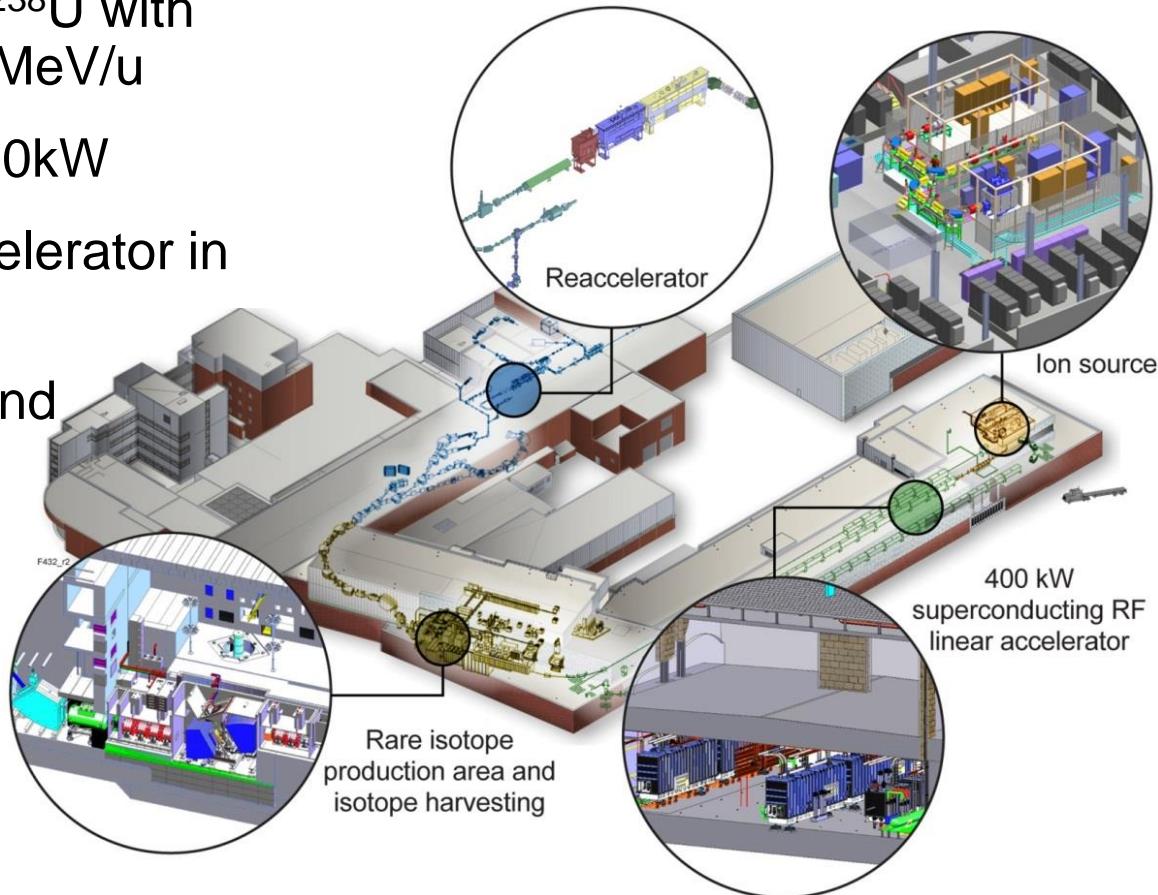
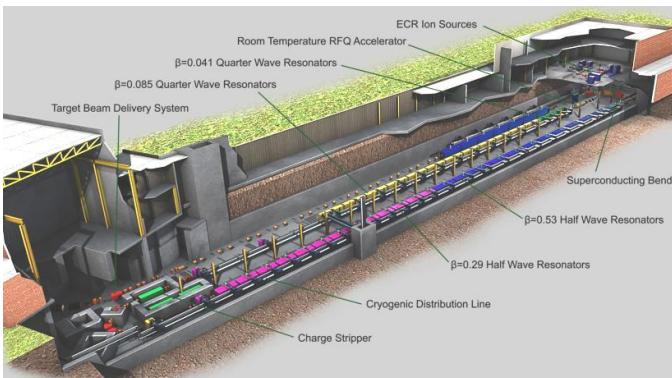
FRIB civil construction from March 2014



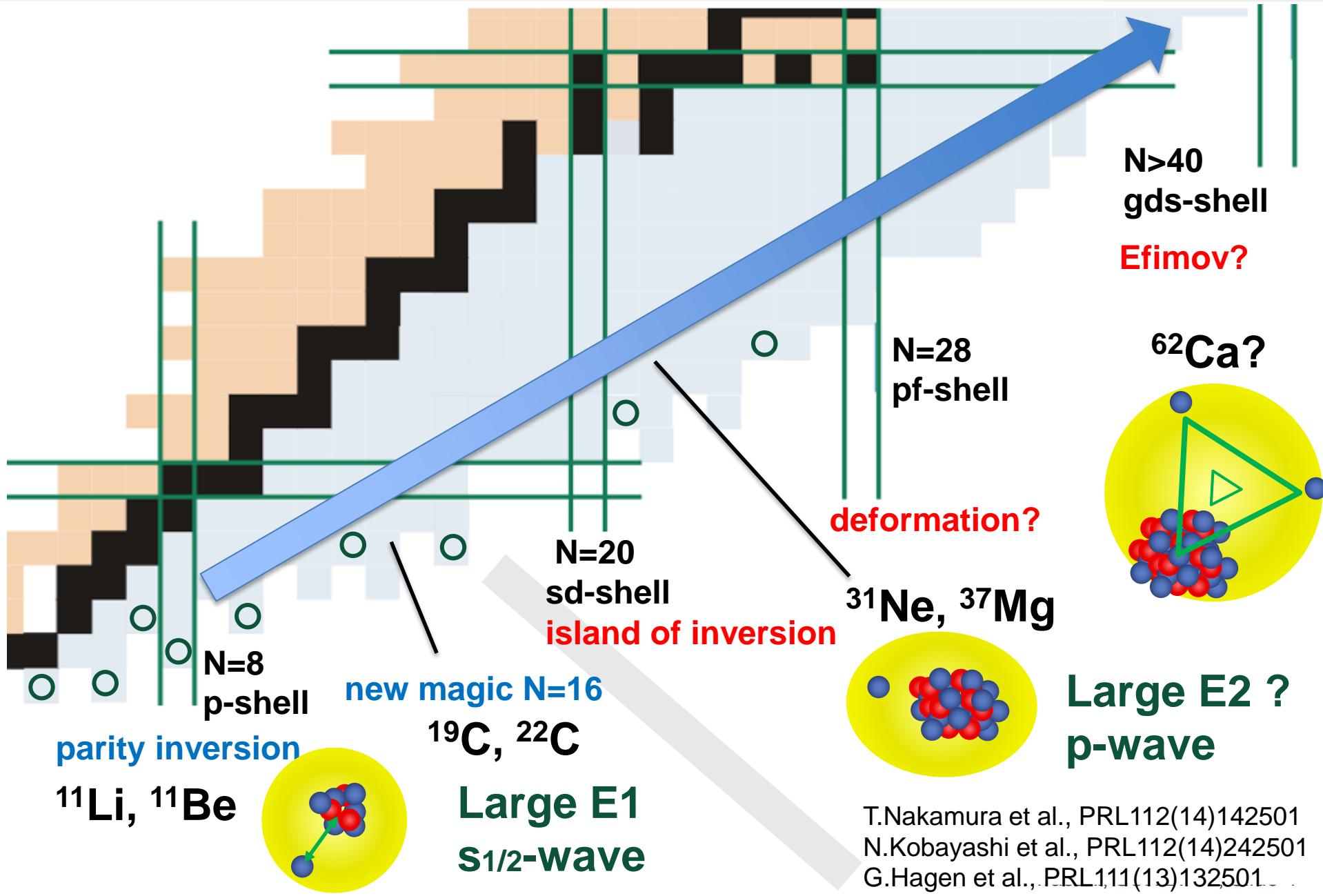
- FRIB construction site on November 4, 2016
- Web cameras at www.frib.msu.edu
- 10 Weeks Ahead of Baseline Schedule
- First beam from ARTEMIS ion source !

Facility for Rare Isotope Beams (FRIB)

- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide beam power up to 400kW
- Highest power heavy ion accelerator in the world
- Fast, stopped, thermalized, and reaccelerated beams

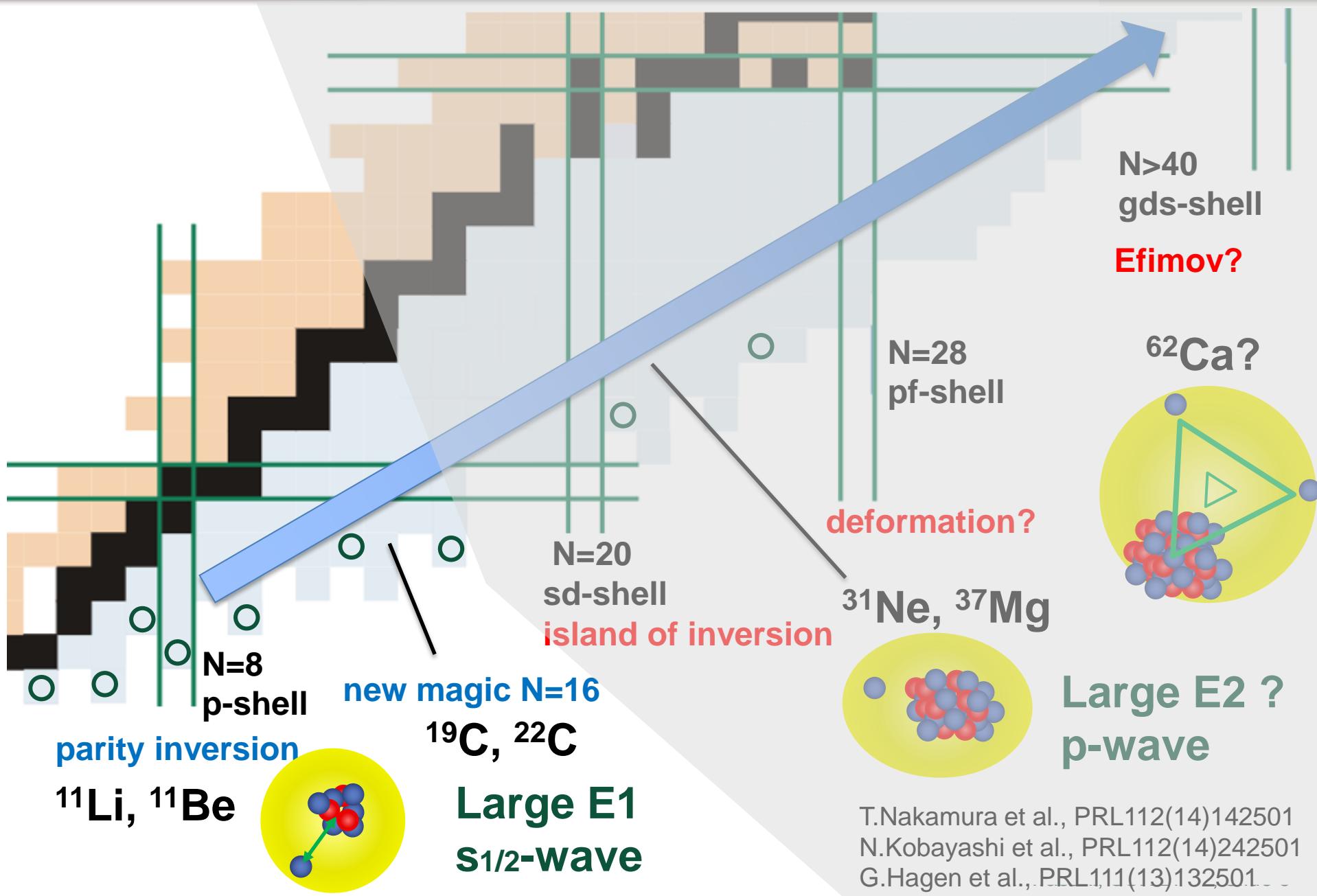


Evolution of halo properties

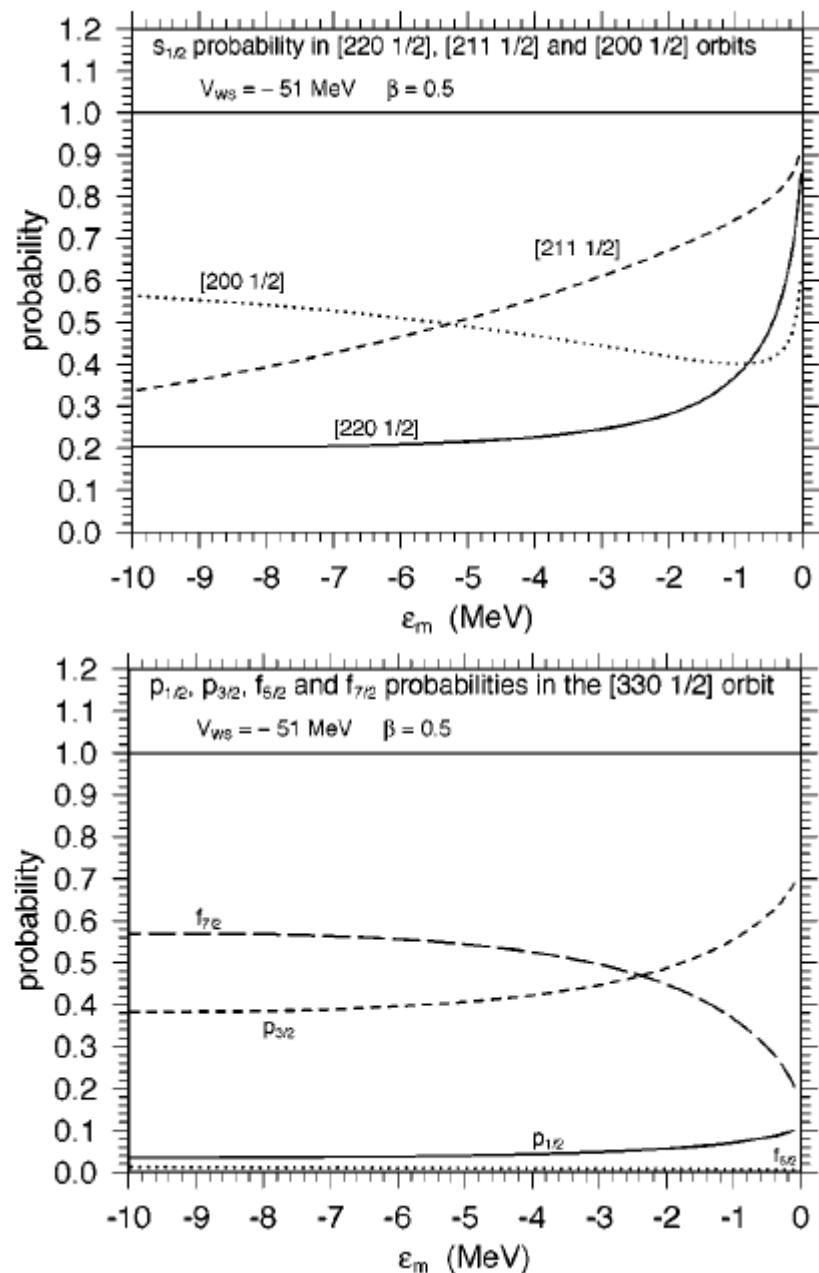


T.Nakamura et al., PRL112(14)142501
N.Kobayashi et al., PRL112(14)242501
G.Hagen et al., PRL111(13)132501

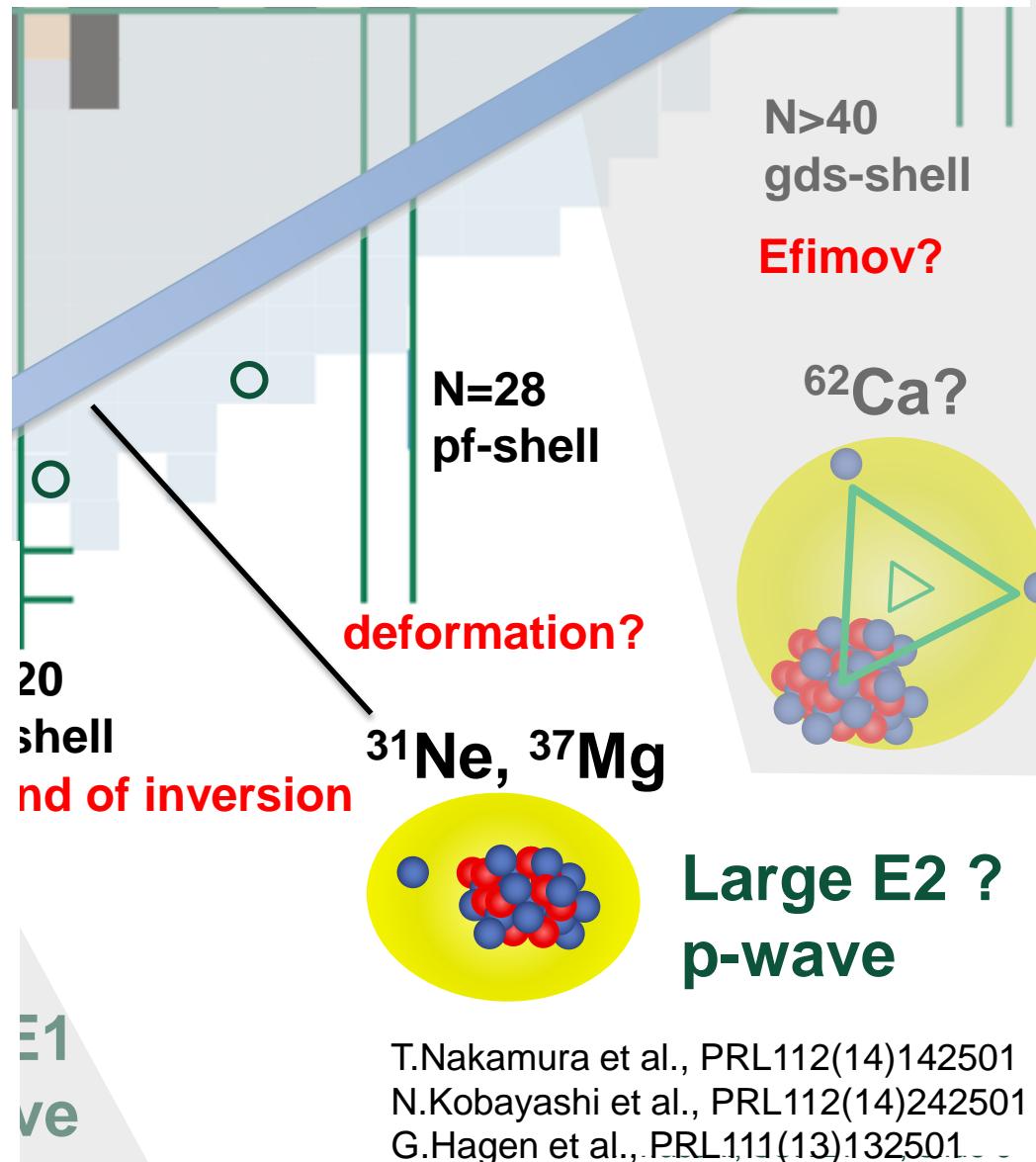
Evolution of halo properties – classic examples



Evolution of halo properties – deformed halo

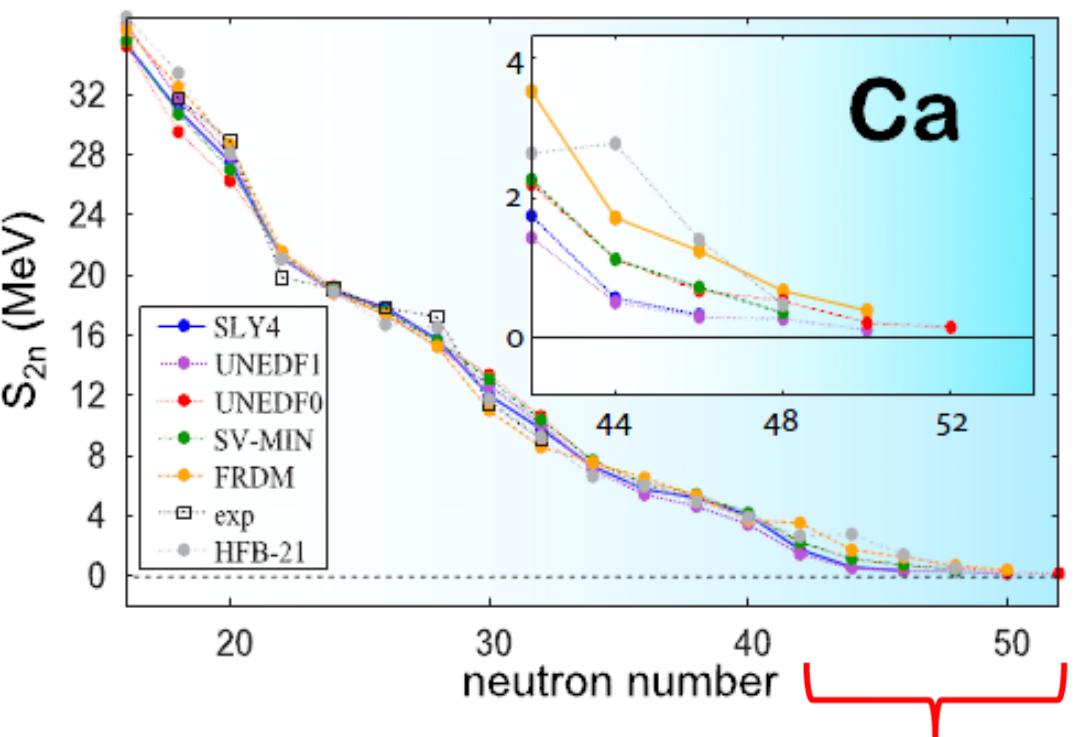


I.Hamamoto, Phys. Rev. C69, 041306(R) (2004)
T.Misu, W.Nazarewicz, S.Aberg, NPA 614, 44 (1997)

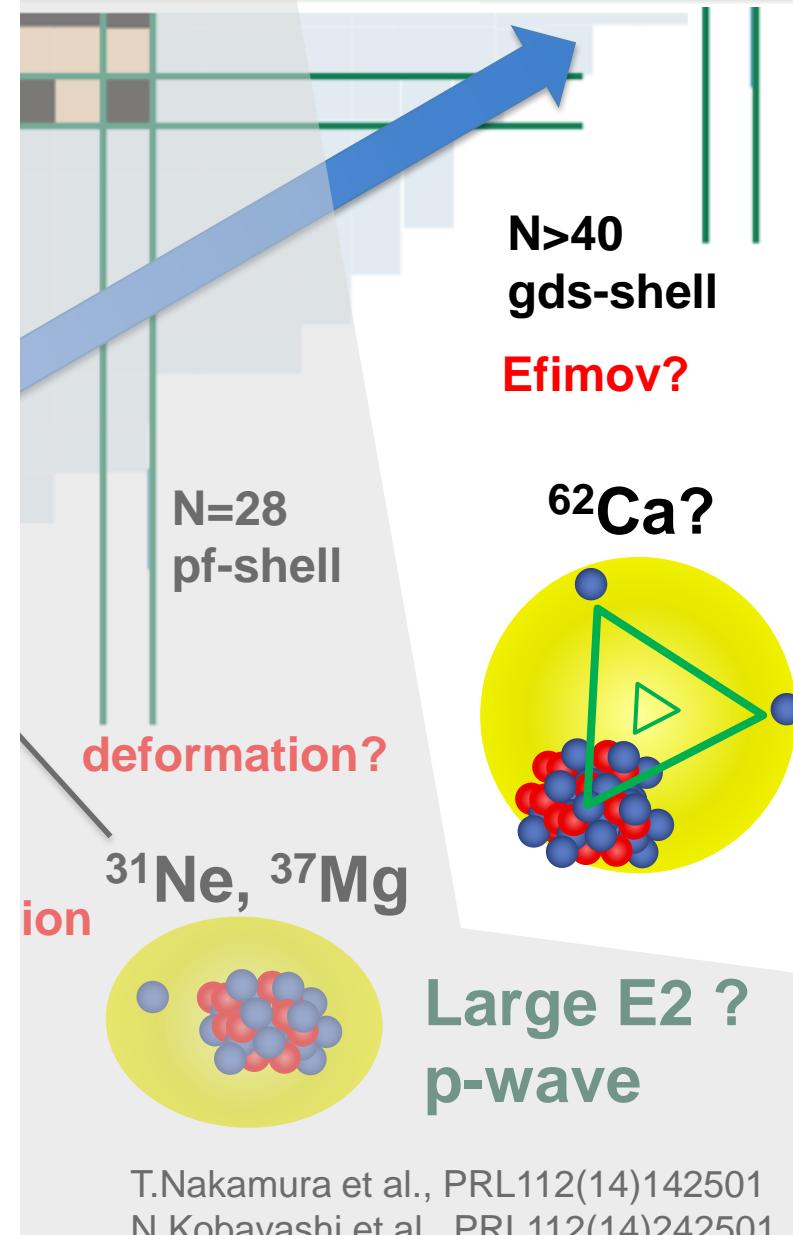


Evolution of halo properties – giant halo?

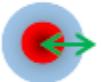
Predictions for Ca driplines
by state-of-the-art EDF calculations



all weakly
bound



Transition strengths and halo properties

Type of halo	Configuration of valence neutron	B(E1) established	B(M1) - <u>to be</u>	B(E2) <u>established-</u>	
Spherical 	Pure $s_{1/2} + \text{core } (0^+)$				 Enhanced
Deformed 	Mixed $(sd) \text{ or } (pf) + \text{core}$				 Favored (unhindered)  Hindered  Depend on core deformation

Large B(E1) – evidence for halo / skin

^{11}Be ($1/2^+ \rightarrow 1/2^-$) : $0.1 \text{ e}^2\text{fm}^2$, 0.36 W.u.

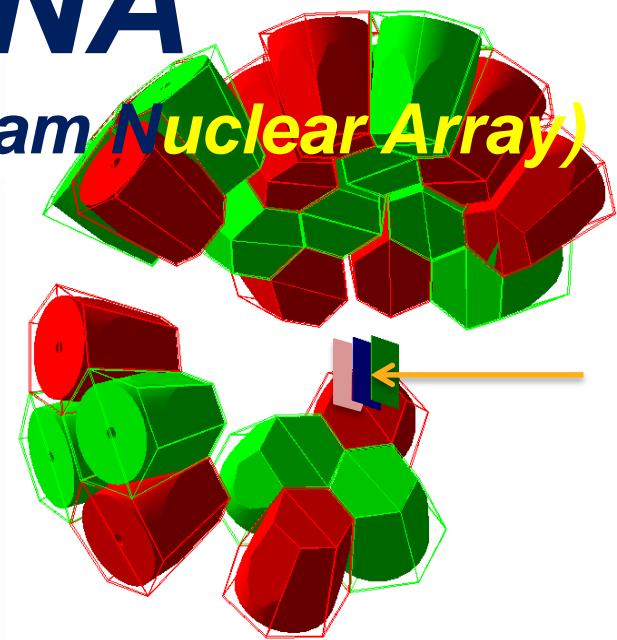
^{68}Ni PDR : $1.2\text{e}^2\text{fm}^2$, 1W.u. (5% of EWSR) O.Wieland et al., PRL102(09)092502

B(M1) B(E2) – characterize halo properties
(mixed, deformed configurations, etc)

New shapes and symmetries ?

Lifetime Measurements with GRETINA

(Gamma-Ray Energy Tracking In-beam Nuclear Array)

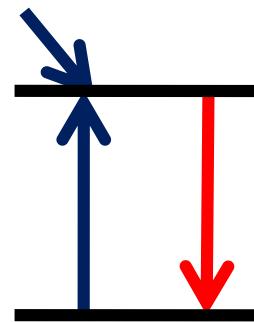
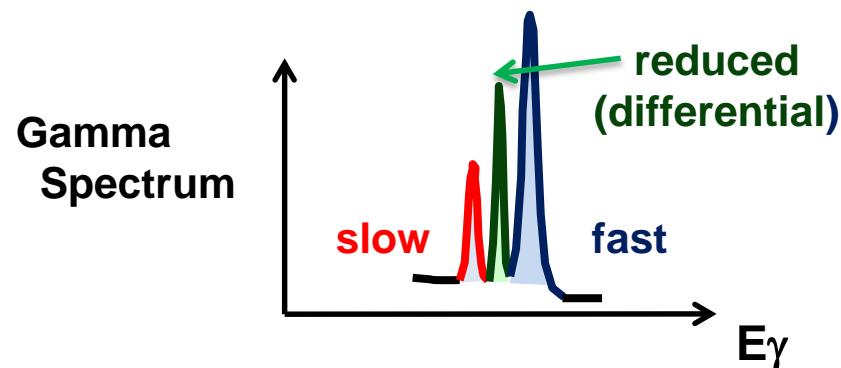
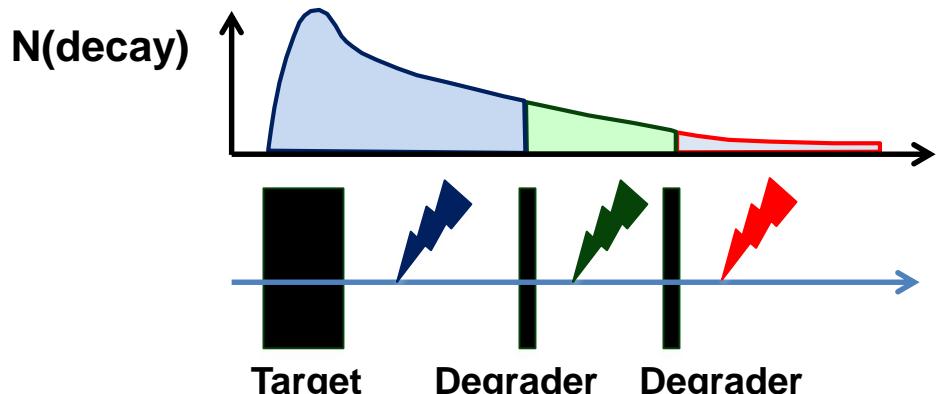


Recoil Distance Method with TRIPLEX

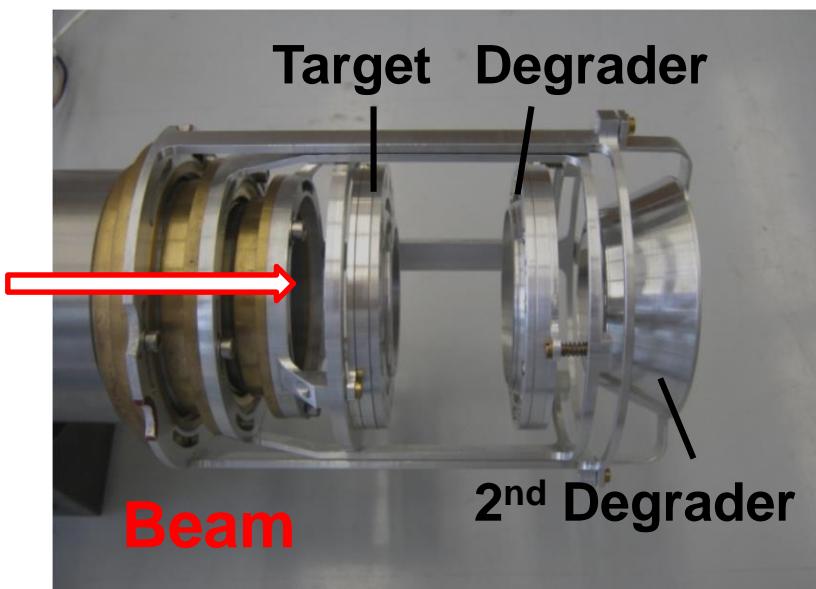
(TRIPLE PLUNGER for EXOTIC BEAMS)

H.Iwasaki et al., NIM A806 (2016) 123

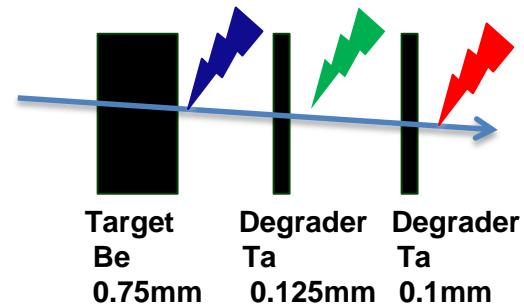
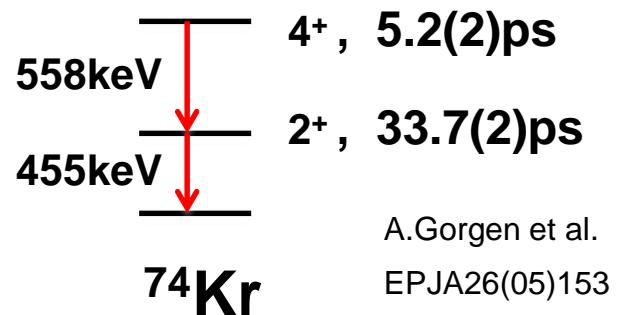
Model-independent approach to quantify transition rates of exotic nuclei with fast beams



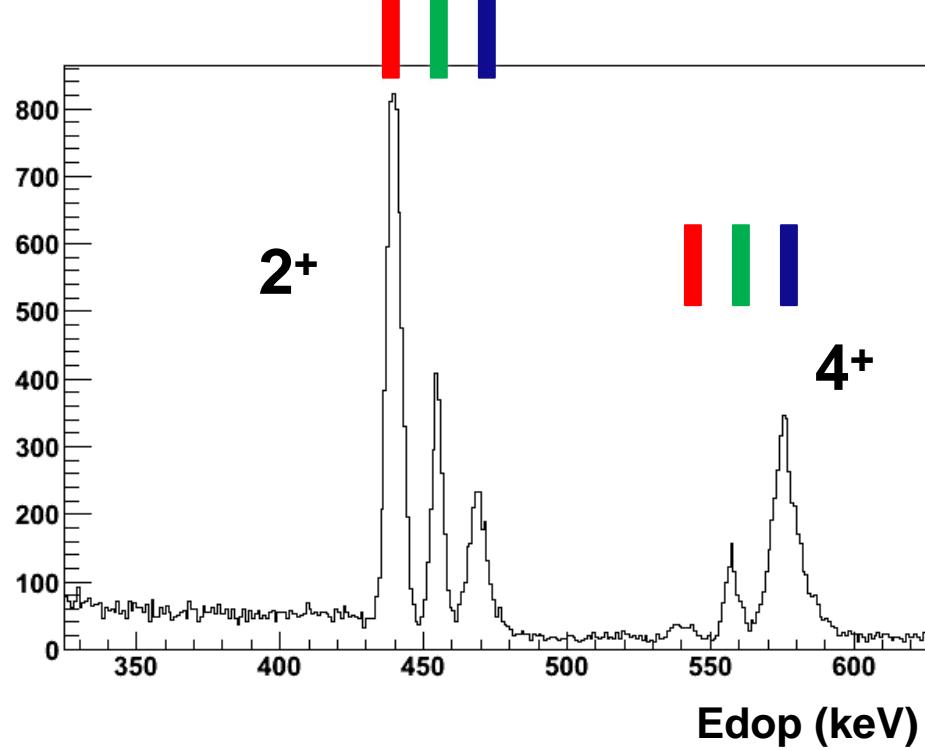
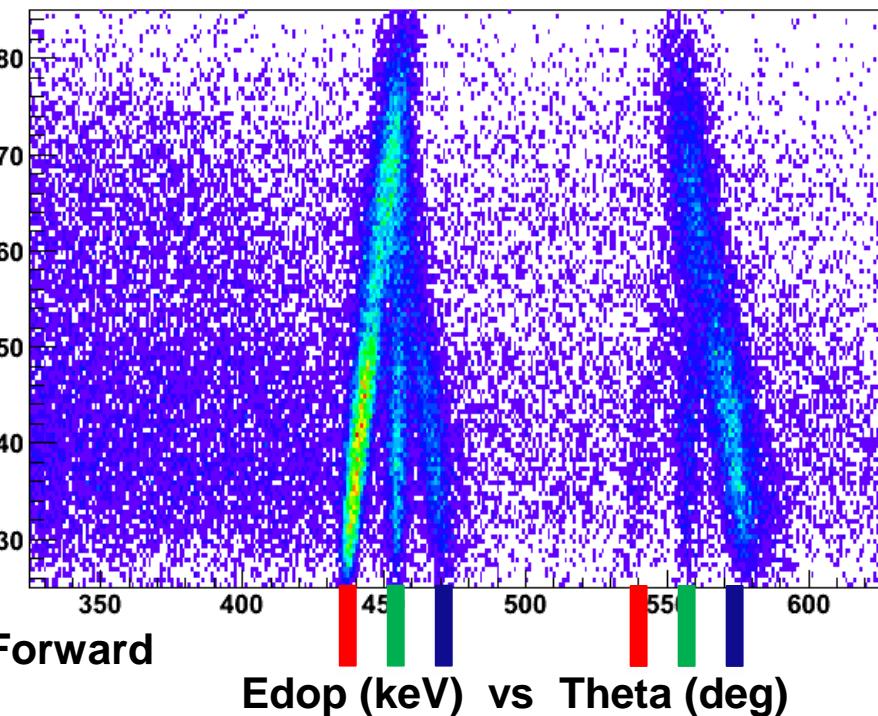
Lifetime
a sensitive probe
for nuclear
structure
... $B(E2)$, $B(M1)$



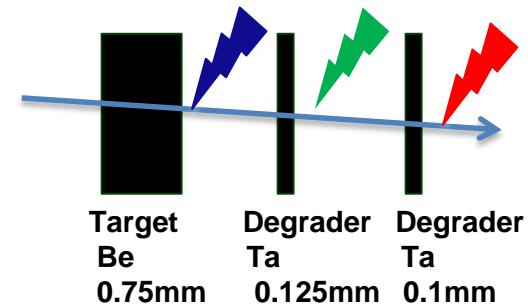
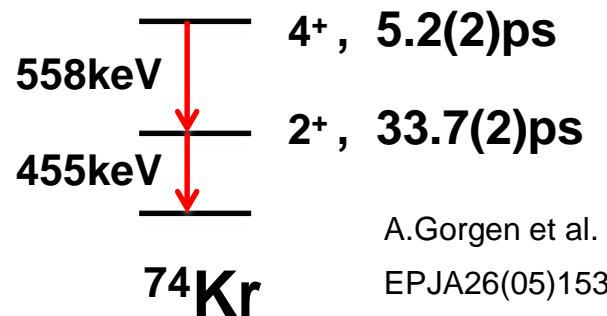
Simulated performance



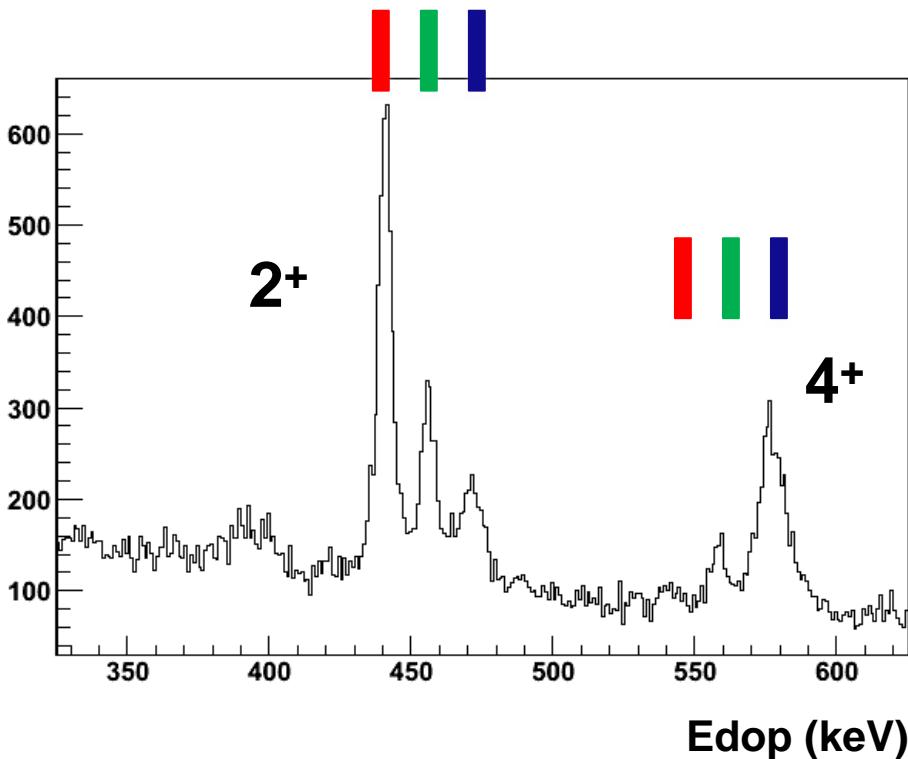
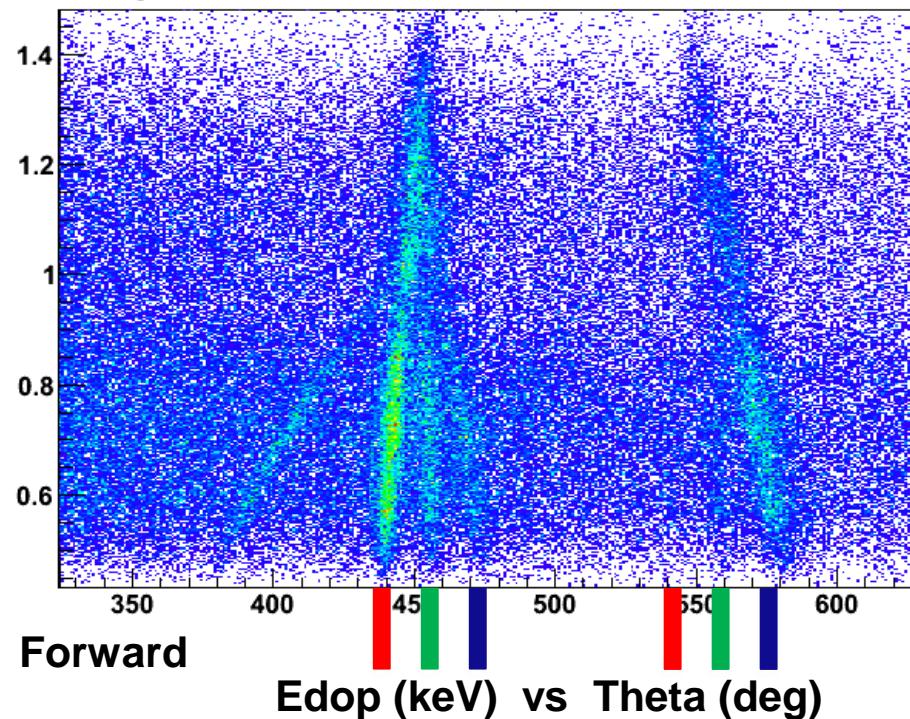
90 deg



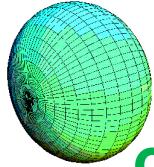
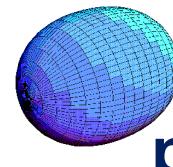
Measured performance



90 deg

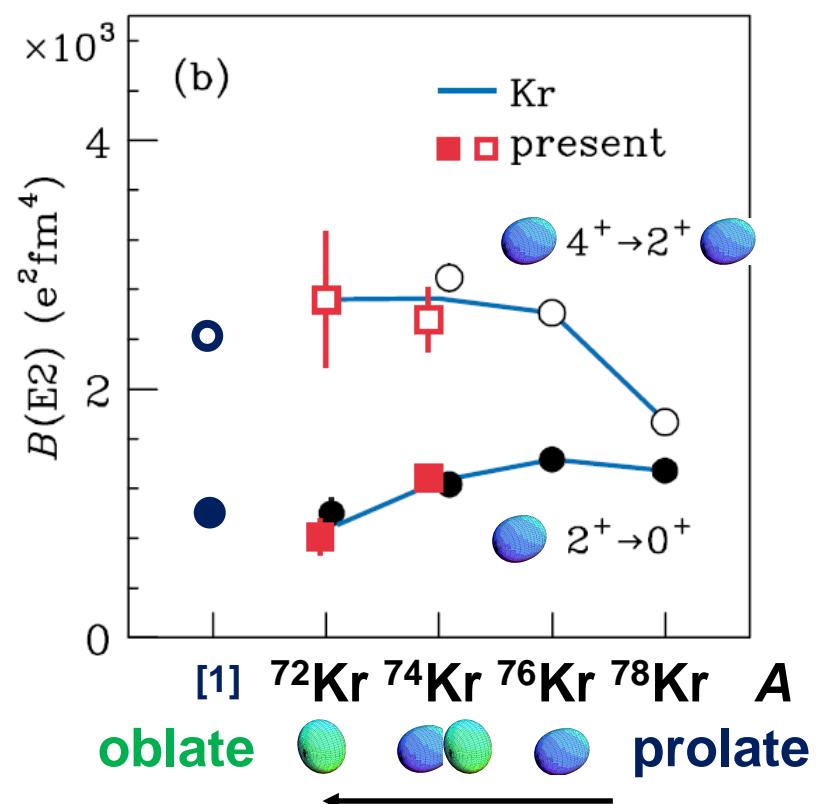
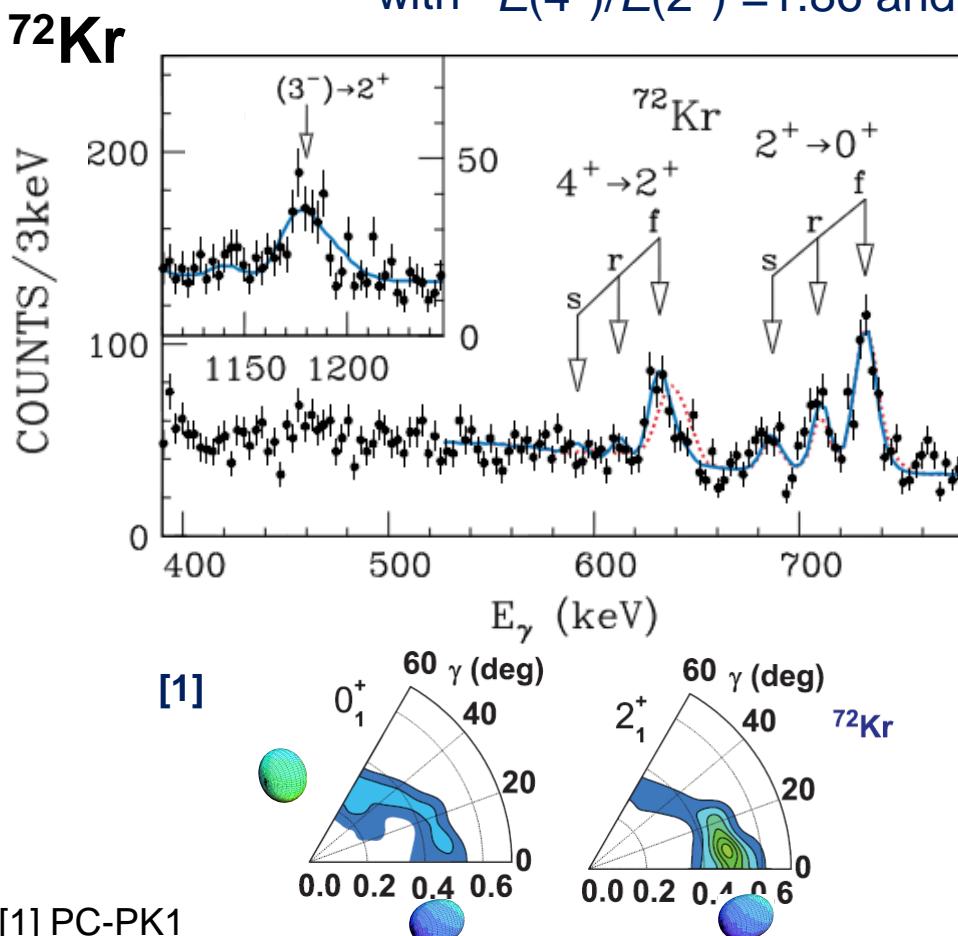


$E(2^+)$, $E(4^+)$ and $B(E2)$ systematics for Kr

Shape evolution between  and **oblate**  **prolate**

Rapid evolution of collectivity in ^{72}Kr

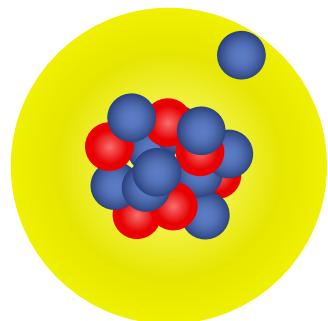
with $E(4^+)/E(2^+) = 1.86$ and $B(E2; 4^+ \rightarrow 2^+)/B(E2; 2^+ \rightarrow 0^+) = 3.4$



$^{74,76}\text{Kr}$: E.Clement et al., PRC 75 (07) 054313

^{72}Kr : H.Iwasaki et al., PRL114 (2014) 142502

Transition rates and Halo properties



Halo properties and responses

Nuclear halo

(new form of nuclei)

^{19}C ($1/2^+_{\text{gs}}$)

^{17}C ($1/2^+_{\text{ex}}$)

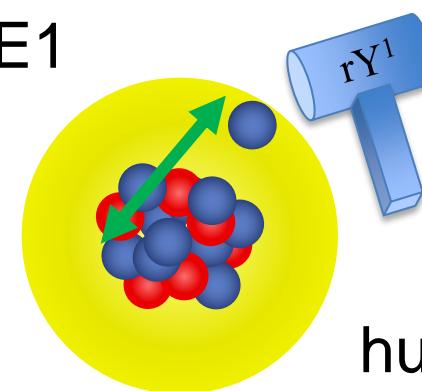
The ground state of ^{19}C is suggested to have the **s-wave** halo character from:

- Mass (binding energy)
- Radius (interaction cross sections)
- Coulomb dissociation (E1)
- (p, p'), knock out, etc

but dynamical (electromagnetic) properties are not well understood:

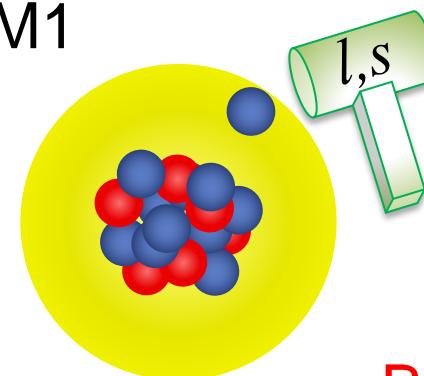
- **M1 transition strength**

E1



huge $B(E1)$

M1



$B(M1) ?$

core(0^+) \times decoupled $s_{1/2}$

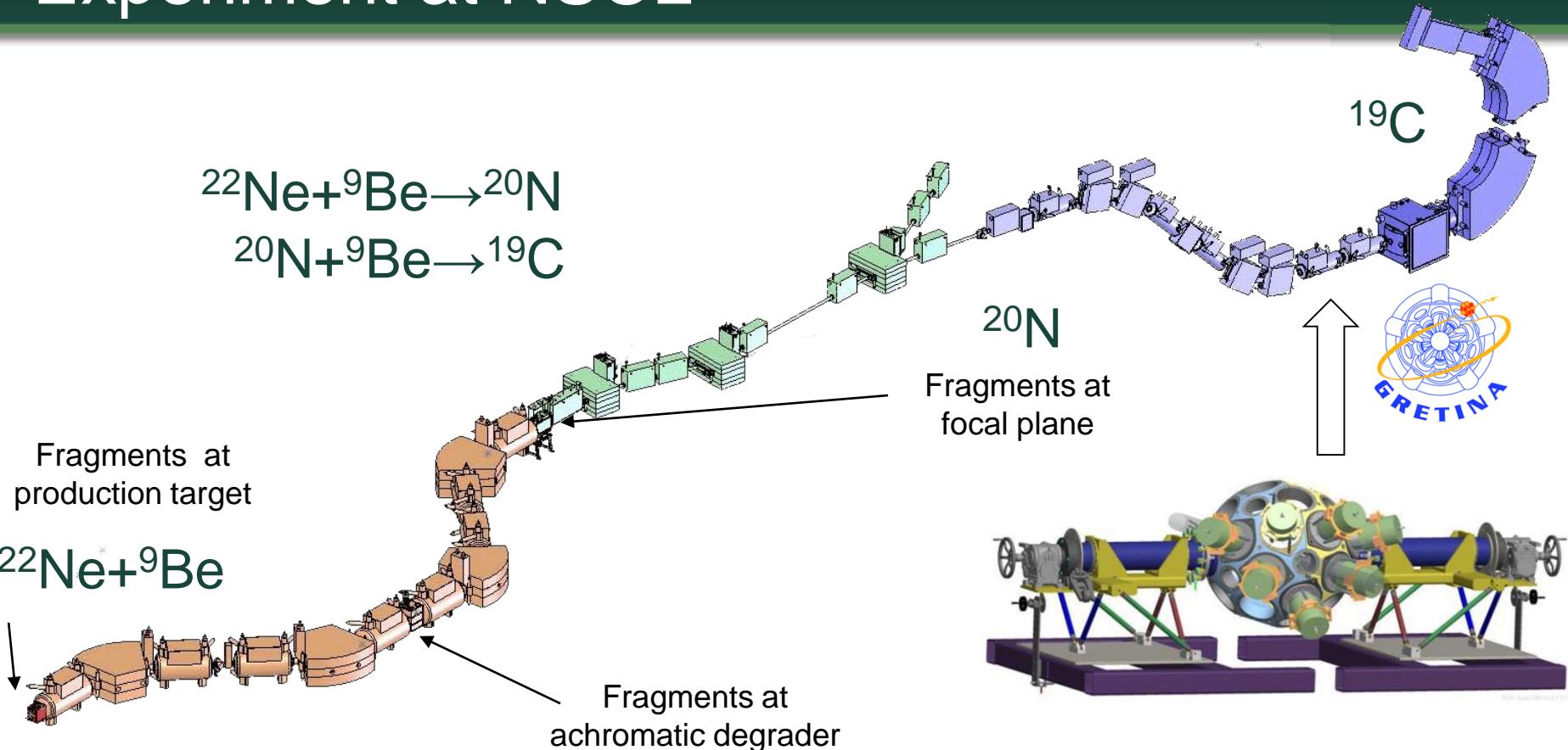
Experiment at NSCL



Fragments at production target



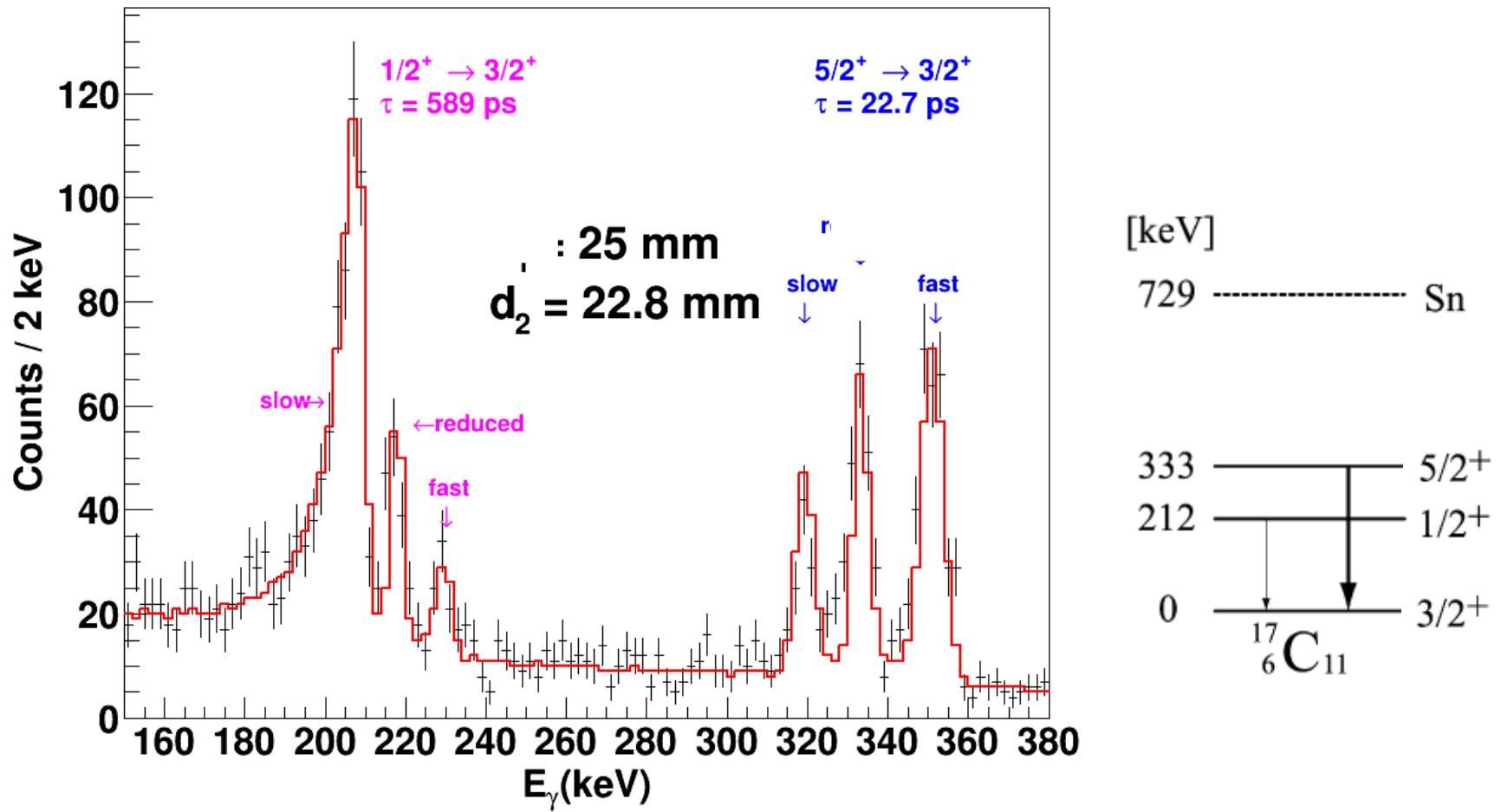
Fragments at achromatic degrader



Driver accelerator

- Fragment separator (A1900 NSCL, FRS GSI, BigRIPS RIKEN, LISE GANIL)
- Identification and beam transport
 - Fast, stopped, re-accelerated beam experiments
 - Secondary reaction, Reaction product identification (S800 spectrograph)

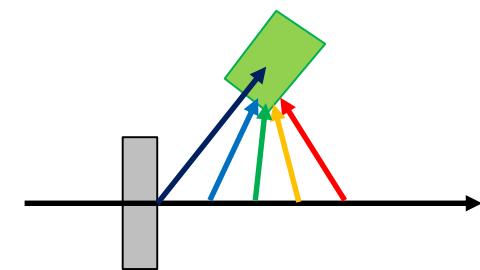
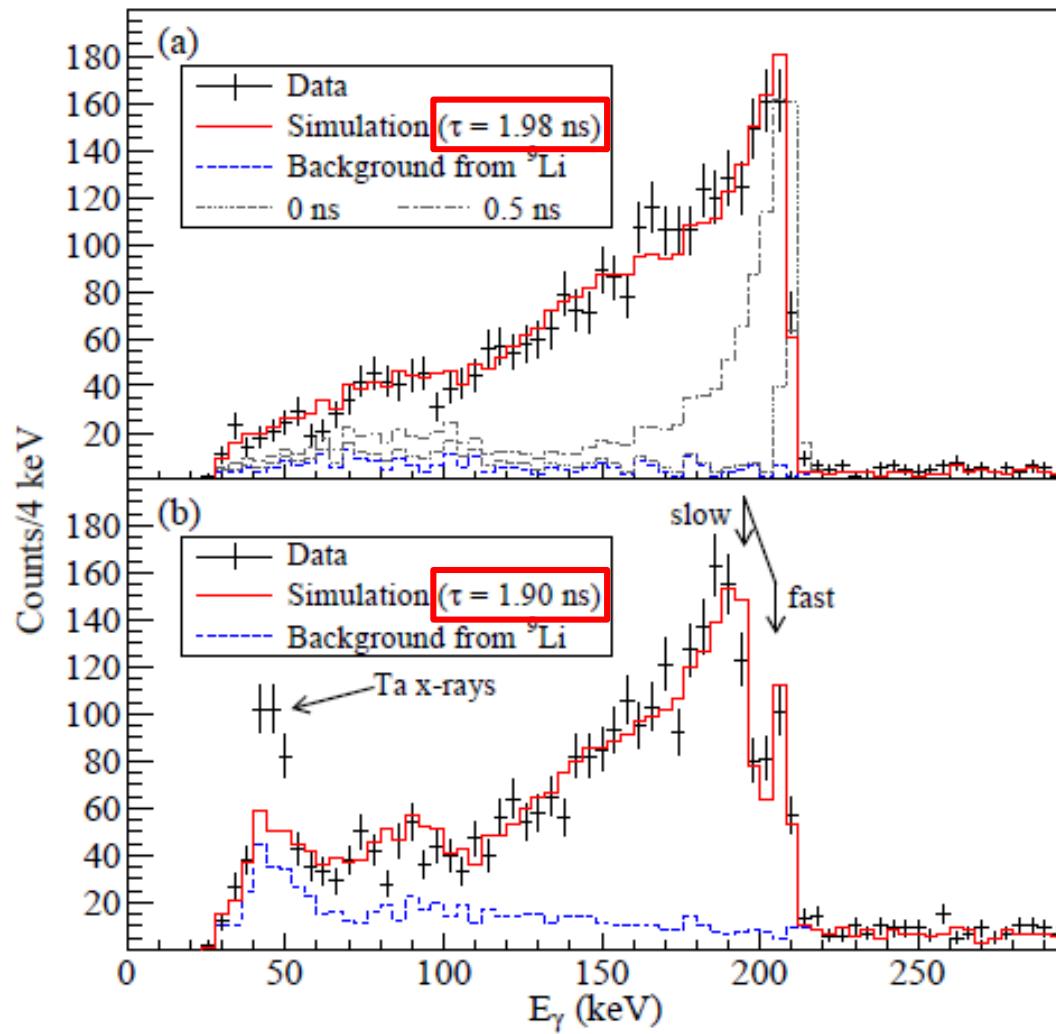
Measured spectrum for ^{17}C



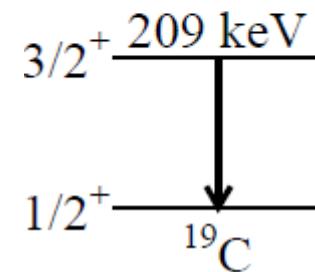
D.Smalley, H.I. et al., PRC92(15)064314
D.Suzuki, H.I. et al., PLB666(08)222

Transition	E_γ (keV)	τ (ps)	$B(M1)$ ($\times 10^{-2} \mu_N^2$)
			present previous
$1/2^+ \rightarrow 3/2_{gs}^+$	218 ± 1	528^{+21}_{-14}	$1.04^{+0.03}_{-0.12}$
$5/2^+ \rightarrow 3/2_{gs}^+$	332 ± 1	$21.8^{+3.4}_{-3.3}$	$7.12^{+1.27}_{-0.96}$

Measured spectrum for ^{19}C

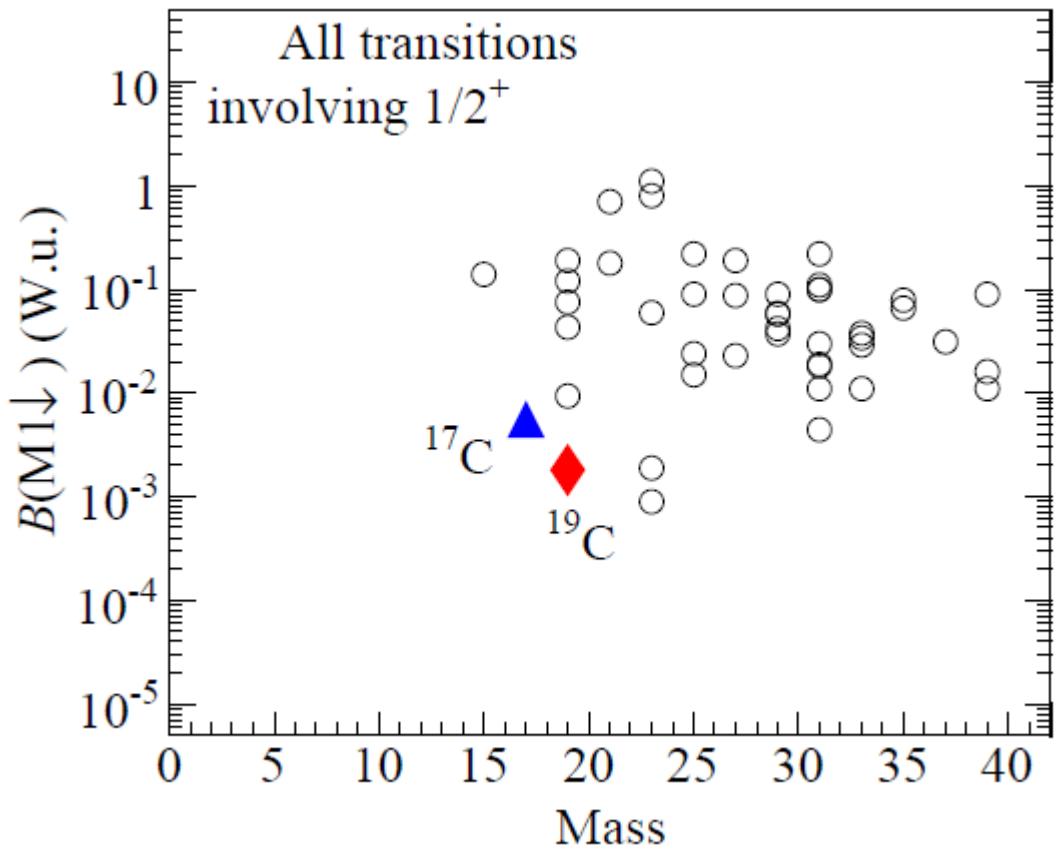
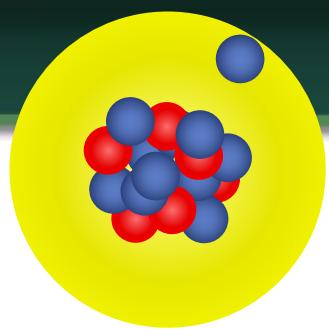


S_n 580 keV



$$B(\text{M}1) = 3.21(25) \times 10^{-3} \text{ mN}^2$$

Hindered B(M1) for $^{17,19}\text{C}$

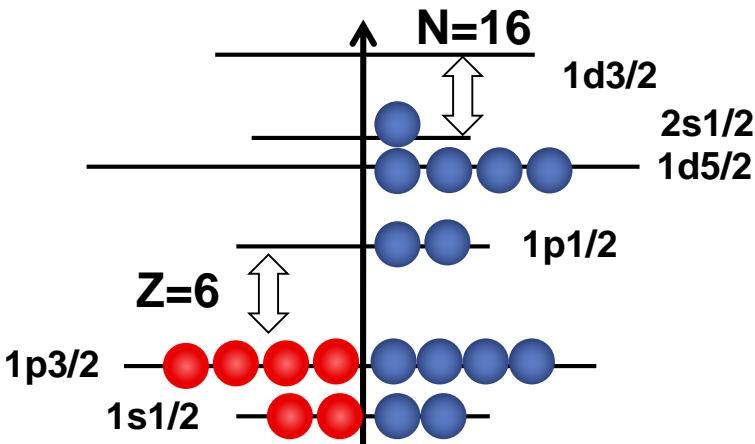


$$|^{19}\text{C}(1/2^+) \rangle = \alpha |(d_{5/2})_{J=0+}^4 \otimes (s_{1/2}) \rangle + \dots$$

$$|^{19}\text{C}(3/2^+) \rangle = \beta |(d_{5/2})_{J=2+}^4 \otimes (s_{1/2}) \rangle + \gamma |(d_{5/2})_{J=3/2+}^3 \otimes (s_{1/2})^2 \rangle + \dots$$

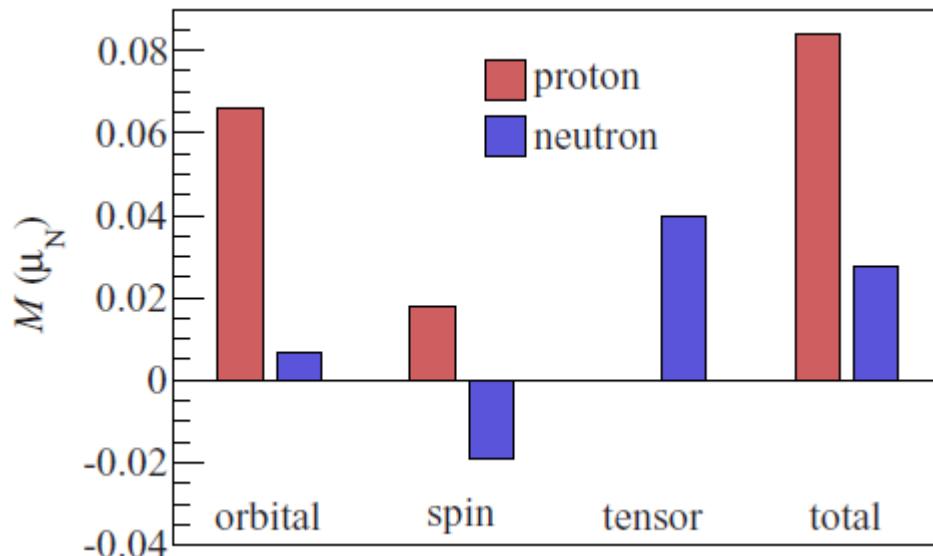
Strongly hindered M1, “spin” response, due to the dominant core(0^+) \times decoupled $s_{1/2}$ (one neutron halo) configuration

$s_{1/2} \leftrightarrow d_{3/2}$ *I-forbidden* M1

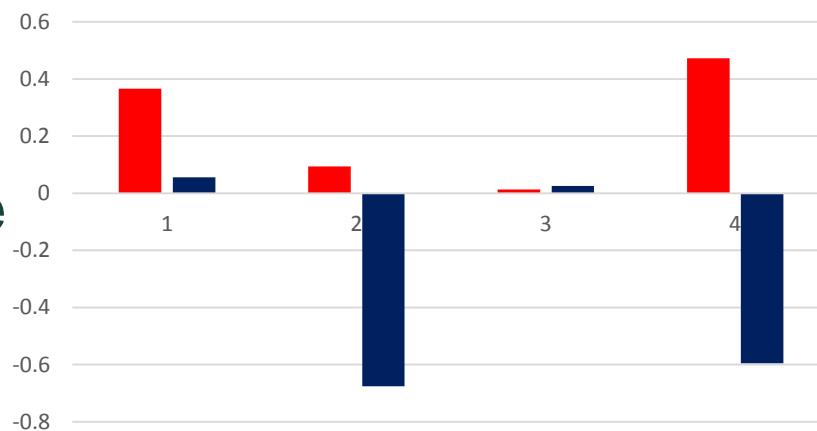


Decomposition of the M1 strength

^{19}C



^{23}Mg
as a
reference



: $M1$ operator is

$$(M1)^{\text{op}} = \sqrt{\frac{3}{4\pi}} \sum_{i,\tau_z} \{ g_{s\tau_z} \vec{s}_{i,\tau_z} + g_{\ell\tau_z} \vec{\ell}_{i,\tau_z} \\ + g_{t\tau_z} \sqrt{8\pi} [Y^2(\hat{r}_{i,\tau_z}) \otimes \vec{s}_{i,\tau_z}]^{(1)} \} \mu_N$$

W.A.Richter, S.Mkhize,
and B.A.Brown.,
PRC78(08)064302

**Measurements for
heavier weakly-bound
 $^{25-33}\text{Ne}$, $^{37-40}\text{Mg}$, $^{58-60}\text{Ca}$...**

Summary

- The advent of rare isotope beams opens the possibility to study exotic nuclei which are more neutron-rich or neutron-deficient compared to stable nuclei in nature, revealing unexpected properties such as nuclear shell and shape evolution and emergence of halos.
- Recent development of the next-generation gamma-ray tracking array GRETINA further enables spectroscopic studies to observe unique forms and dynamics of new, exotic isotopes.
- As such examples, studies of magnetic response in halo nuclei are presented and the hindered M1 transitions in the neutron-rich $^{17,19}\text{C}$ isotopes have been discussed as unique phenomena characteristic of exotic nuclei.

Collaborators in GRETINA lifetime studies

LBNL

: I-Yang Lee, A.Macchivelli, P.Fallon, R.Clark,
C.Campbell, M.Cromaz, H.Crawford



DOE

Thennessee
SFU/TRIUMF

: D.Miller, R.Grzywacz, M.Madurga, K.Kolos,
: P.Voss TRIUMF: P.Navratal TU-Darmstadt : R.Roth
J.Langhammer

Cologne
York

: A.Dewald, T.Braunroth
: R.Wadsworth

U.of Tokyo : T.Otsuka
T.Suzuki

CMU

: K.Wimmer, A.Westerberg, C.Bancroft, D.Barofsky, J.Lloyd

BNL

: E.McCutchan, T.Johnson, A.Sonzogni,

UoM, Lowell

: C.Lister, P.Chowdhury, V.singh, E.Merchan

FSU

: I.Wiedenhoever, P.Cottle, M.Riley, D.Santiago, J.Parker

GANIL

: A.Lemasson

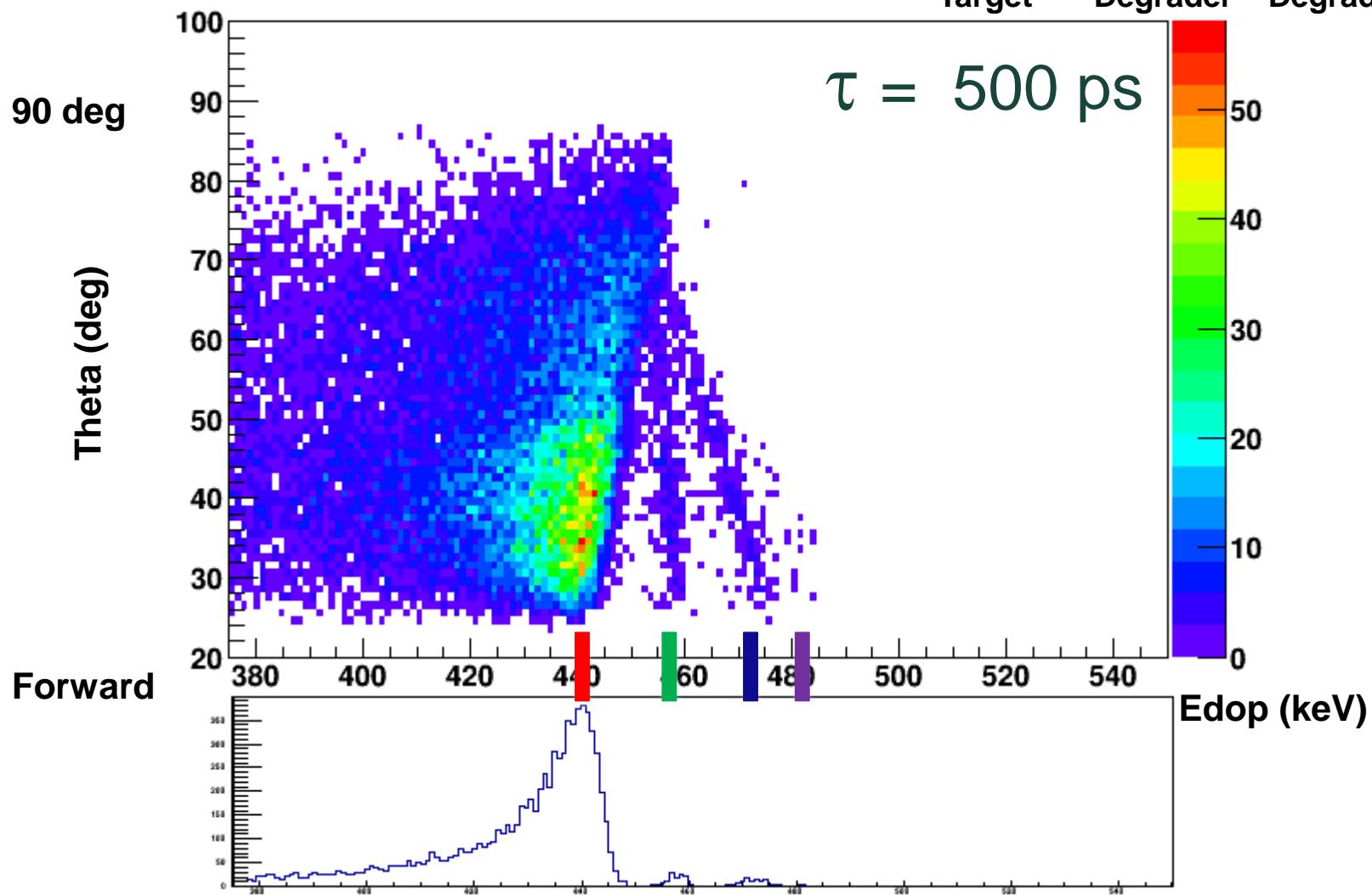
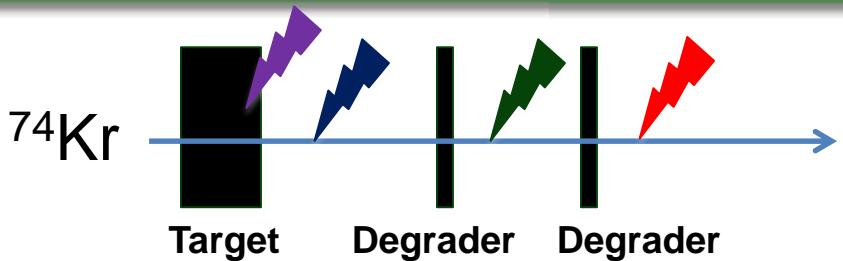
NSCL

: C.Morse, K.Whitmore, C.Loelius, D.Smalley, A.Brown,
A.Gade, D.Weisshaar, D.Bazin, J.Berryman, T.Baugher,
S.Strogerg, V.Bader, E.Lunderberg, C.Langer, F.Recchia



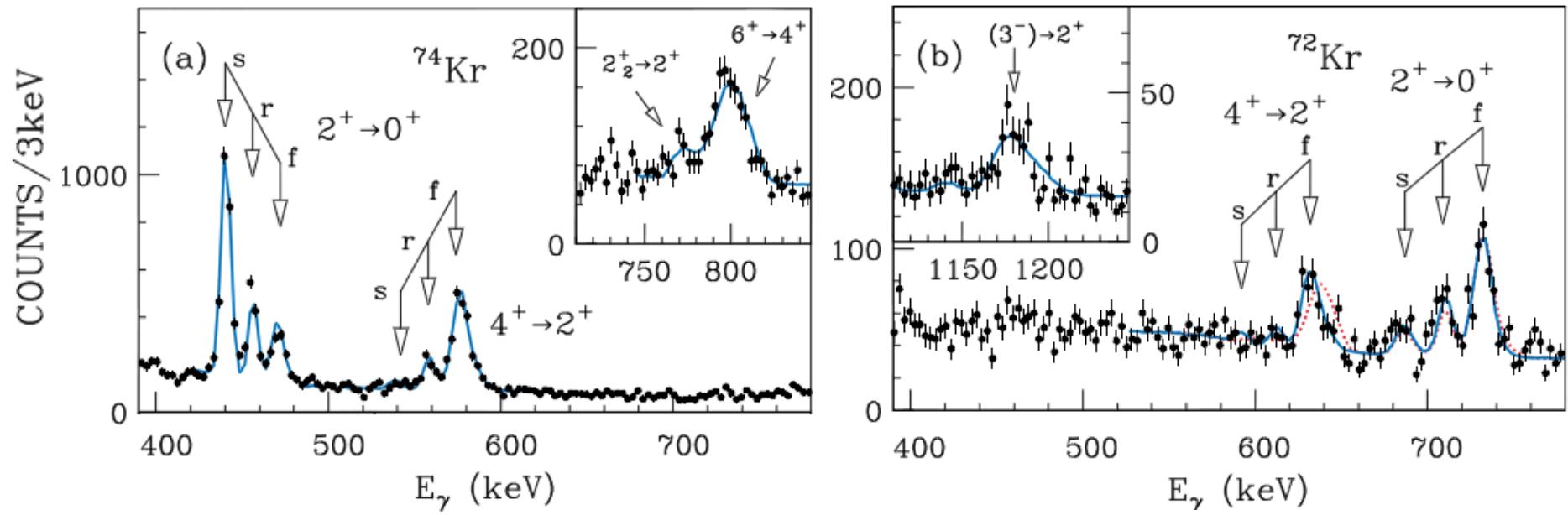
Thank you

Sensitivity to lifetime



Results for ^{74}Kr and ^{72}Kr

**Model independent
B(E2) determination**

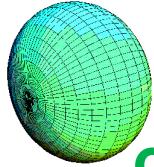
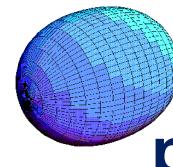


A	Transition	E_γ (keV)	τ_{exp} (ps)	B(E2) present	B(E2) previous
^{74}Kr	$2^+ \rightarrow 0^+$	455.6	32.2(22)	1290(90)	1223(22) [1]
	$4^+ \rightarrow 2^+$	557.7	5.9(6)	2560(260)	2895(111) [1]
^{72}Kr	$2^+ \rightarrow 0^+$	709.7	5.6(10)	810(150)	999(129) [2]
	$4^+ \rightarrow 2^+$	611.7	3.5(7)	2720(550)	...

H.Iwasaki et al., PRL112 (2014) 142502

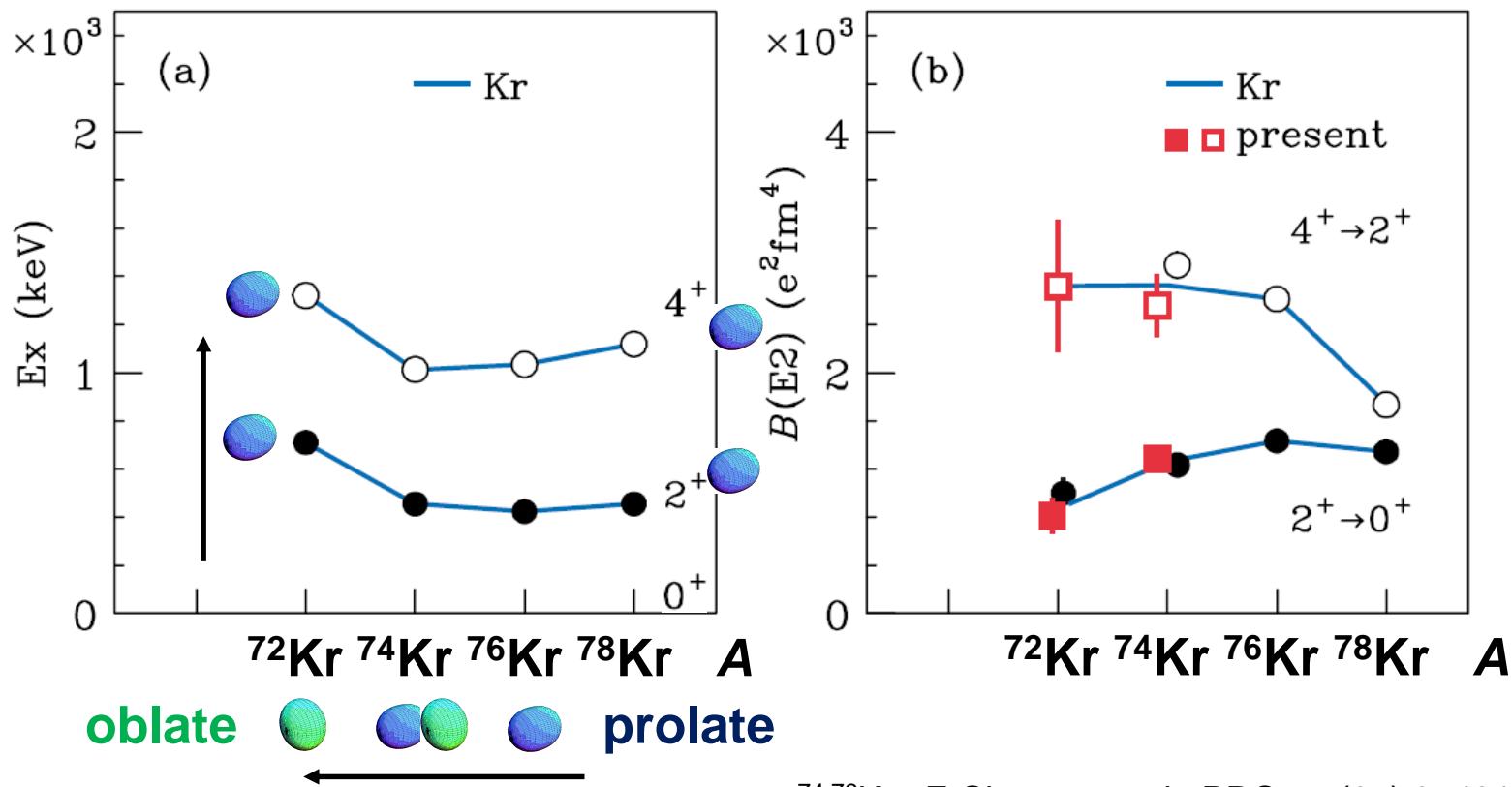
[1] A.Gorgen et al., EPJA 26 (2005) 153
[2] A.Gade et al., PRL95 (2005) 022502

$E(2^+)$, $E(4^+)$ and $B(E2)$ systematics for Kr

Shape evolution between  and **oblate**  **prolate**

Rapid evolution of collectivity in ^{72}Kr

with $E(4^+)/E(2^+) = 1.86$ and $B(E2;4^+\rightarrow 2^+)/B(E2;2^+\rightarrow 0^+) = 3.4$



$^{74,76}\text{Kr}$: E.Clement et al., PRC 75 (07) 054313

*) e.g. ^{72}Kr : H.Dejbakhsh et al., PLB249(1987)195, H.Iwasaki et al., PRL114 (2014) 142502

Lowering $s_{1/2}$ orbit characteristic of C

Main neutron configuration
 ^{17}C

$$|^{17}\text{C}(1/2^+)> = \alpha |(d_{5/2})_{J=0}^2 \otimes (s_{1/2})> + \dots$$

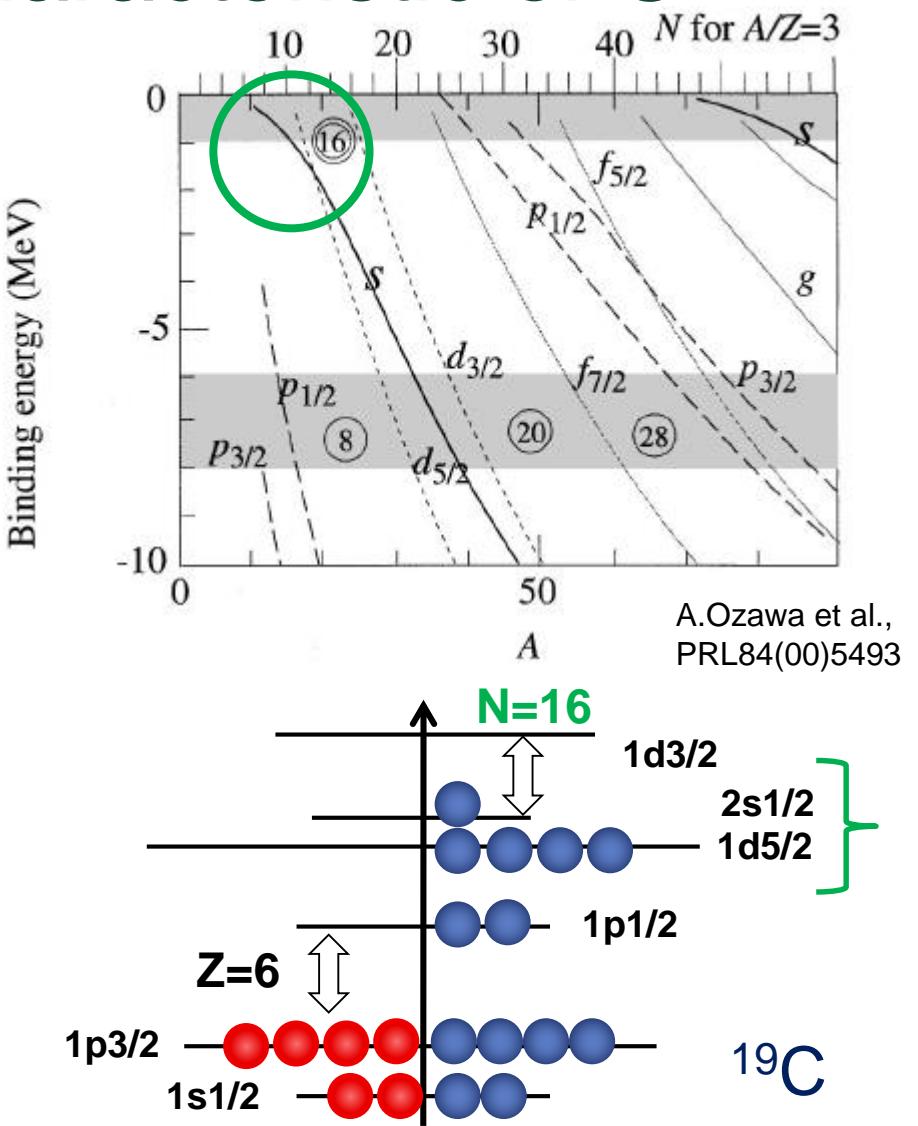
$$|^{17}\text{C}(3/2_{g.s.}^+)> = \beta |(d_{5/2})_{J=2}^2 \otimes (s_{1/2})> + \gamma |(d_{5/2})_{J=3/2}^3 \otimes (s_{1/2})> + \dots$$

^{19}C

$$|^{19}\text{C}(1/2^+)> = \alpha |(d_{5/2})_{J=0}^4 \otimes (s_{1/2})> + \dots$$

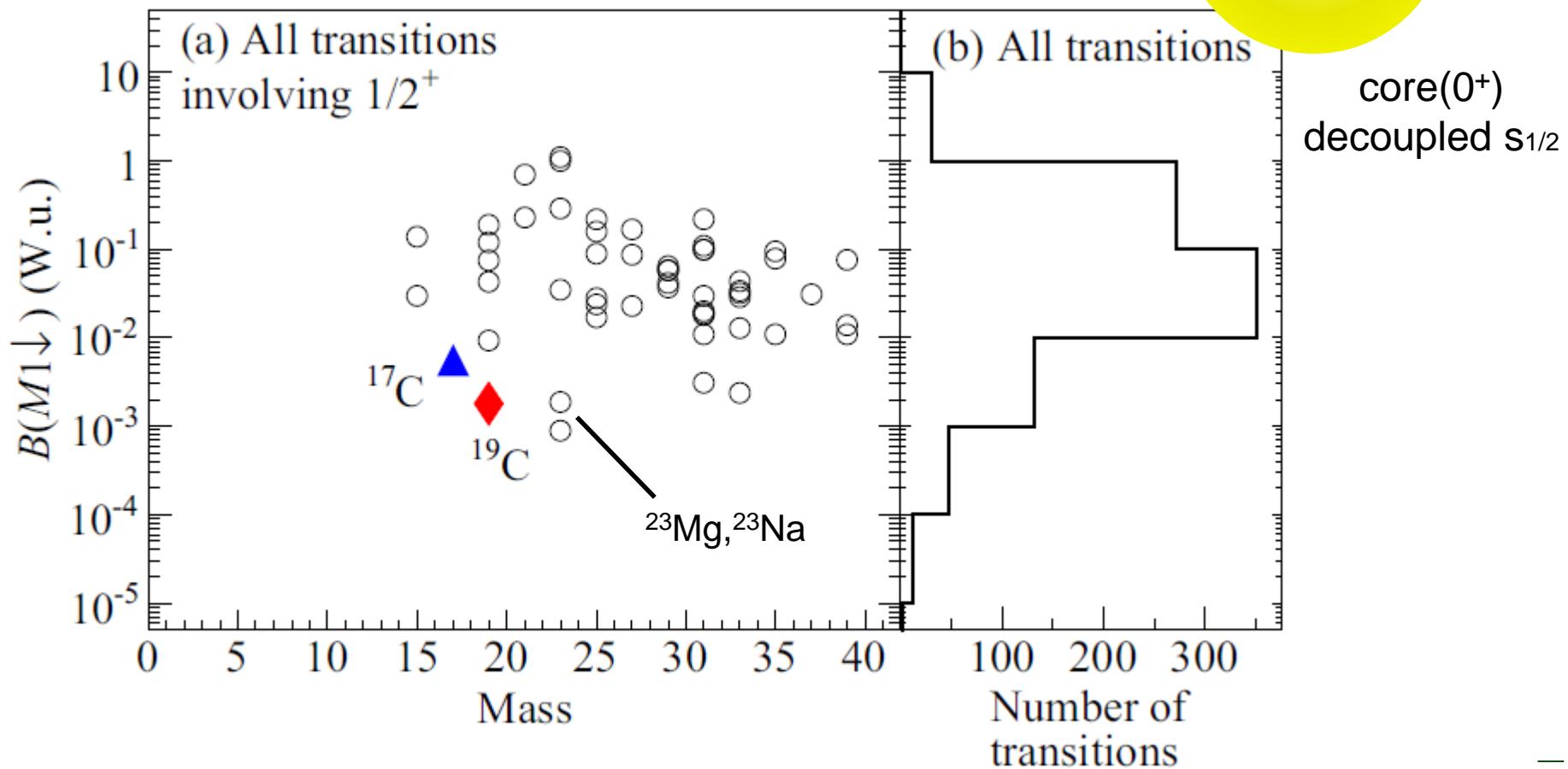
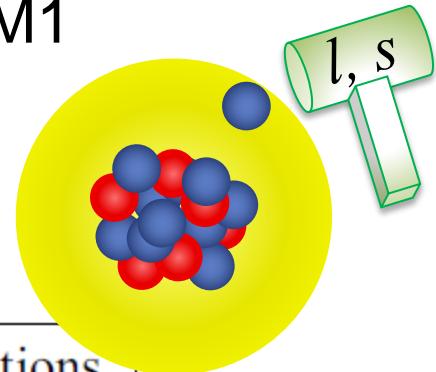
$$|^{19}\text{C}(3/2^+)> = \beta |(d_{5/2})_{J=2}^4 \otimes (s_{1/2})> + \gamma |(d_{5/2})_{J=3/2}^3 \otimes (s_{1/2})^2 > + \dots$$

$$\alpha^2 = 50\text{-}60\% \quad \beta^2 = \gamma^2 = 20\text{-}40\%$$



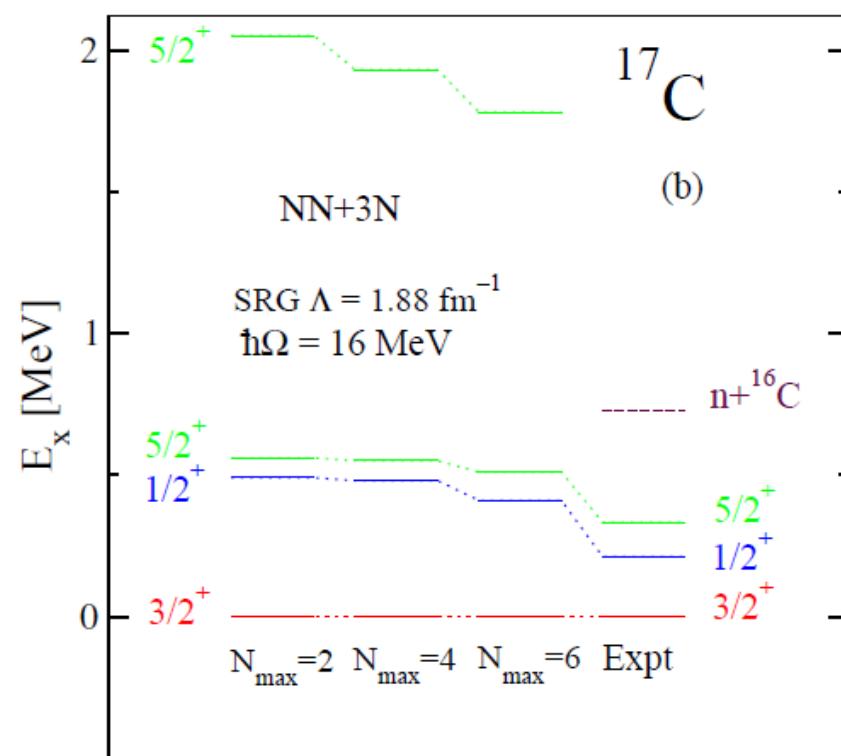
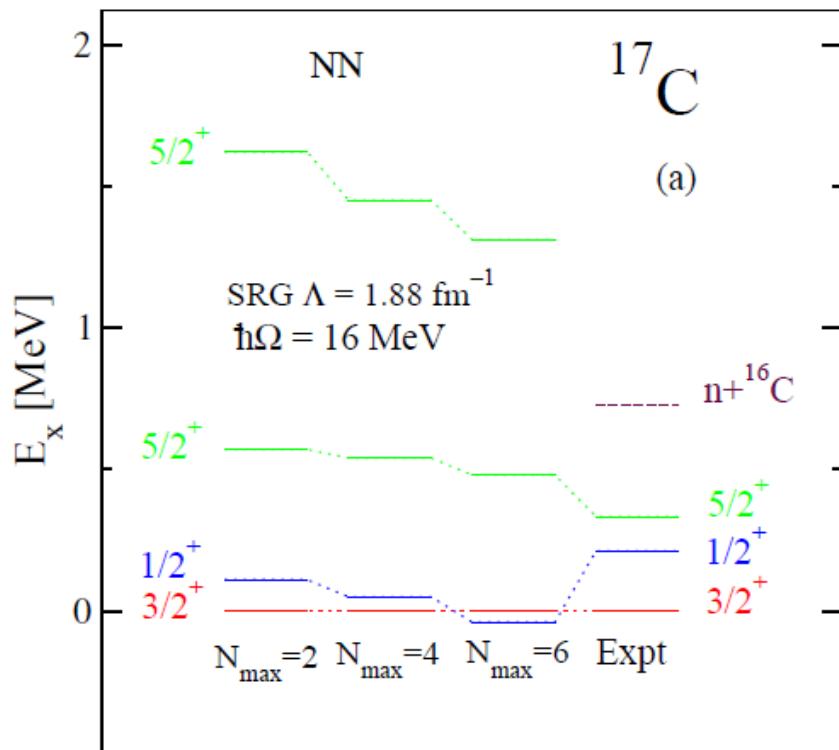
Hindered B(M1) for $^{17,19}\text{C}$

M1



Comparison with ab-initio calculations IT-NCSM and IT-NCSMC calculations

(by P.Navratil, R.Roth, J.Langhammer)

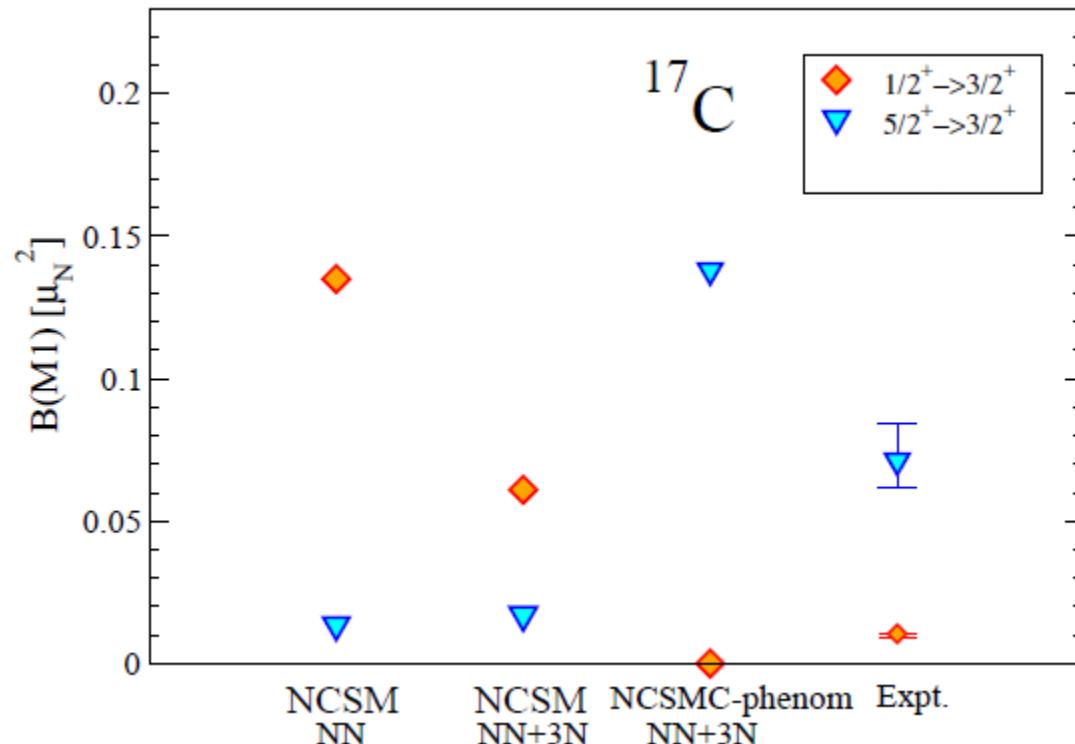


R.Roth and P.Navratil, Phys. Rev. Lett. 99 (2007) 092501
J.Langhammer et al., Phys. Rev. C 91 (2015) 021301 (R)

Comparison with ab-initio calculations

IT-NCSM and IT-NCSMC calculations

(by P.Navratal, R.Roth, J.Langhammer)



$$|\Psi_A^{J\pi T}\rangle = \sum_{\lambda} c_{\lambda} |A\lambda J^{\pi} T\rangle \quad (\text{A-body})$$

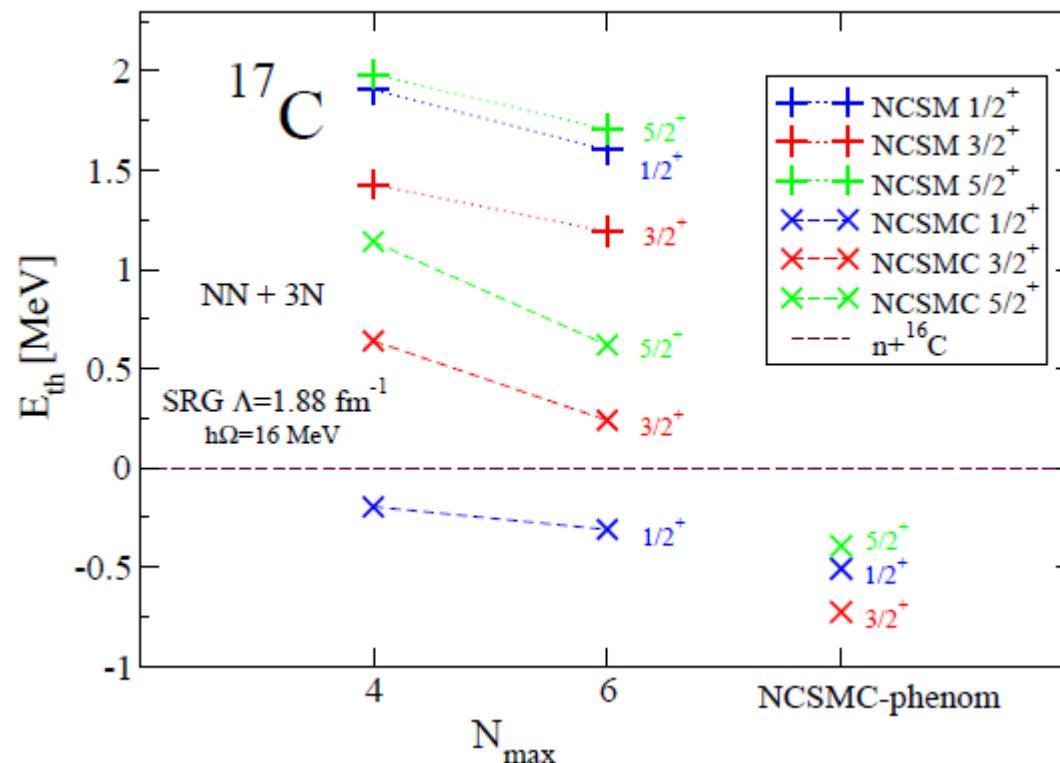
$$+ \sum_{\nu} \int dr r^2 \frac{\gamma_{\nu}(r)}{r} \hat{A}_{\nu} |\Phi_{\nu r}^{J\pi T}\rangle \quad (\text{A-a,a})$$

$$\begin{pmatrix} H_{\text{NCSM}} & \bar{h} \\ \bar{h} & \bar{\mathcal{H}} \end{pmatrix} \begin{pmatrix} c \\ \chi \end{pmatrix} = E \begin{pmatrix} 1 & \bar{g} \\ \bar{g} & 1 \end{pmatrix} \begin{pmatrix} c \\ \chi \end{pmatrix}$$

Including continuum enhances the S-wave component for the 1/2+ state and reduces B(M1)

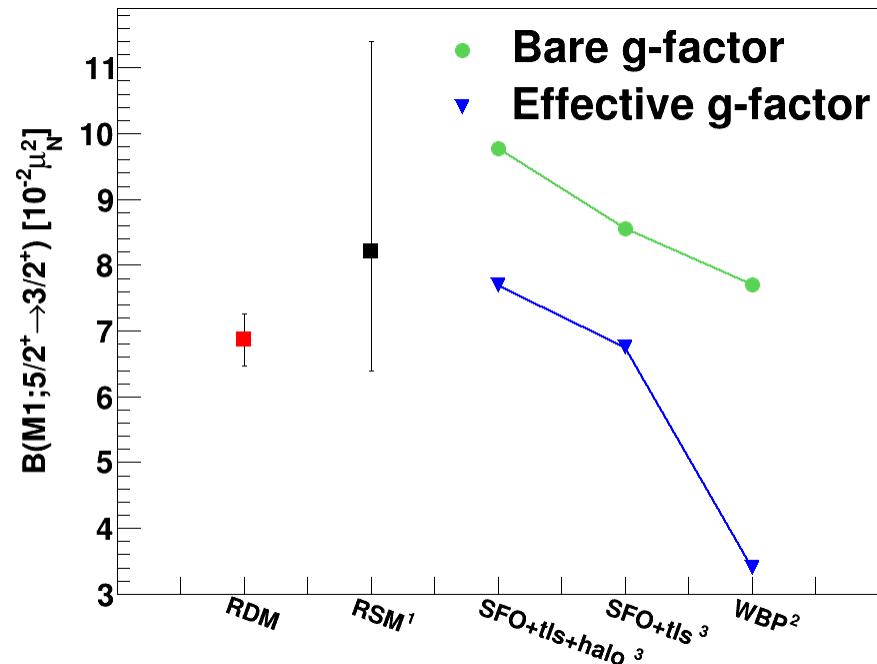
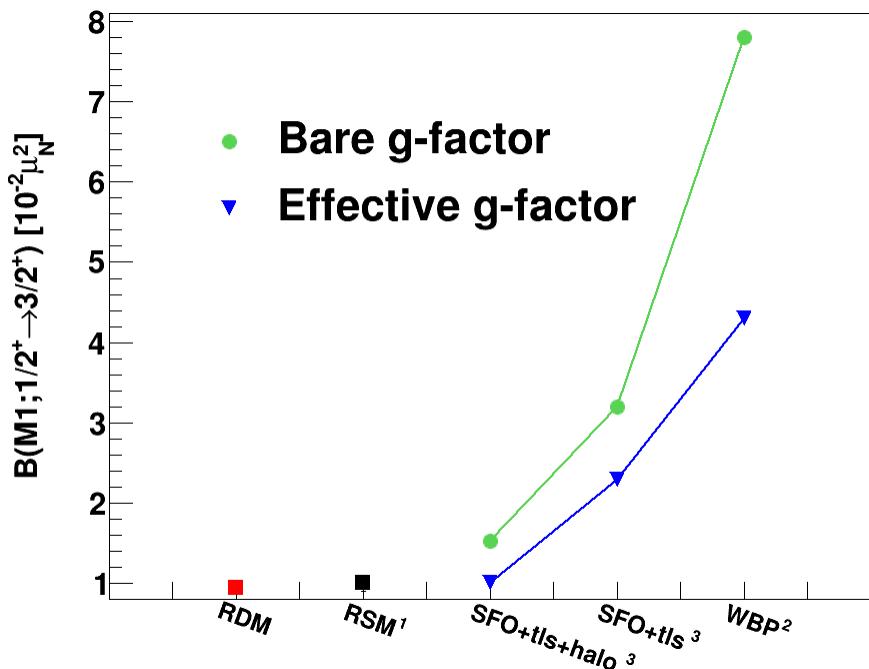
Comparison with ab-initio calculations IT-NCSM and IT-NCSMC calculations

(by P.Navratil, R.Roth, J.Langhammer)



Comparison with large-scale shell model

Data (■) agree with shell model calculations involving loosely-bound effects and effective g factors (T.Suzuki,T.Otsuka PRC78(2008)061301R)



Data also support

RSM: D.Suzuki PLB666 (08) 222

corrections to make the T=1 d_{3/2}-d_{5/2} matrix element more repulsive
(could be due to **3NF effects**) in SFO-tls

corrections to reduce TBME for s_{1/2} orbitals (could be due to **loosely-bound (halo) effects**) in SFO-tls-halo

