Nuclear Physics Research at CNS

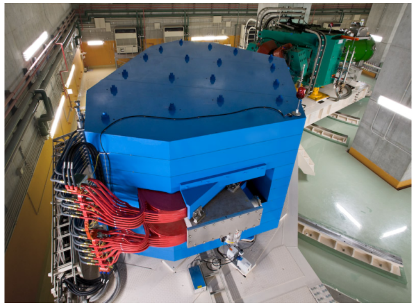
Center for Nuclear Study (CNS),
the University of Tokyo
S. Shimoura
下浦　享

東京大学大学院理学系研究科附属
原子核科学研究センター

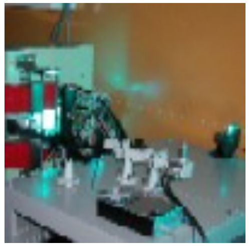
Center for Nuclear Study (CNS)

http://www.cns.s.u-tokyo.ac.jp/

Nuclear Astrophysics (CRIB) incl. Accerlerator[Kubono]



Exotic Nuclei (GRAPE)



Spin Physics (Pol. Target)

SHARAQ Project in RI Beam Factory

Quark Physics

We don't have accelerator, but large-scale detector system

CNS Summer School (from 2002)

9th CNS-EFES Summer School (Aug, 18-25,2010)

Summer School for Young scientists including 10 Chinese
10th school will be held in August 2011.

In-beam spectroscopy of exotic nuclei

- Nuclei far from the stability line (extreme in isosopin) via direct reaction
- Nuclei of high spin (extreme in spin) via fusion reaction

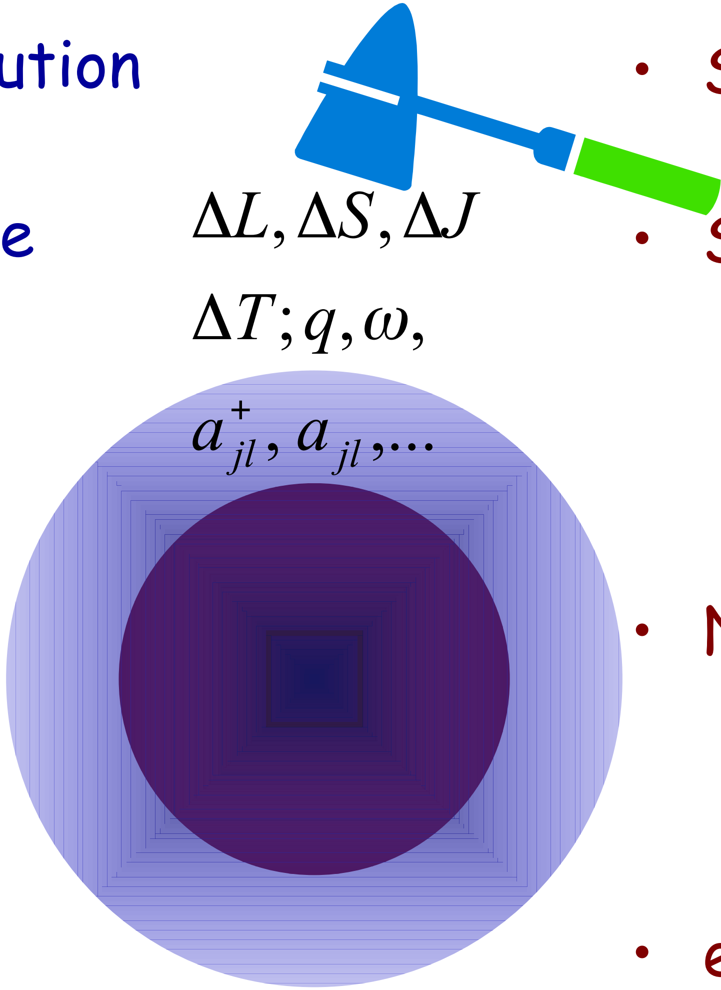
Nuclear response probed by RI beam

- New modes in Nuclei
- Spectroscopy of nuclear system beyond dripline

Studies of Nuclei over the Nuclear Chart

Direct Reactions

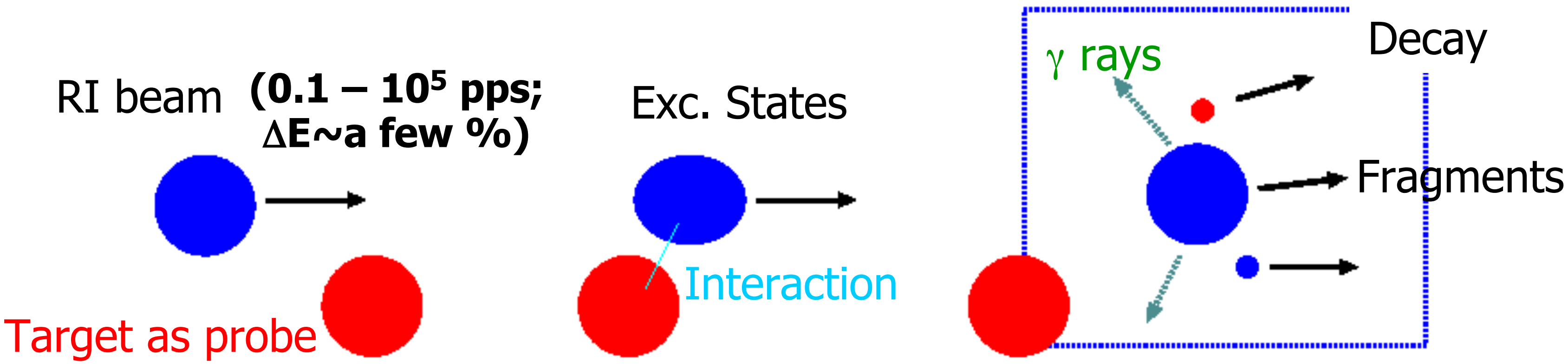
- Size/ρ-distribution
  - Skin/Halo
- Shell Structure
  - New magic #
  - Isospin / Deformation
- New modes
  - IVE1
  - ISE0, ISE1
- etc.



- Size/ρ-distribution
  - σ_R, elastic scat.
- Shell Structure
  - Mass / S_n, S_{2n}
  - Inelastic scatt.
    - Low lying states
  - Knockout / Transfer
- New modes
  - Coulex
  - Inelastic scatt.
  - CEX
- etc.

Mean field / Correlation …

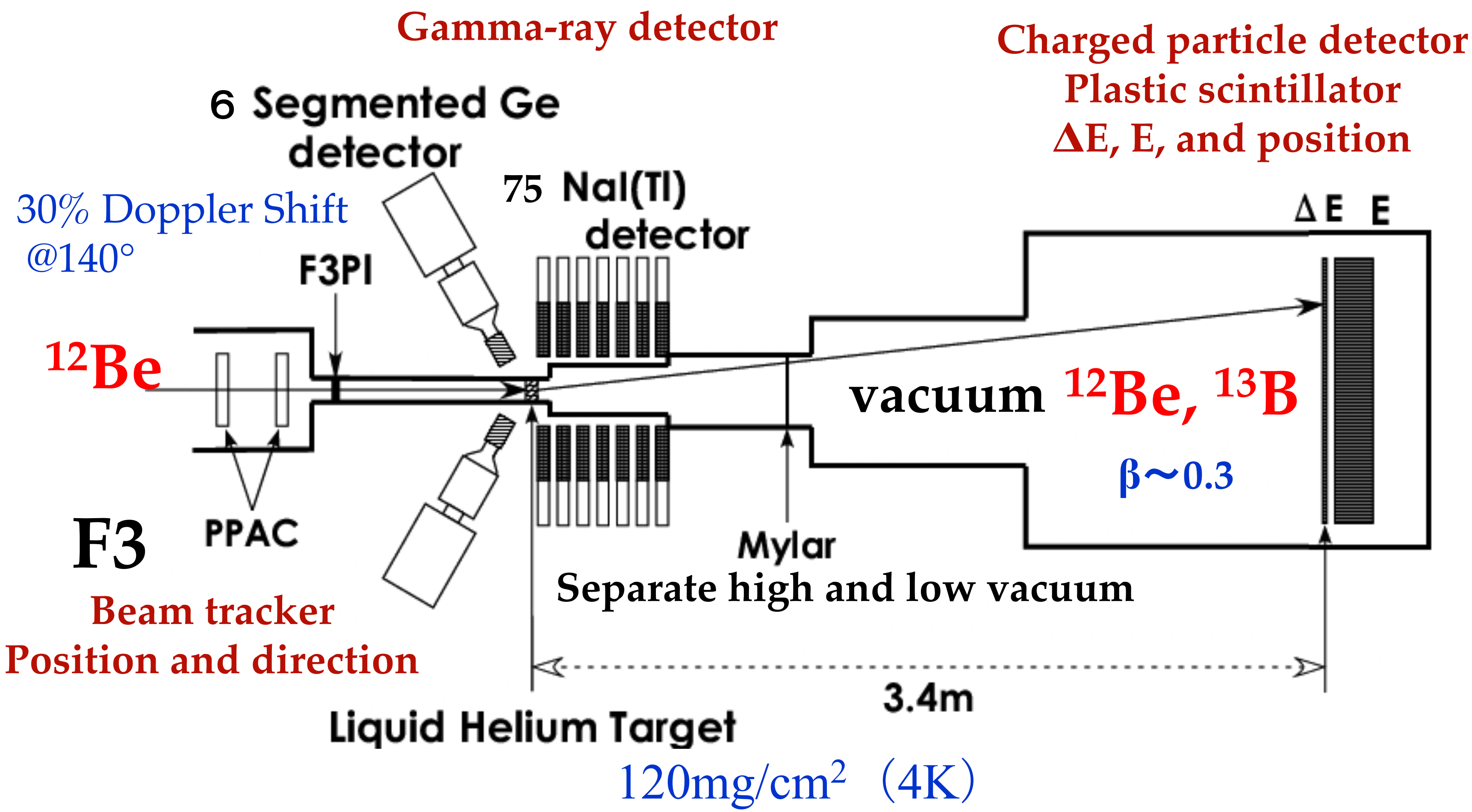
Inverse Kinematics w/ RI beam



- Formation of Excited States of Exotic Nuclei
  - Direct reactions and their selectivities
- In-beam spectroscopy measuring decay products
  - Invariant-mass/γ-ray spectroscopy
    - Particle detectors at forward angles (kin. focus.)
    - Gamma detectors surrounding target (Doppler shift)
  - Missing-mass spectroscopy
    - Recoil & Active Target Measurement
    - Dispersion Matching/Measurement

Typical Setup of Experiment

inverse kinematics



H. Ryuto et al., NIMA 555 (2005) 1

Probes for direct reactions

- Heavy Nuclei: Strong Coulomb Field
  - Coulomb Excitation, Coulomb Dissociation
    - E1, E2, (M1) / Isovector
- H, D, ^{4}He [Liquid targets]
  - Inelastic Scattering
    - Isovector (H) / **Isoscaler**(H, D, ^{4}**He**)
    - Spin-Flip (H, D) / **Spin-Non-Flip** (H, D, ^{4}**He**)
  - Charge Exchange
    - Fermi type (H) / Gamow-Teller type (H, D)
  - Nucleon Transfer
    - **(α,t), $(\alpha,^{3}$He)** Reaction
  - Knockout
- Other (Be, C, …)
  - Inelastic Scattering
  - Knockout / Fragmentation

Dirty RI beams and/or Changing Target

↓

Same Nucleus can be populated via Different Processes without changing Detector System

Observables - reaction/decay meas.

- Yields (Cross Sections) / Lifetime / Width
  - Spectra : As a function of Exc. Energy (+ incident energy)
  - Properties of populated states (←Selectivity)
- Angular Distribution / Momentum Transfer

  Reliable Reaction Models with small numbers of parameters
  - Assignment of L → J^{π}
  - Eikonal Model [Knockout]
  - Virtual Photon / **DWBA** / Coupled Channels

    [Coulex, Inelastic, Transfer]
  - **Optical Potential / Transition Density**
    - **Folding Model with Density Dependent Effective Interaction**
- Angular Correlation / Alignments
  - Assignment of J^{π}

Cross sections as a function of …

(α,α') and (α,t) reactions on exotic nuclei at intermediate energy

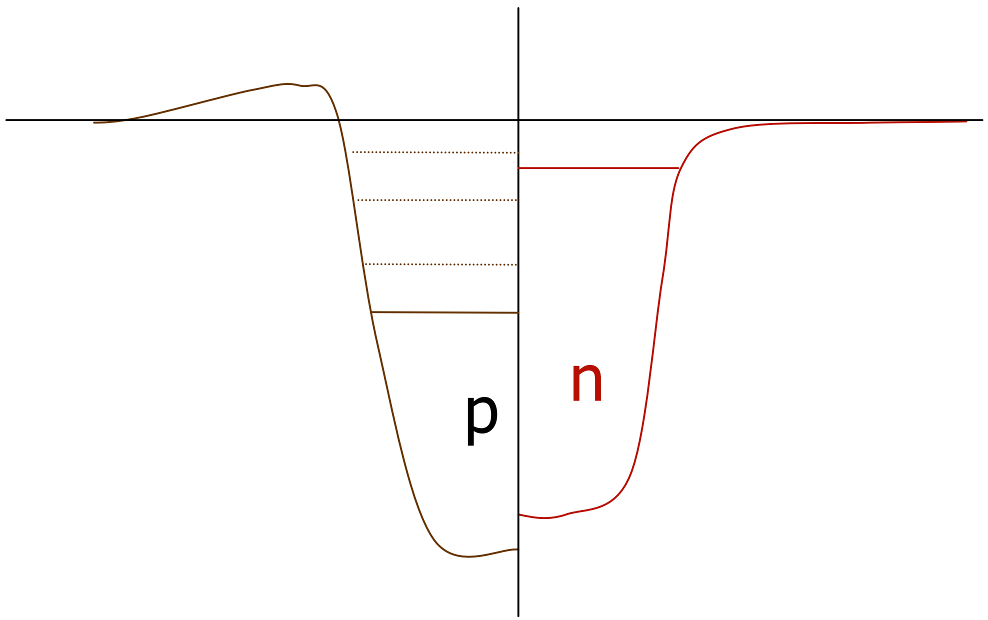
- Alpha inelastic scattering
  - Cluster states in ^{12}Be
  - Isoscaler responses in ^{14}O
- Nucleon transfer from alpha
  - Proton intruder state in neutron-rich nuclei ^{13}B
  - Evolution of LS splitting ^{23}O

Nucleon Transfer from ^4He @ 30-50 A MeV

- Proton Single particle states in neutron-rich nuclei
  - **$^4He(^{12}Be,^{13}B\gamma)$**

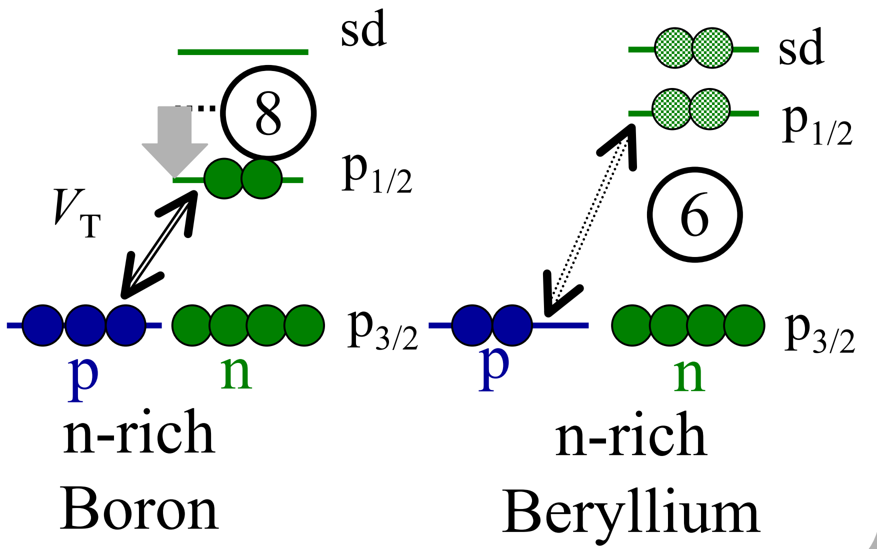
    [S. Ota et al., Phys. Lett. B 666 (2008) 311]
  - **$^4He(^{22}O,^{23}F\gamma)$,** [$^4He(^{23}F,^{23}F\gamma)$, $^4He(^{24}F,^{23}F\gamma)$, $He(^{25}Ne,^{23}F\gamma)$] utilizing cocktail beams

    [S. Michimasa et al., Phys. Lett. B 638 (2006) 146]



N-rich N=8 Nuclei

Spin-orbit splitting between $\nu p_{1/2}$ & $\nu p_{3/2}$ depend on the number of protons in $\pi p_{3/2}$ orbit attracting $\nu p_{1/2}$ orbit



^{12}Be

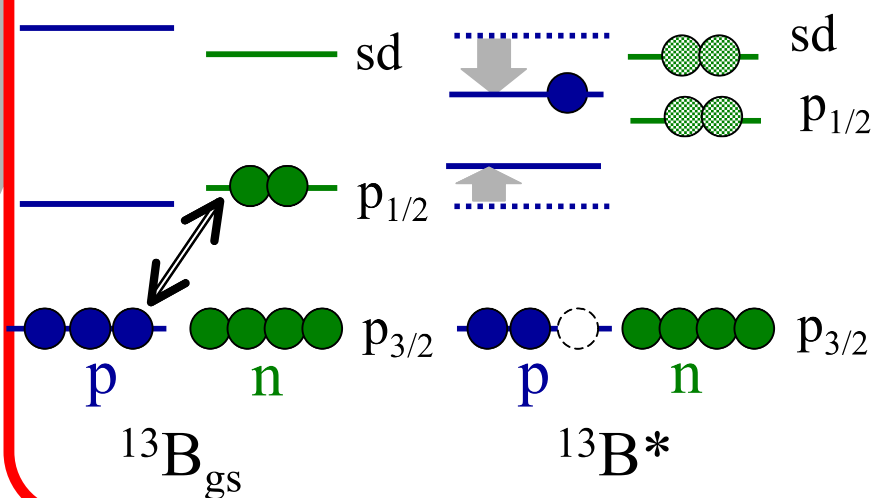
- **Low-lying 2^+ state**
- **Low-lying 1^- state**
- **Low-lying 0^+_2 state**

Magicity loss in N=8

Deformed ground state

Change of Boron Proton Shell as a function of configuration

Deformed mean field?



Proton intruder state

^{13}B

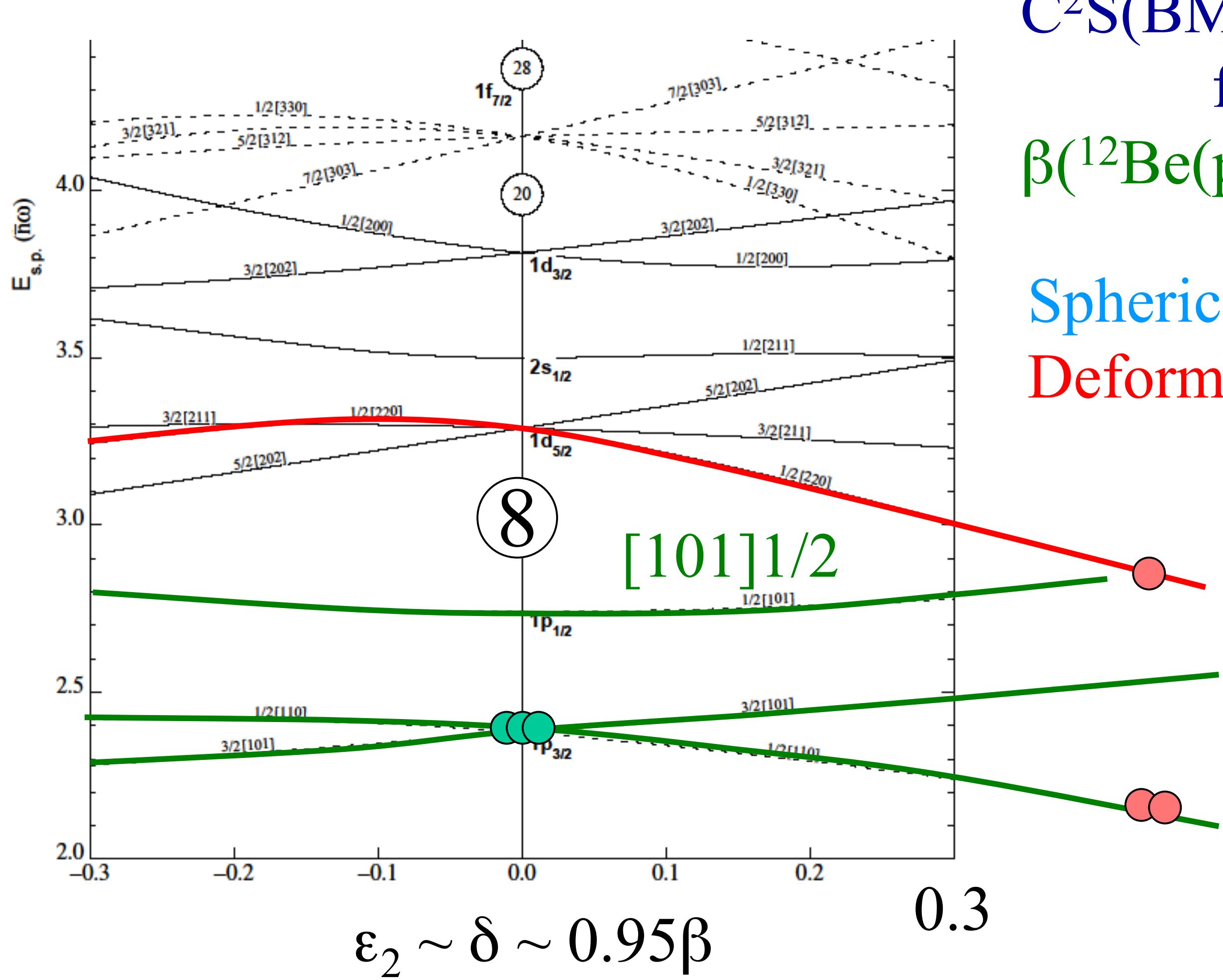
- **Spherical ground state**
- **How about excited states?**
  - **Deformed core + proton?**

$^{4}He(^{12}Be,^{13}B\gamma)$ @ 50 *A* MeV

Deformed ^{12}Be core + 1 proton ?

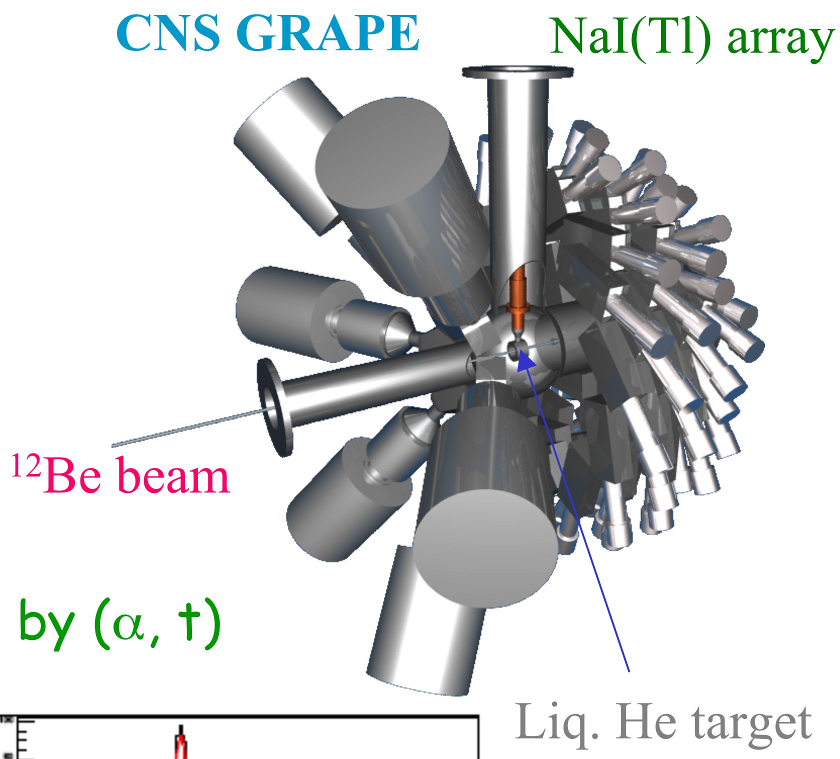
$C^2S(BM) \sim 0.27$
for δ=0.4
$\beta(^{12}Be(p,p'))\sim 0.6\text{-}0.7$

Spherical G.S.
Deformed Excited $1/2^+$?

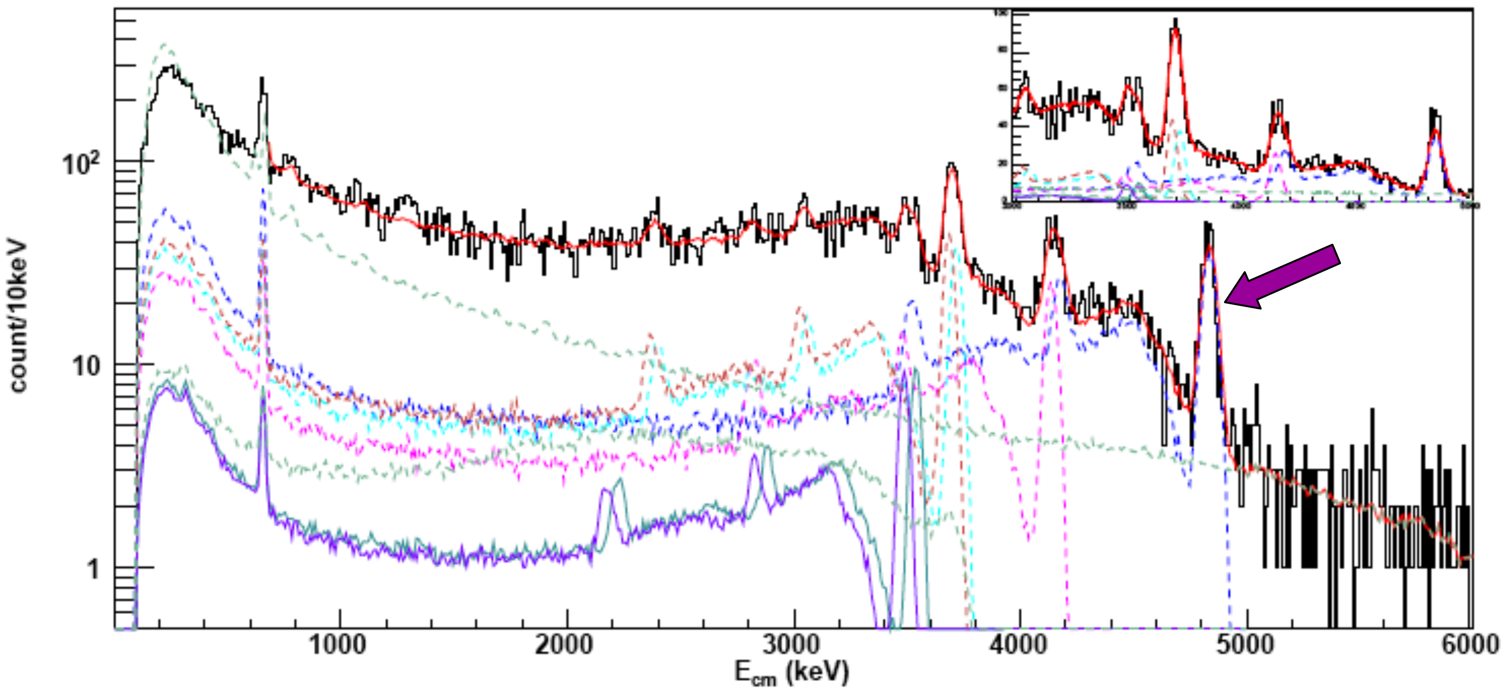


$^4He(^{12}Be,^{13}B\gamma)$ @ 50 *A* MeV

$\beta \sim 0.25c$

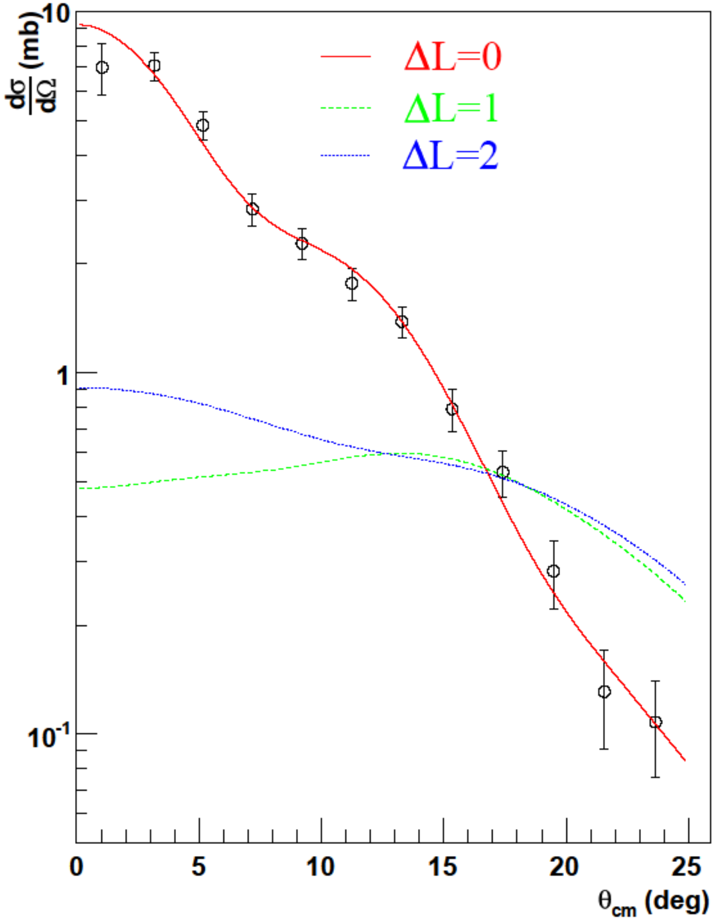


4.83 MeV states strongly excited by (α, t)



$^{4}He(^{12}Be,^{13}B\gamma)$ @ 50 *A* MeV

Angular Distribution of ^{13}B coin. with **4829** keV γ



FR-DWBA (DWUCK5)

Optical Potential:

$^{12}C + ^{4}He$ (entrance)

$^{12}C + ^{3}He$ (exit)

L=0 -> $J^{\pi} = 1/2^{+}$

$C^2S \sim 0.2$

-> Proton "single particle" state on ^{12}Be

$^{13}B(1/2^+_1)$

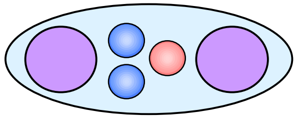
Present calc.

Hyper deformation ?

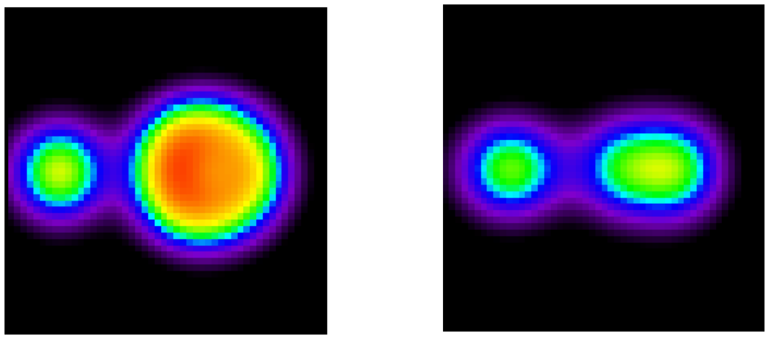
$1/2^+_1$ $\beta = 0.73$

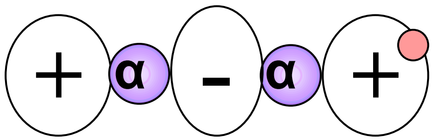
$E_x \approx 8\,\mathrm{MeV}$

$$3\hbar\omega = (sd)_\pi (sd)^2_\nu$$



neutron proton





Proton intruder state
in neutron-rich nuclei

4He(12Be,13Bγ) Experiments
By Ota et al.

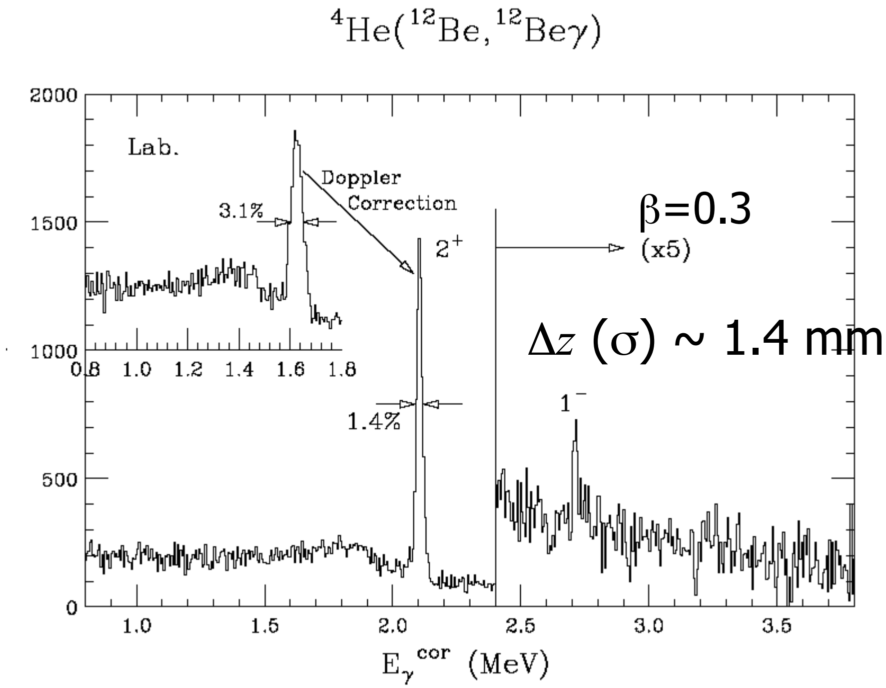
$1/2^+$ $E_x \approx 5\,\mathrm{MeV}$

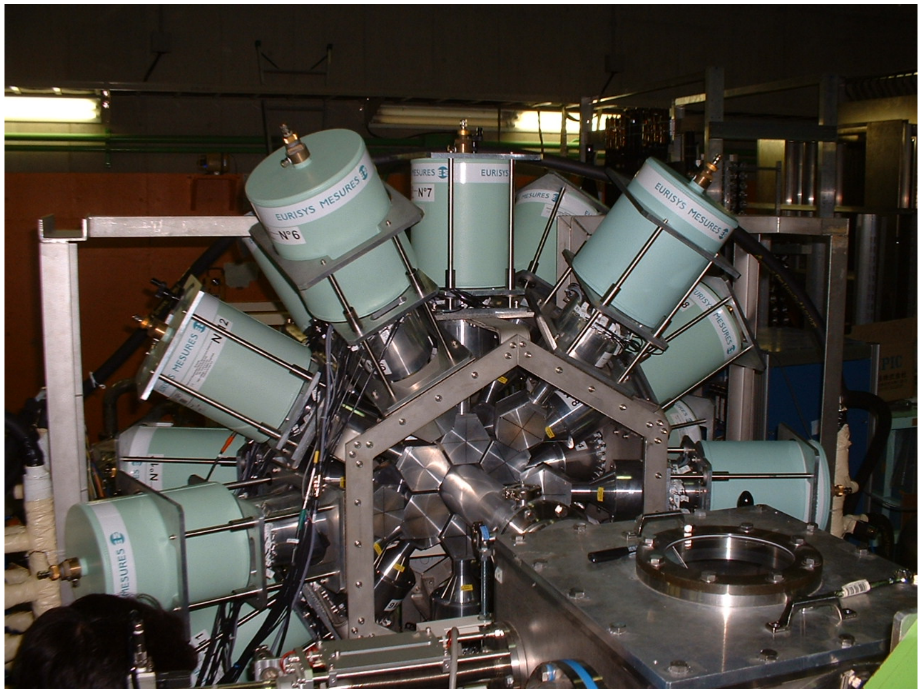
By Kanada-Enyo

CNS-GRAPE

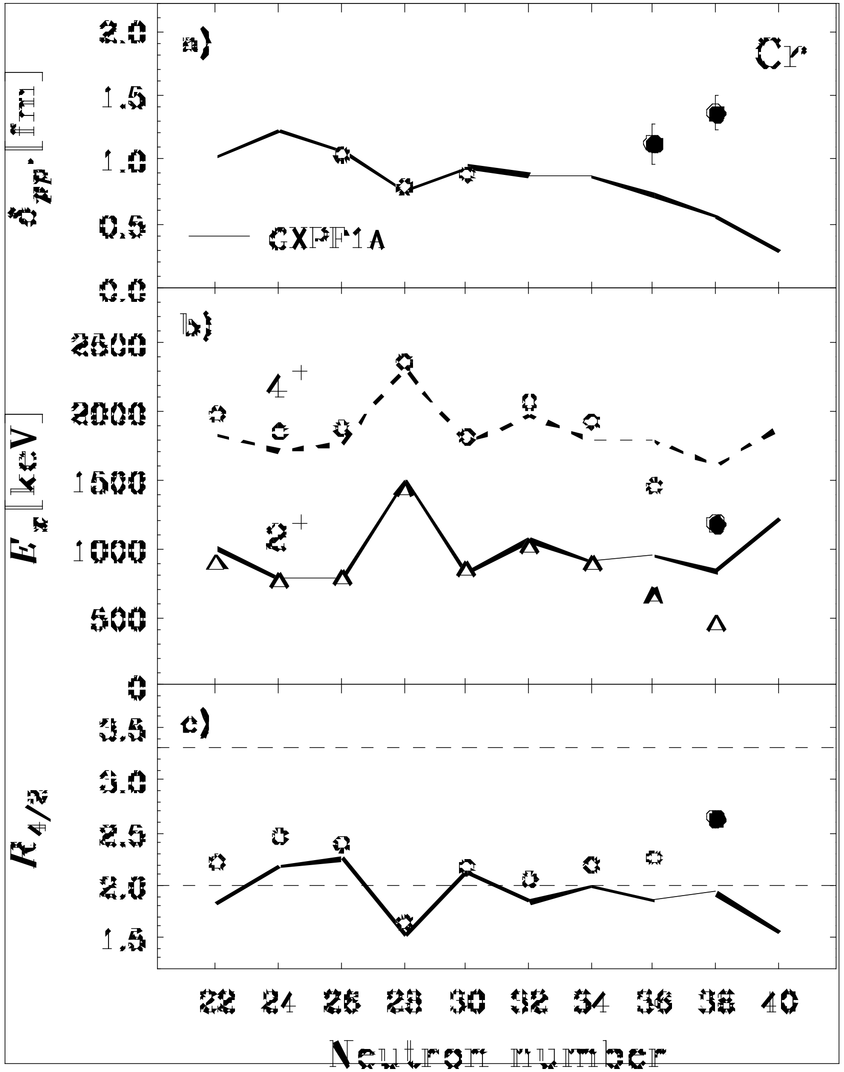
Gamma-**R**ay detector **A**rray with **P**osition and **E**nergy sensitivity

- High Resolution
  - 2.5 keV intrinsic resolution for 1.3 MeV γ
- High Sensitivity
  - $\varepsilon\Omega$ ~ 5 % for 1 MeV γ
- Position Sensitive
  - Resolution of Doppler Correction ~ 1 %





Lifetime measurements of 2^+, 4^+states in $^{60,62}Cr$ by Recoil Distance method



N.Aoi et al. PRL102, 012502 (2009)

- Recent study of $^{60,62}Cr$ by N.Aoi et al.
- (p,p') experiment at RIPS
- New deformed region near ^{60}Cr
  - Deformation length δpp'
  - Ex(2+), Ex(4+)
  - R4/2
- Shell model with GXPF1A
  - pf shell up to N=34
  - pf + gd N≧ 36
- B(E2) by life time

Proposal for RIBF exp.

Spin polarization

Polarization Study of Unstable Nuclei

SPIN plays a more active role in unstable nuclei than in stable nuclei.

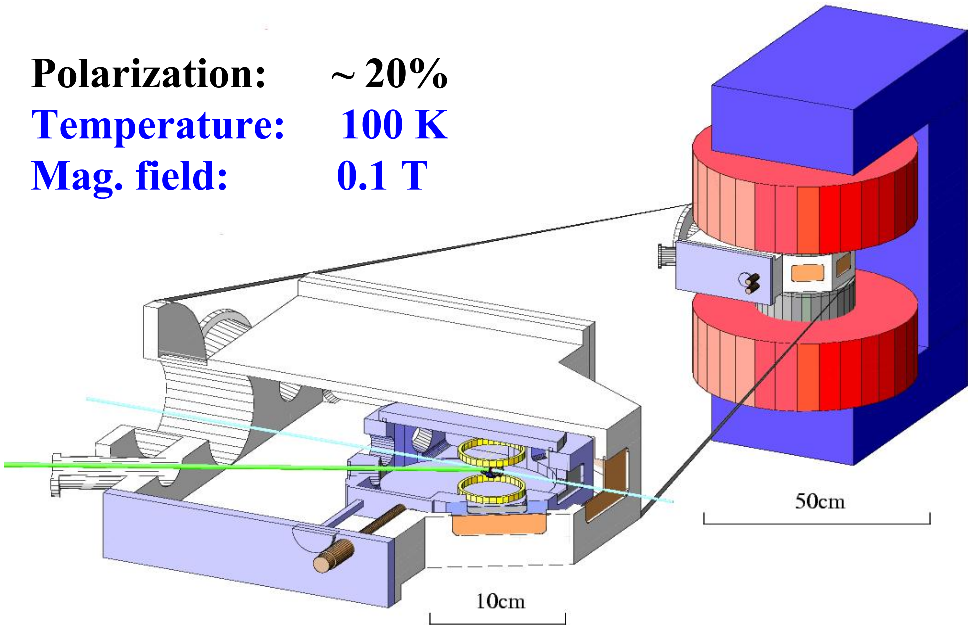
Tensor force effects, change of spin-orbit coupling strength...

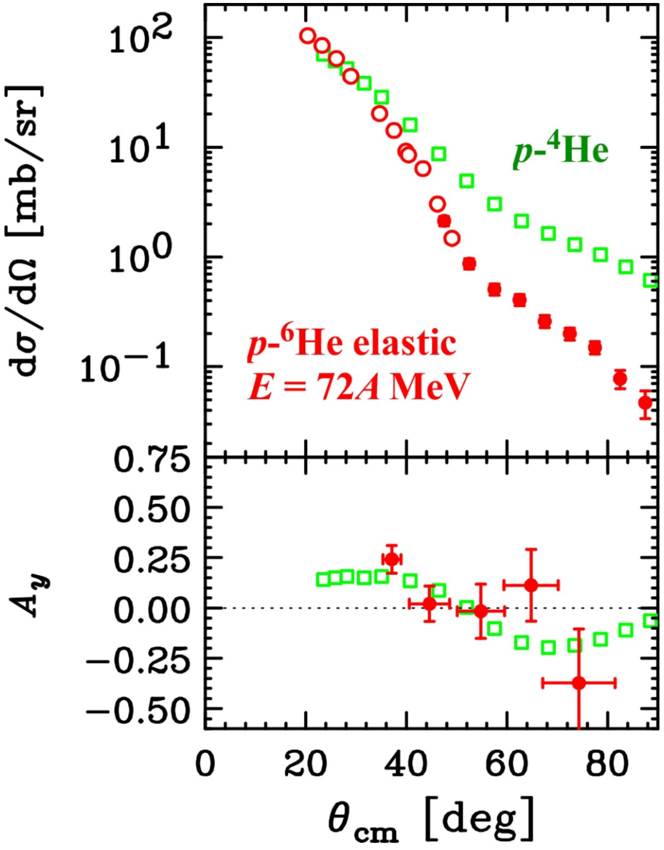
Scattering of spin-polarized protons should shed a new light onto physics of unstable nuclei.

T. Uesaka, S. Sakaguchi et al., PRC **82**, 021602(R) (2010)

CNS Polarized Proton Target
applicable to RI beam exp.

Polarization: ~ 20%
Temperature: 100 K
Mag. field: 0.1 T





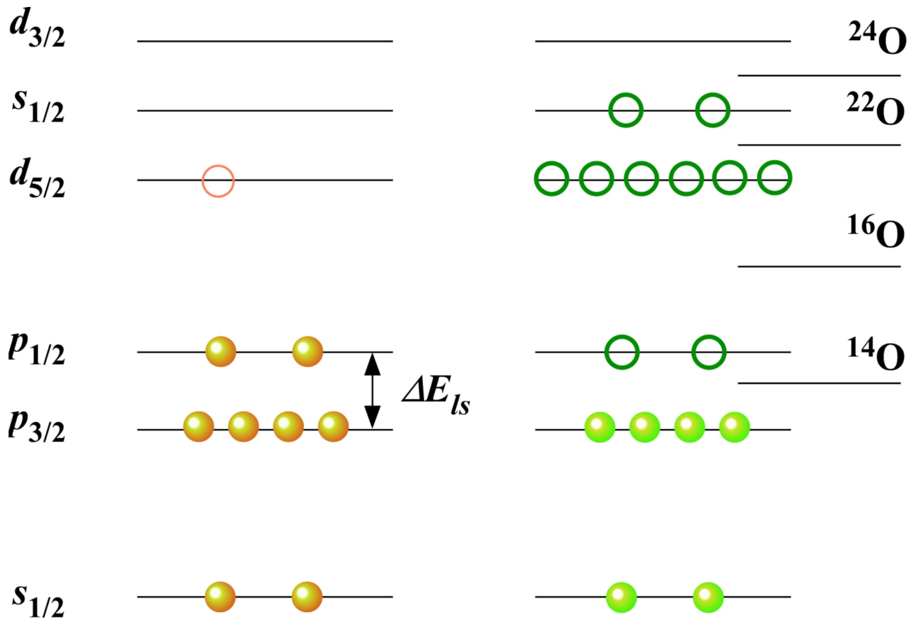
Planned experiment at RIBF

How spin-orbit coupling strength changes as a function of Z/N?

- a key to understand shell regularity far from the stability line

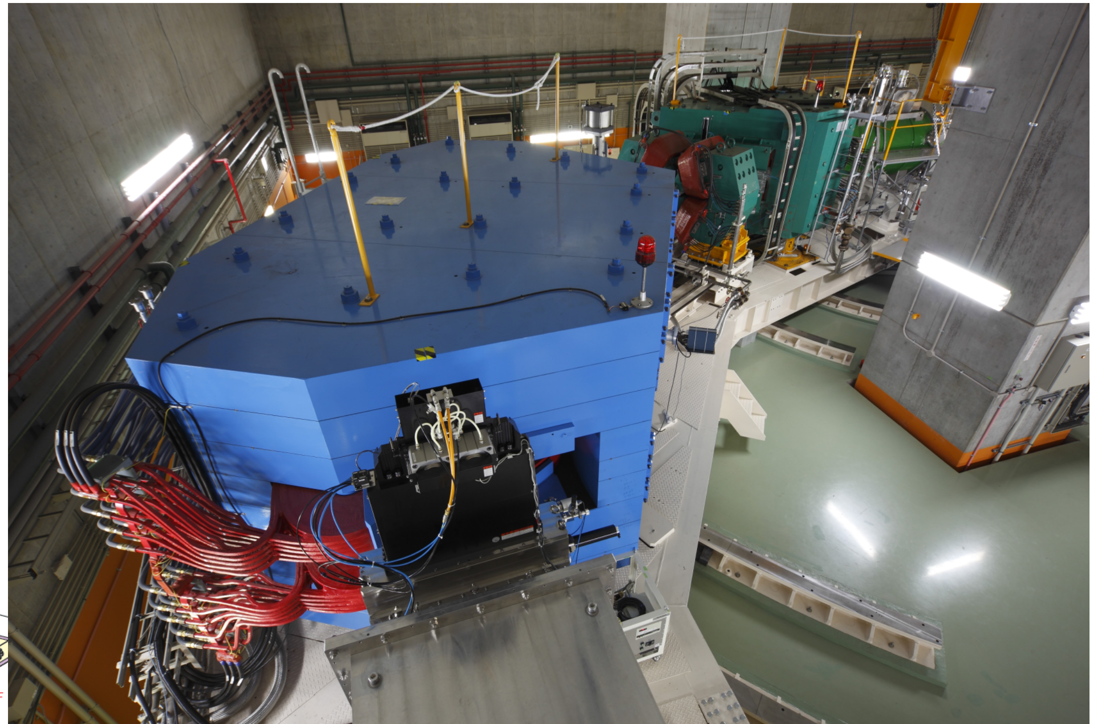
Single hole state spectroscopy of oxygen isotopes
via the (p,pN) knockout reaction
with the polarized target (T. Uesaka et al.)
^{14}O, ^{20}O, ^{23}O, ^{24}O

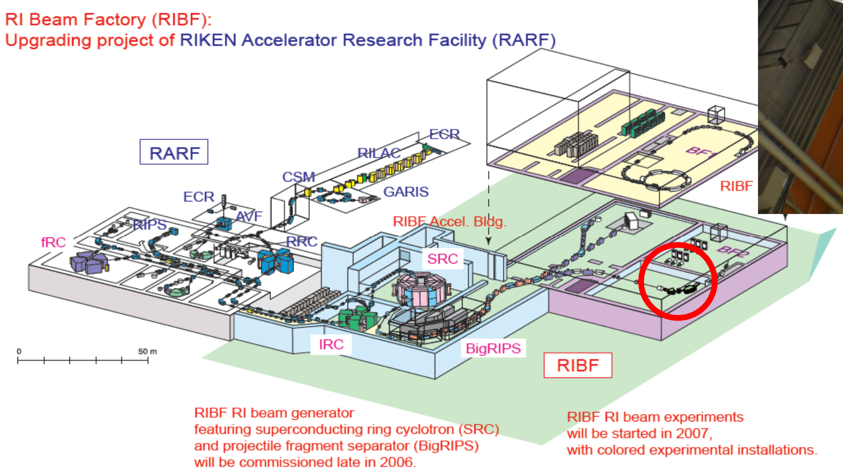
Momentum dependence of dσ/dΩ
⇒ L and S-factor
Analyzing power (A_y)
⇒ J



SHARAQ Project

SHARAQ is a HIGH-RESOLUTION magnetic spectrometer constructed at RIBF by University of Tokyo - RIKEN collaboration.



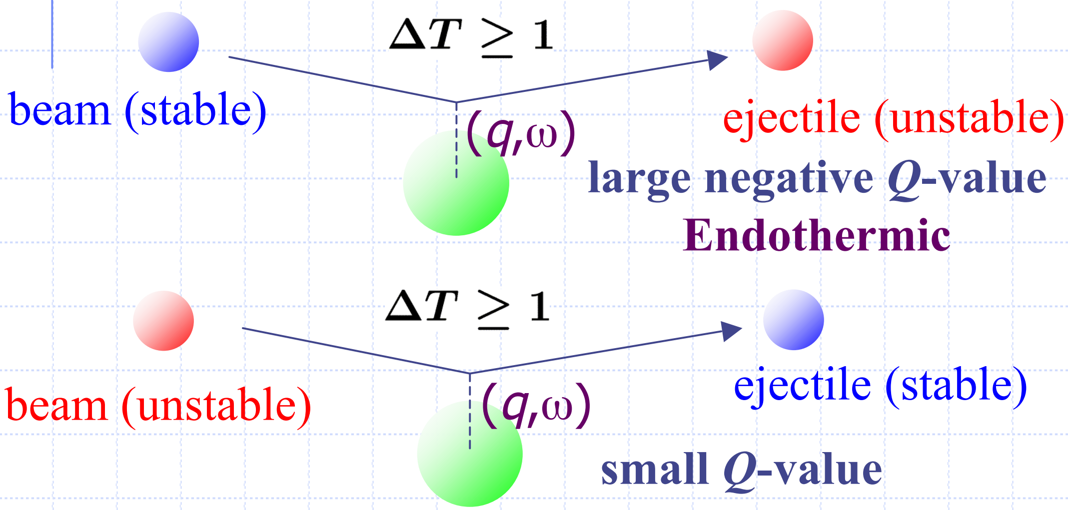


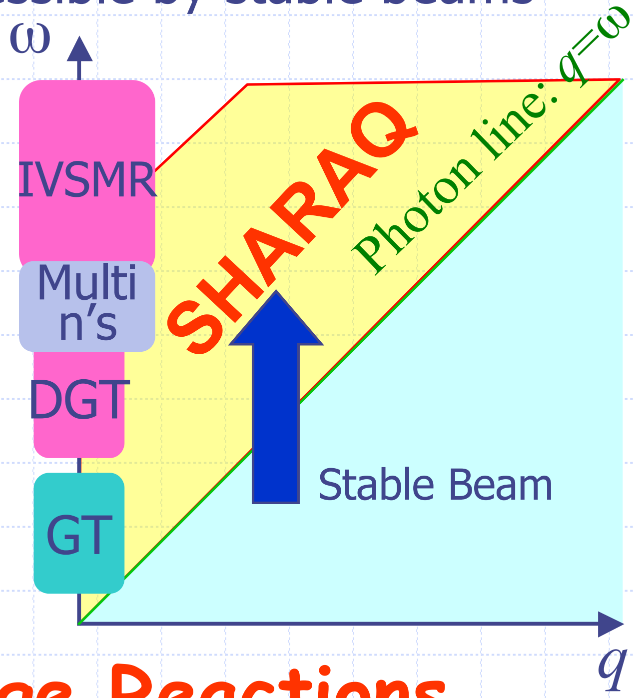
SHARAQ

Spectroscopy with High-resolution Analyzer & RadioActive Quantum beams

RI Beam (E = 150—400 MeV/A) as a new PROBE to nuclear systems

- Large Isospin — iso-tensor excitations
- Large internal energy — (q,ω) inaccessible by stable beams





Exothermic Charge Exchange Reactions

RI beam induced reactions as new spectroscopic tools

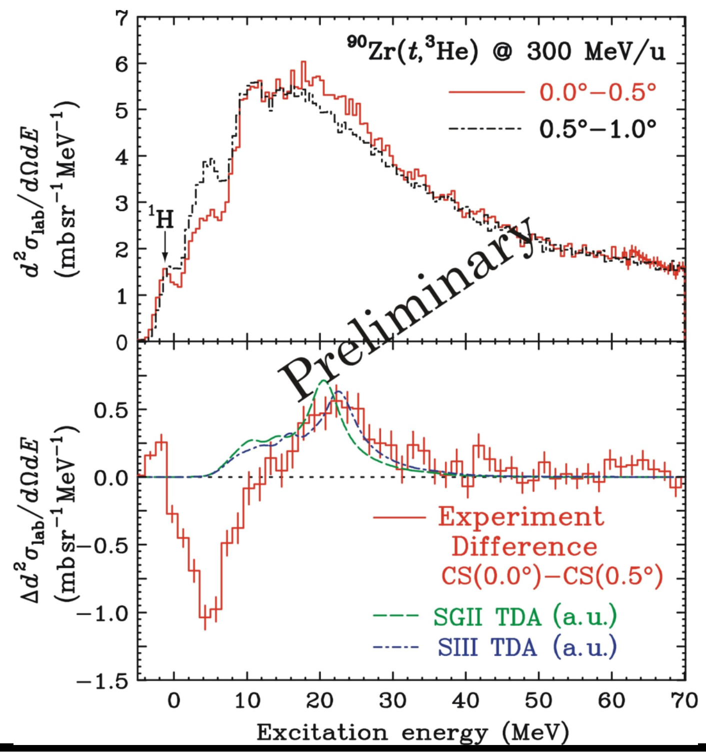
RI beam induced charge exchange reactions:

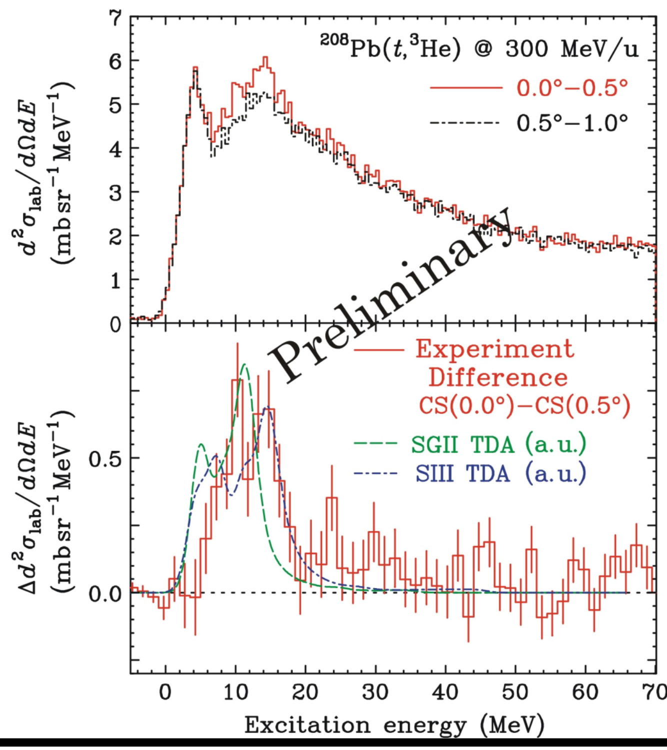
new spectroscopic tool to reveal hidden nature of nuclear system

Transferred quantum numbers (ΔS, ΔT, ΔL . . .)

Kinematical region (*q* transfer)

FIRST experiment : (t,^{3}He) exp. to search for β^+-type IVSMR



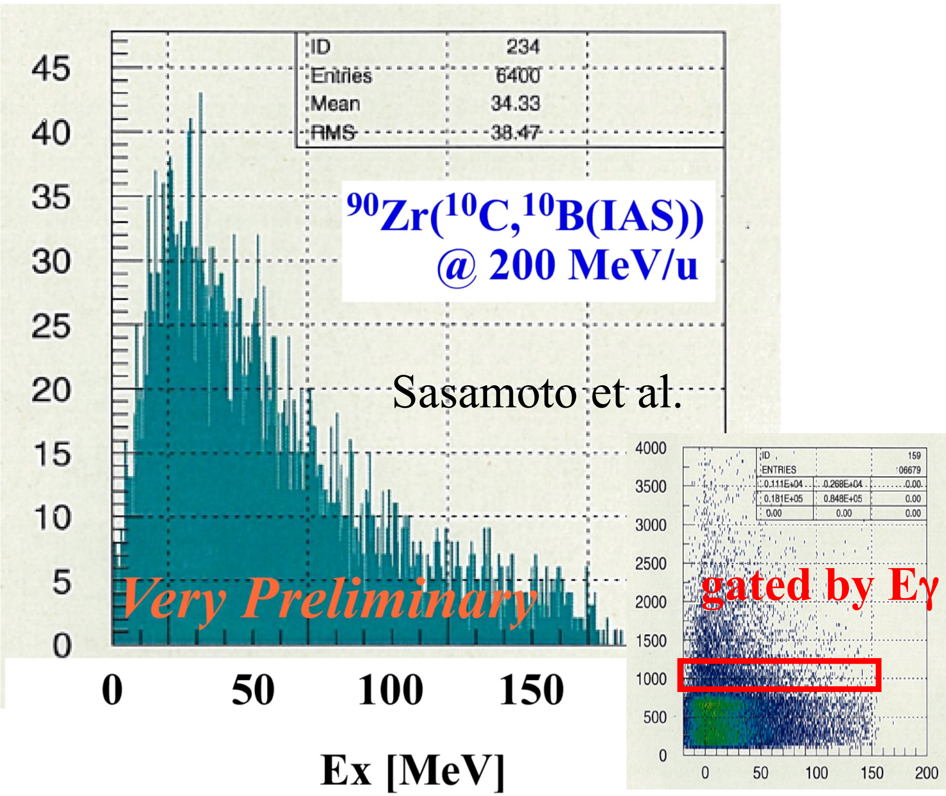


Hot Results from October-2010 runs

$(^{10}C,^{10}B(IAS))$ @ 200 MeV

ΔS=0, ΔT=1 selectivity (unique)

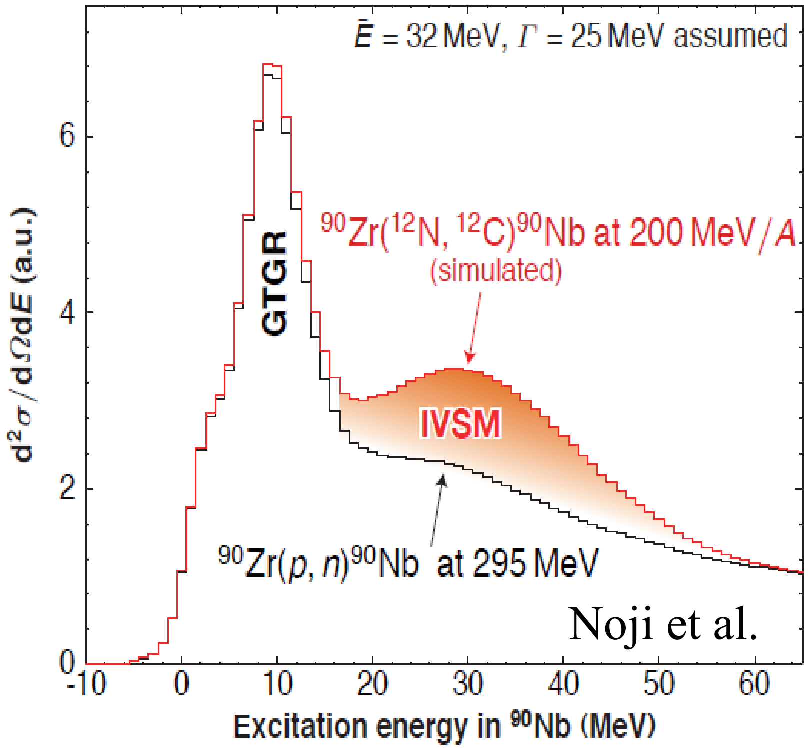
1022 keV g-ray is a signature of DS=0



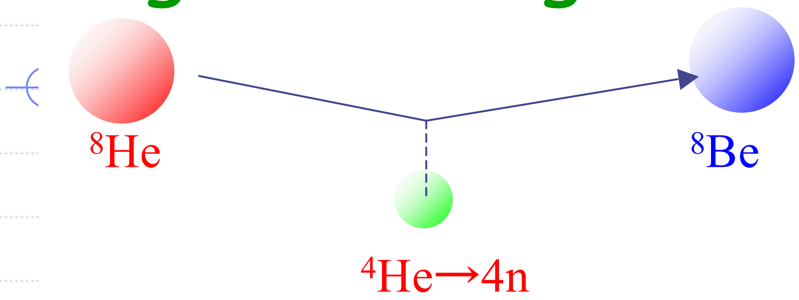
$(^{12}N,^{12}C)$ @ 200 MeV

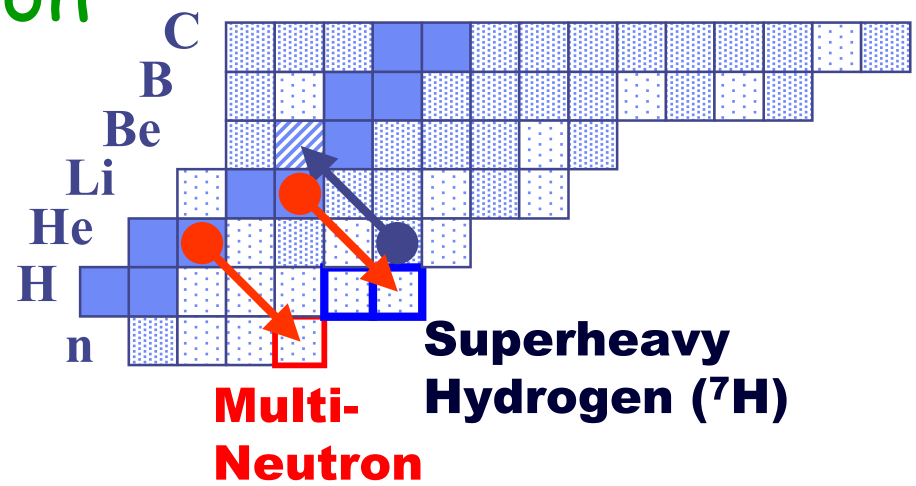
"recoil-less" excitation of
isvector spin monopole states

EXOTHERMIC reaction (Q ≫ 0)

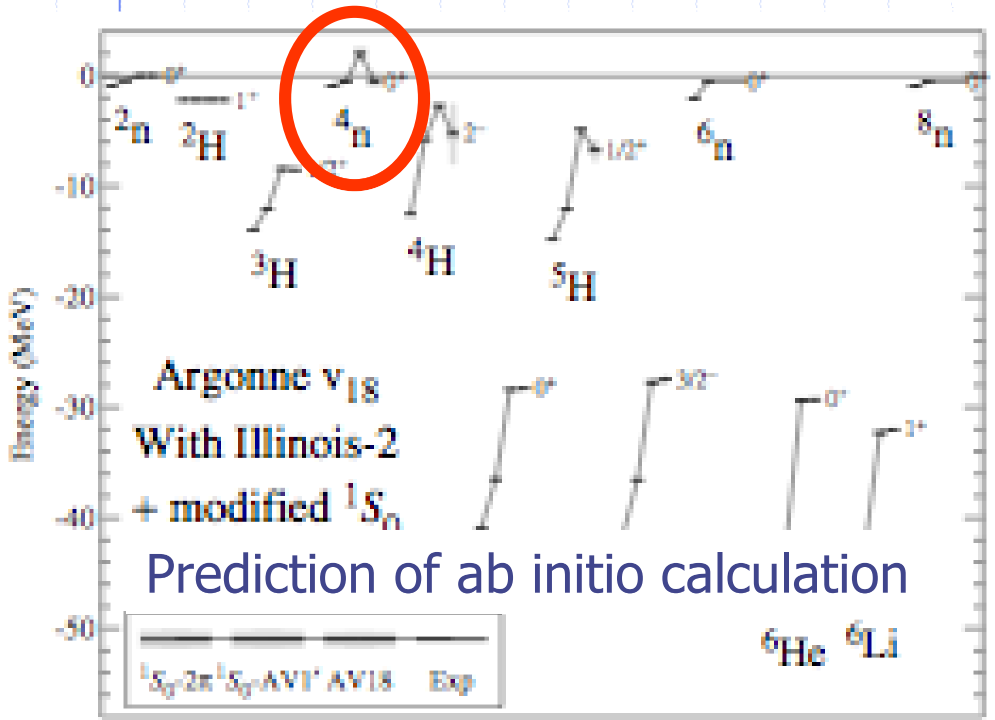


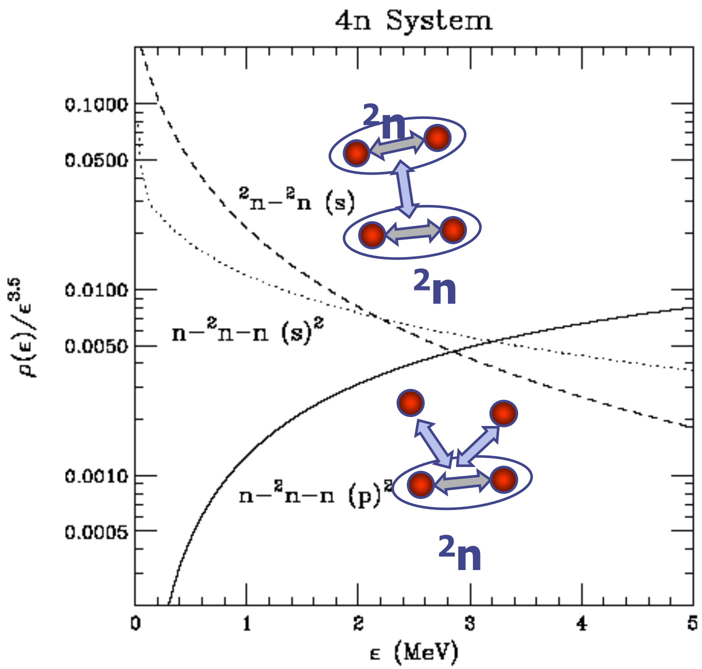
Tetra-neutron system using exothermic charge exchange reaction





Recoil-less 4n system using internal energy of ^{8}He





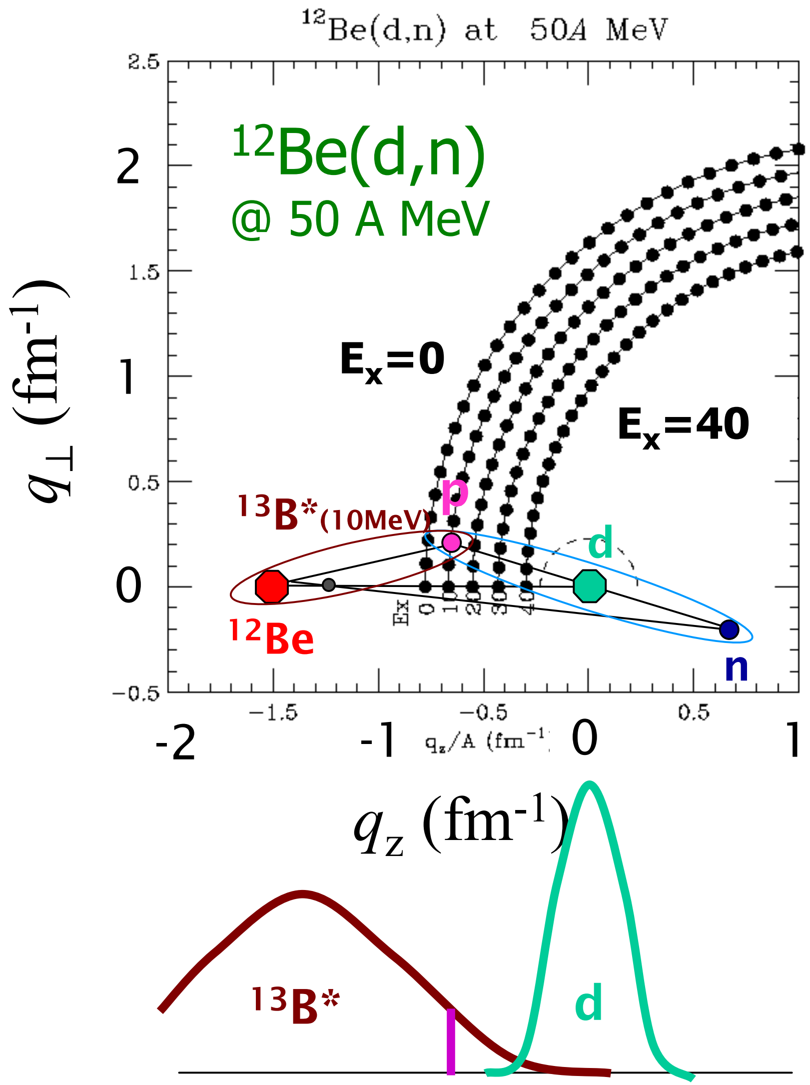
Summary

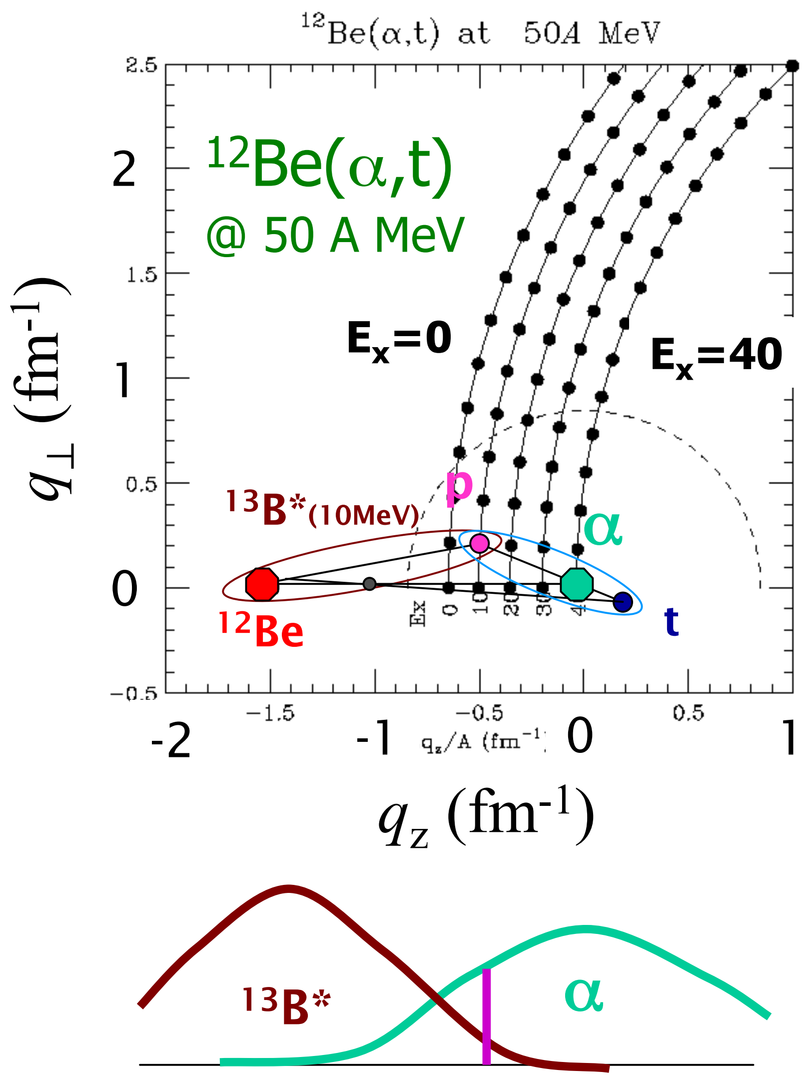
- Direct Reactions combined with invariant-mass/γ spectroscopy are powerful tools to investigate excited states in exotic nuclei
  - Cluster states
  - Isoscaler responses
- Nucleon transfer reactions at 30-100 A MeV from α are useful for searching single-particle states
  - Single particle structure
  - Structure change in excited state
- High-spin studies using fusion reaction (SD)
- Now and then :

  SHARAQ spectrometer and/or gamma-detector GRAPE
  - Exothermic CX reactions (IVM, IVSM, Tetra-neutron…)
  - Lifetime measurement using recoil distance method
  - High momentum components, n-n correlations, etc

Thank you

Proton Transfer in Momentum Space



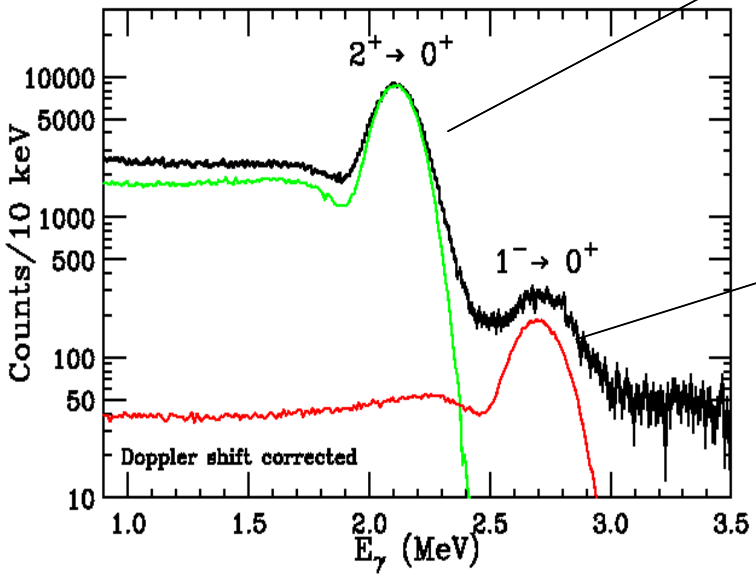


$^{4}He(^{12}Be, ^{12}Be\ \gamma)$ at 60 A MeV

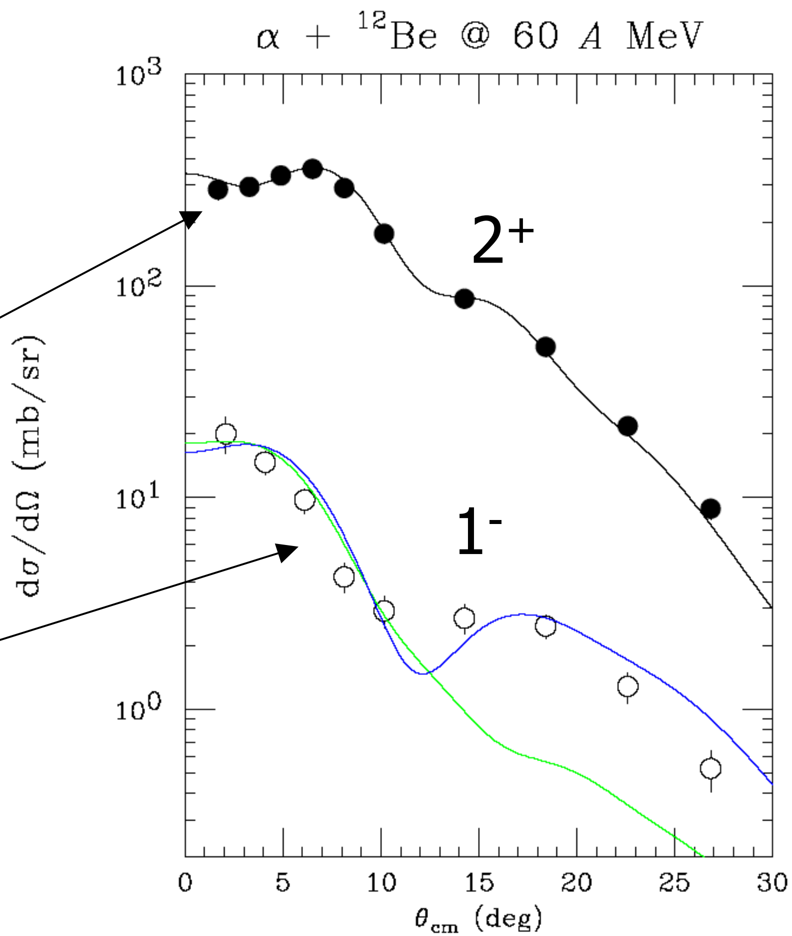
γ spectrum coincident with ^{12}Be ejectiles

2.1 & 2.7 MeV States excited by (α, α')

DWBA [col. FF & folding pot.]



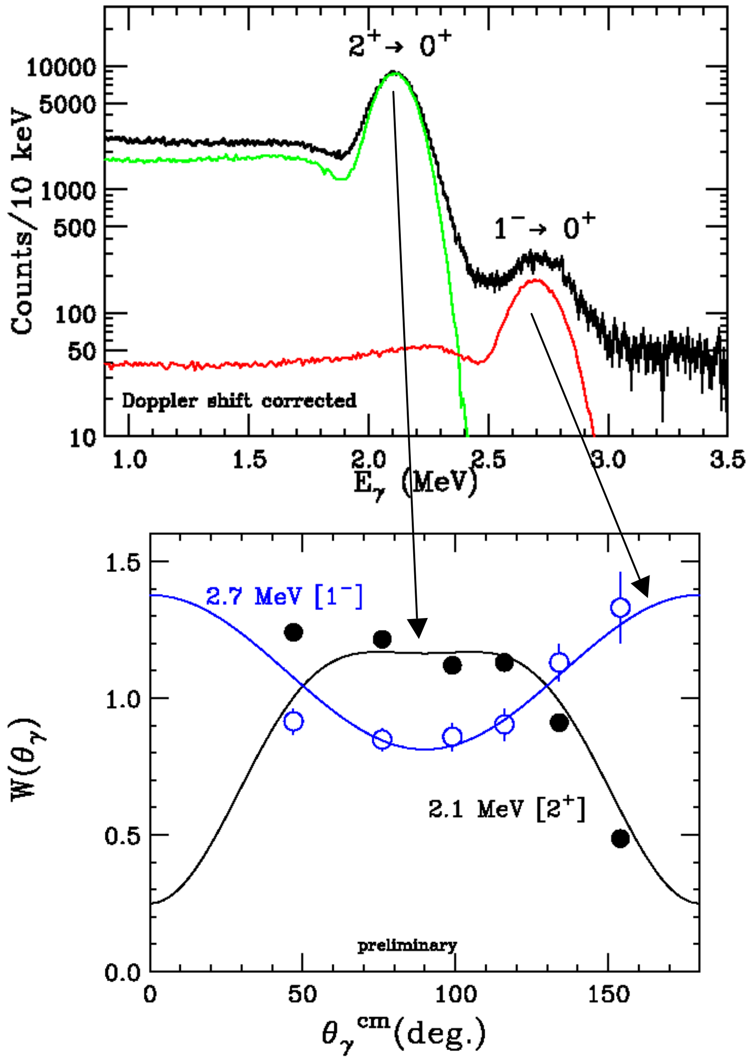
Angular Distributions of $^{12}Be^*$



$^4He(^{12}Be, ^{12}Be\ \gamma)$ at 60 A MeV

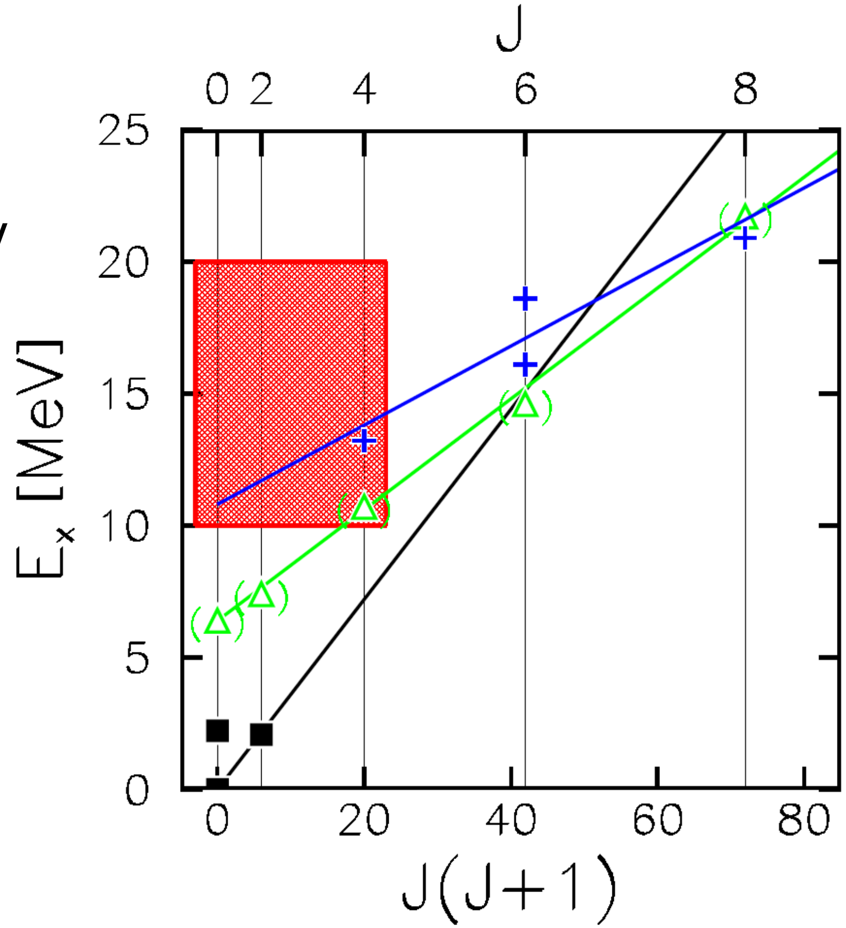
Angular distribution of γ–decay after (α,α')

- 2.1 & 2.7 MeV States excited by (α, α')
- Alignments of $^{12}Be^*$ Anisotropic Angular Distribution of γ
- Consistent with Prediction of DWBA calculation assuming 2^+ & 1^- excitation, resp.
- Confirmation of 1^- assignment for 2.7 MeV state



Alpha inelastic scattering to highly excited cluster states

- $^4He(^{12}Be, ^{12}Be^* \rightarrow ^6He+^6He)$ & $^4He(^{12}Be, ^4He+^8He)$ @ 60 A MeV
  - Cluster states in ^{12}Be
  - Invariant mass
  - L=0, 2, (4) excitations
    - Multipole Decomposition Analysis (MDA) including decaying process



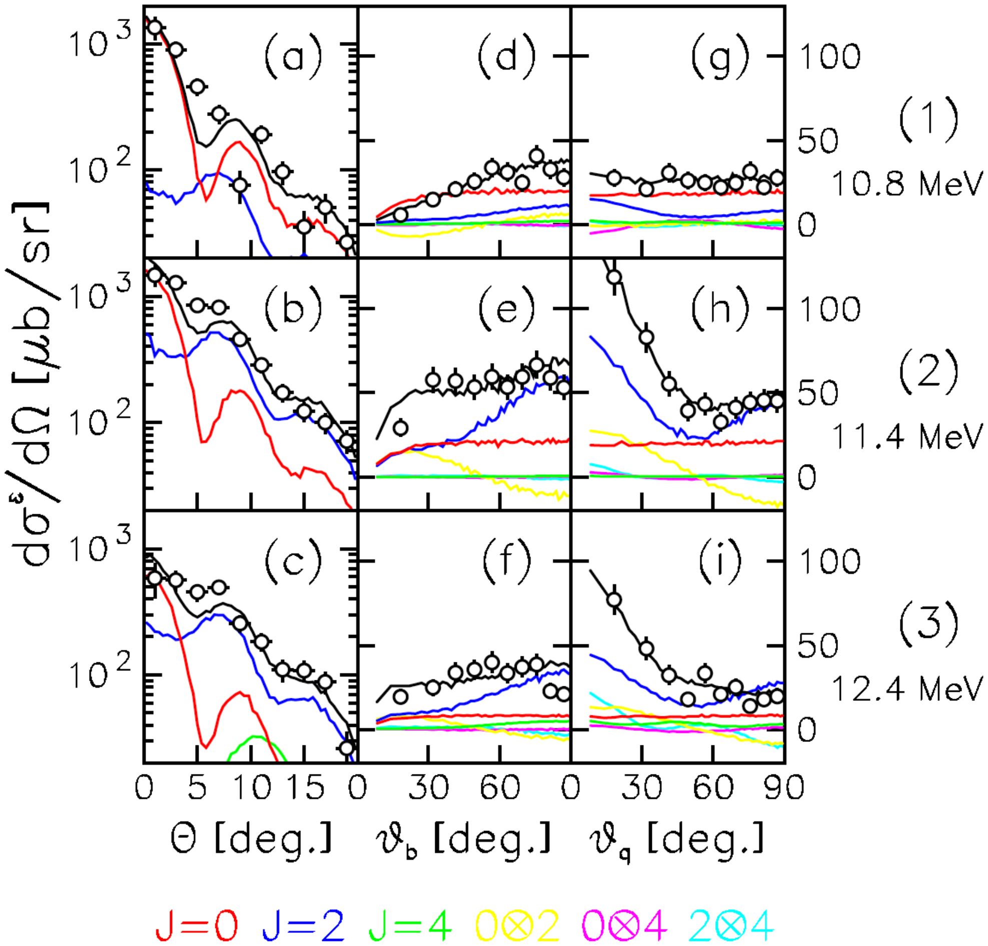
$^4He(^{12}Be, ^{12}Be^* \rightarrow ^6He + ^6He)$
Angular Distribution & Angular Correlation

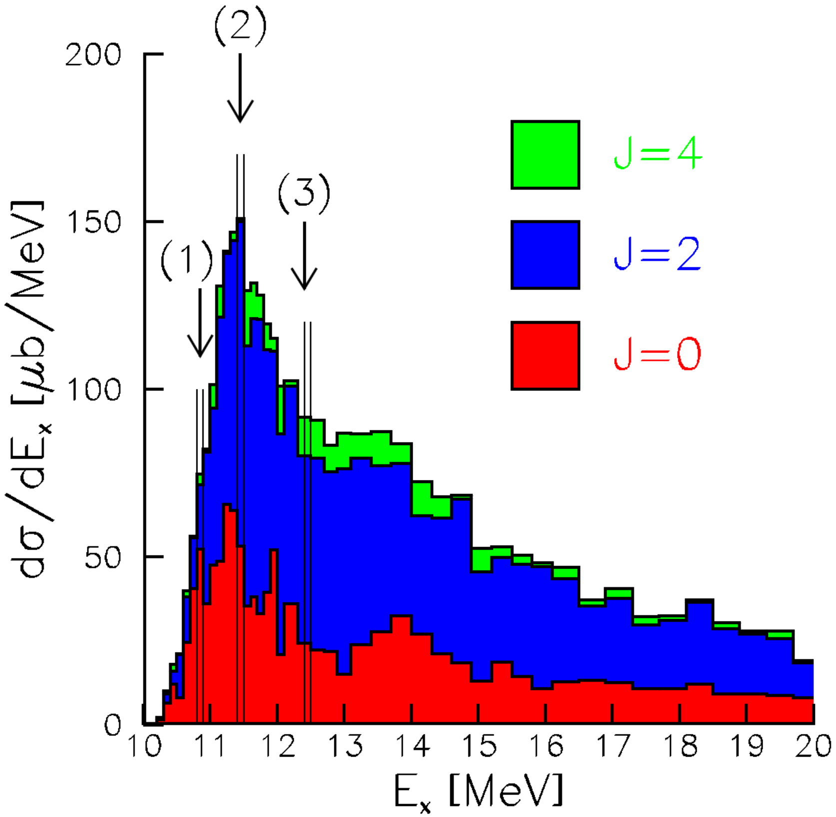
Angular distribution of (α,α')

Angular correlation of $^6He+^6He$ Decay (interference)

MDA analysis

$$\frac{d^2\sigma}{d\Omega_{inel}d\Omega_{decay}} = \left| \sum_{l,m} \alpha_l \beta_{lm}(\theta) Y^*_{lm}(\Omega_{decay}) \right|^2$$





$^{4}He(^{12}Be, ^{12}Be^{*})$: Deduced levels (0^{+}, 2^{+})

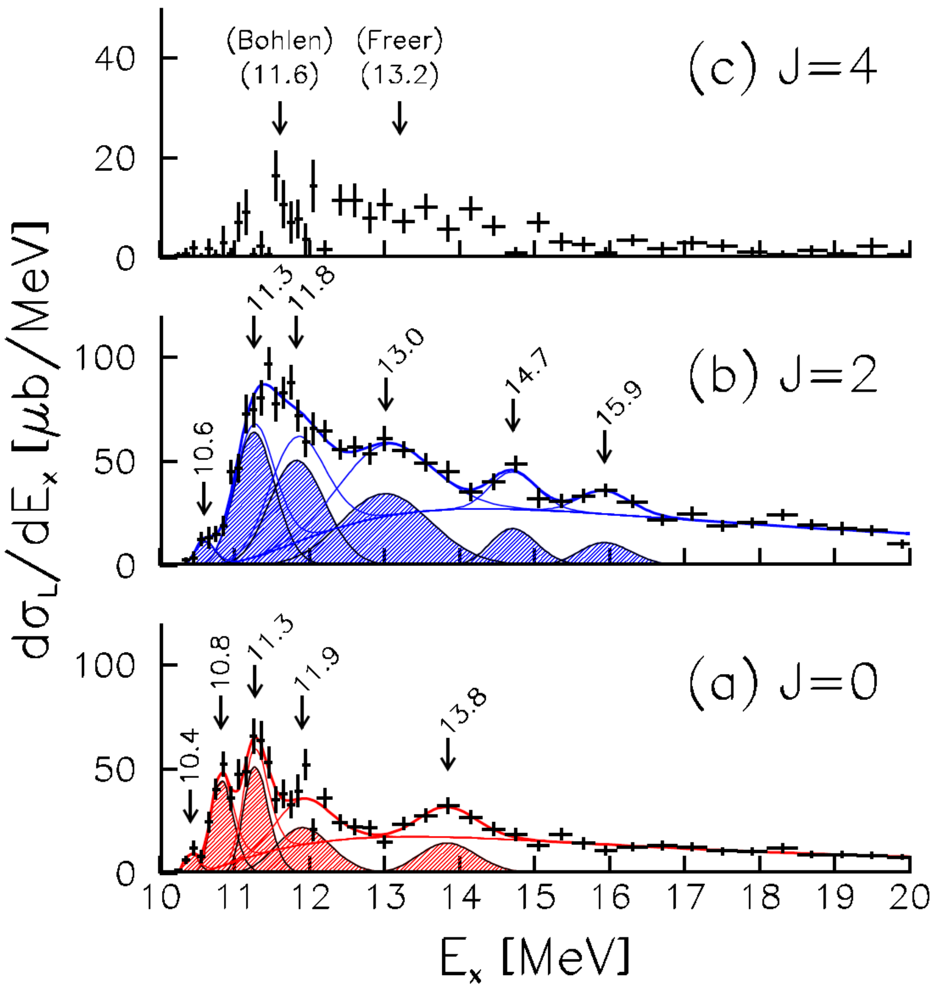


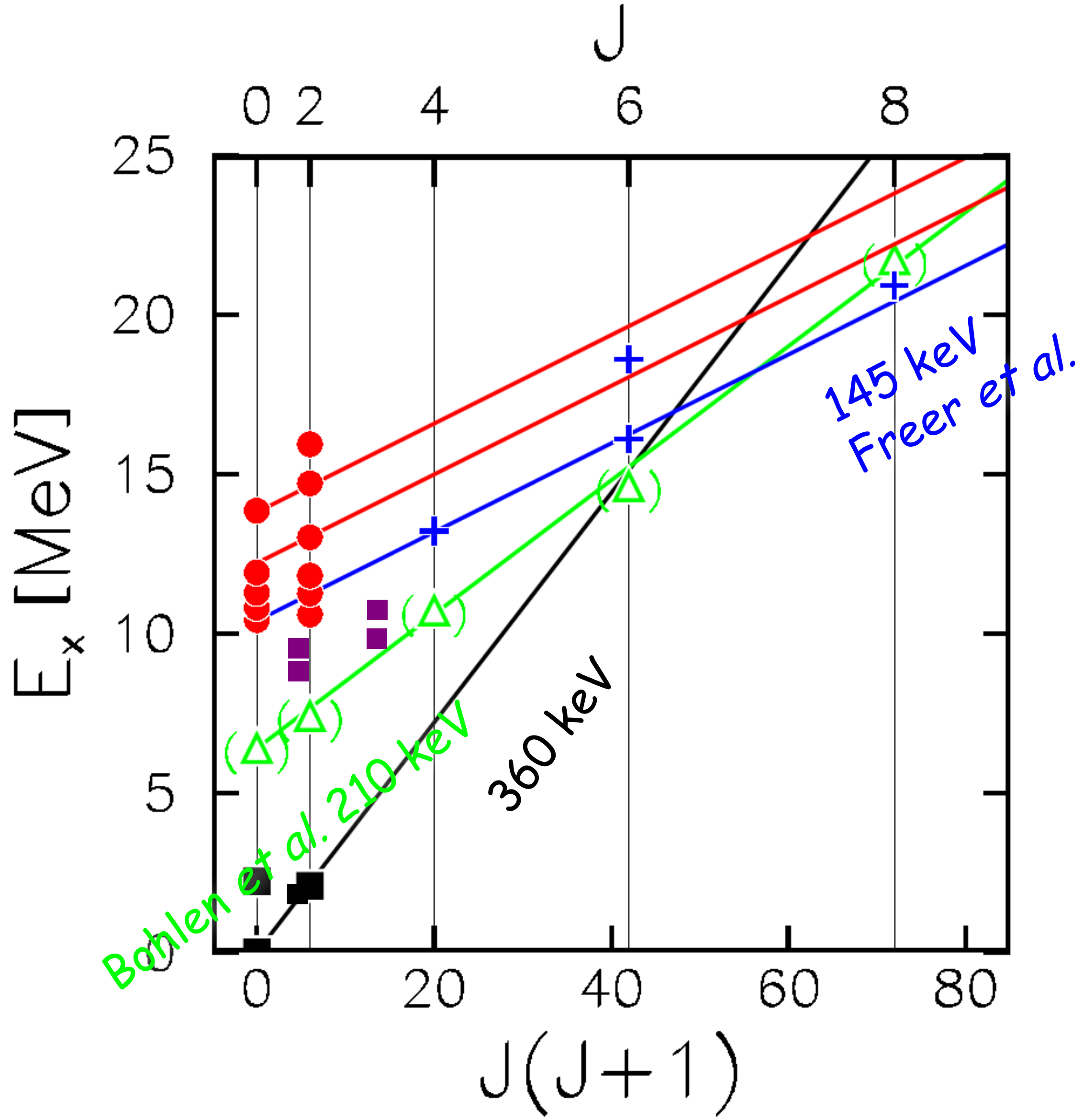
Table 5.1: Results of the fit to excitation energy spectra.

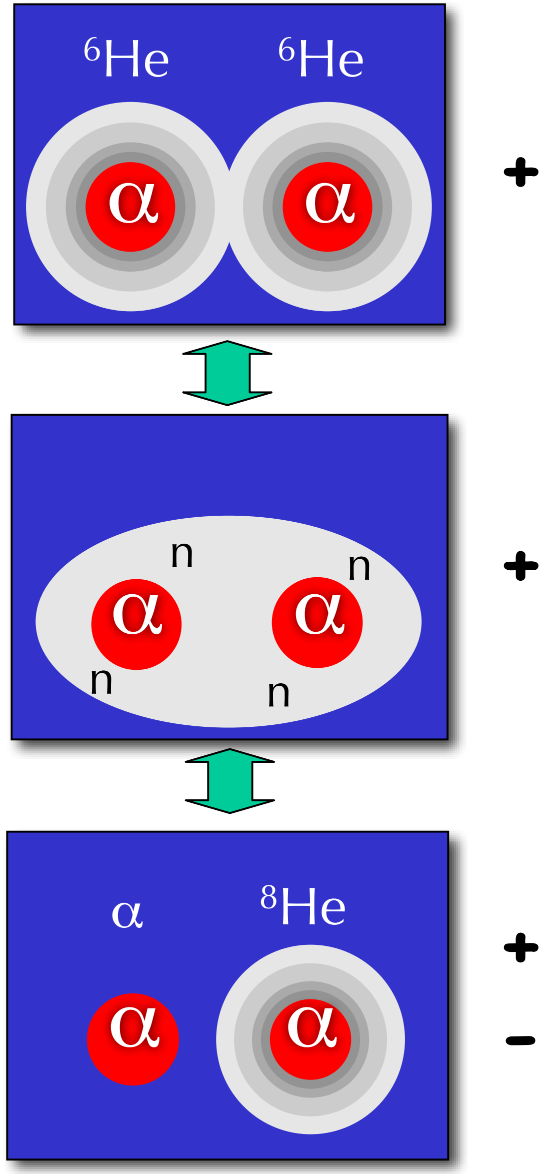
J^{π}	E_R [MeV]	$\sigma_R(E_R)$ [μb]	Γ_R [MeV]	$\sigma_R/\Delta\sigma_R$	significance 100%−(%)
0^{+}	10.41(4)	2.2(7)	0.0090(28)	3.1	0.73
	10.82(3)	16(4)	0.18(12)	4.6	0.006
	11.27(3)	21(5)	0.12(25)	4.1	0.006
	11.91(10)	20(6)	0.72(16)	3.6	7.28
	13.83(9)	14(5)	0.63(33)	3.0	0.91
2^{+}	10.60(5)	3.9(1.0)	0.20(4)	4.0	1.20
	11.26(6)	43(9)	0.51(5)	5.0	0.35
	11.82(12)	47(10)	0.75(9)	4.9	0.35
	13.01(12)	52(9)	1.29(14)	5.6	0.002
	14.71(7)	14(3)	<0.37[†]	4.4	2.70
	15.93(10)	10(3)	<0.65[†]	3.6	5.76

[†]C.L. 68%

Same method (with odd *l*) is applied for $^{4}He+^{8}He$ channel (preliminary)

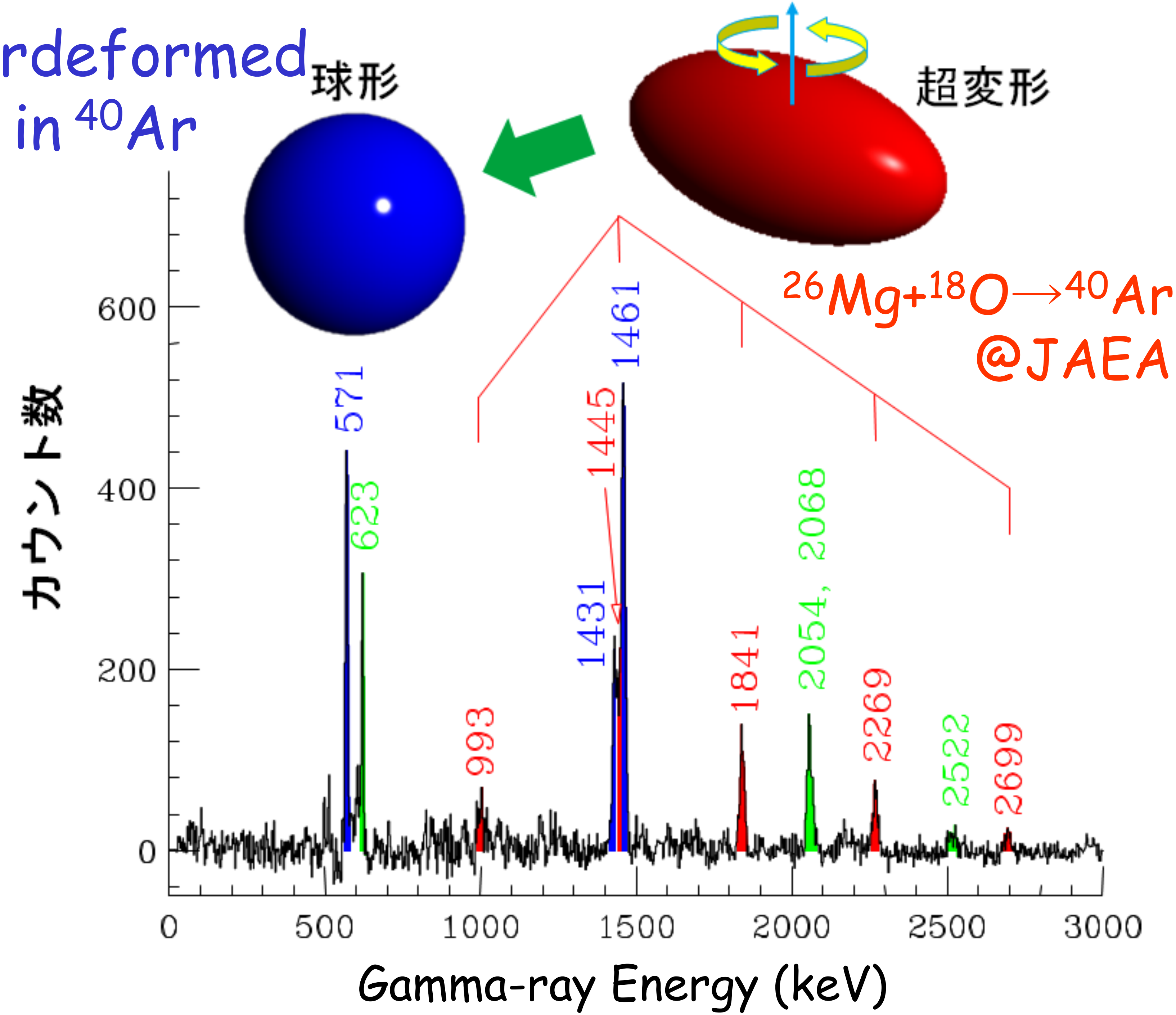
$^{4}He(^{12}Be,\ ^{12}Be^{*}\rightarrow{}^{6}He+{}^{6}He,\ {}^{4}He+{}^{8}He)$



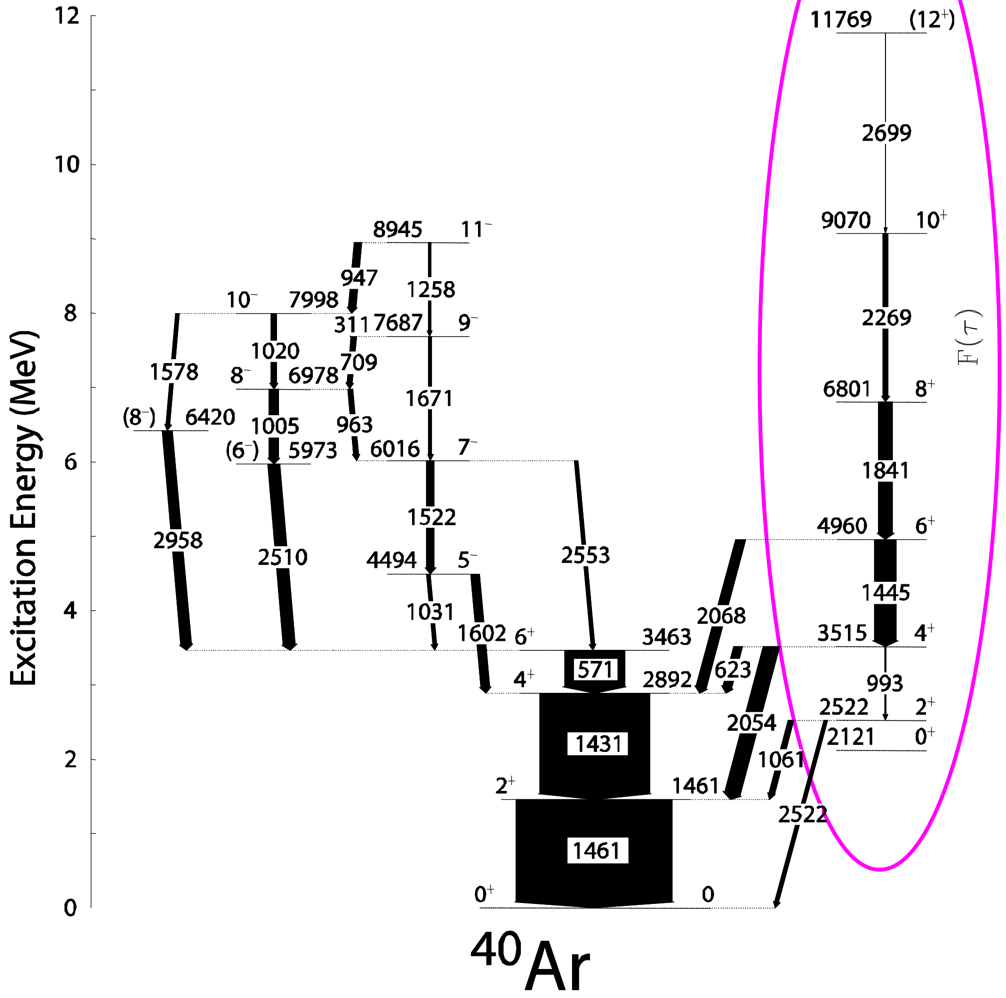


High-spins using Fusion reaction

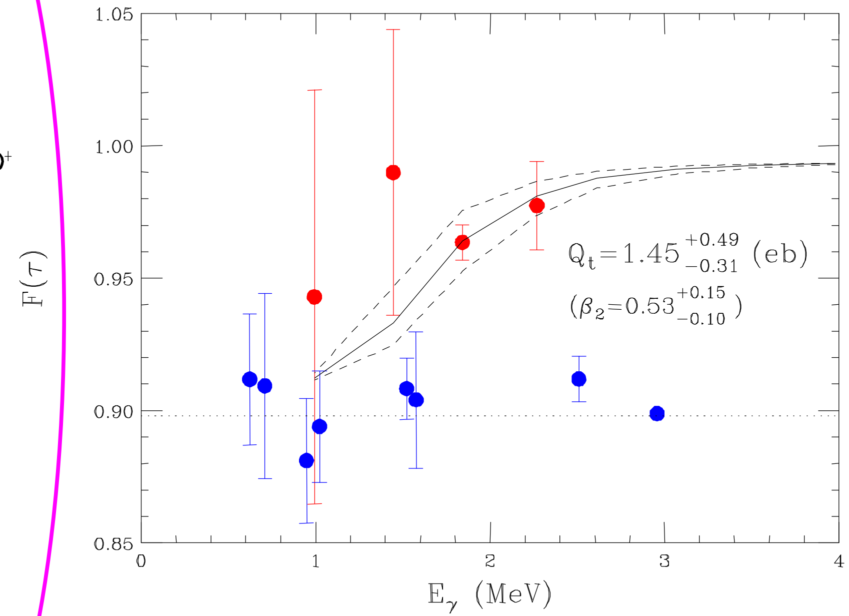
Superdeformed band in ^{40}Ar



Level scheme of ^{40}Ar



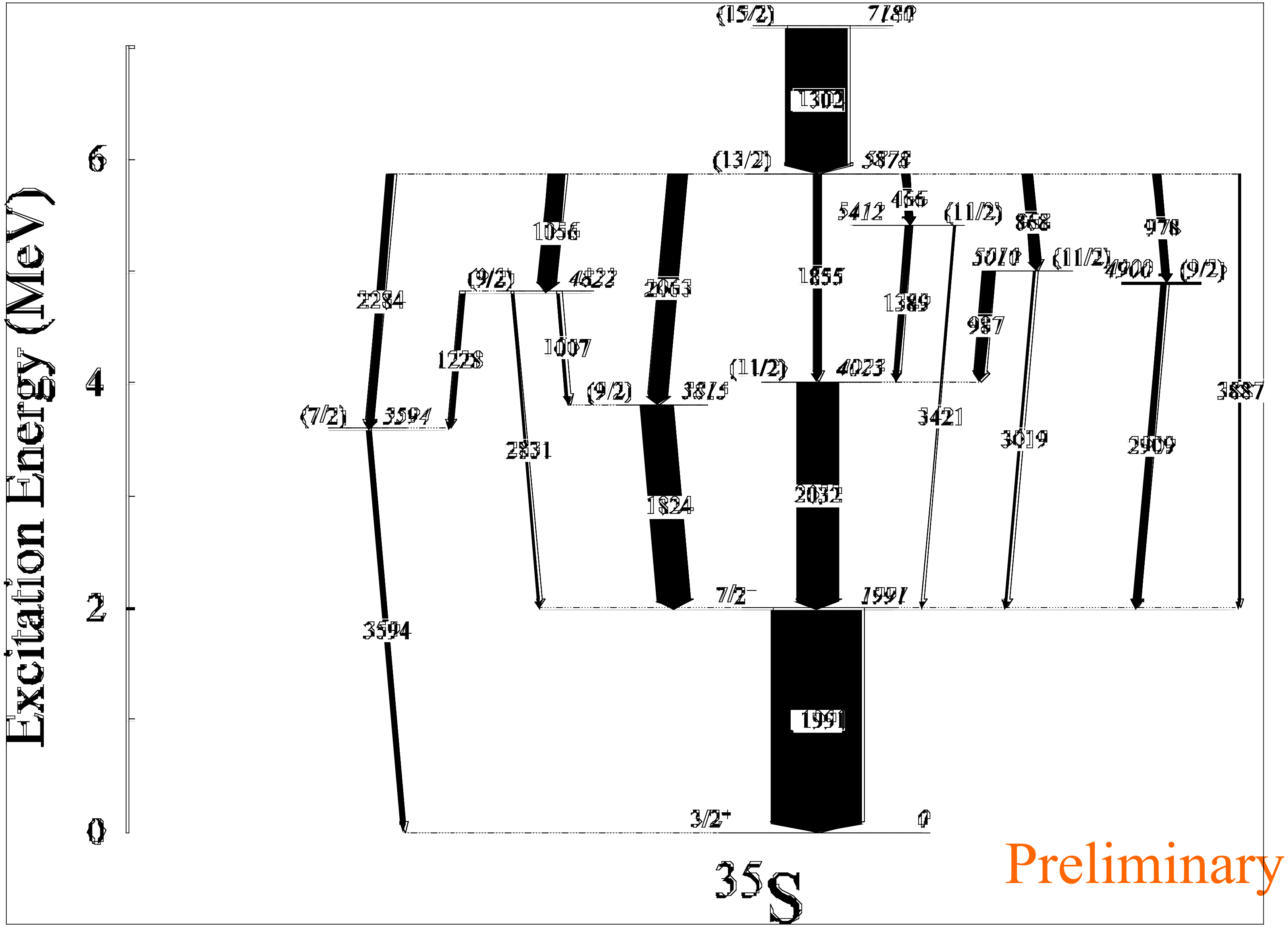
Residual Doppler –shift analysis



$\beta_2(^{40}Ar) \sim 0.53 \rightarrow$ SD

$\beta_2(^{36}Ar) = 0.46(3)$

Level scheme of ^{35}S



Exp. @ Tohoku