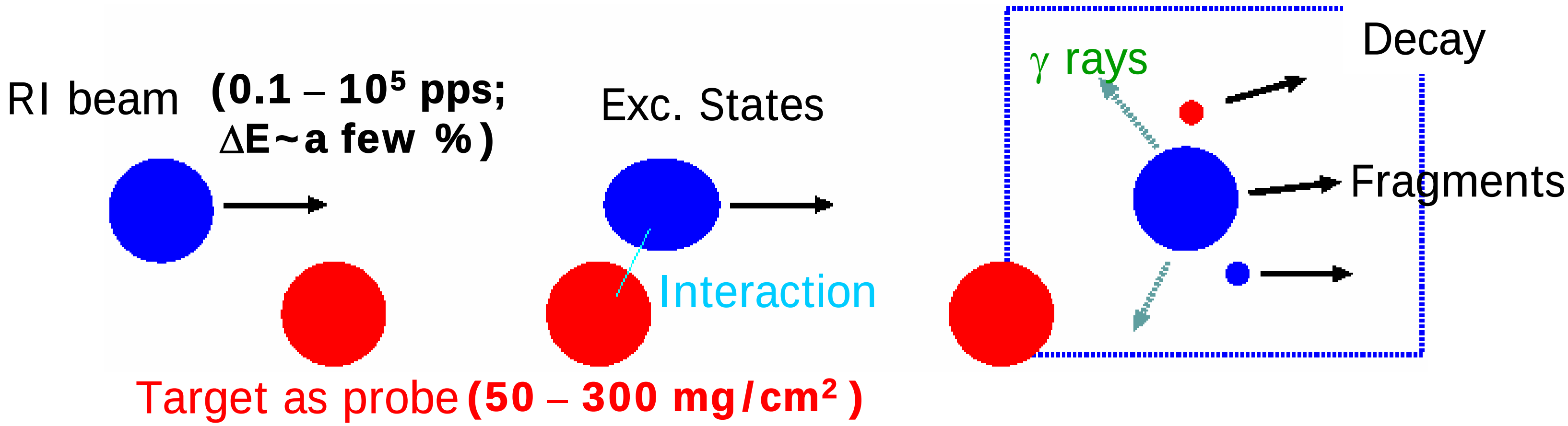
Structure change in light neutron-rich nuclei via nucleon transfer reaction

CNS, University of Tokyo
S. Shimoura

Collaborators

- *CNS / Univ. Tokyo*
  - M. Niikura, M. Tamaki, A. Saito, E. Ideguchi, M. Notani, T. Teranishi, S. Kubono, H. Iwasaki, S.S.
- *RIKEN*
  - **S. Michimasa** (^{23}F*), K. Yamada, T. Gomi, N. Imai, H. Baba, S. Takeuchi, T. Minemura, Y. Yanagisawa, N. Aoi, Z. Elekes, M. Kurokawa, H. Sakurai, T. Motobayashi, M. Ishihara
- *Rikkyo Univ.*
  - Y.U. Matsuyama, S. Kanno, E. Takeshita, T. Fukuchi, K. Kurita, K. Ieki
- *Kyoto Univ.*
  - **S. Ota** (^{13}B*), T. Fukui, T. Murakami

Inverse Kinematics w/ RI beam (30-100 MeV/u)



- 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 (kinematical focus)
    - Gamma detectors surrounding target (Doppler shift)

Probes for direct reactions (30-100 MeV/u)

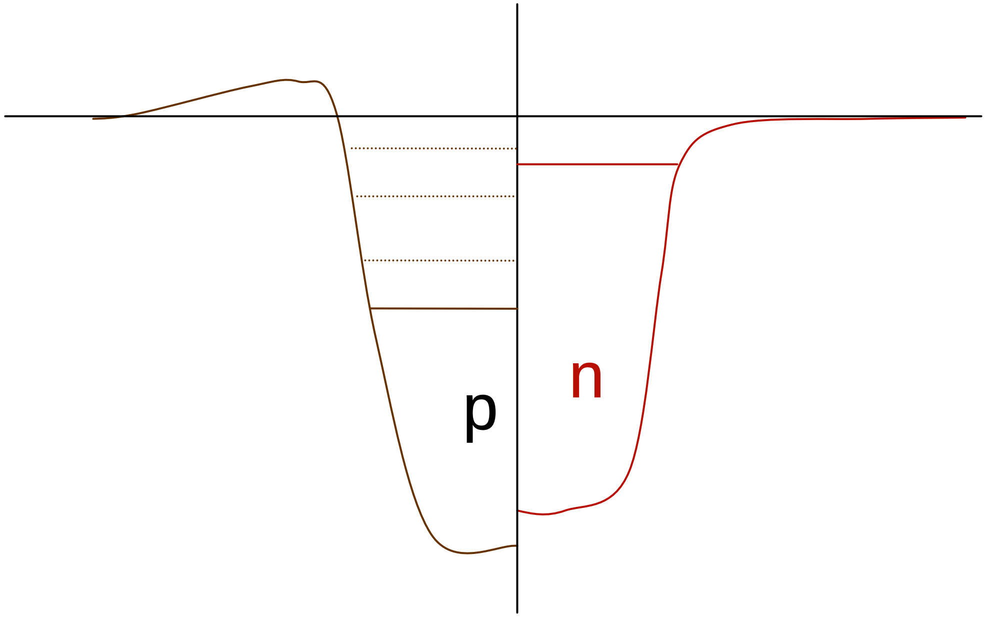
- Heavy Nuclei: Strong Coulomb Field
  - Coulomb Excitation, Coulomb Dissociation
    - E1, E2, (M1) / Isovector
- H, D, ^{4}He [Liquid targets]
  - Inelastic Scattering
    - Collective / single-particle states (odd nuclei)
    - Isovector (H) / Isoscaler(H, D, **^{4}He**)
    - Spin-Flip (H, D) / Spin-Non-Flip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

Motivation for transfer reactions

Structure information of nuclei as functions of N and Z

Shell Evolution : Single particle states

- Spectroscopy of proton (unoccupied) single particle states in neutron-rich nuclei



Nucleon (Proton) Transfer

- (d,n), (^{3}He,d), (α,t), ...

Incident energy higher than 30 MeV/u

✓ Thicker target (100~200 mg/cm^2)

✓ Less distortion effect

✓ Less multi-step process

✓ Same optical potential as inelastic excitation

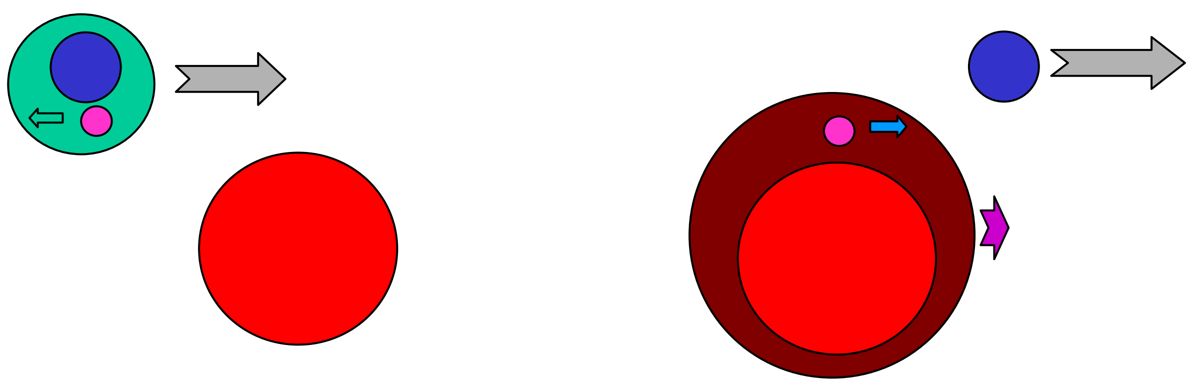
✓ Identification by comparing with other direct reactions

But

x Momentum mismatch

Momentum Matching Condition

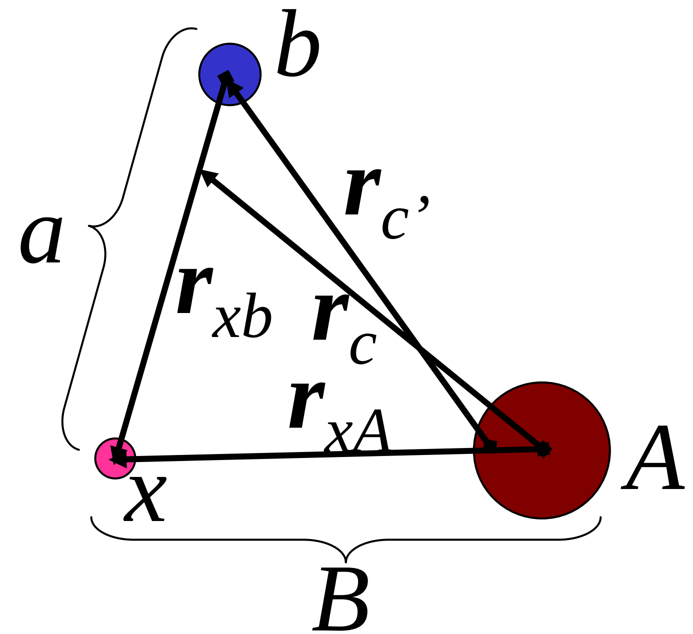
- As if "Getting off from the moving train (projectile) to platform (target)"
  - Internal motion in the train (Fermi motion in the projectile) along the opposite direction of the train (target)
  - Motion on the platform (Fermi motion of the nucleon on the target) along the direction of the train



$$\underset{[c]}{a+A} \rightarrow \underset{[c']}{b+B}$$

$$a=(b+x)$$

$$B=(A+x)$$



Plane Wave Born Approx.

$$T_{PW}^{\text{Post}} = \langle \phi_{c'} | V_{xb} + V_{bA} | \phi_c \rangle$$

$$T_{PW}^{\text{Prior}} = \langle \phi_{c'} | V_{xA} + V_{bA} | \phi_c \rangle$$

$$\langle \phi_{c'} | V_{xb} | \phi_c \rangle = -\frac{1}{(2\pi)^3} \frac{\hbar^2}{2\mu_{xb}} \left(k_{xb}^2 + \kappa_a^2\right) \int d^3 r_{xb} \psi_a(\vec{r}_{xb}) e^{i\vec{k}_{xb}\cdot\vec{r}_{xb}} \int d^3 r_{xA} \psi_B^*(\vec{r}_{xA}) e^{-i\vec{k}_{xA}\cdot\vec{r}_{xA}}$$

$$\langle \phi_{c'} | V_{xA} | \phi_c \rangle = -\frac{1}{(2\pi)^3} \frac{\hbar^2}{2\mu_{xA}} \left(k_{xA}^2 + \kappa_B^2\right) \int d^3 r_{xb} \psi_a(\vec{r}_{xb}) e^{i\vec{k}_{xb}\cdot\vec{r}_{xb}} \int d^3 r_{xA} \psi_B^*(\vec{r}_{xA}) e^{-i\vec{k}_{xA}\cdot\vec{r}_{xA}}$$

$$\vec{k}_{xb} = \frac{b}{a}\vec{k}_c - \vec{k}_{c'} \; ; \; \vec{k}_{xA} = \vec{k}_c - \frac{A}{B}\vec{k}_{c'}$$

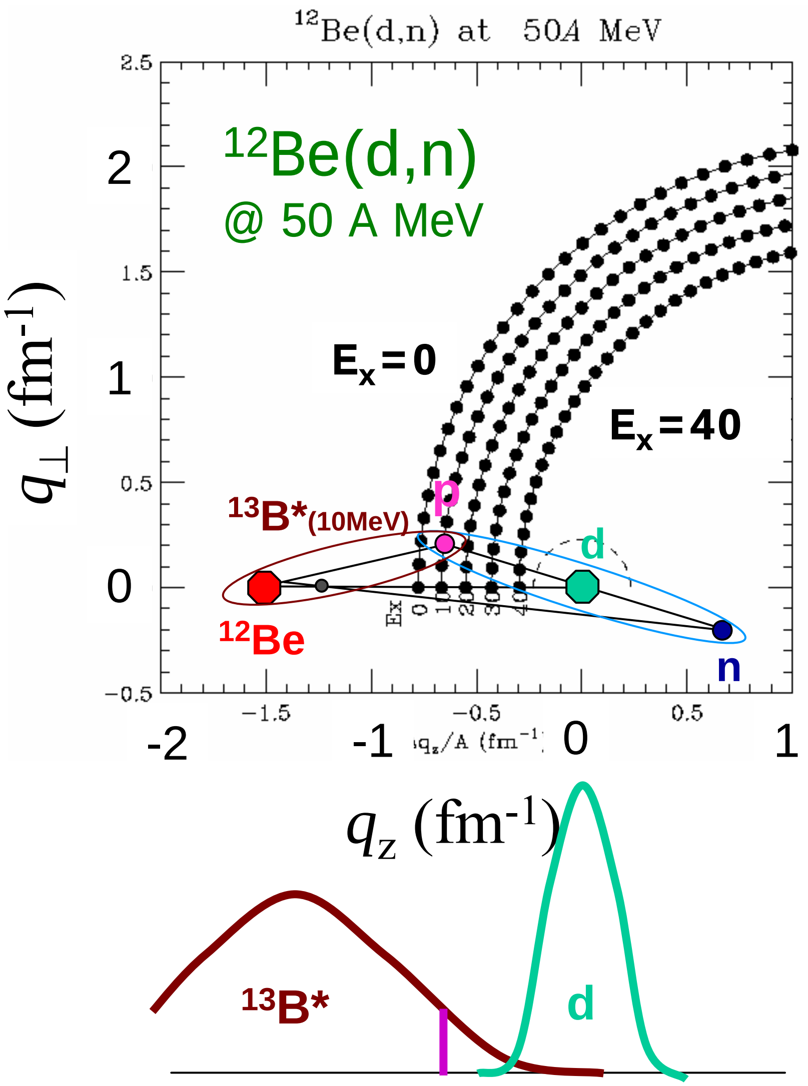
$$\frac{\hbar^2 \kappa_a^2}{2\mu_{xb}} = \varepsilon_a \; ; \; \frac{\hbar^2 \kappa_B^2}{2\mu_{xA}} = \varepsilon_B$$

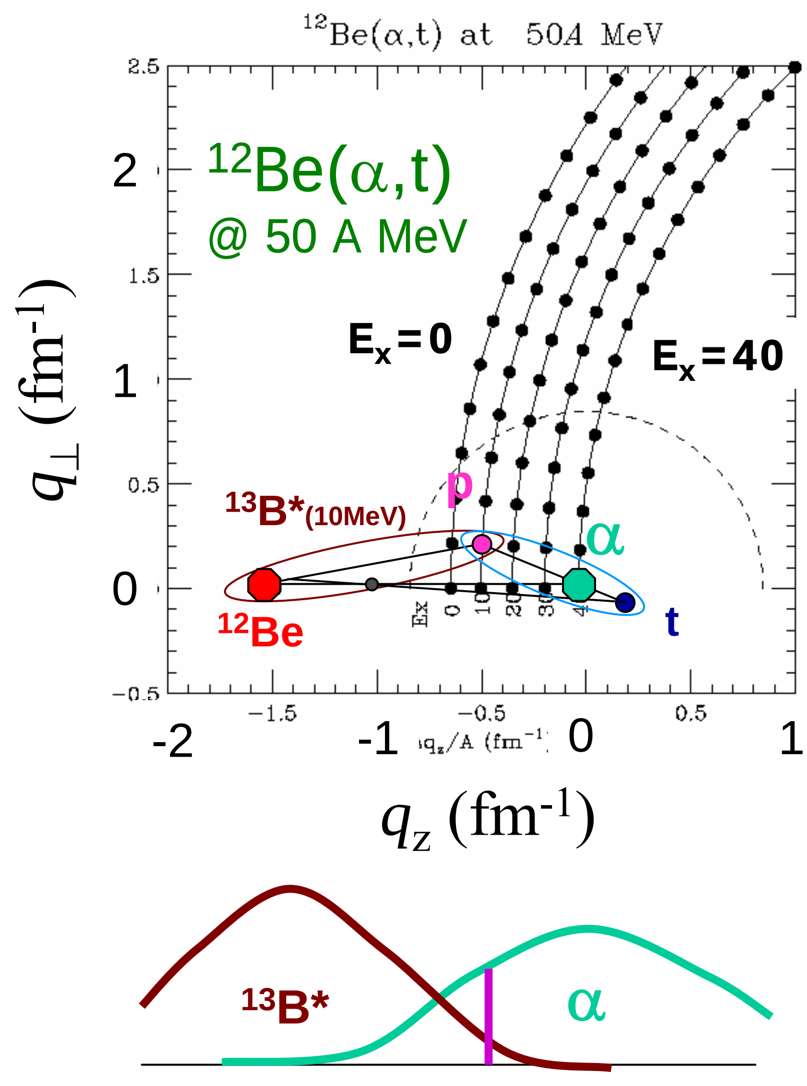
Fourier Transforms of wave functions of nucleon (x) in a and B

Same value but different expressions

Binding energies of a and B

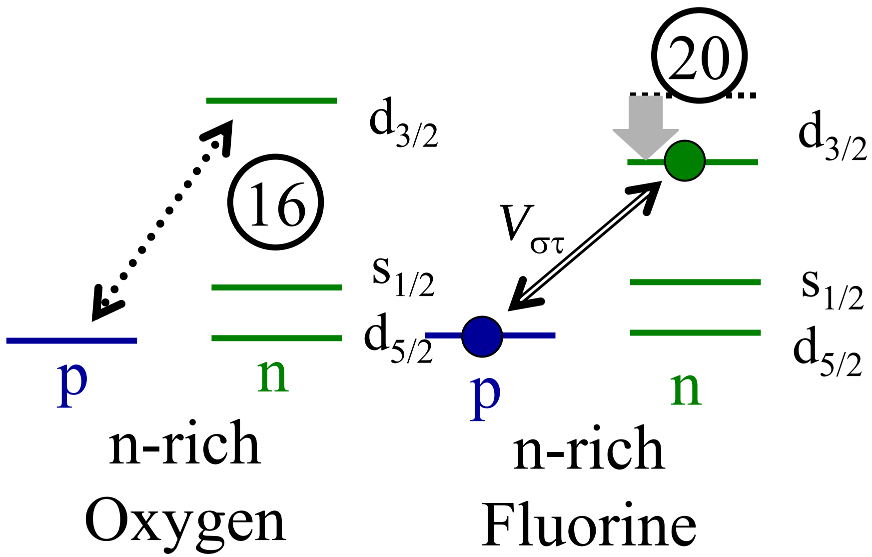
Proton Transfer in Momentum Space

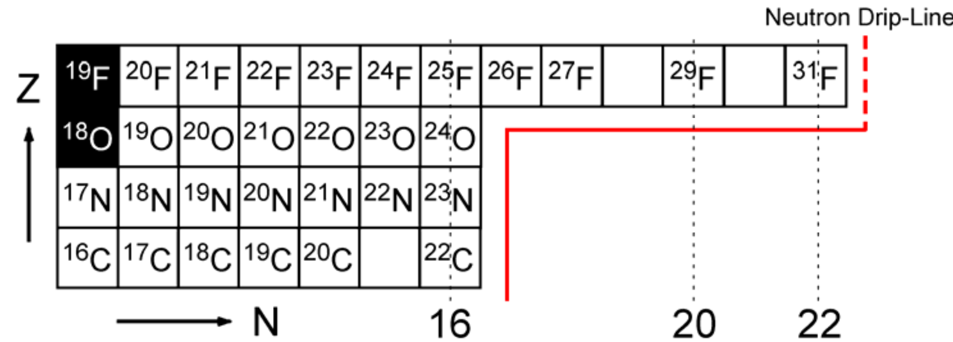




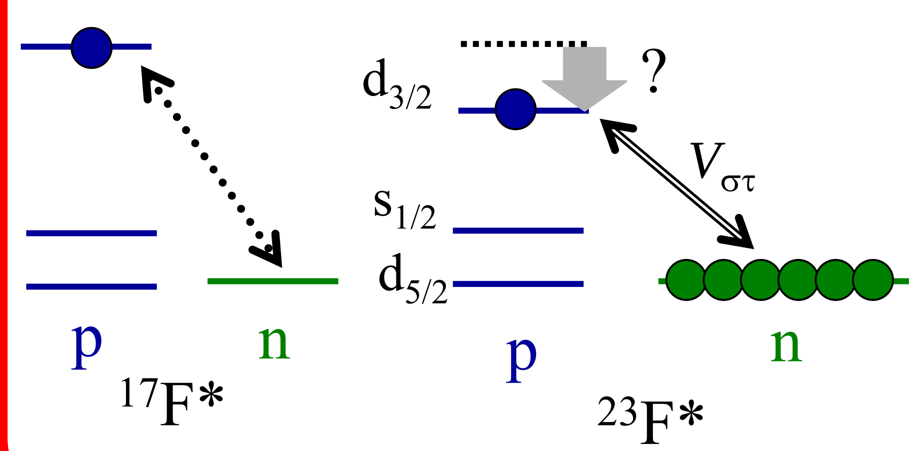
Exotic Magic Number at N=16 (Z~8)

Spin-orbit splitting between $\nu d_{3/2}$ & $\nu d_{5/2}$ depend on the number of protons in $d_{5/2}$ orbit attracting $\nu d_{3/2}$ orbit by $V_{\sigma\tau}$



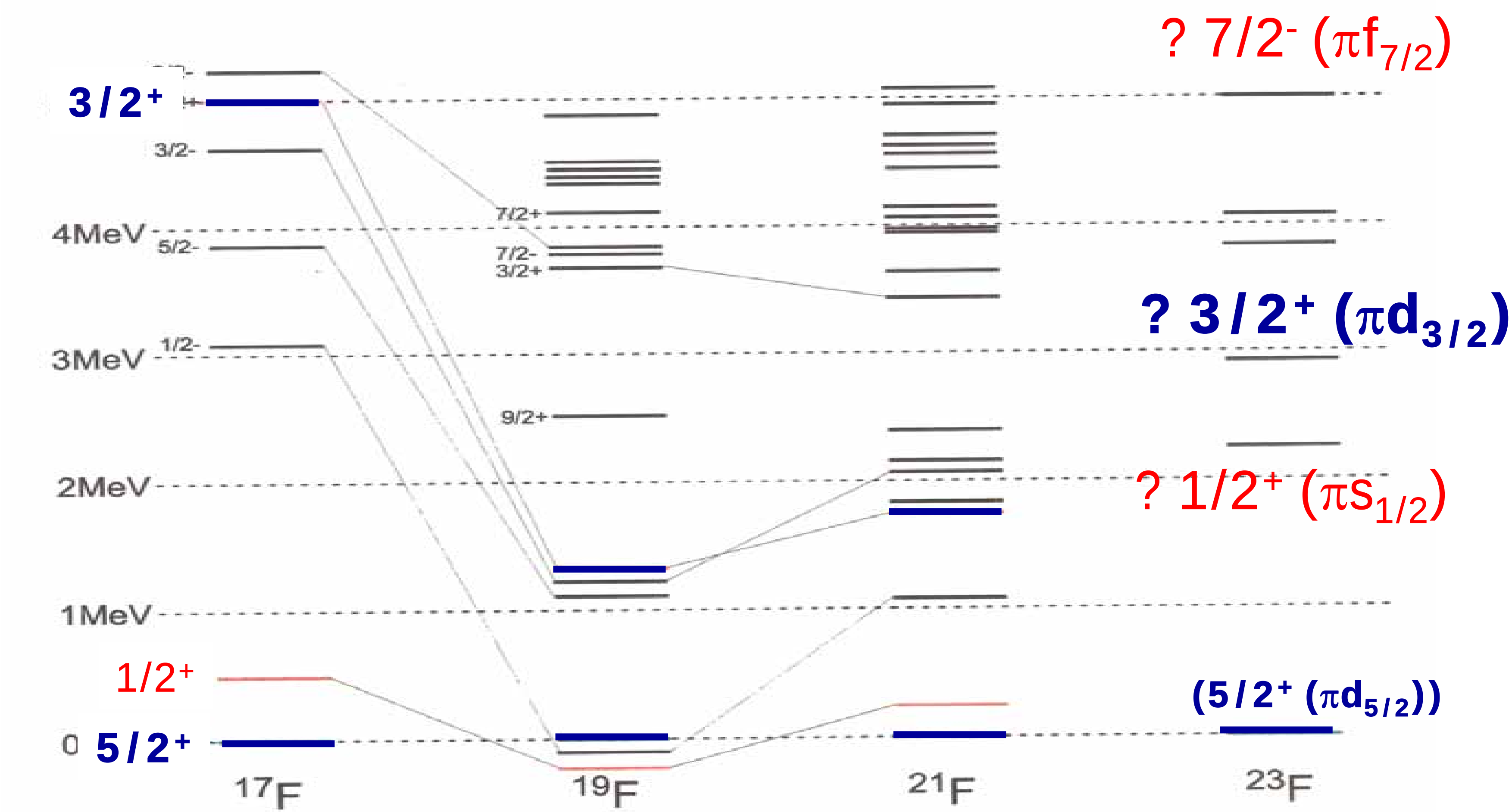


Change of Fluorine Proton Shell as a function of Neutron number



Excitation energy of $3/2^+$ S.P. state in ^{17}F & ^{23}F ?

Known Energy Levels of Fluorine Isotopes



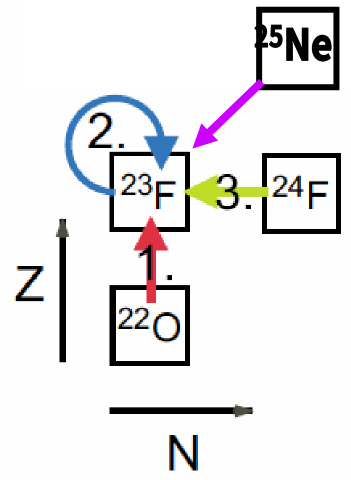
N=	8	10 Deformed	12	14
Ex(O(2^+))	6.92	1.99	1.64	3.21

$^4He(^{22}O,^{23}F\gamma)$, $^4He(^{23}F,^{23}F\gamma)$, $^4He(^{24}F,^{23}F\gamma)$, $^4He(^{25}Ne,^{23}F\gamma)$

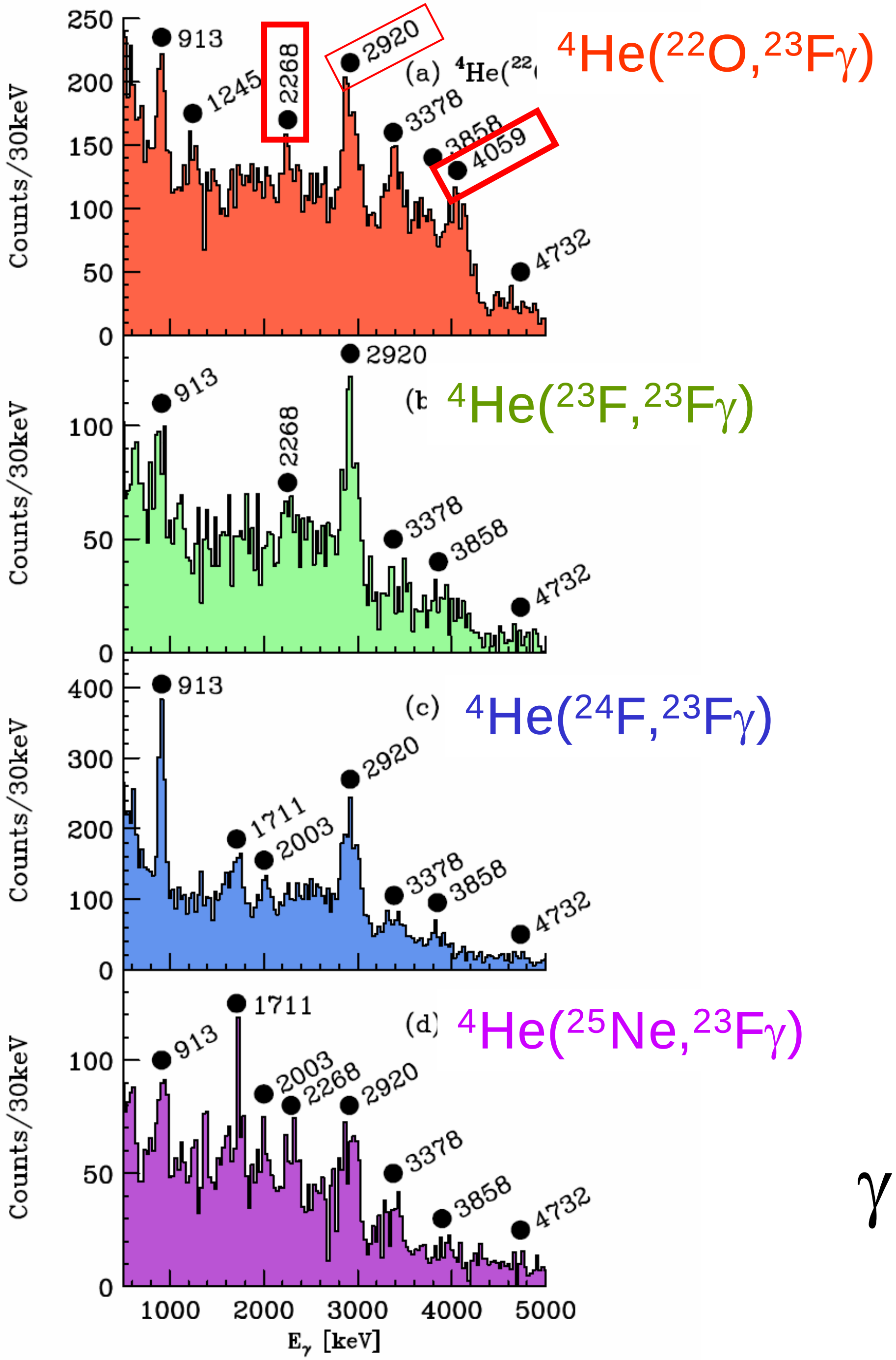
- Use of Cocktail beam (^{22}O, ^{23}F, ^{24}F , ^{25}Ne)
- Gamma ray measurement coincident with ^{23}F ejectile

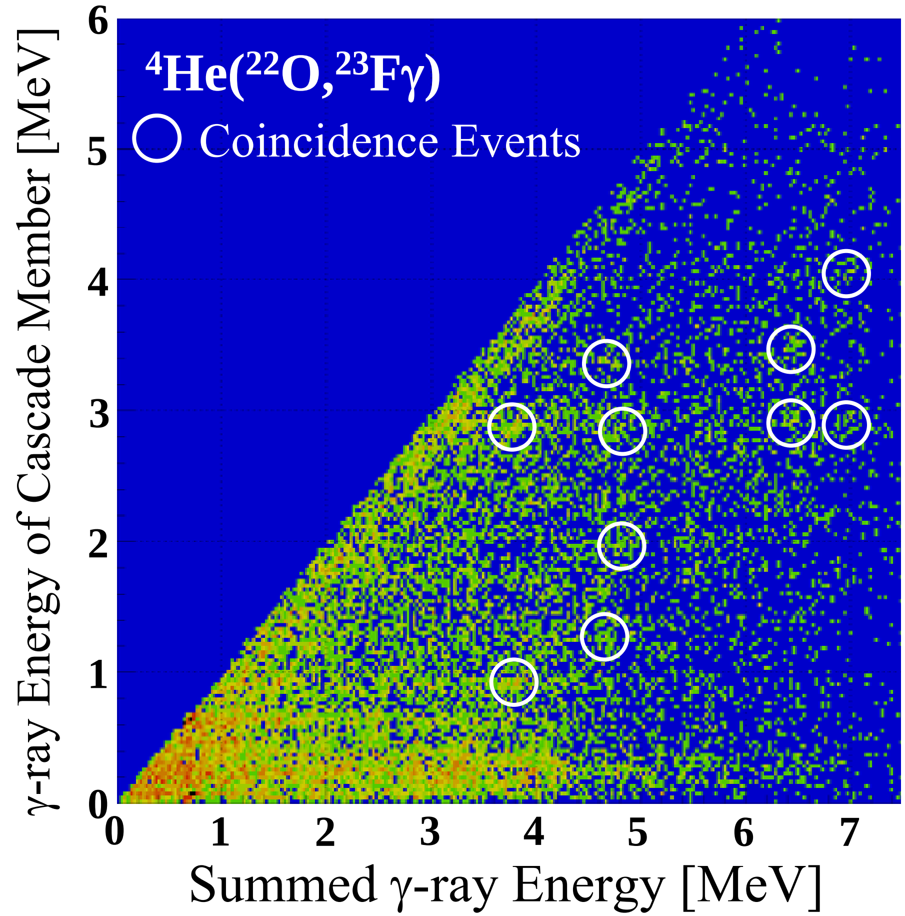
Three Different Reactions Approaching ^{23}F

1. $^4He(^{22}O,^{23}F\gamma)$: Proton Pickup Reaction
2. $^4He(^{23}F,^{23}F\gamma)$: Inelastic Scattering
3. $^4He(^{24}F,^{23}F\gamma)$: Knockout
4. **$^4He(^{25}Ne,^{23}F\gamma)$:**



1. Proton S.P. states ($5/2^+$, $1/2^+$, $3/2^+$)
2. Collective states; Non-spin-flip states ([core 2+]⊗S.P. state, etc)
3. Neutron hole states

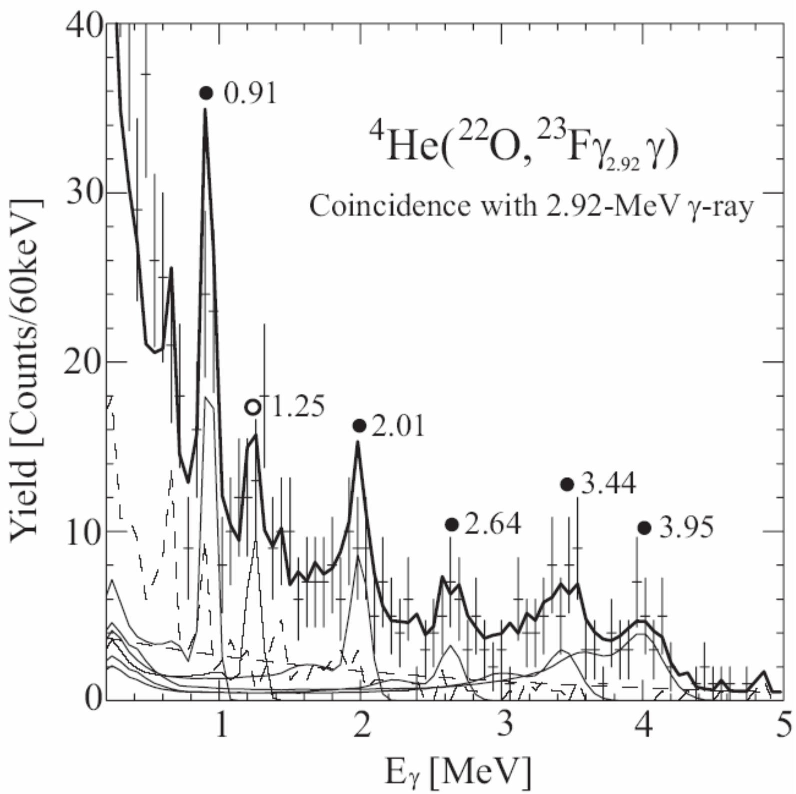


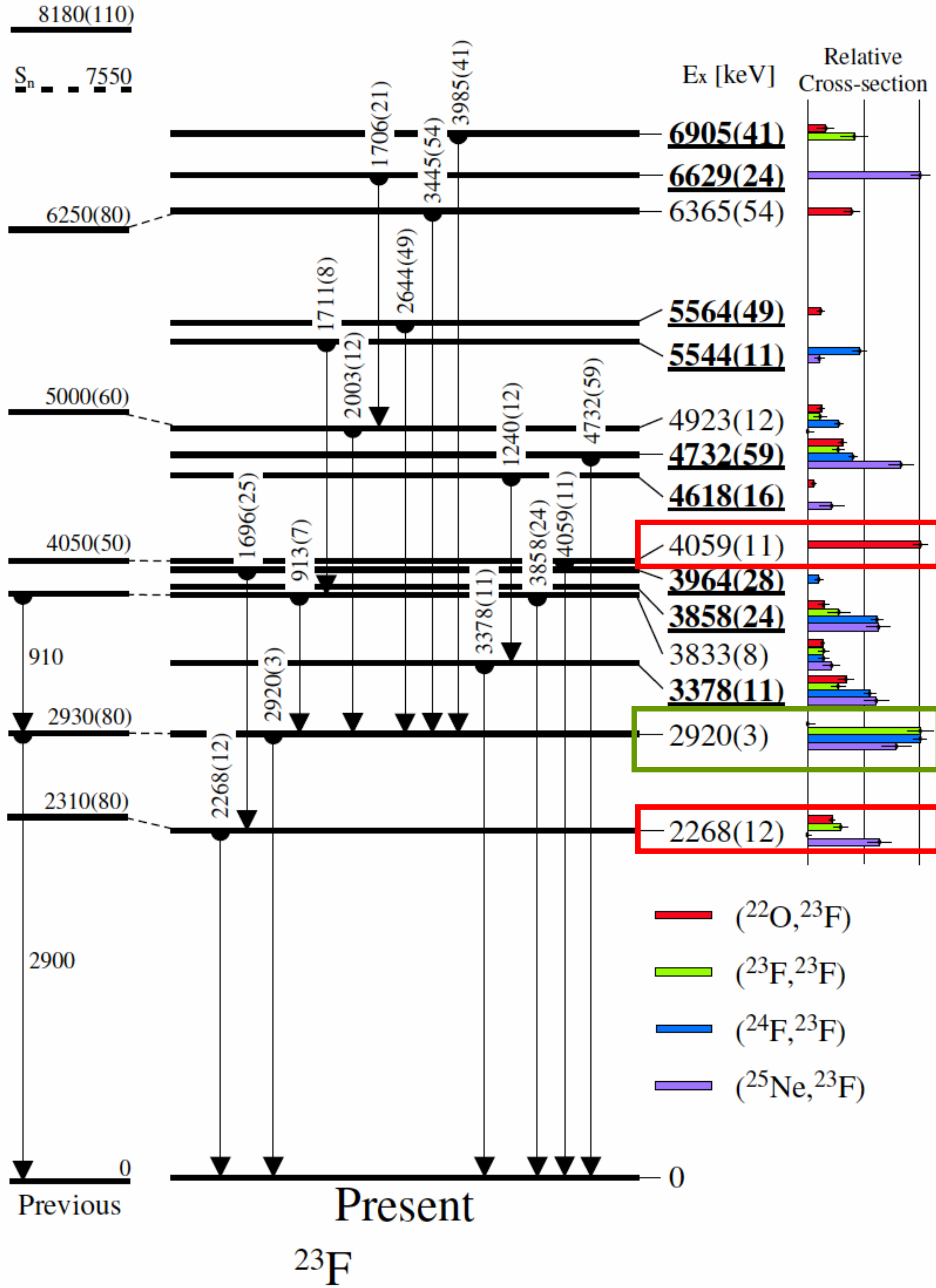


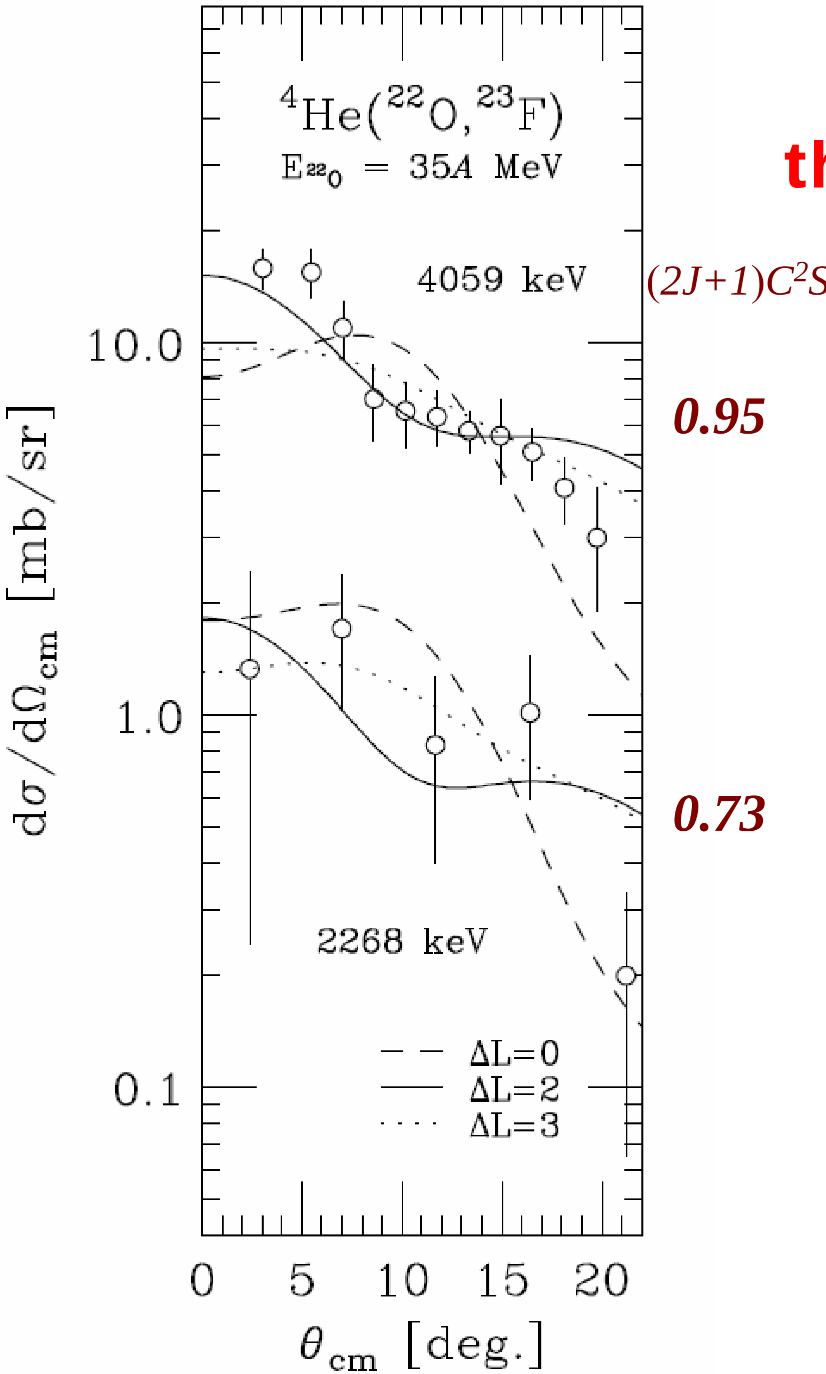
γ ray spectra

Level Scheme of ^{23}F

Fitting using response functions by GEANT3 simulations







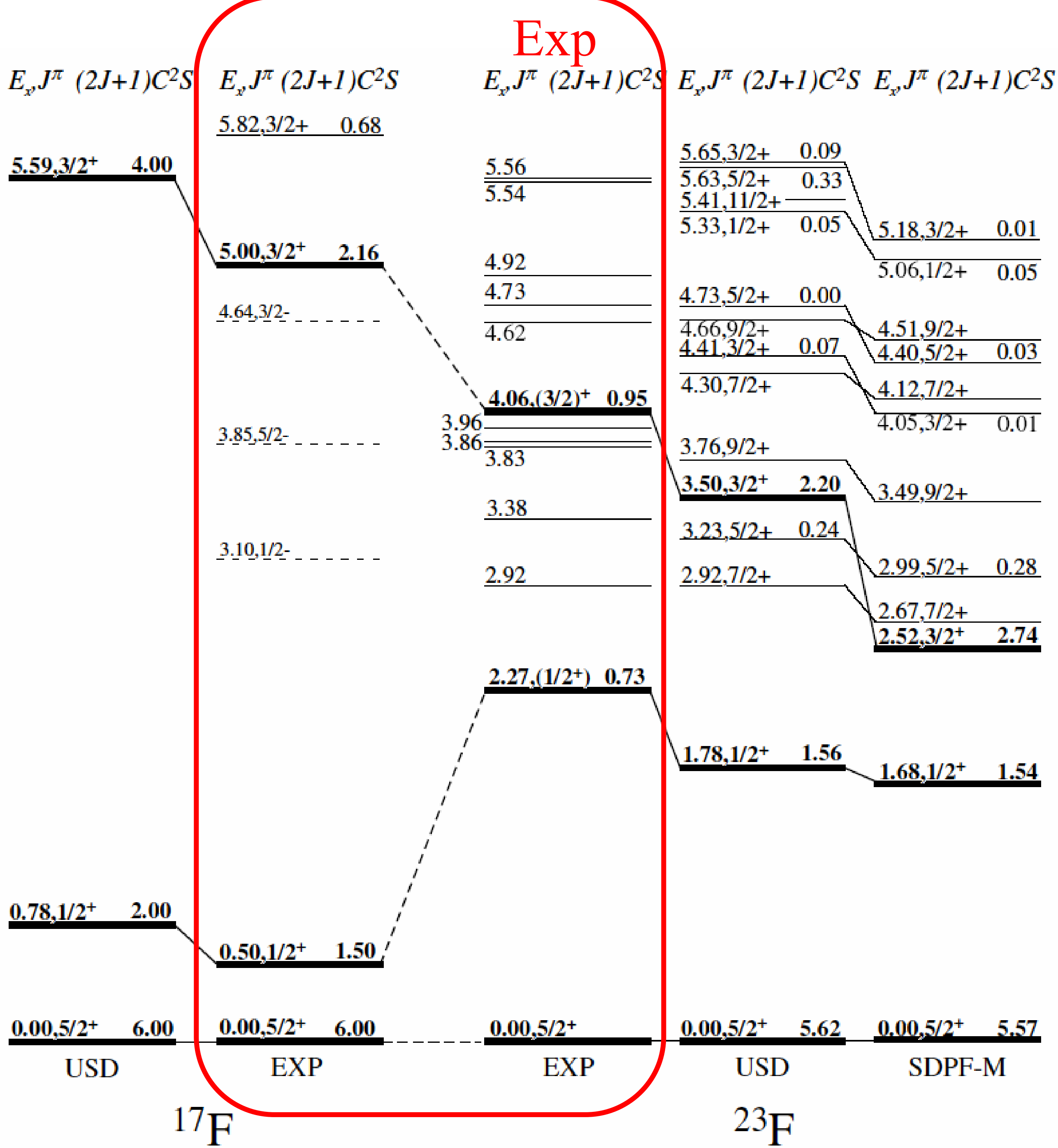
Angular Distributions for the 4.06- and 2.37-MeV state

J^π and spectroscopic factors of excited states by DWBA analysis.

- Optical Potentials
  of the $^{22}O+\alpha$ and the $^{23}F+t$ channels deduce from angular distributions for $^{22}O(\alpha,\alpha')$ and $^{23}F(\alpha,\alpha')$

The 4.06-MeV state :
Single particle state in *d*.

The 2.27-MeV state : consistent with Single particle state in the *s*.



Comparison with Shell Model Calculations

LS splitting of proton single particle energy may be larger than stable nuclei because of neutron-richness

$$V_{LS} \propto \frac{1}{r}\frac{d}{dr}V(r)\left(\vec{l}\cdot\vec{s}\right)$$

[1] B.A.Brown, http://www.nscl.msu.edu/~brown/resources/SDE.HTM

[2] T.Otsuka, *private communication.*: predicts N=16 magic number

N-rich N=8 Nuclei

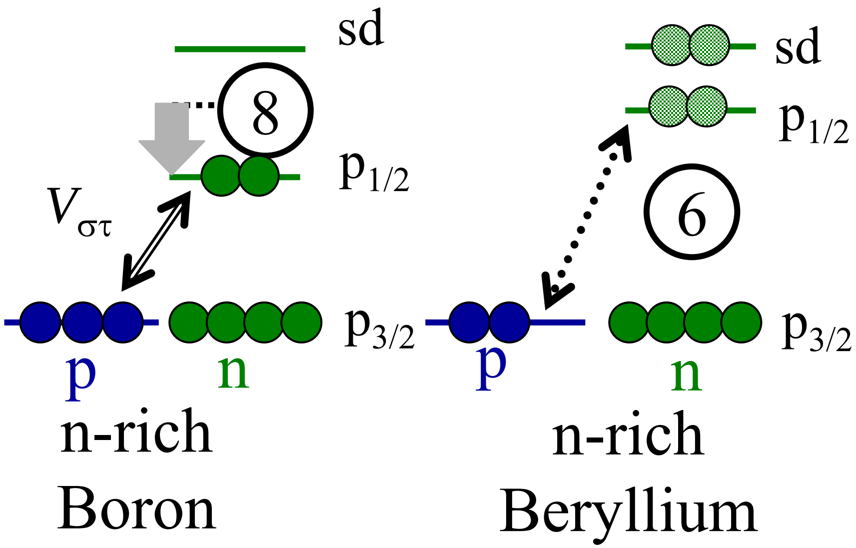
^{12}Be

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

Magicity loss in N=8

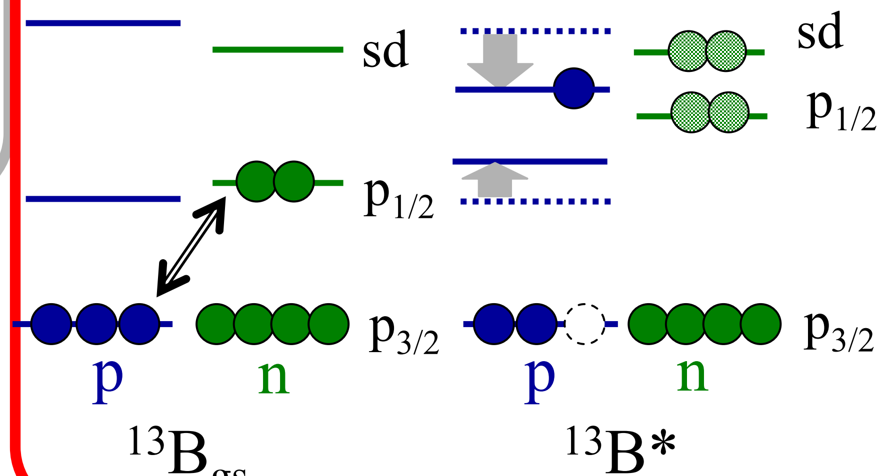
Deformed ground state

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



Change of Boron Proton Shell as a function of configuration

Deformed mean field?



^{13}B

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

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

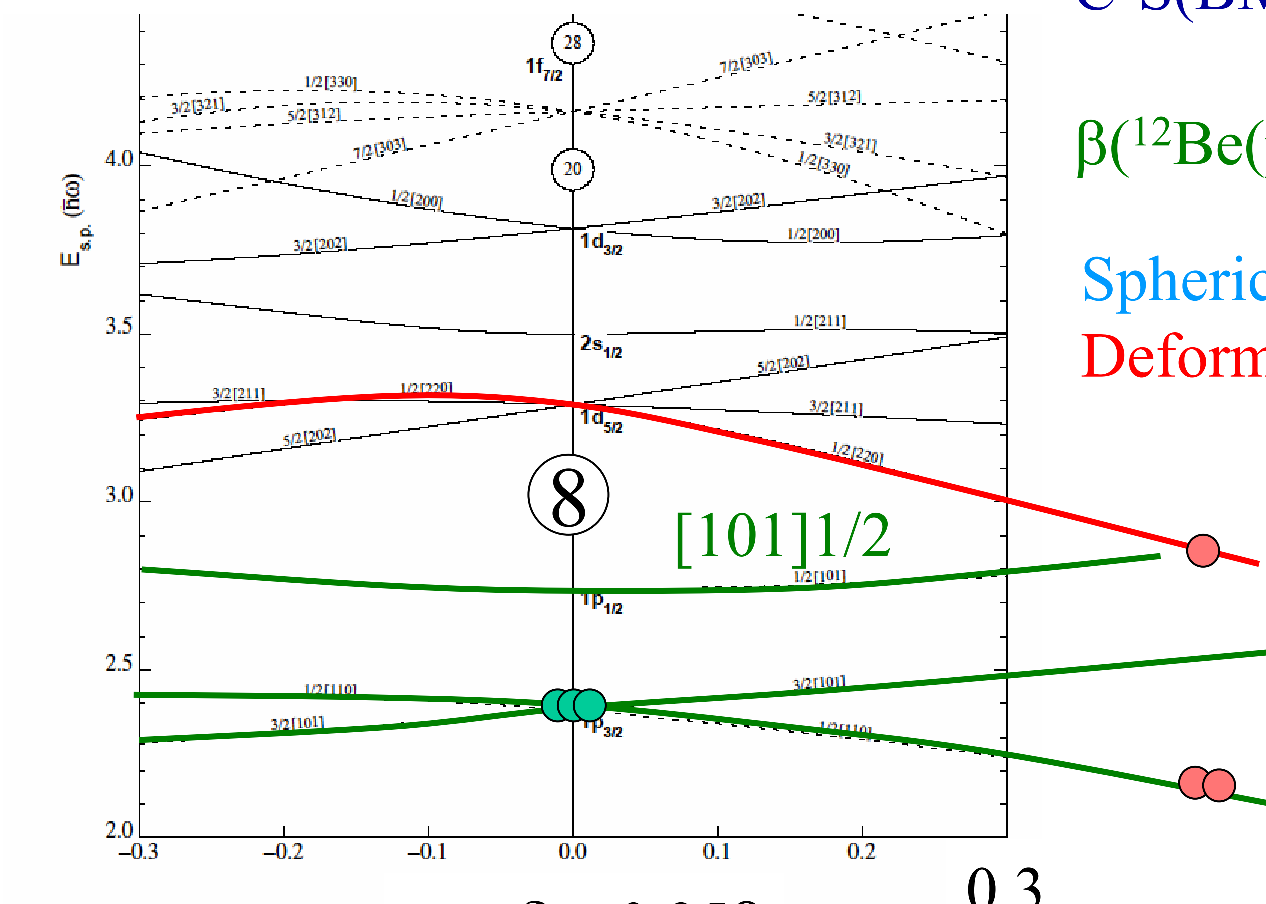
Deformed ^{12}Be core + 1 proton ?

$C^2S(BM) \sim 0.27$
for $\delta=0.4$

$\beta(^{12}Be(p,p')) \sim 0.6\text{-}0.7$

Spherical G.S.

Deformed Excited $1/2^+$?



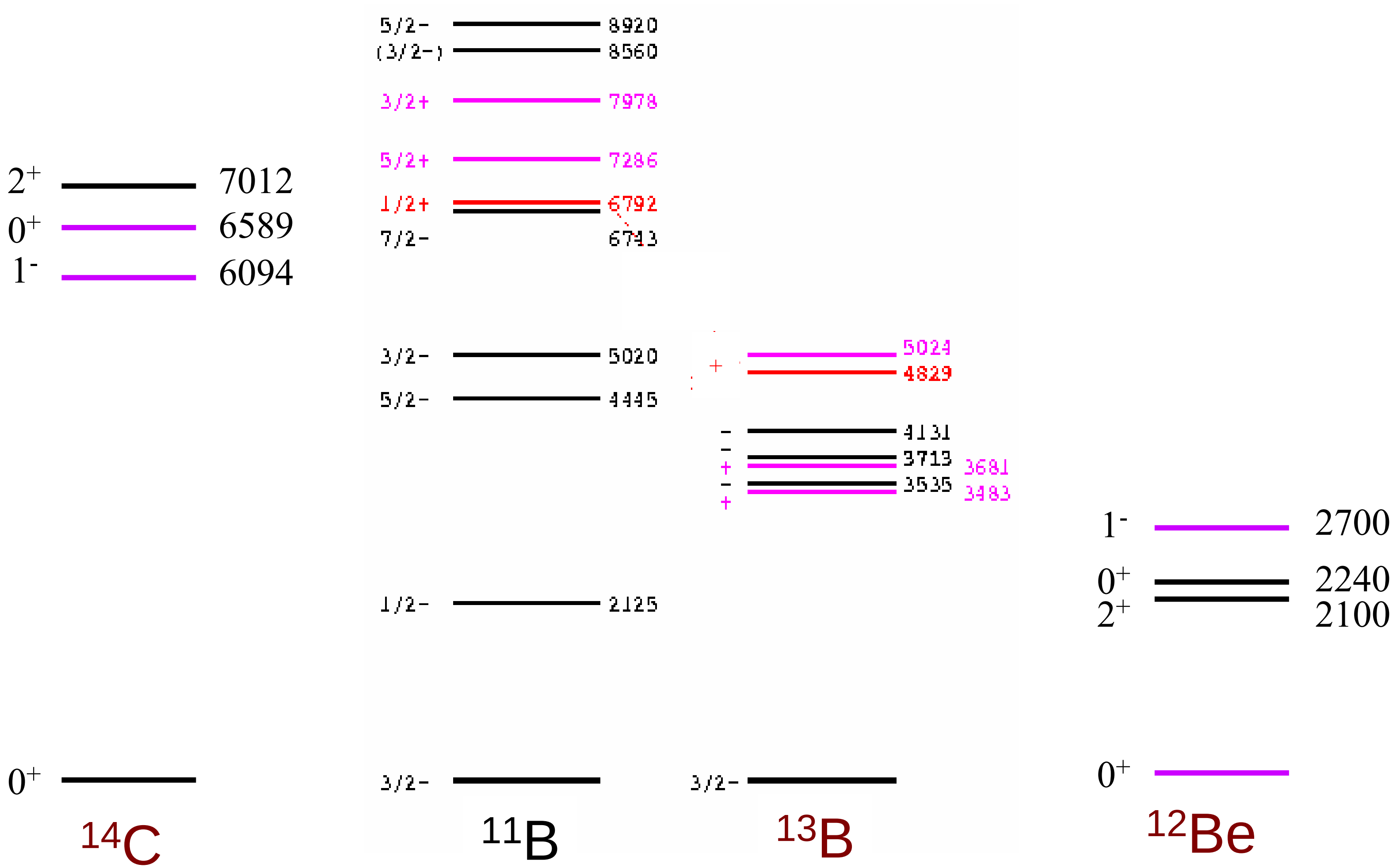
[220]1/2

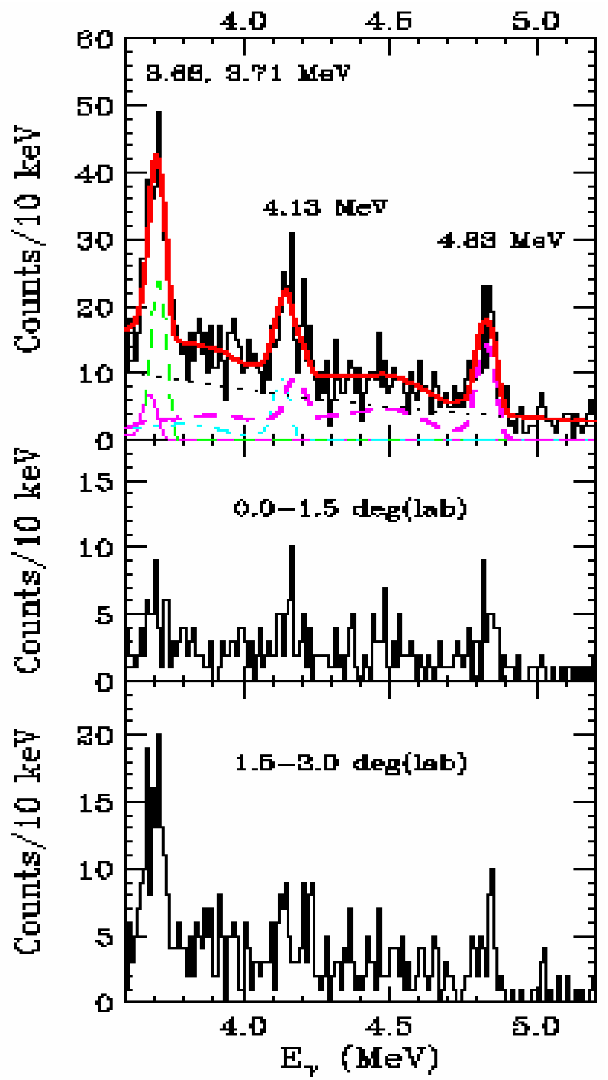
[101]3/2

[110]1/2

$\varepsilon_2 \sim \delta \sim 0.95\beta$

Spectra of ^{14}C, ^{12}Be, ^{11}B, and ^{13}B

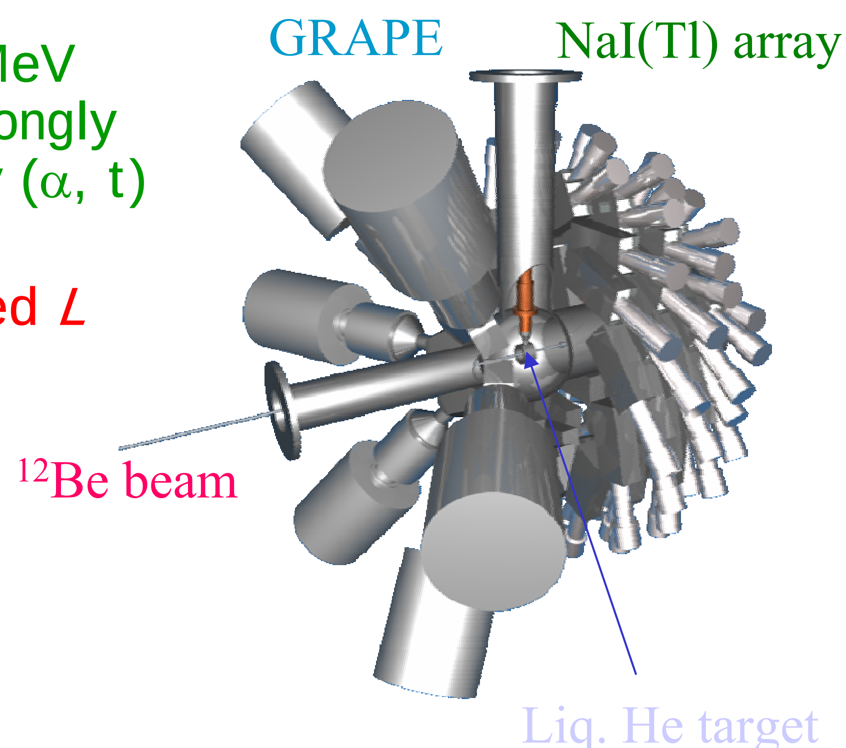




^{4}He(^{12}Be,^{13}Bγ) @ 50 *A* MeV

3.71 & 4.83 MeV states strongly excited by (α, t)

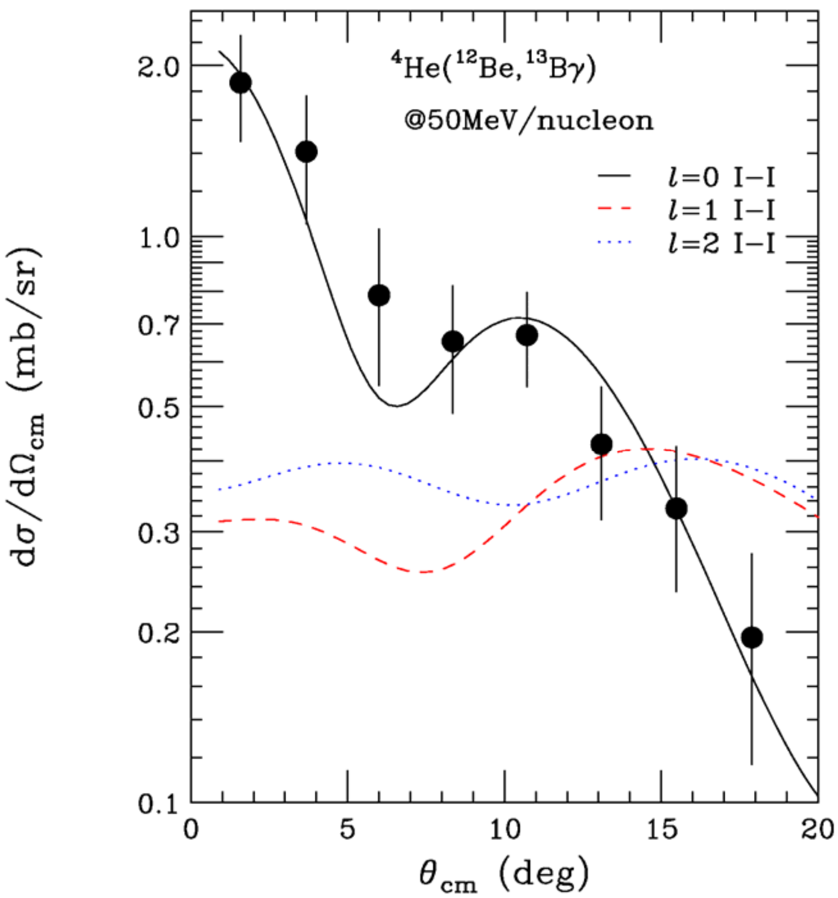
Different transferred *L*



[keV]	^{4}He(^{12}Be, ^{13}B γ)X	^{11}B(t,p) ^{13}B	^{9}Be(^{14}B, ^{13}B)	^{14}Be(β n)	^{16}O(^{14}N, ^{17}F) ^{13}B	^{12}C(^{14}C, ^{13}N)^{13}B	^{12}C(^{13}C, ^{12}N)^{13}B	^{12}C(^{15}N, ^{14}O)^{13}B
4829	1.00	0.03			1.00	0.34		
4131	0.59(13)	1.00	0.40			0.23	0.78	0.39
3713	0.95(18)	0.25				1.00	1.00	1.00
3681	0.48(16)	0.38	1.00					
3534	0.31(12)	0.19		1.00				
3482	0.06(13)	0.06	0.60					

^{4}He(^{12}Be,^{13}Bγ) @ 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)

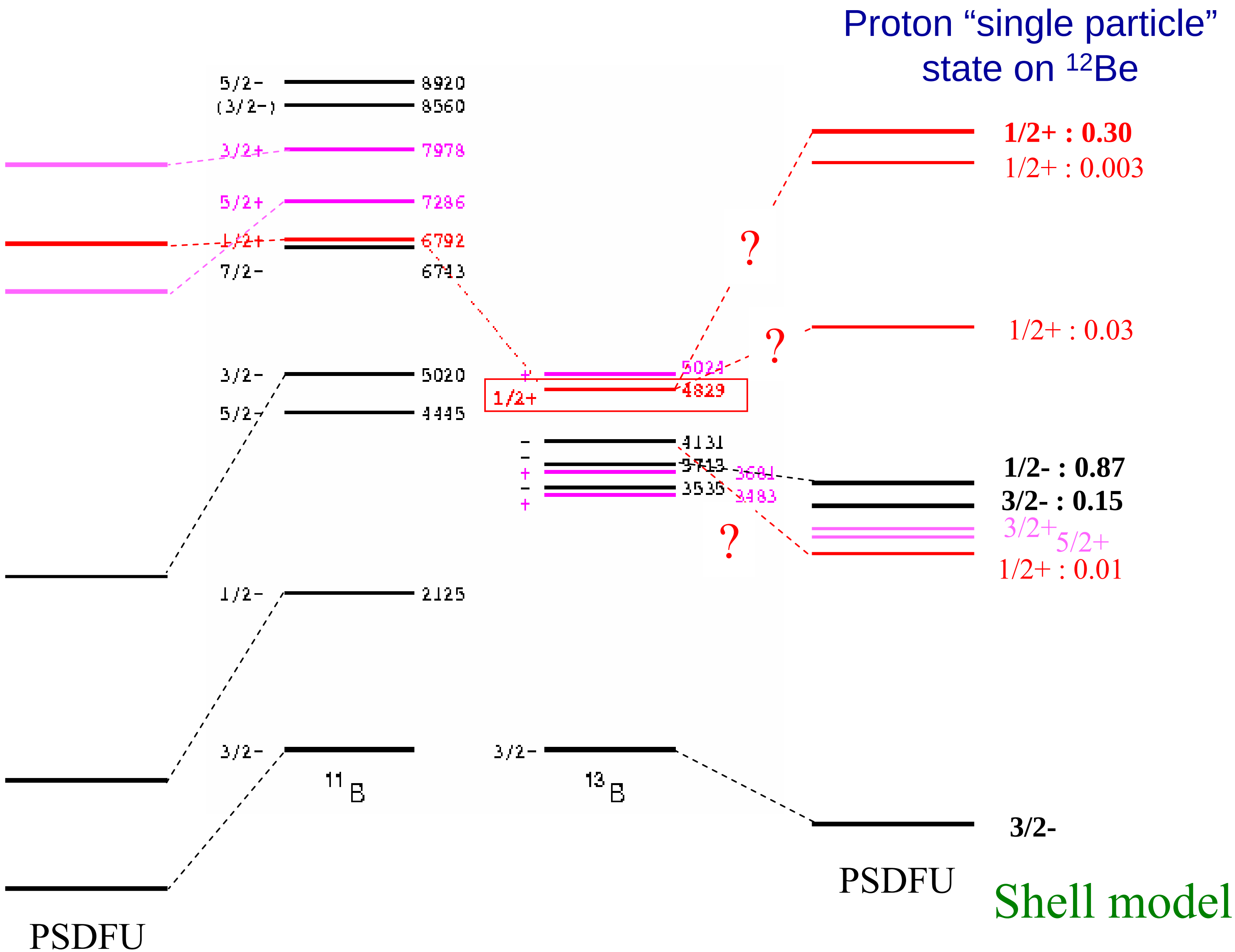
L=0 -> $J^{\pi} = 1/2^{+}$

$C^2S = 0.1 – 0.2$

dep. on Potentials

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

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



$1/2^+$ state in $^{13}B^*$ Configuration

$$\left|{}^{12}\mathrm{Be}_{gs}\right\rangle = \alpha\left|(\pi p)^2(\nu p)^6\right\rangle + \beta\left|(\pi p)^2(\nu p)^4(\nu sd)^2\right\rangle + \ldots$$

$0\hbar\omega$ $2\hbar\omega$

$|\alpha|^2 \sim |\beta|^2 \sim 0.5$

deformation

Deformed ^{12}Be core + 1 proton

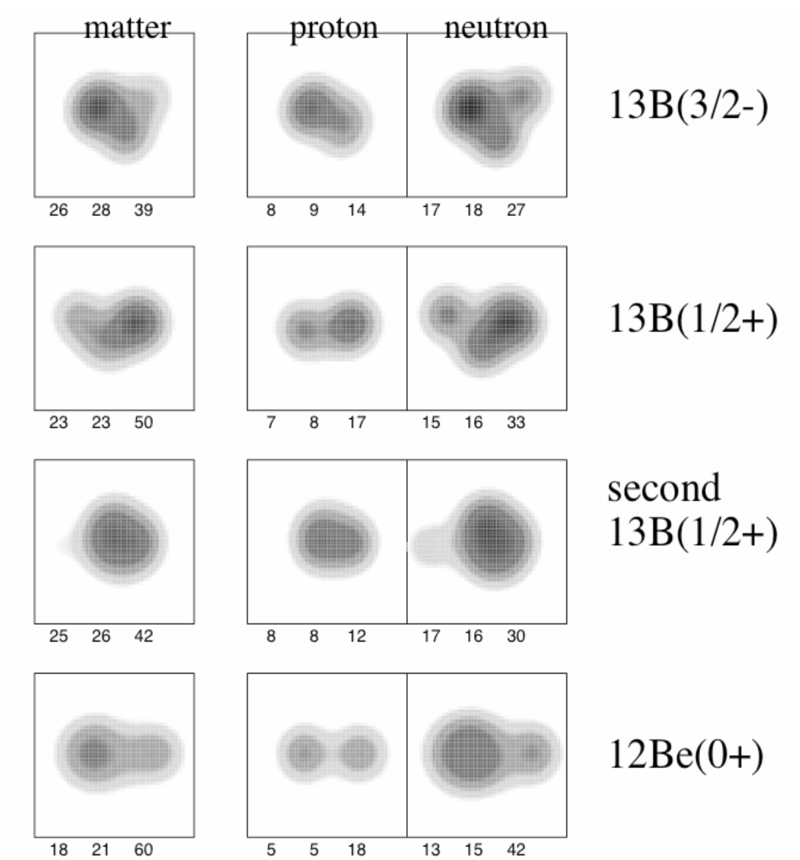
$1\hbar\omega$ $3\hbar\omega$

$$\left|{}^{13}\mathrm{B}^*(1/2^+)\right\rangle = \alpha'\left|(\pi p)^2(\pi sd)(\nu p)^6\right\rangle + \beta'\left|(\pi p)^2(\pi sd)(\nu p)^4(\nu sd)^2\right\rangle$$

$$+ \gamma'\left|(\pi p)^2(\nu p)^6(\nu sd)\right\rangle + \delta'\left|(\pi p)^2(\nu p)^4(\nu sd)^3\right\rangle + \ldots$$

$$C^2S = \left\langle {}^{13}\mathrm{B}^*(1/2^+)\middle| {}^{12}\mathrm{Be}_{gs} + p(\ell = 0)\right\rangle \approx \alpha\alpha' + \beta\beta'$$

1/2$^+$ state in ^{13}B* by AMD Kanada-Enyo prelim.



- $1/2^+_1$ ：変形した状態
  - 70% ν1 hω
  - 30% π1hω+ν2hω
    - 陽子の励起状態
  - ^{12}Beの基底状態の配位混合を反映した状態
- $1/2^+_2$ ：球形の状態
  - π1hω+ν0hω
- 本実験では、$1/2^+_1$状態が励起？

Summary

- (α,t) and (α,^{3}He) reactions at intermediate energy can be used for spectroscopy of single-particle states in exotic nuclei.
- Spectroscopy of ^{23}F was also performed by (α,t) reaction combined with inelastic and knock-out reactions
- Level scheme was constructed for ^{23}F
- Spin-orbit splitting of $3/2^+$ and $5/2^+$ was not so small as predictions of shell models.
- γ-ray spectroscopy of ^{13}B excited by Proton Transfer (^{12}Be,^{13}Bγ) reaction was measured.
- The 4.8-MeV state have J^π of $1/2^+$ and an proton *S*-factor of =0.1~0.2 by DWBA analysis
  - Differs from standard shell-model prediction
  - It might be contain [220]$1/2^+$ configuration on the deformed ^{12}Be core.
  - $1/2^+_1$ state in AMD calculation
- (α,t), (α,^{3}He) reaction on ^{32}Mg and ^{34}Si was measured recently by using position-sensitive Ge array, GRAPE. N-rich nuclei around N~20