Broad resonances in light proton-rich nuclei

Shumpei Koyama
GANIL

Nuclear physics at the edge of stability
ECT*
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Mirror symmetry

D. D. Warner et al., Nat. Phys. 2 311

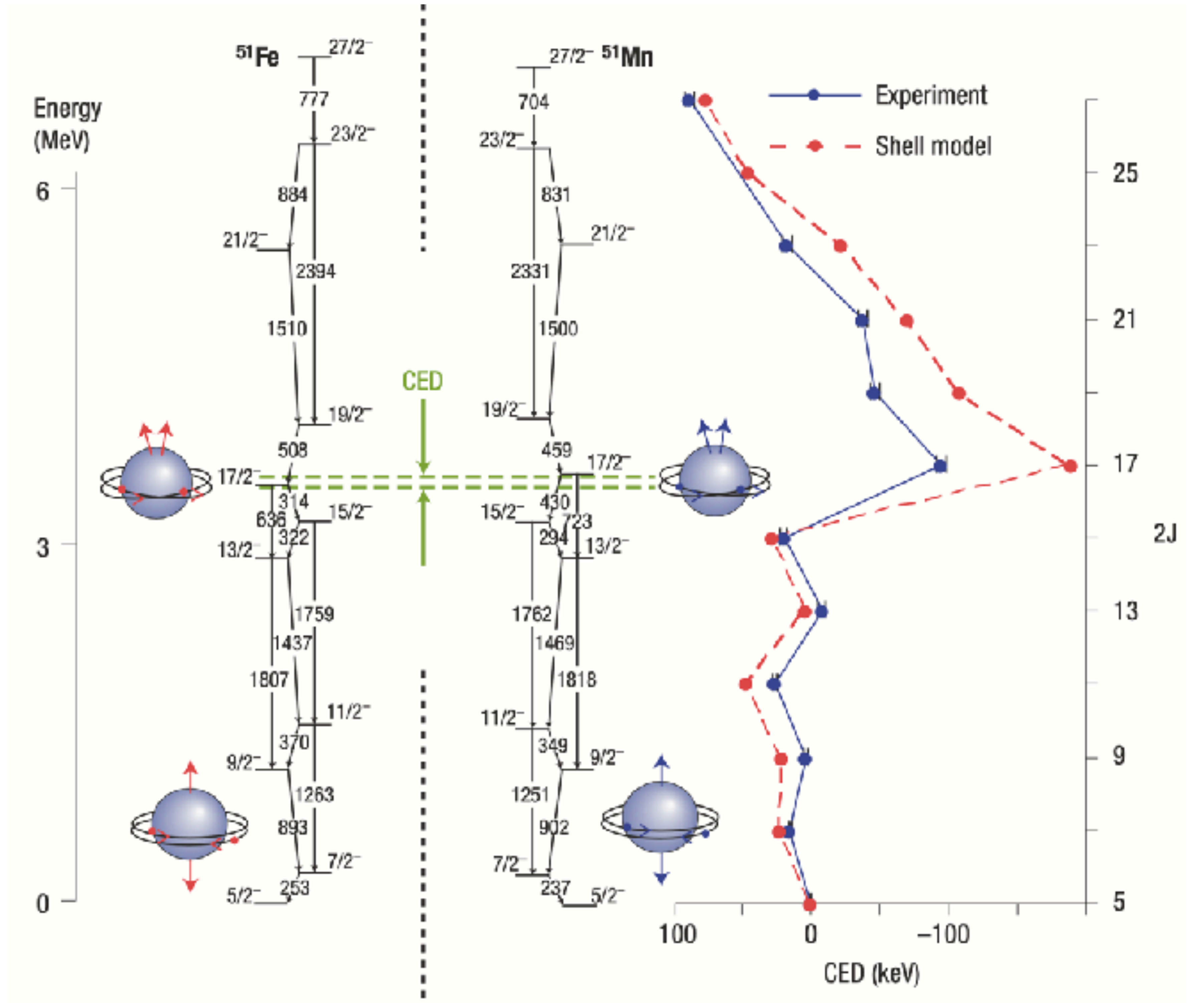
Same structure of mirror nuclei Z <-> N

Almost the same level scheme

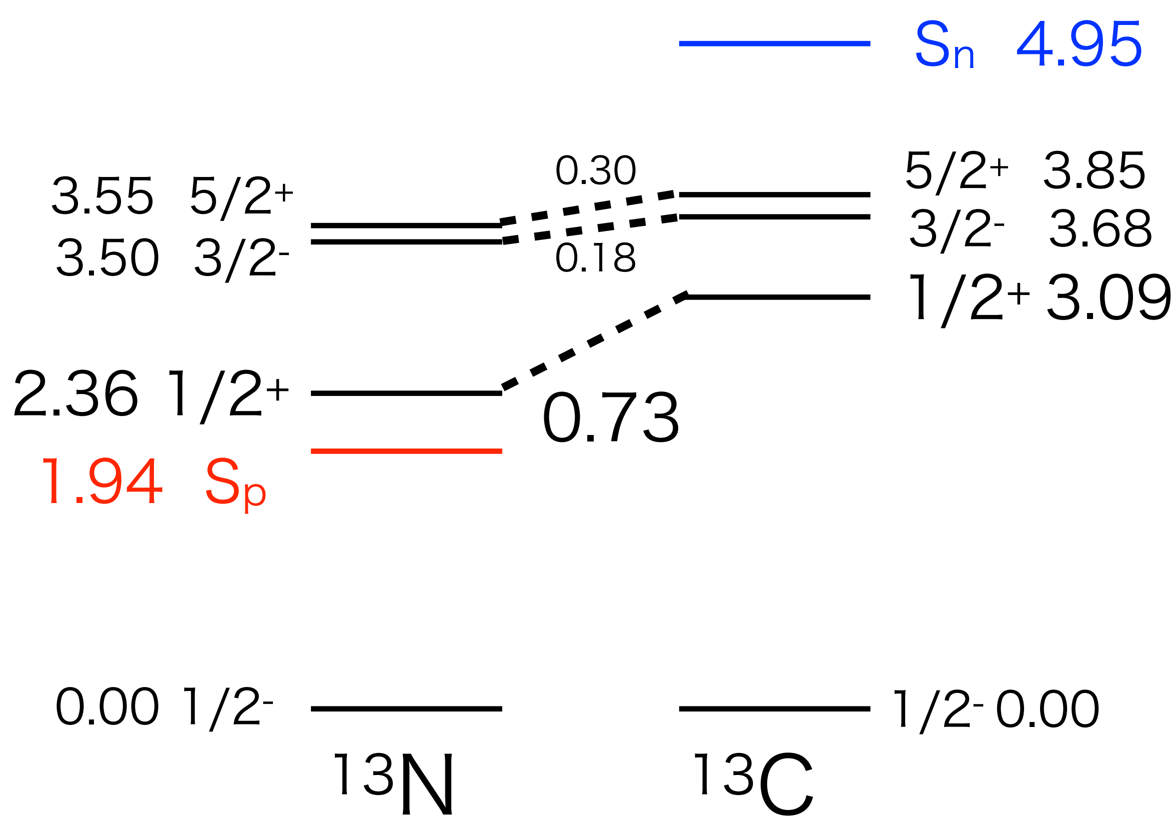
-> Small mirror energy difference (MED)

Large MED for high spin states systematically observed in A ~ 30 - 60

M. A. Bentley S. M. Lenzi PPNP 59 497



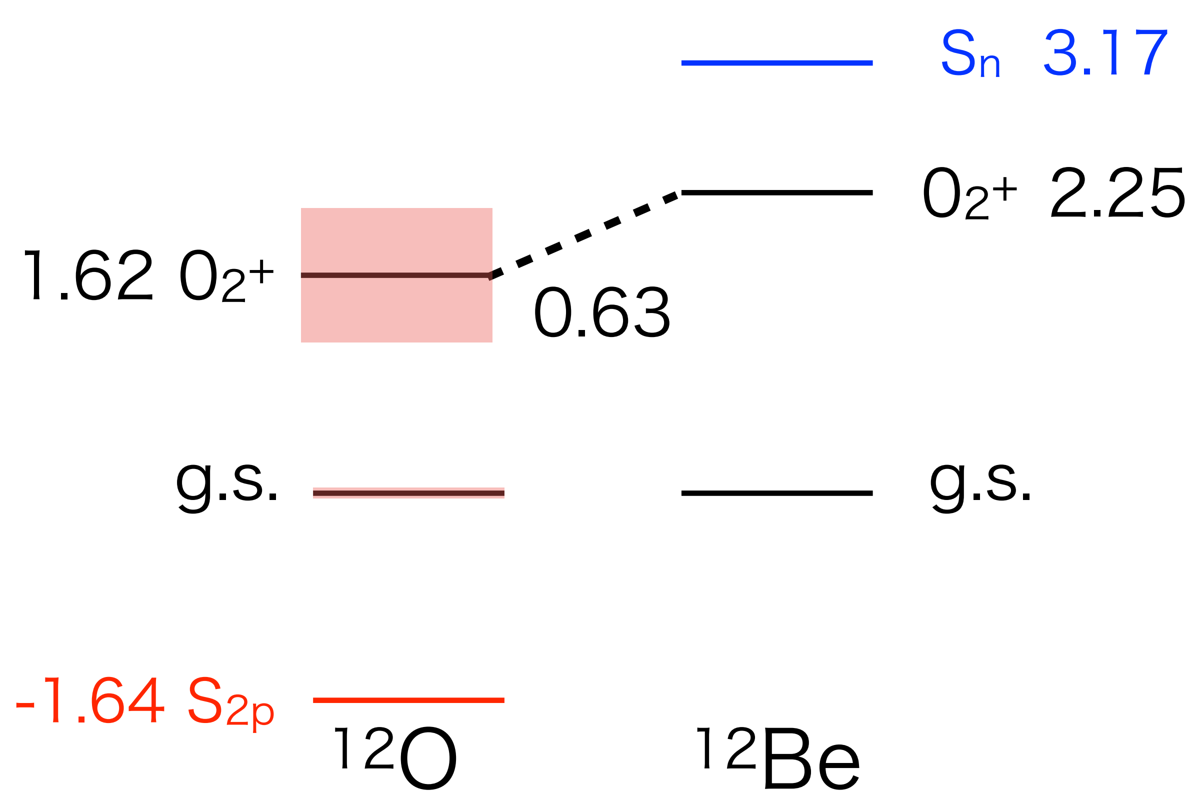
Thomas-Ehrman shift



Large MED for s-wave states in ^{13}N and ^{13}C

Energy gain in proton-rich nucleus by lower Coulomb repulsive energy of s-wave proton than other high L orbits

J. B. Ehrman, PR 81 412 (1951)
R. G. Thomas, PR 88 1109 (1952)



Large MED for exotic mirror nuclei such as ^{12}O and ^{12}Be 0_2^+

D. Suzuki et al., PRC 93 024316

Different threshold property
Effect of continuum coupling

^{8}C and ^{8}He

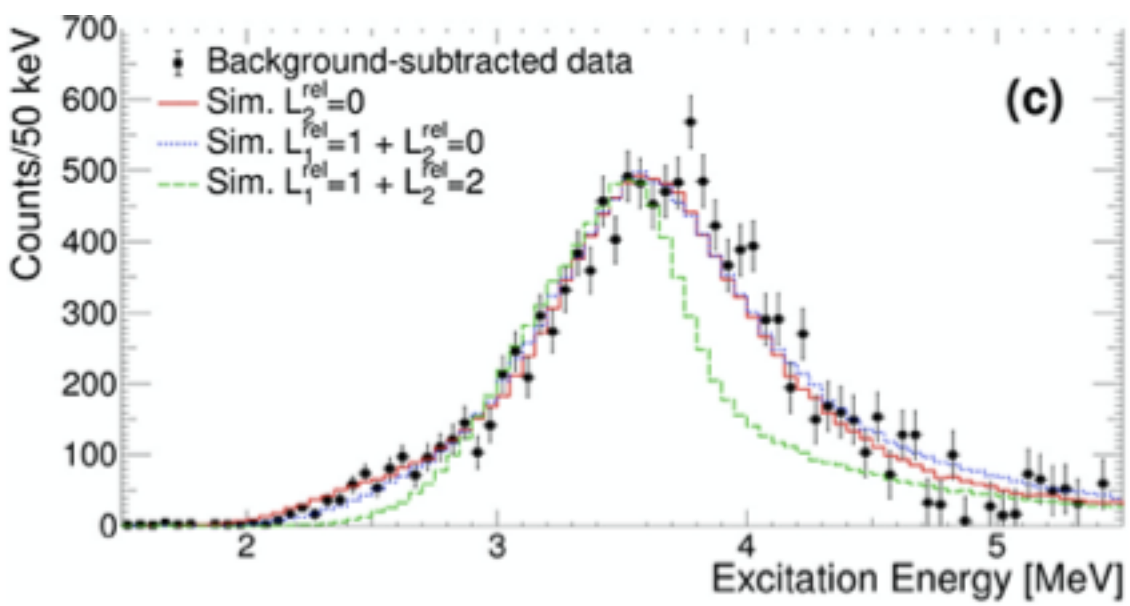
The most proton-neutron unbalanced mirror pair ^{8}C-^{8}He

Different threshold property

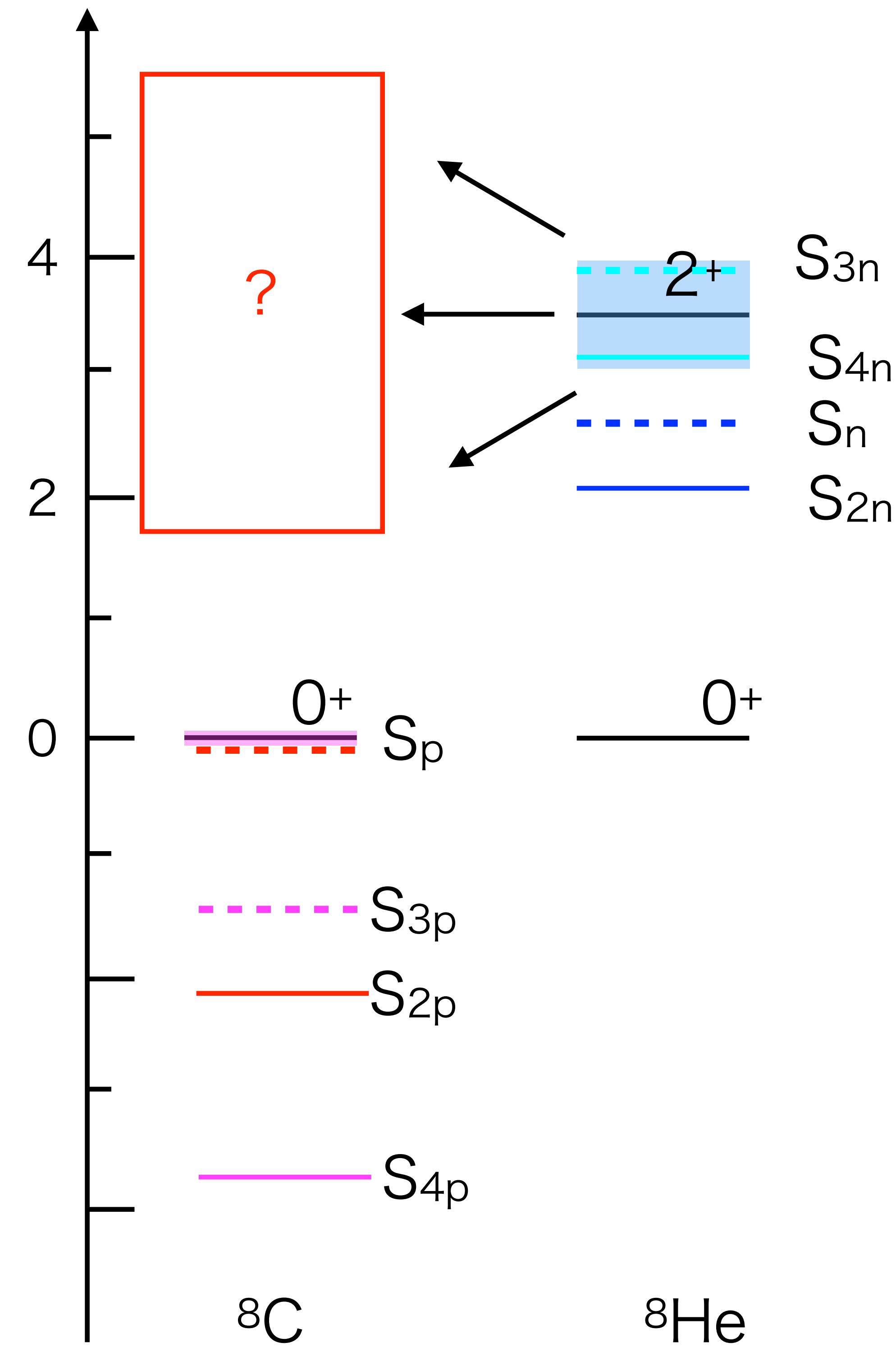
^{8}C : 4p unbound g.s.

^{8}He : bound g.s.

Resonance 2^+ state with Γ=0.89(11) MeV



M. Holl et al., PLB 822 136710 (2021)



^{8}C 2^+ state, not ever observed and expected large Γ

->How is MED if both mirror states are resonances with large Γ?

Highly excited state

Low level density in light nuclei

$^{5}Li \rightarrow {}^{4}He + p$

3/2- 0.0 MeV Γ = 1.23 MeV

1/2- 1.5 MeV Γ = 6.60 M

(No states ever observed between)

3/2+ 16.9 MeV Γ = 0.27 MeV

In proton-rich N=2 isotope

^{6}Be, ^{7}B, ^{8}C?

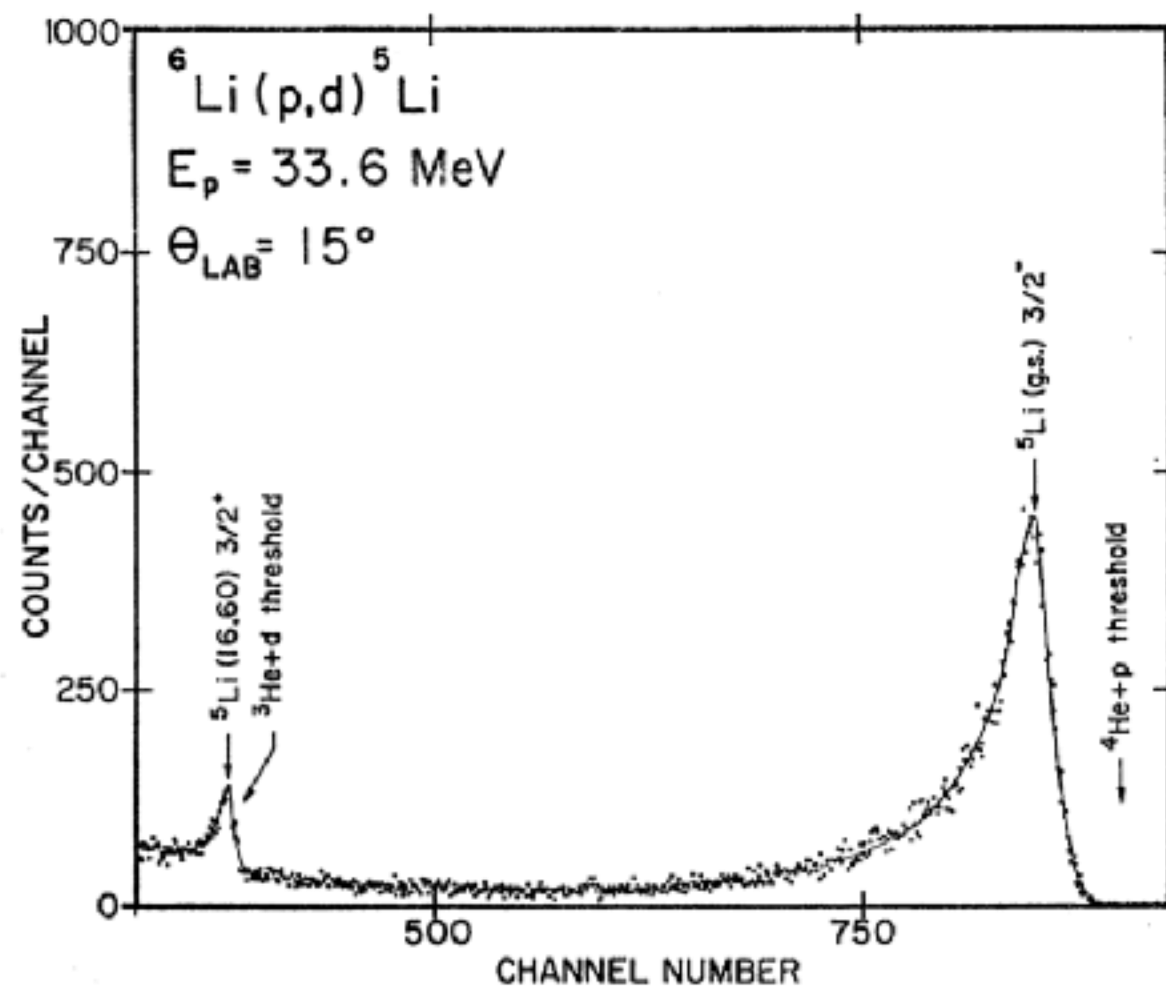
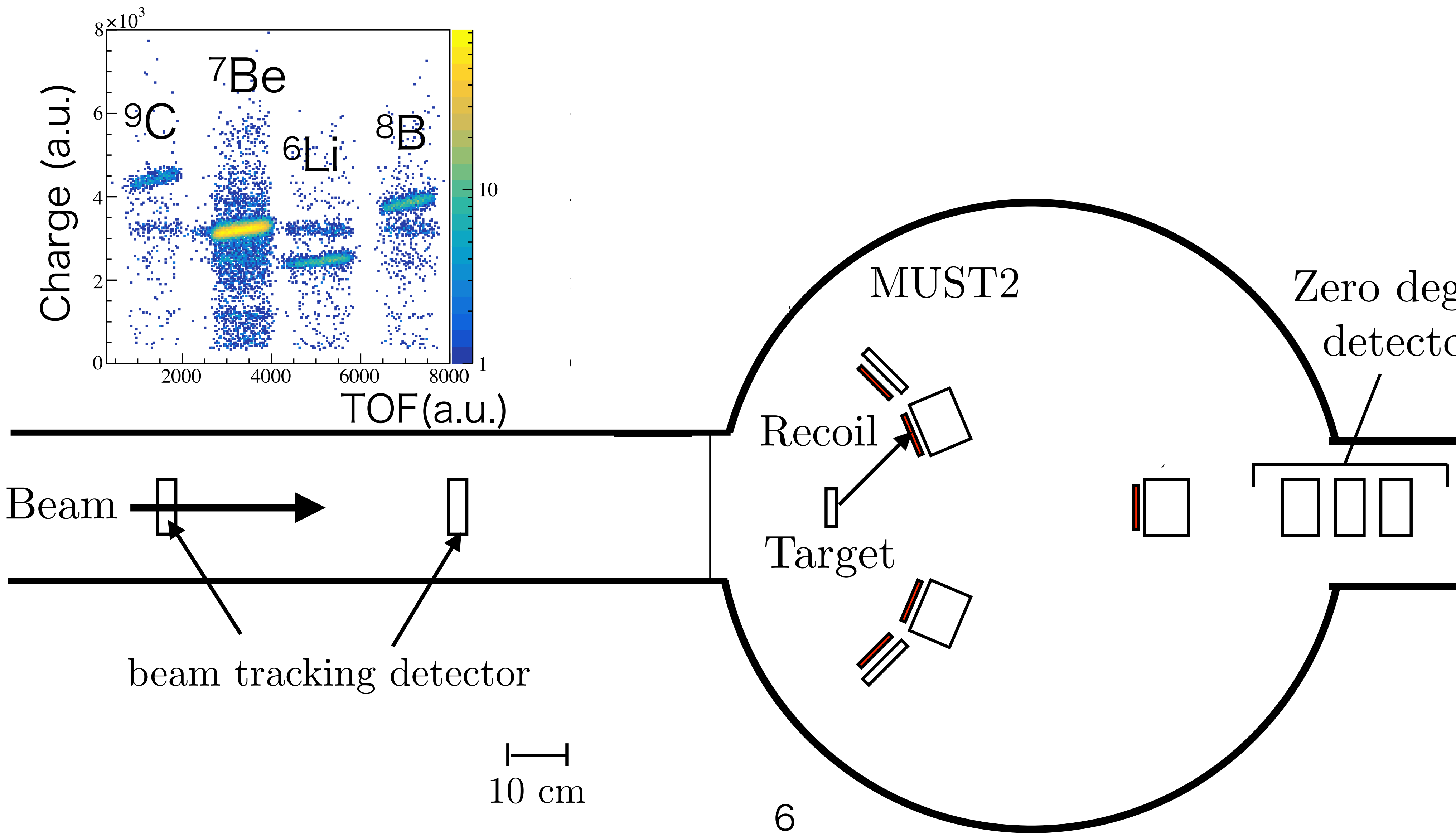


FIG. 2. $^{6}Li(p,d)^{5}Li$ deuteron spectrum at 15°. The long tail on the ground-state peak may include a contribution from a previously reported $J^{\pi}=\frac{1}{2}^{-}$ state.

L. A. Kull , PR 163 1066 (1967)

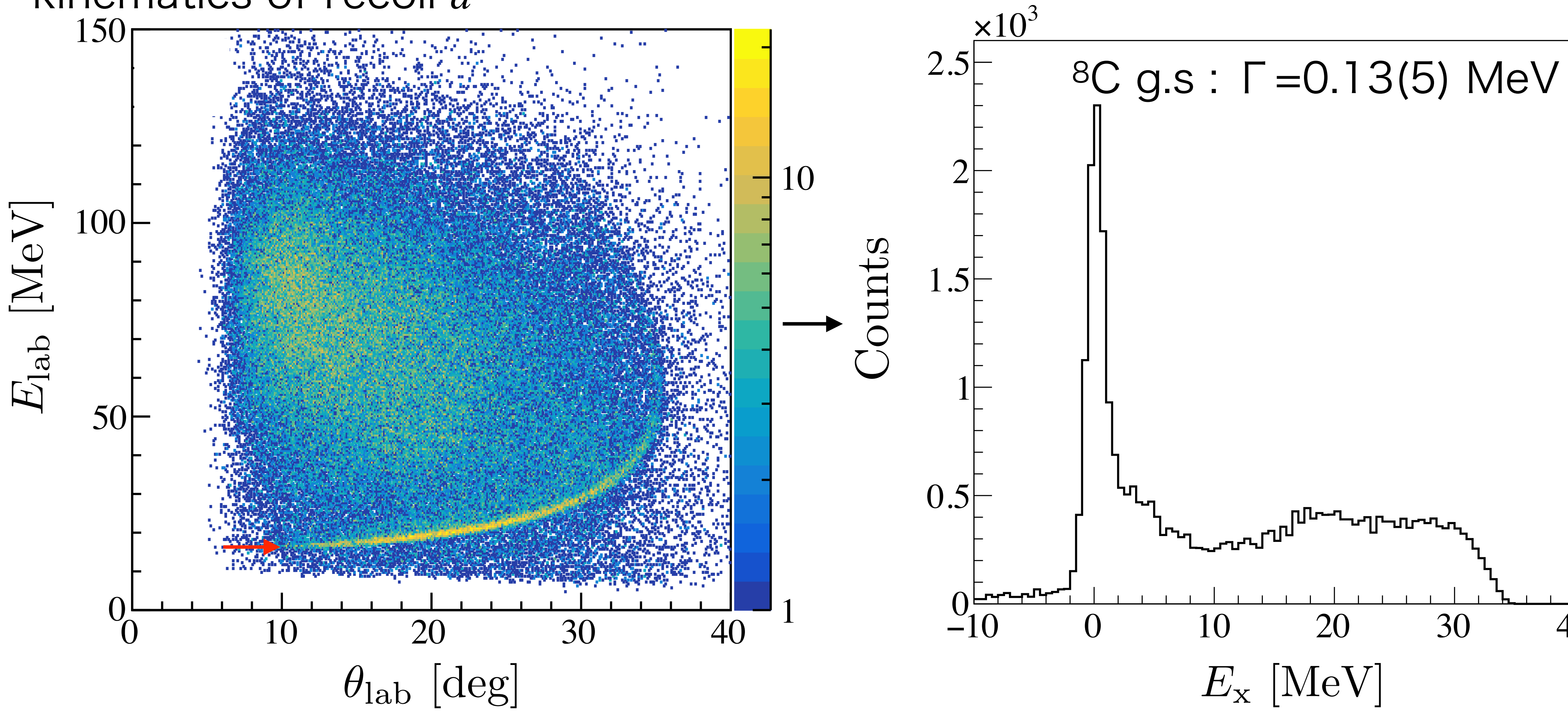
Experimental setup

- Resonance states in ^{8}C were investigated via missing mass method with the LISE spectrometer at GANIL
- ^{9}C beam includes its isotones ^{8}B, ^{7}Be and ^{6}Li
- States in ^{8}C were populated via the (p,d) reaction
- Thin Liquid hydrogen target was developed NIMA 1010 165477 (2021)
- Recoil deuteron were detected by charged particle detector MUST2 -> PID and kinematics reconstructed



^{9}C(p,d)^{8}C Ex spectrum

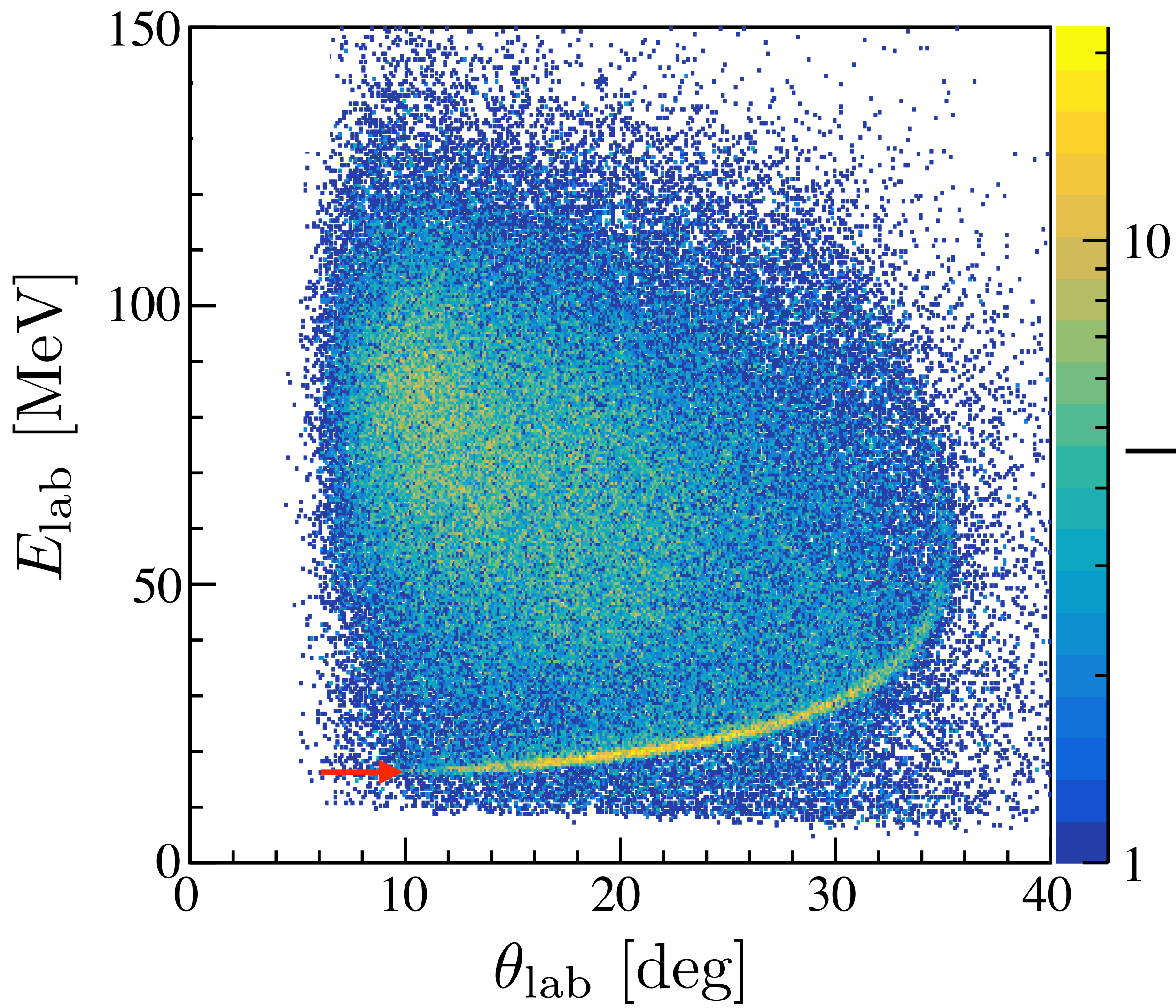
kinematics of recoil d

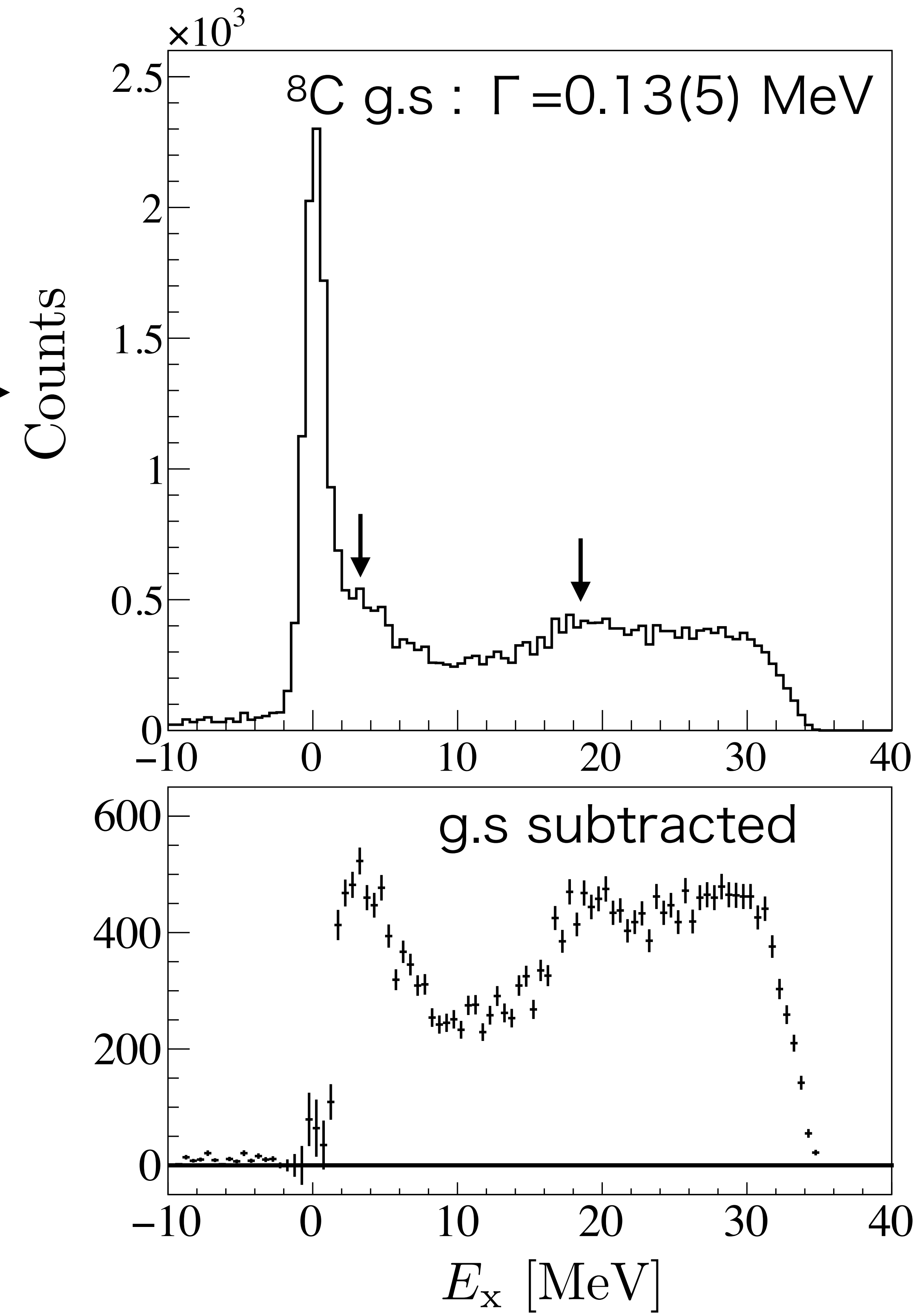


- Clear kinematic curve of g.s. of ^{8}C
- Narrow peak of g.s. of ^{8}C,
  σ (Ex) (r.m.s.) = 0.5 MeV

^{9}C(p,d)^{8}C Ex spectrum

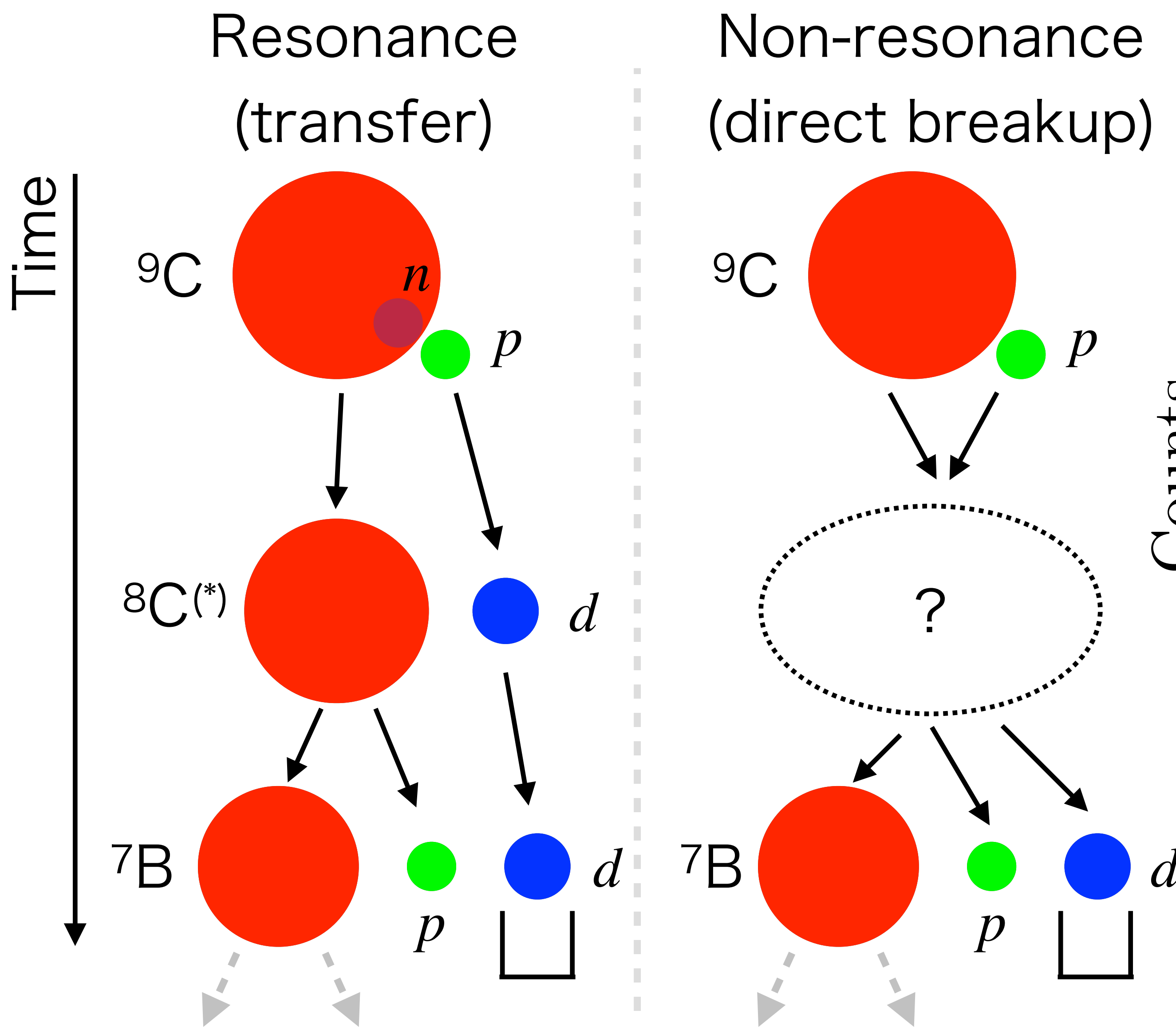
kinematics of recoil d

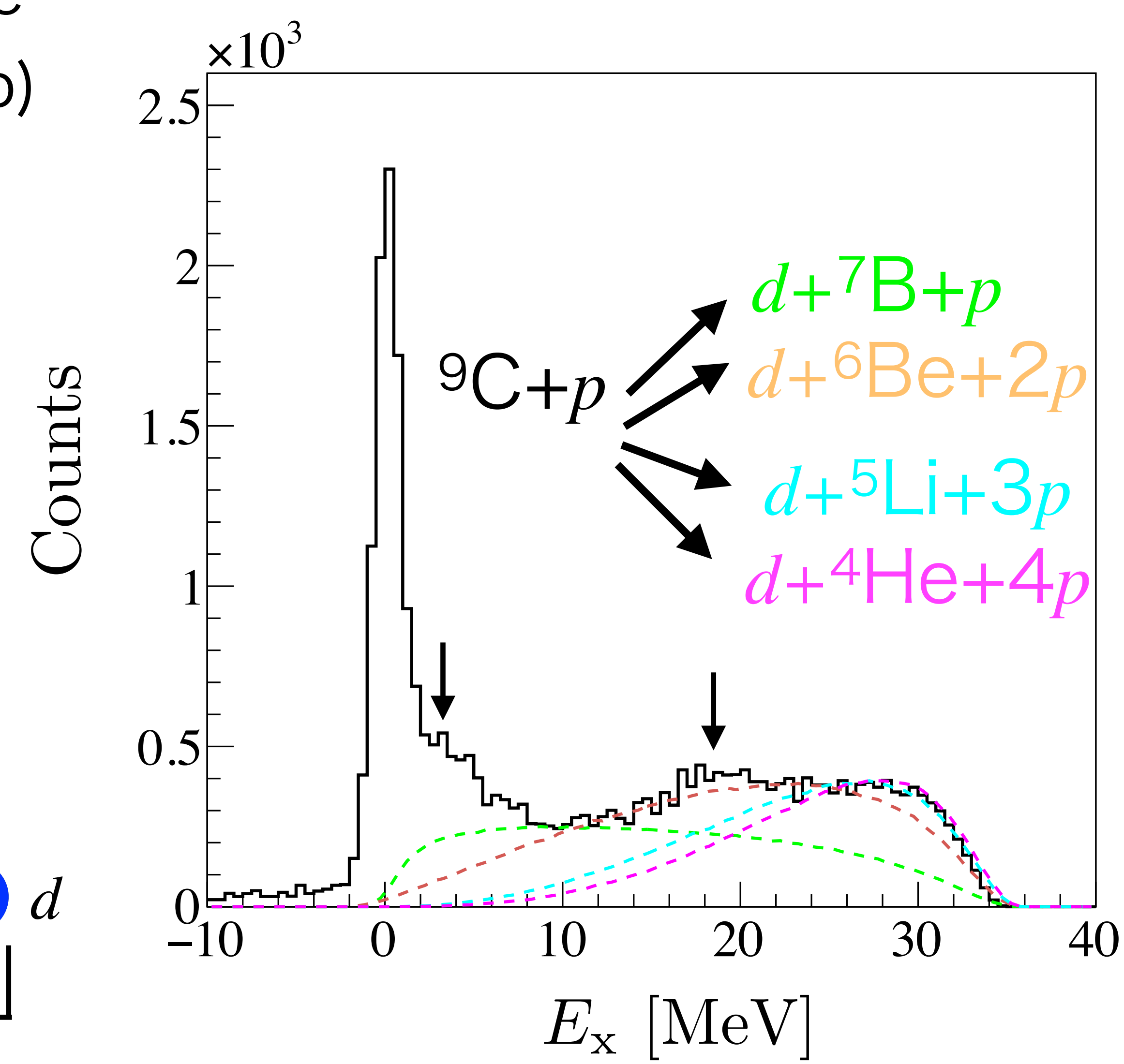




- Clear kinematic curve of g.s. of ^{8}C
- Narrow peak of g.s. of ^{8}C,
  σ(Ex) (r.m.s.) = 0.5 MeV
- Bumps Ex ~ 3 and 18 MeV

Non-resonance distribution





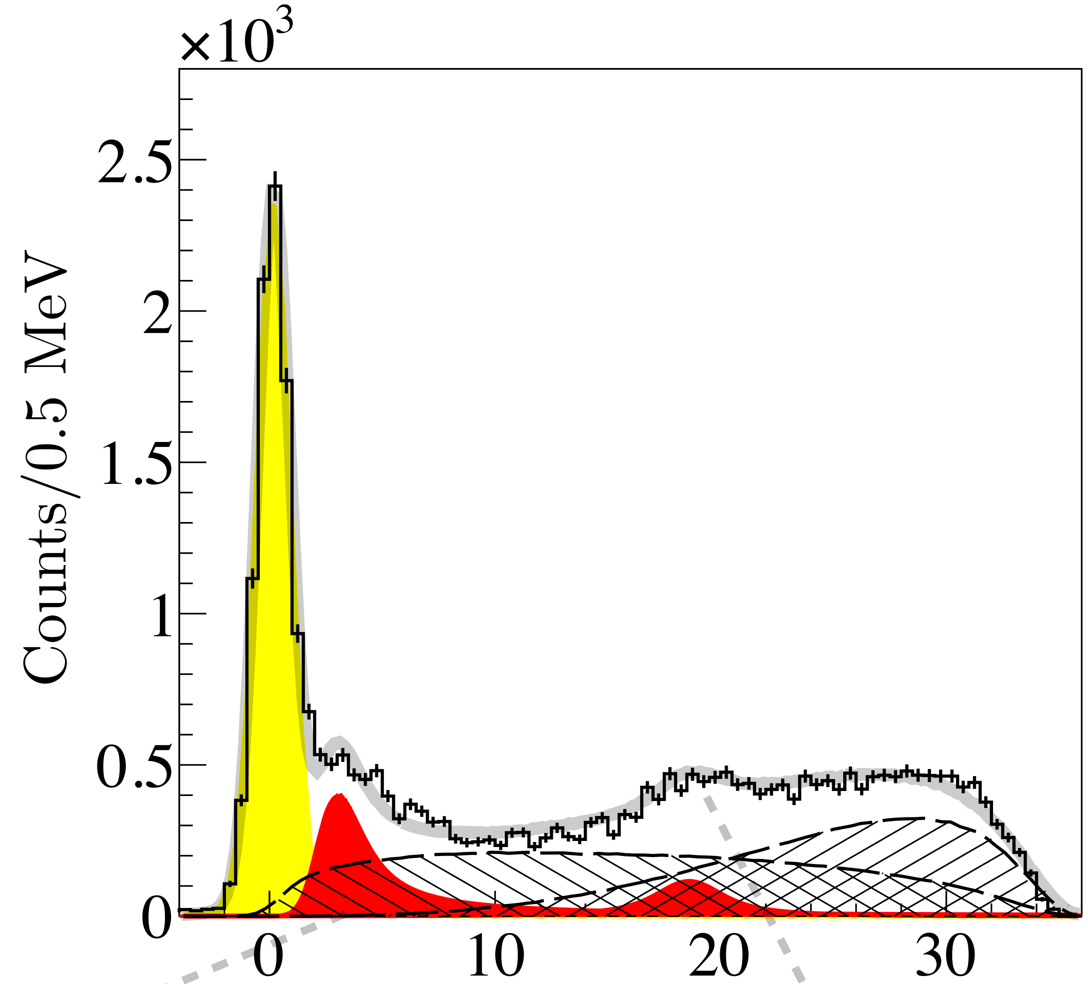
Non-resonance distributions generated by the simulation assuming direct breakup process (uniform phase space)

-> None of the distributions can reproduce the bumps around 3 and 18 MeV

$^{9}C(p,d)^{8}C$ Fitting

Voigt function for resonance

$$\int_{-\infty}^{\infty}\left(\frac{1}{2\pi}\frac{\Gamma}{(E_{\mathrm{x}}-E)^2+\Gamma^2/4}\right)\left(\frac{1}{\sqrt{2\pi}\sigma_{\mathrm{exp}}}\exp\left(-\frac{E^2}{2\sigma_{\mathrm{exp}}^2}\right)\right)\mathrm{d}E$$



Energy dependent width

$$\Gamma(E_{\mathrm{x}}) = 2\gamma^2 \underline{P_l(E_{\mathrm{x}})}$$

penetrability

based on *R*-matrix theory

-> Asymmetric shape

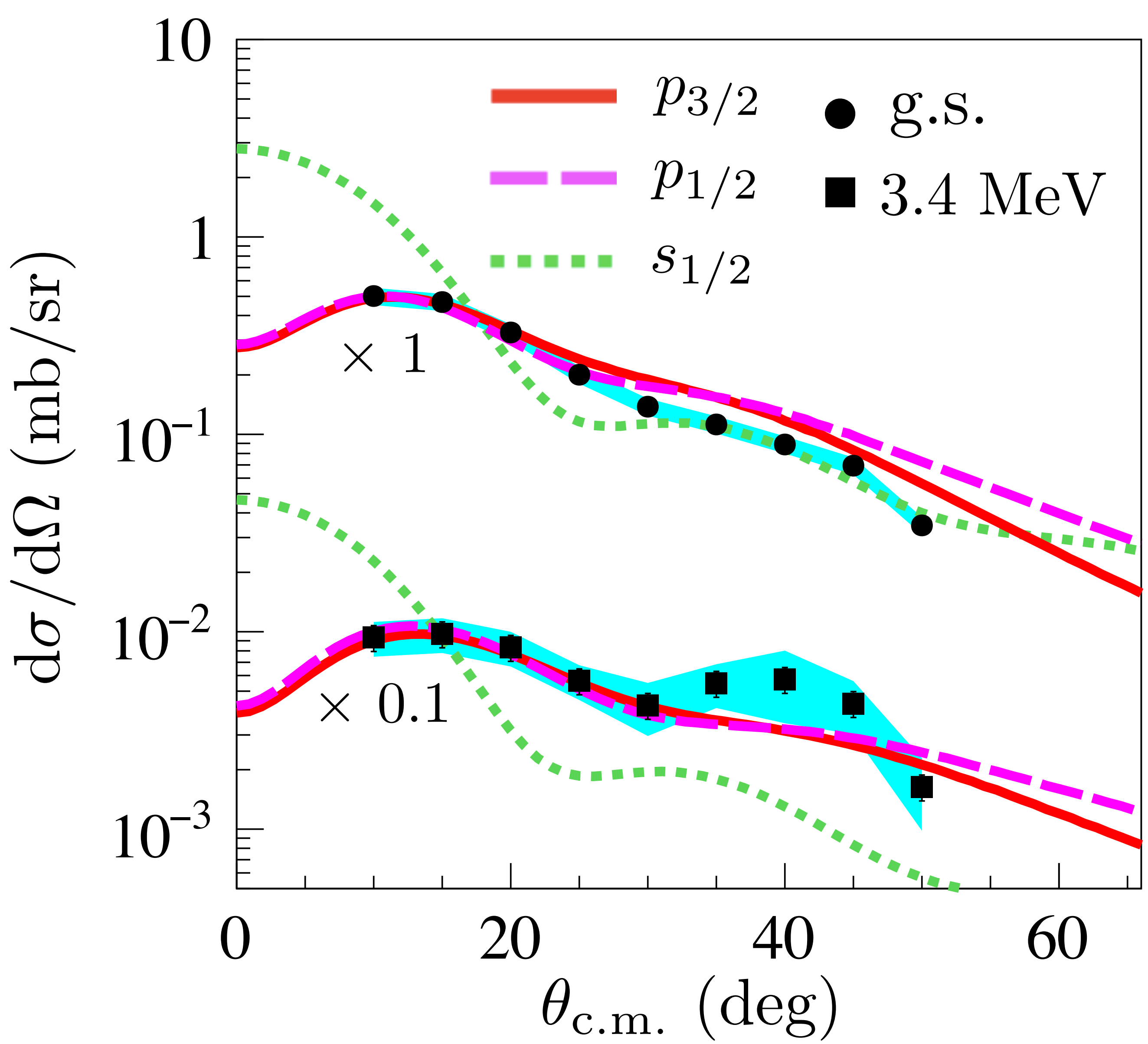
E_x = 18.1(3) MeV,
Γ =4.3(6) MeV

E_x = 3.4(2) MeV,
Γ = 3.0(4) MeV

Asymmetric Voigt function
(close to threshold S_p = -0.1 MeV)

Non-resonance
Only two components have finite amplitudes while amplitudes of the other two are consistent with 0 by the result of the fitting

Angular distribution



Angular distributions of g.s. and 3.4 MeV state are compared with DWBA calculation.

DWUCK5 with global optical potential

R. Varner et al., PR 201 57

adiabatic treatment

J. D. Harvey et al., PRC 3 636

Both states agree with neutron transfer from p-shell

-> J^{π} of 3,4 MeV state: 0^+, 1^+, 2^+

Shell model calculation of C^2S with two interaction (Cohen-Kurath and YSOX)

-> Only g.s. and 2^+ have large C^2S

-> J^{π} of 3.4 MeV state : 2^+

^{8}C first 2^{+} state

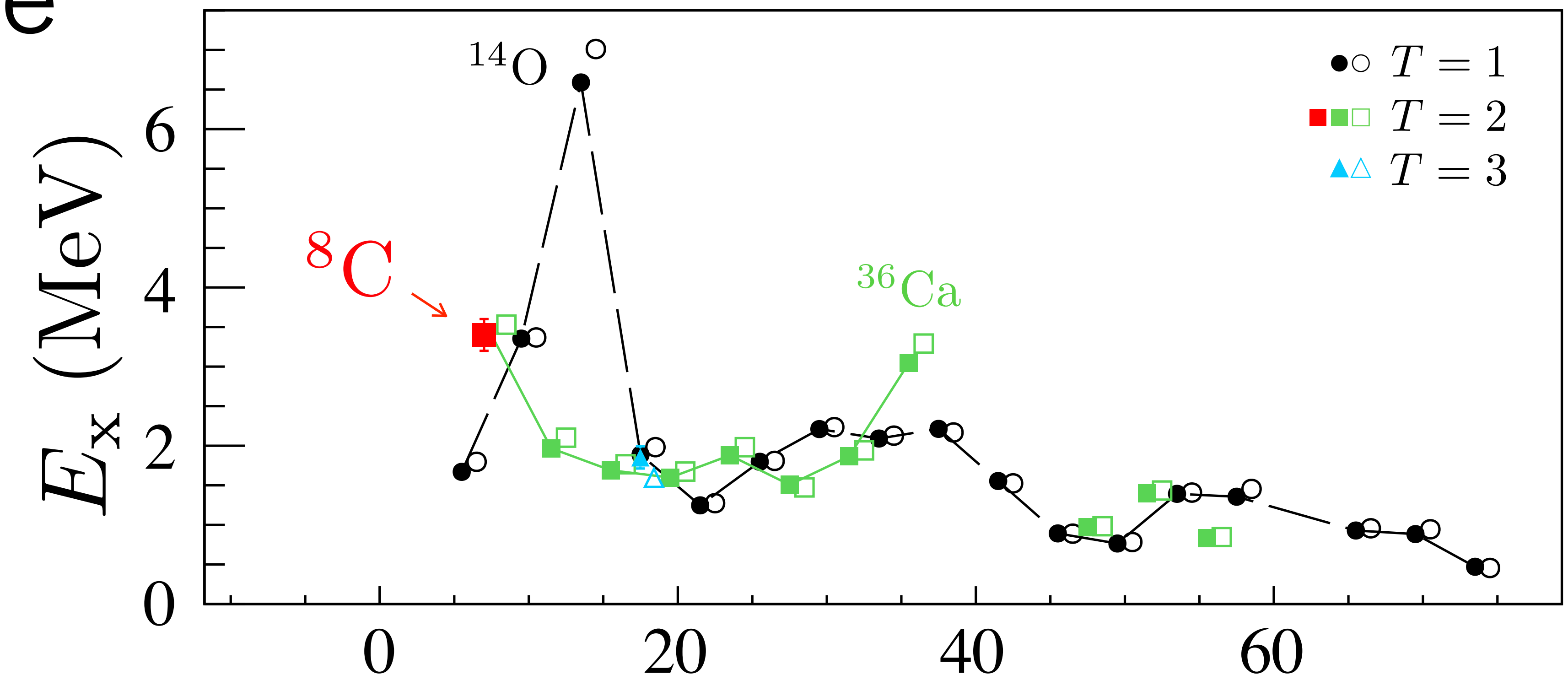
Ex of 2^{+} energy

- High excitation energy of ^{8}C and ^{8}He among T=2 nuclei

MED

- The mirror energy difference of ^{8}C-^{8}He 2^{+} excited states is -0.14(20) MeV
- Systematics for mirror energy difference of other 2^{+} states—> Moderate mirror energy difference

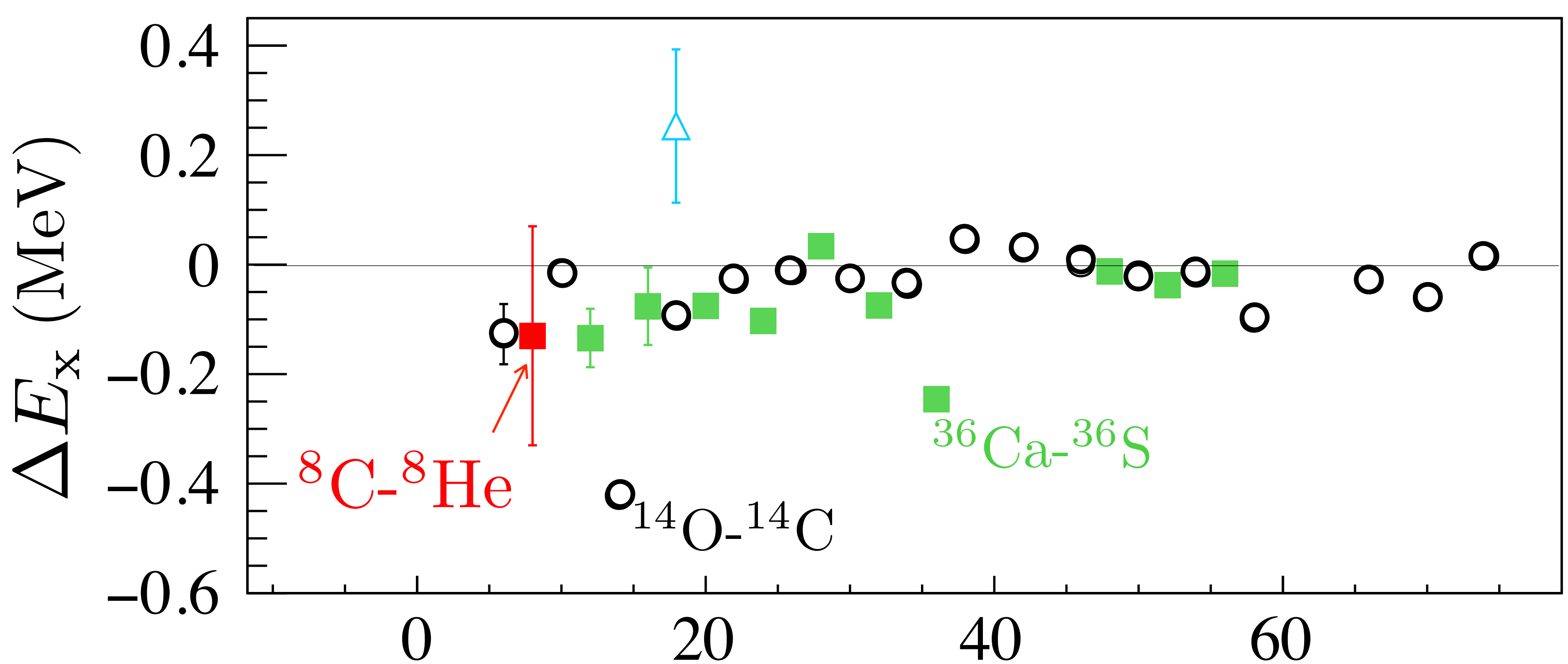
Known 2^{+} Ex of mirror pair



^{8}He 2^{+} Ex from most recent exp.

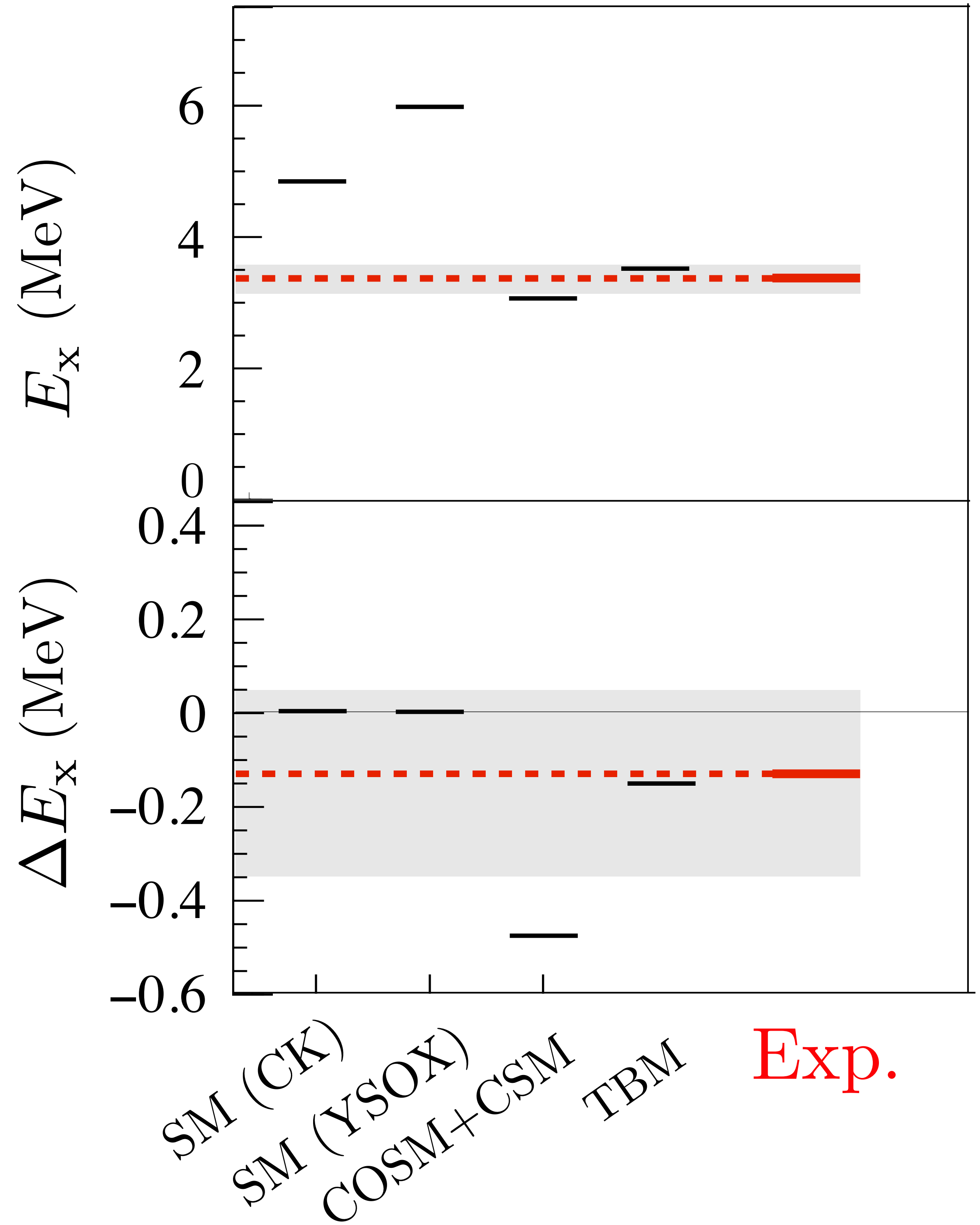
M. Holl et al., PLB 822 136710 (2021)

MED of 2^{+} states



Shell model calculation

- Shell model calculation with CK and YSOX interactions
  - Bound state approximation
  - Higher Ex than exp.
  - No isospin dependence
  - 1p1h from $1p_{3/2}$ to $1p_{1/2}$
- Cluster Orbital Shell model (COSM) + Complex Scaling method (CSM)
  - Both bound and unbound (α+ 4N) of ^{8}C and ^{8}He
  - Ex well reproduced
  - ΔEx over estimate
  - 1p1h from $1p_{3/2}$ to $1p_{1/2}$
- TBM (Two Body Model) to be discussed …



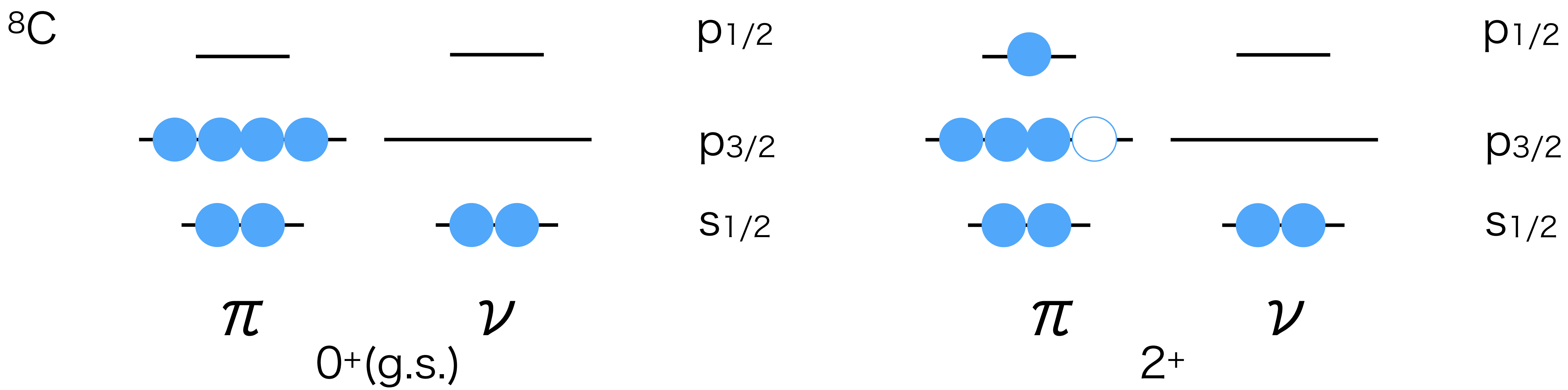
KSHELL for Shell model calc.
N. Shimizu et al., Compt. Phys. Commun. 244 372 (2019)

CK interaction
S. Cohen, D. Kurath., 73 1 (1965)
YSOX interaction
C. Yuan et al., PRC 822 104 044306(2012)

COSM+CSM
T. Myo et al., PRC 822 104 044306(2021)

Two body model calculation

- Effect of continuum - difficult to fully include in theoretical calculation
  -> Simpler model



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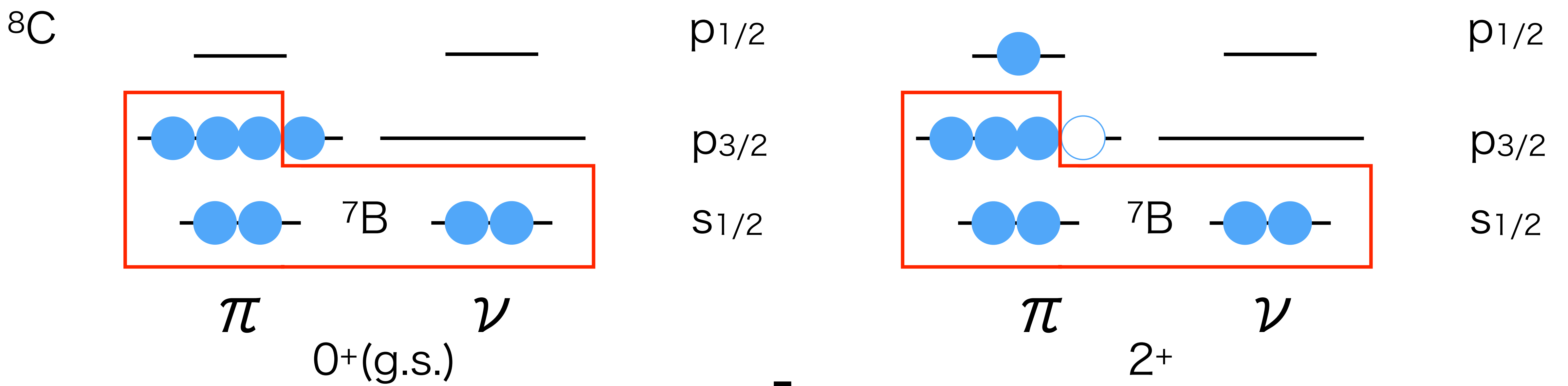

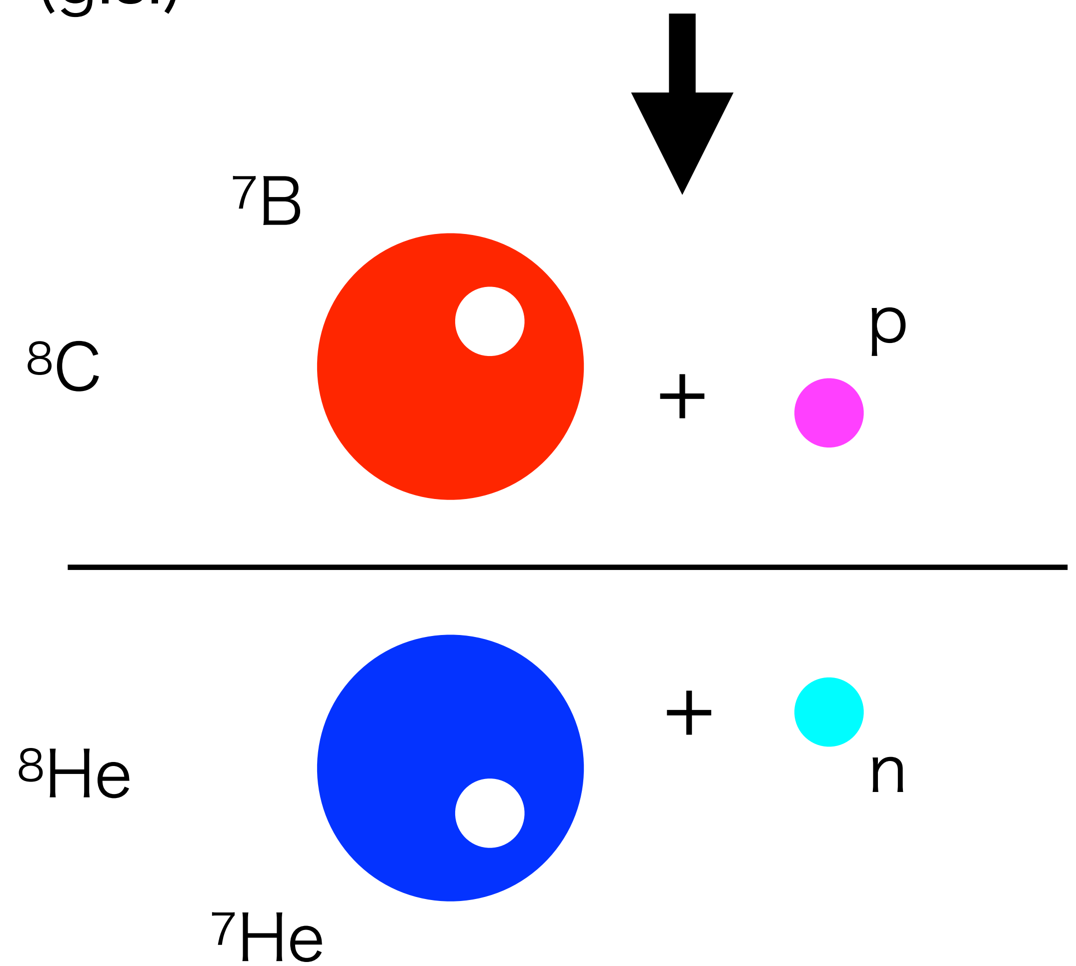

"Valence" p/n in

0+ - $p_{3/2}$

2+ - $p_{1/2}$

Two body model calculation

- Relative motion of $^7B/^7He$ + p/n
- Solving radial part of the Schrödinger equation
- Potential : Woods-Saxon + SO + Centrifugal + Coulomb A. Bohr and B. Mattelson, Nuclear Structure Vol. I I
- Varying the depth of WS-potential (V_0)
- Numerov method
- For resonance, energy with phase shift passes through 90°

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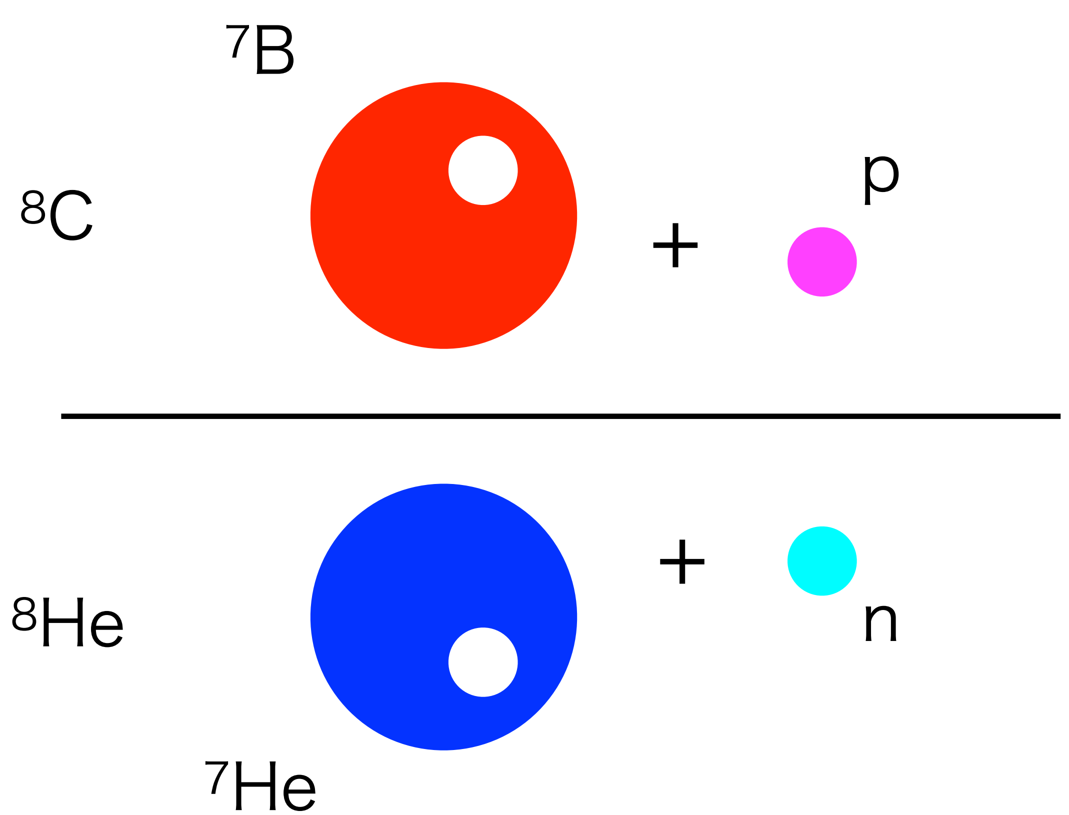

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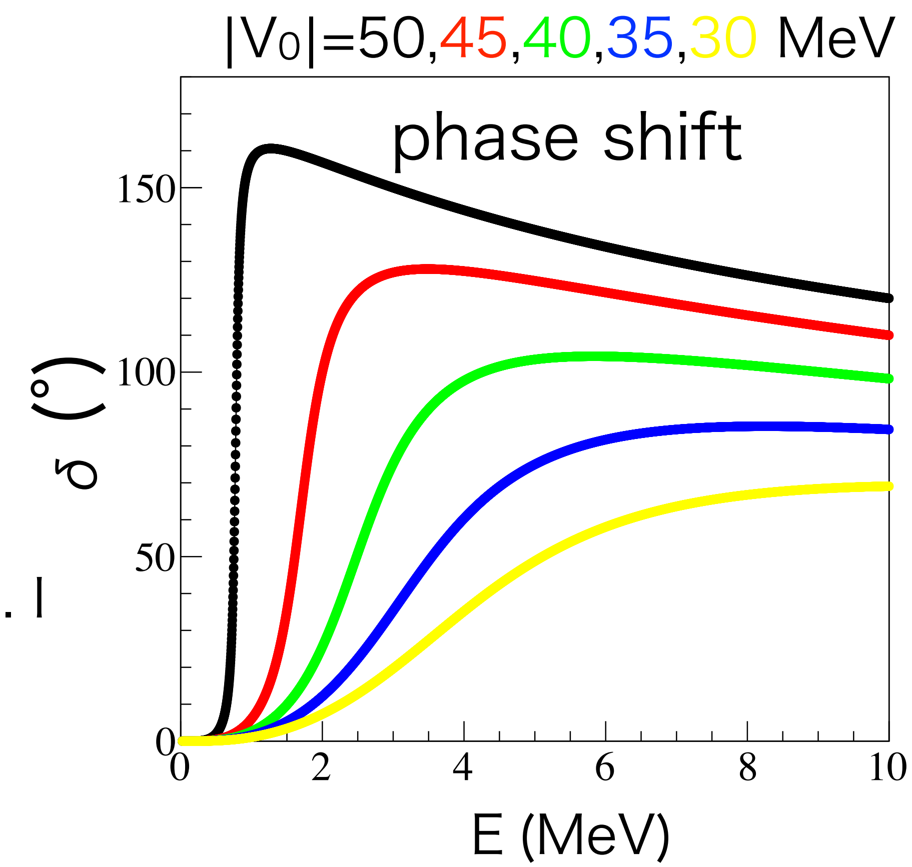

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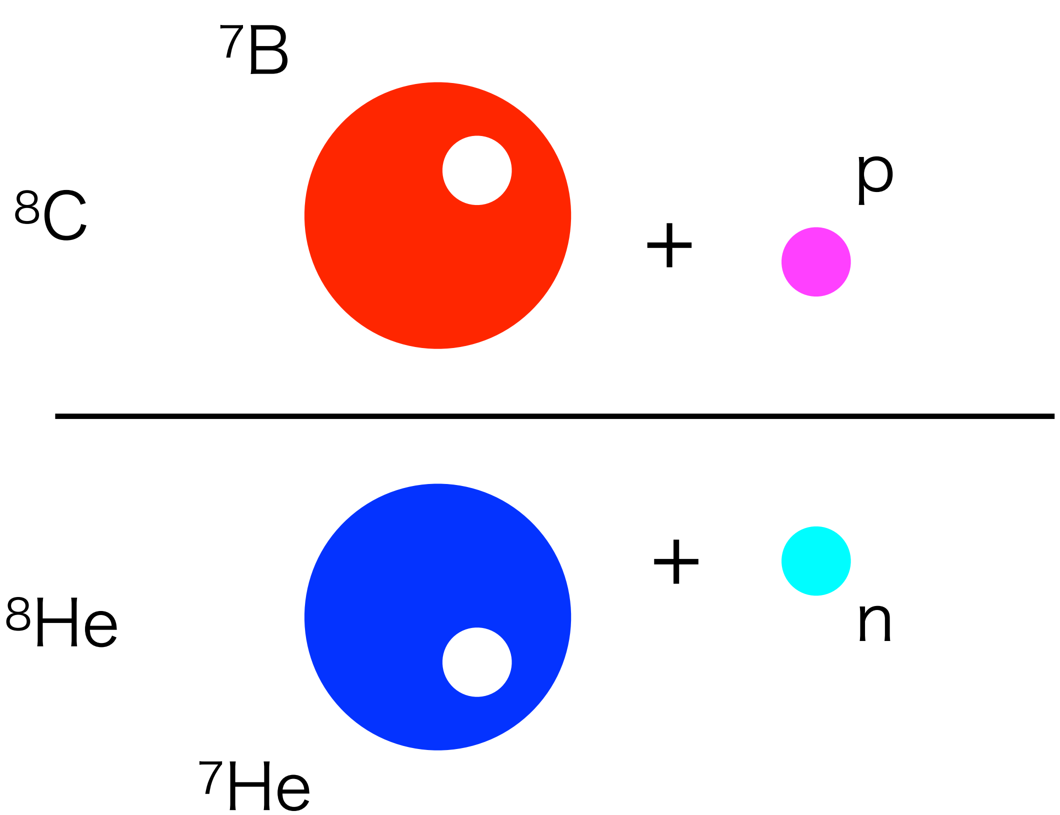
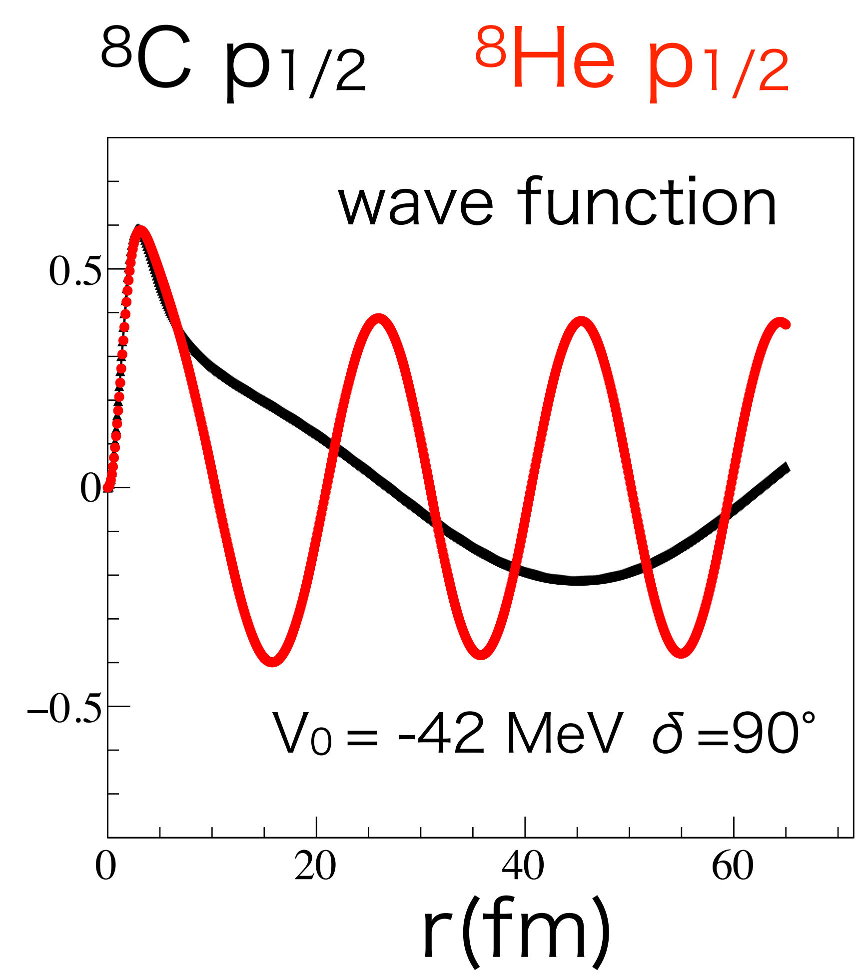
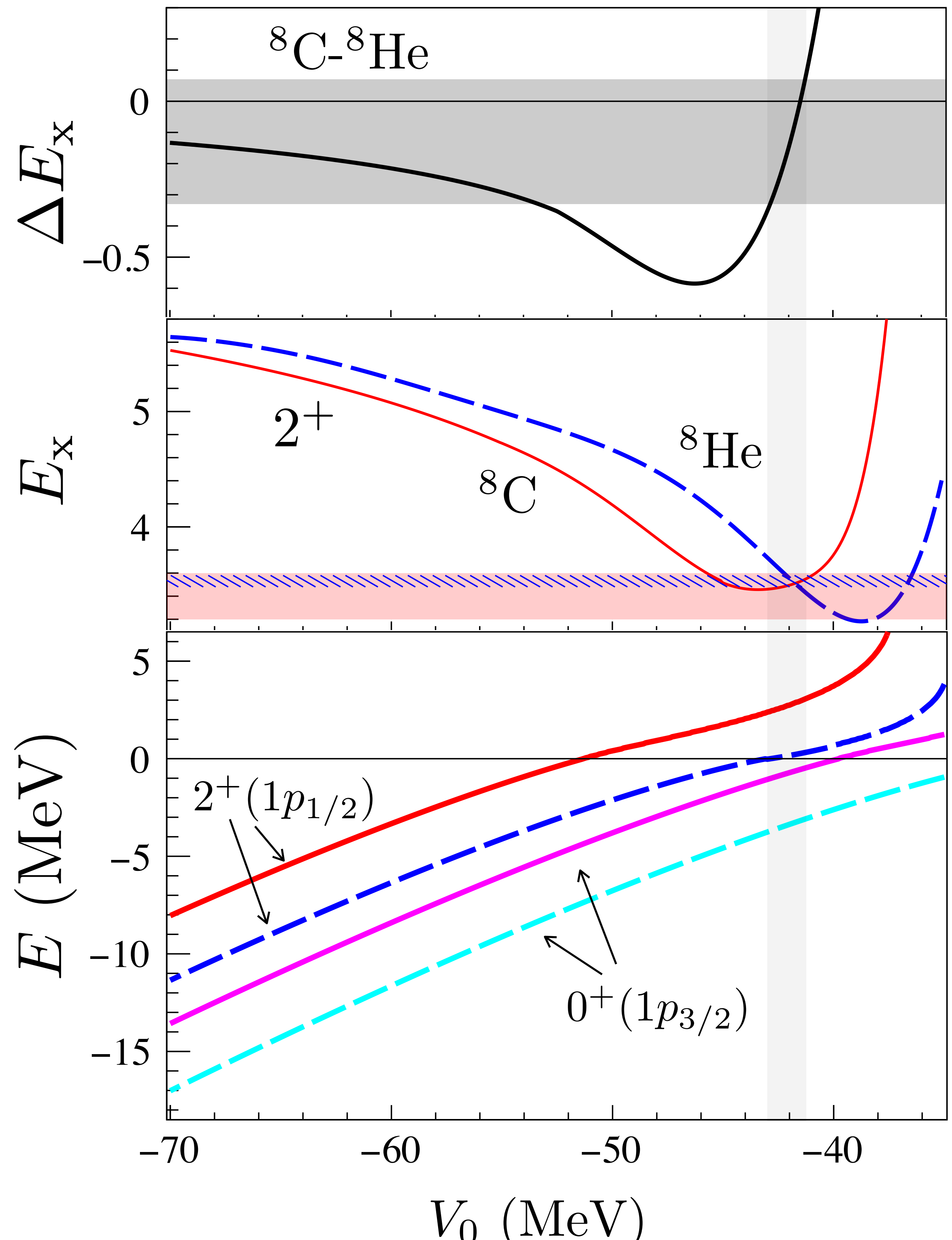




Two body model calculation

ΔEx = Ex(^{8}C) - Ex(^{8}He)

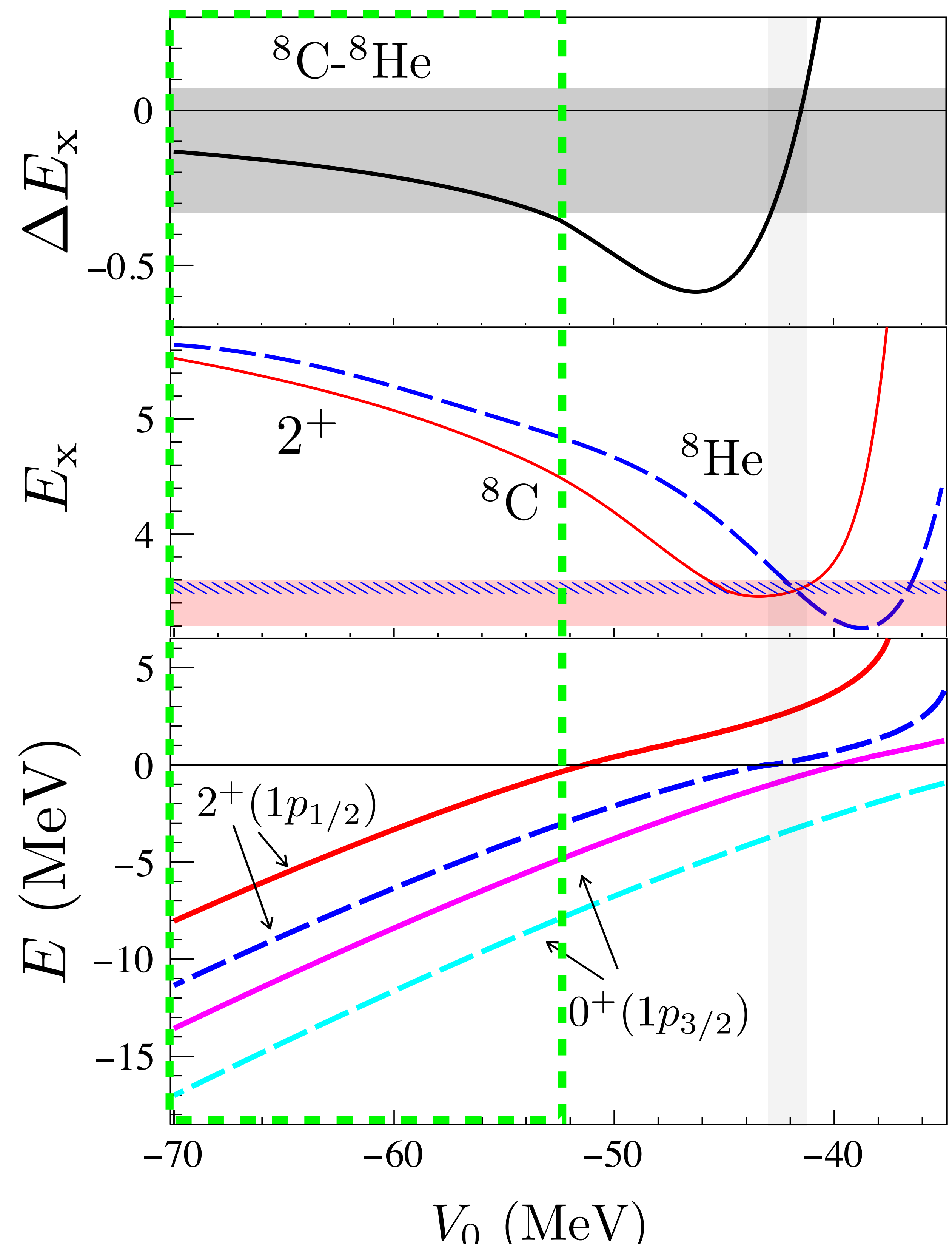
=$(E_{p1/2}-E_{p3/2})_{^{8}C}$ - $(E_{p1/2}-E_{p3/2})_{^{8}He}$



Strongly bound region

- V_0 = -70 ~ -52 MeV
- All of 4 states are well bound
- Ex of 2^+ decreasing smoothly, higher than the experimental values and close to SM calc. with bound state approximation
- MED ~ -0.2 MeV, rather constant

$\Delta Ex = Ex(^8C) - Ex(^8He)$
$= (E_{p1/2} - E_{p3/2})_{^8C} - (E_{p1/2} - E_{p3/2})_{^8He}$

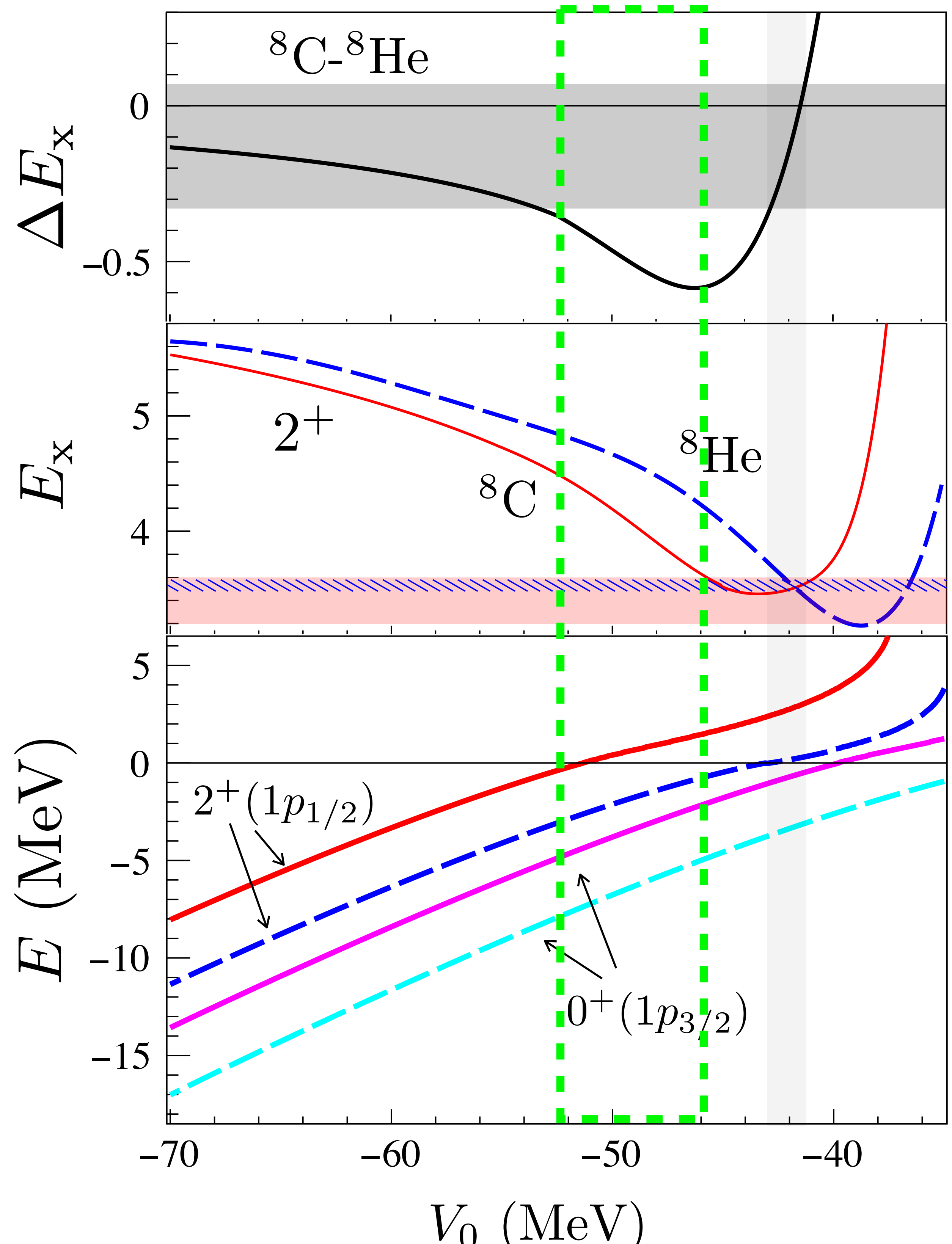


Weekly bound, unbound region

$\Delta Ex = Ex(^8C) - Ex(^8He)$
$= (E_{p1/2} - E_{p3/2})_{^8C} - (E_{p1/2} - E_{p3/2})_{^8He}$

- V_0 = -52 ~ -45 MeV
- MED becomes larger
- ^8C 2^+ decreasing rapidly
- ^8C 2^+ is getting weekly bound and finally unbound though the others are still well bound

cf. Thomas-Ehrman shift



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- V_0 = -52 ~ -45 MeV
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- ^8C 2^+ decreasing rapidly
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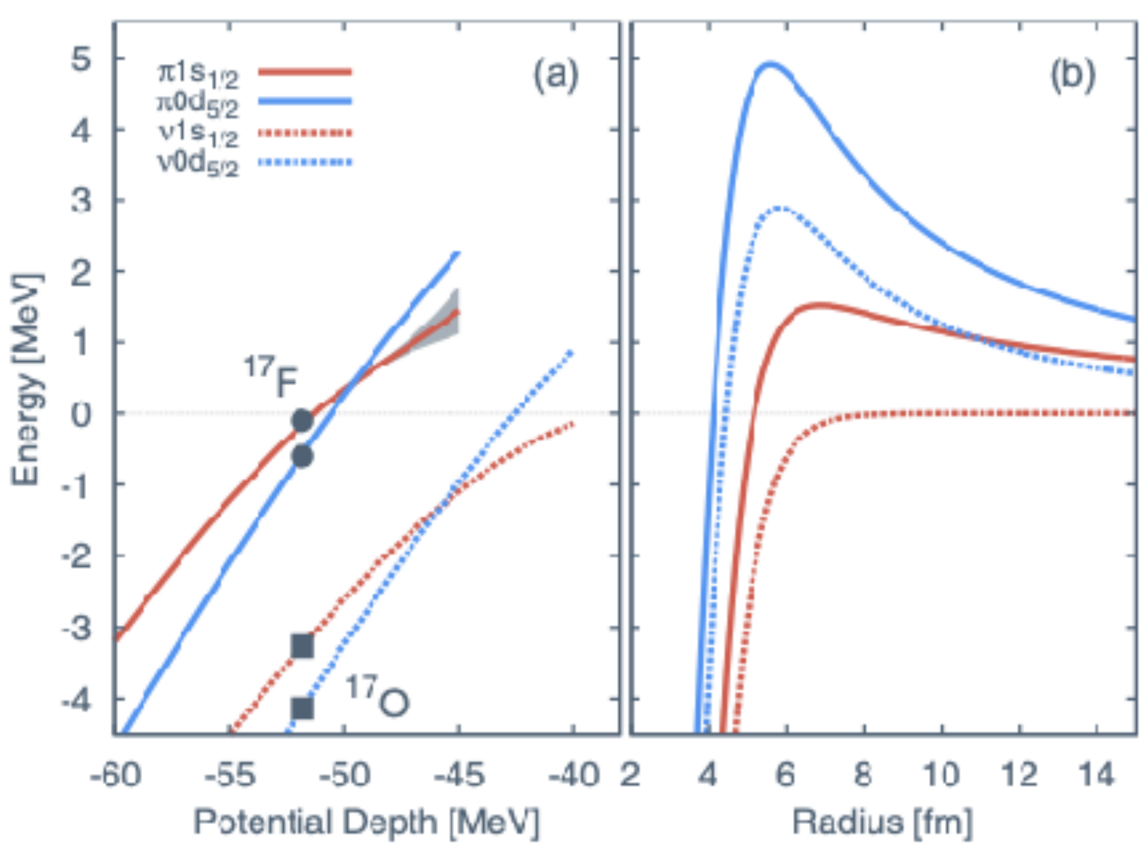
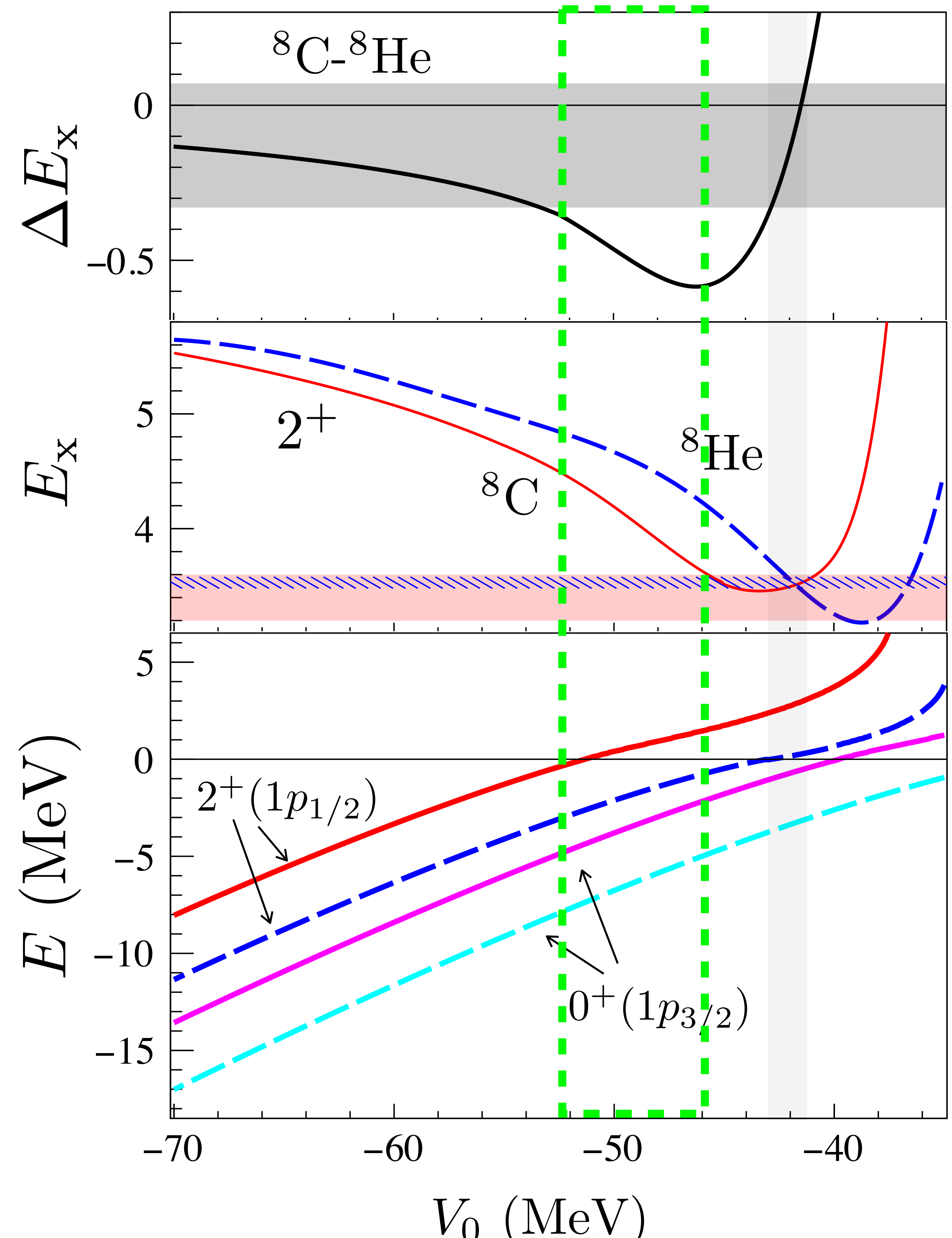
cf. Thomas-Ehrman shift

- Extra stability of s-wave by the tunneling effect



C. R. Hoffman et al., PRC 94 024330 (2016)

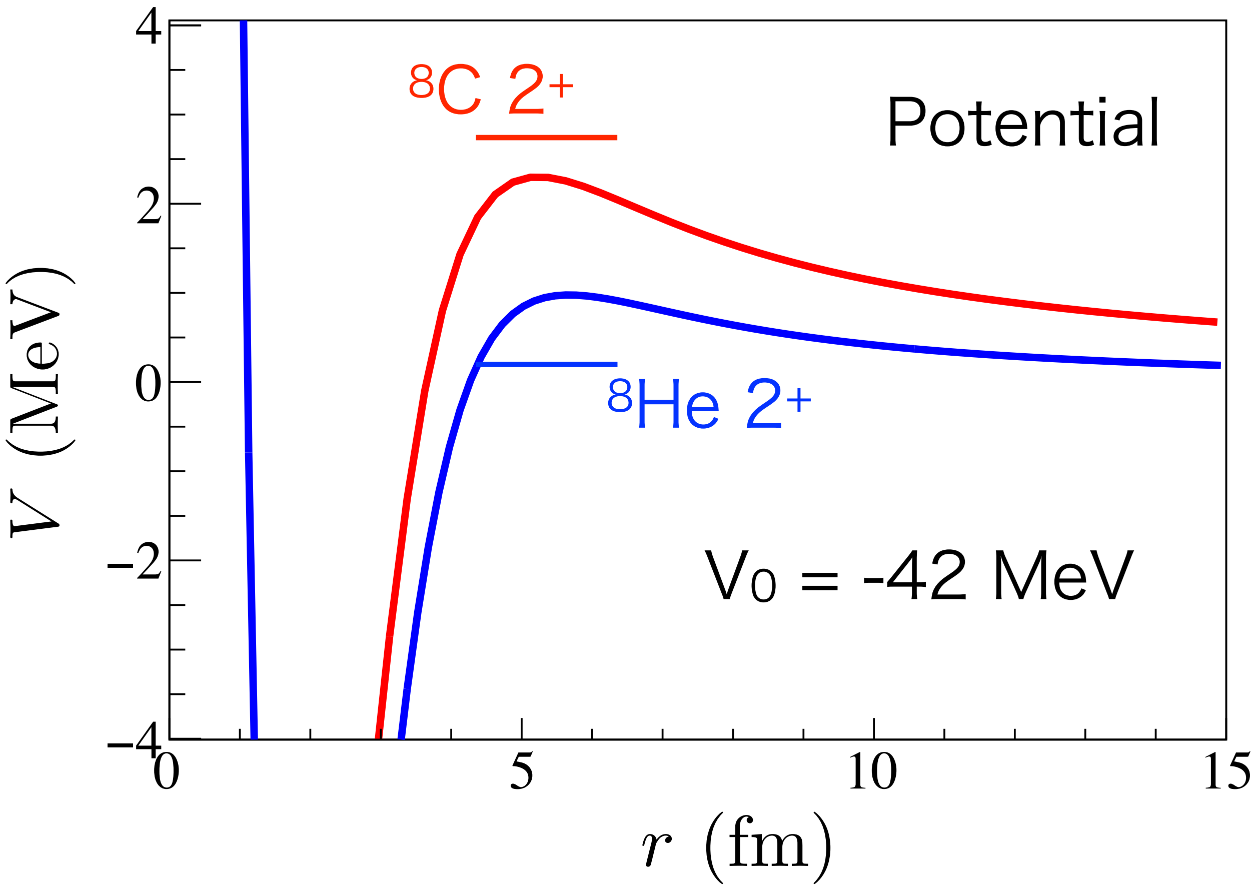


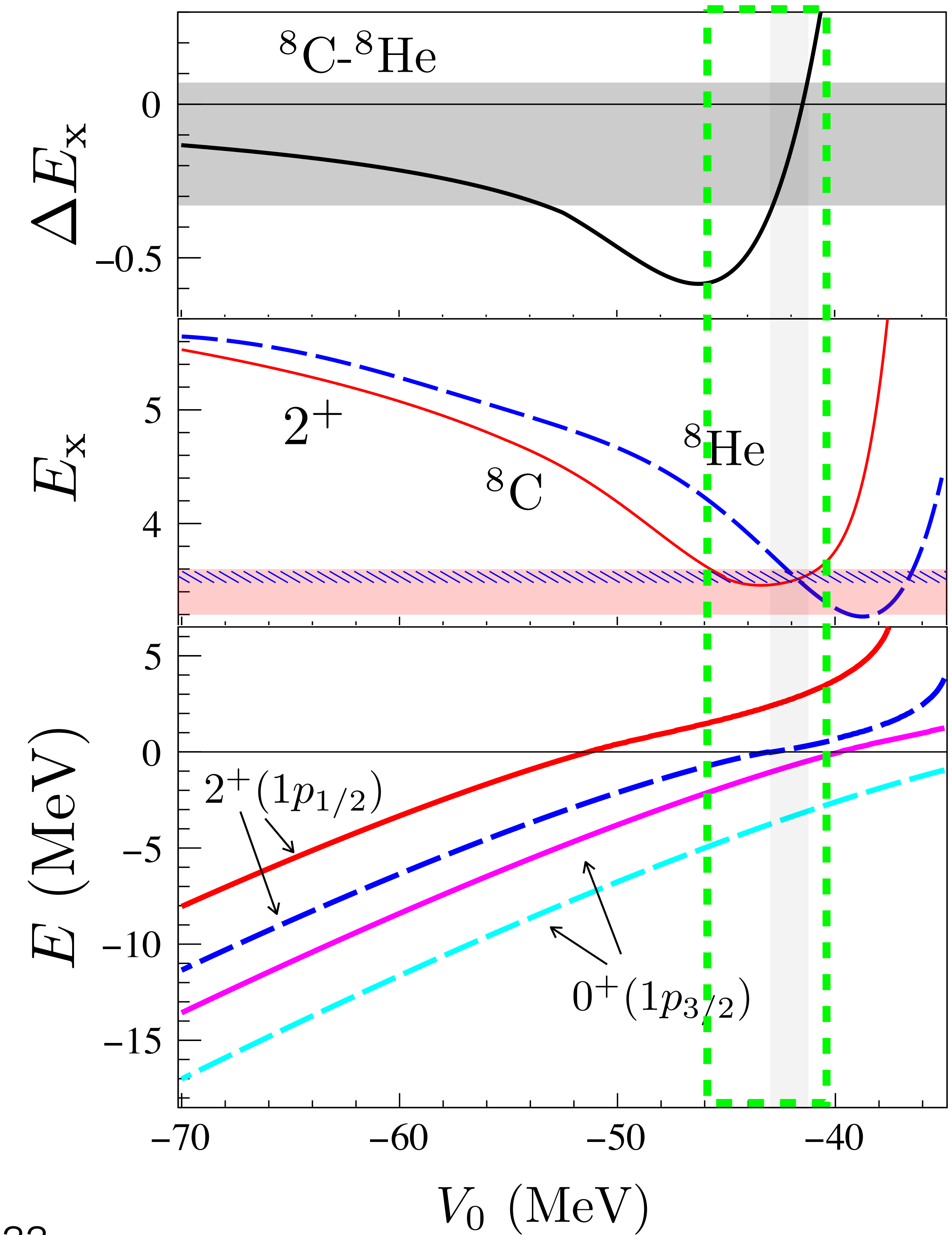
Unbound region

- V_0 = -45 ~ -40 MeV
- MED becomes smaller
- ^{8}C 2$^+$ constant, while ^{8}He 2$^+$ decreasing rapidly
- ^{8}C 2$^+$ is above Coulomb barrier
- ^{8}He 2$^+$ is getting to weakly bound and unbound finally
- Both MED and Ex well reproduced at V_0 ~ -42 MeV

ΔEx = Ex(^{8}C) - Ex(^{8}He)

=$(E_{p1/2}-E_{p3/2})_{^8C}$ - $(E_{p1/2}-E_{p3/2})_{^8He}$





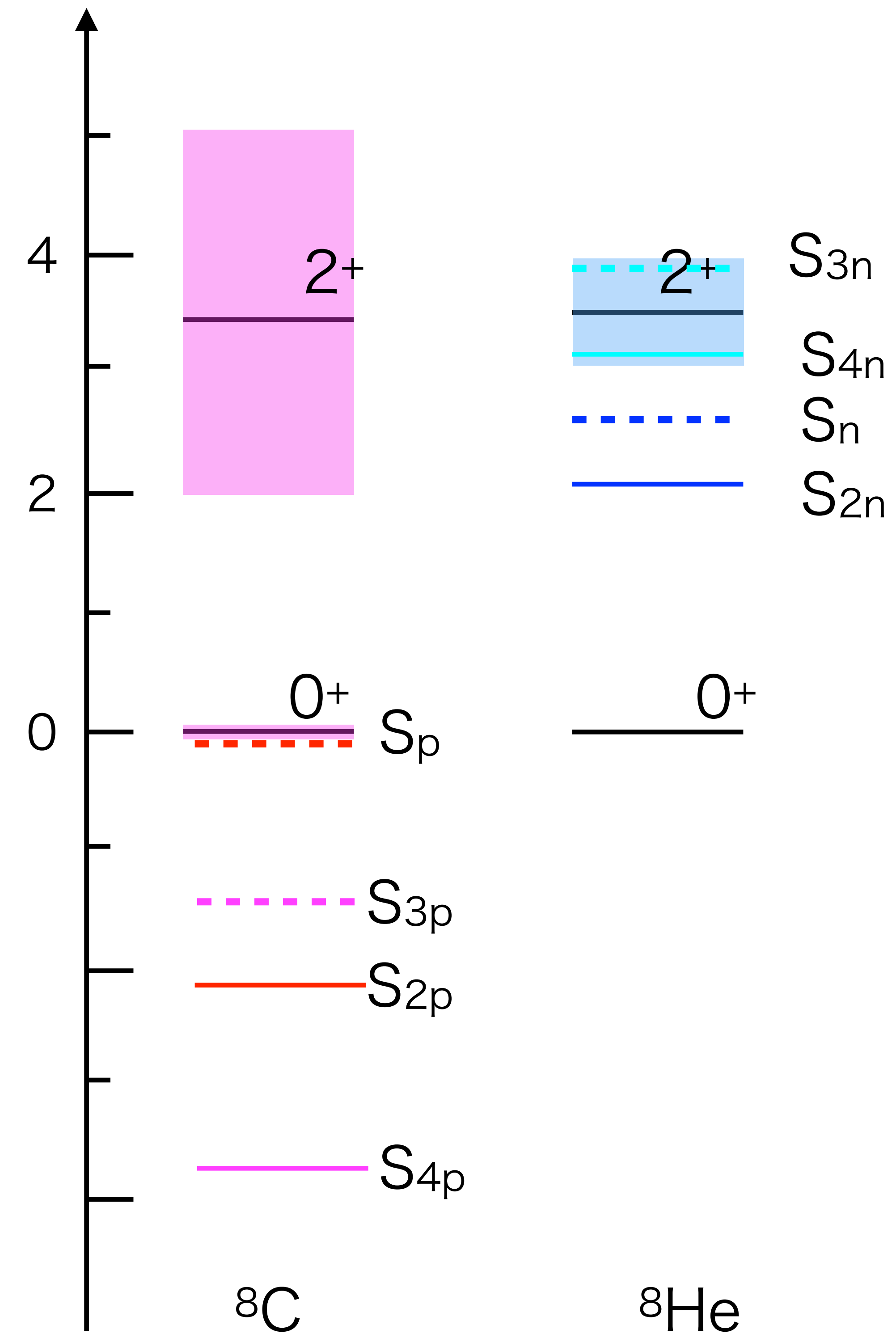
Perspective

- Though MED and Ex well reproduced at V_0 ~ - 42 MeV, total decay widths are underestimated

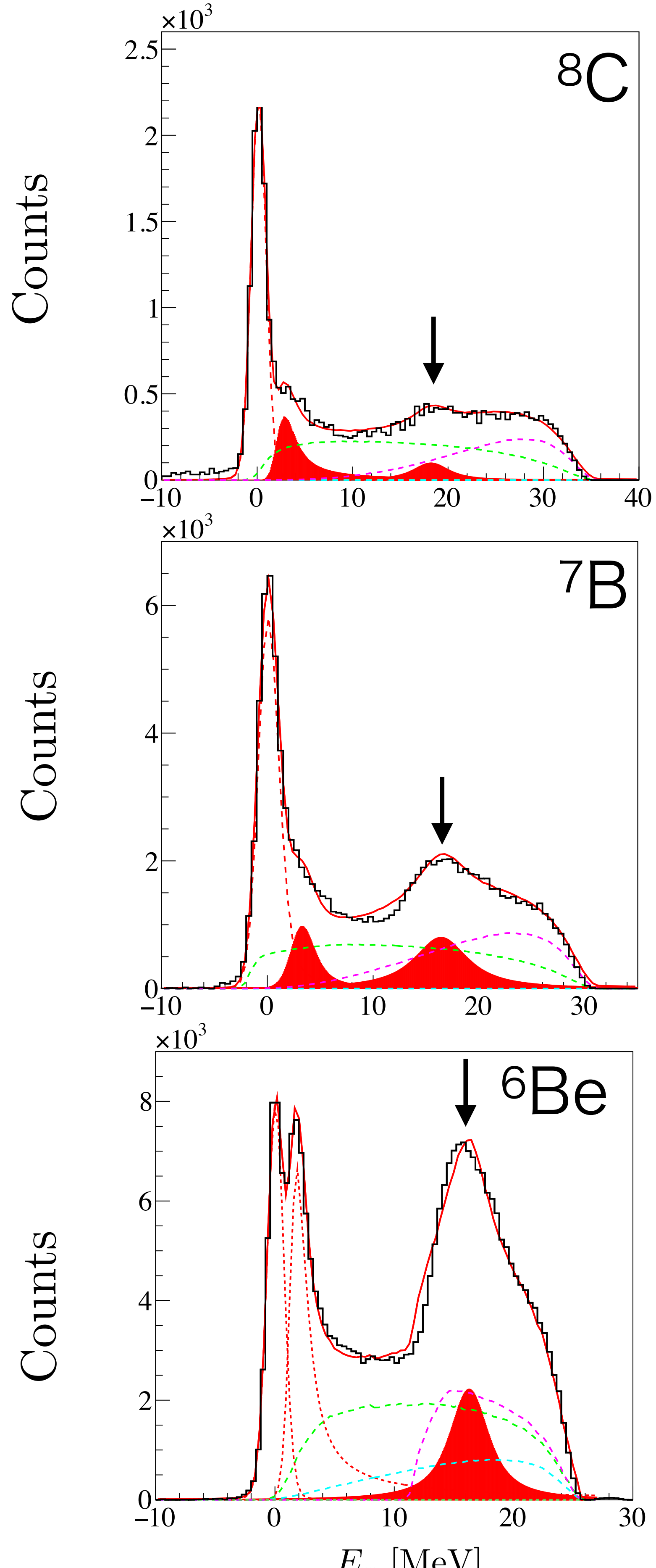
$^8C : \Gamma_{exp}$ = 3.0(4) MeV, Γ_{TBM} = 2 MeV

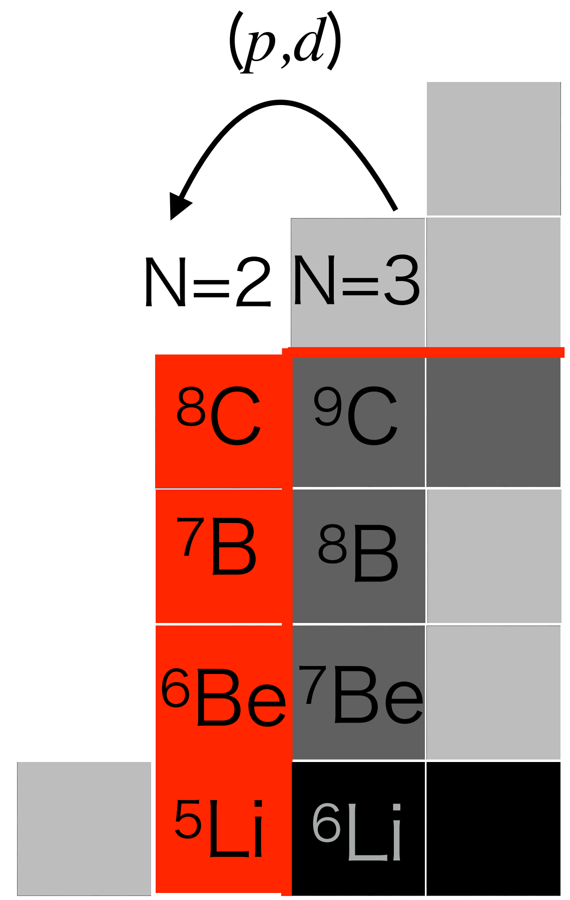
$^8He : \Gamma_{exp}$ = 0.89(11) MeV, Γ_{TBM} = 0.1 MeV

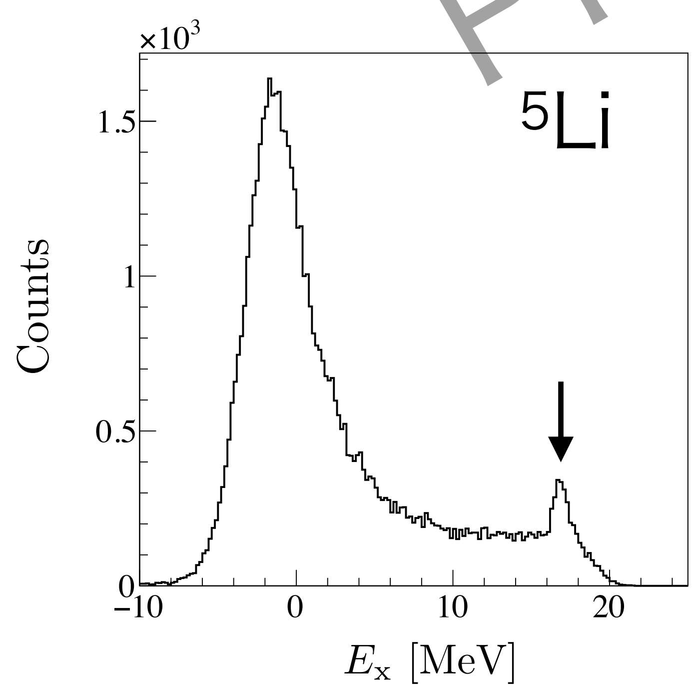
- Only 1 p/n emission is included in the current model
- Approach to include many body correlation



Spectra of N=2 isotones







New resonance states were observed

^{8}C E_x = 18.1(3) MeV, Γ =4.3(6) MeV

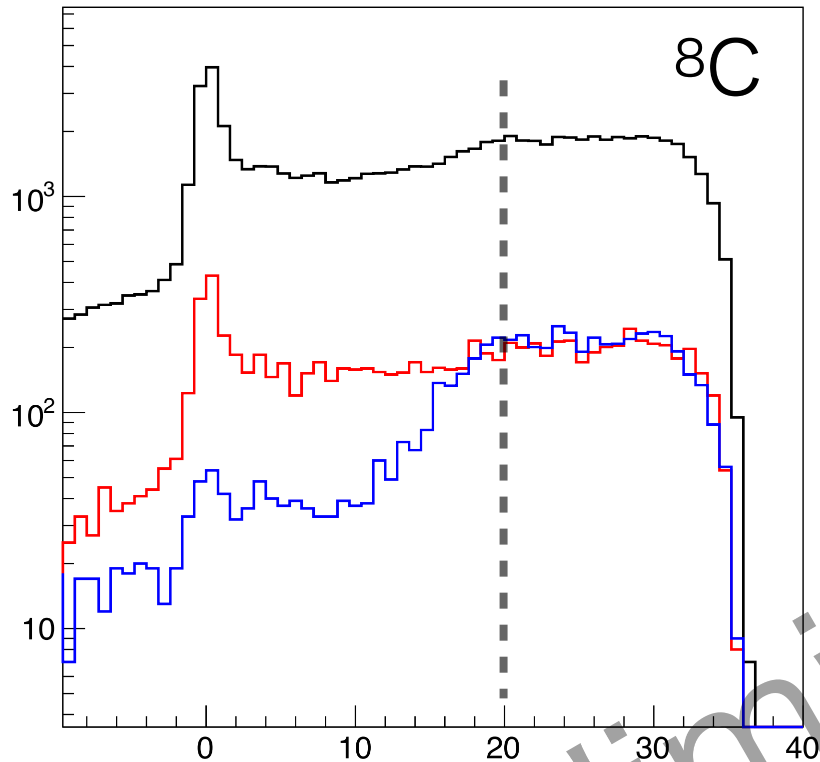
^{7}B E_x = 16.2(3) MeV, Γ =5.6(9) MeV

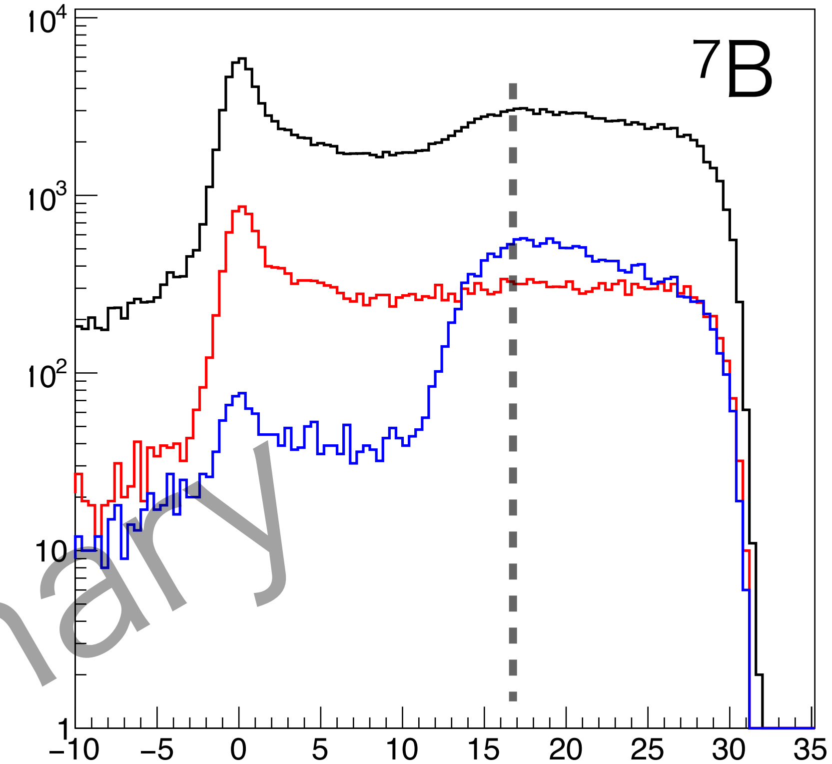
^{6}Be E_x = 16.1(3) MeV, Γ =3.0(4) MeV

Known resonance state

^{6}Li E_x = 16.87 MeV, Γ =0.267 MeV, $J^\pi = 3/2^+$

Decay mode



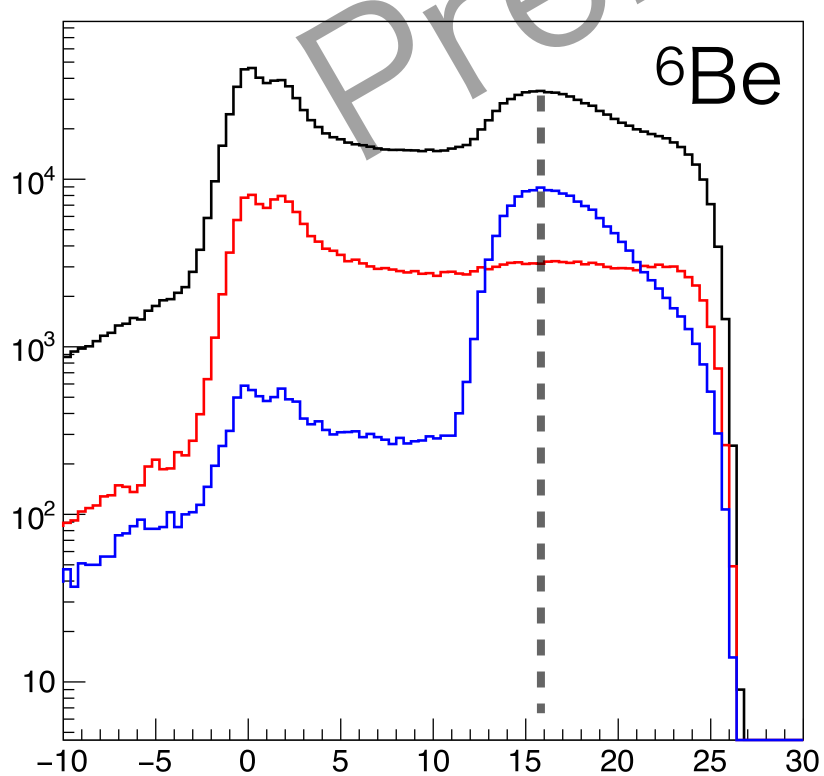


w/o gate

α coincidence

^{3}He coincidence

(coincidence in MUST2)



States around 17 MeV -> ^{3}He coin.

States around 0 MeV -> α coin.

(small ^{3}He coincidence with states around 0 MeV due to the miss-PID)

-> Resonances around 17 MeV mainly decay via ^{3}He emission, not α

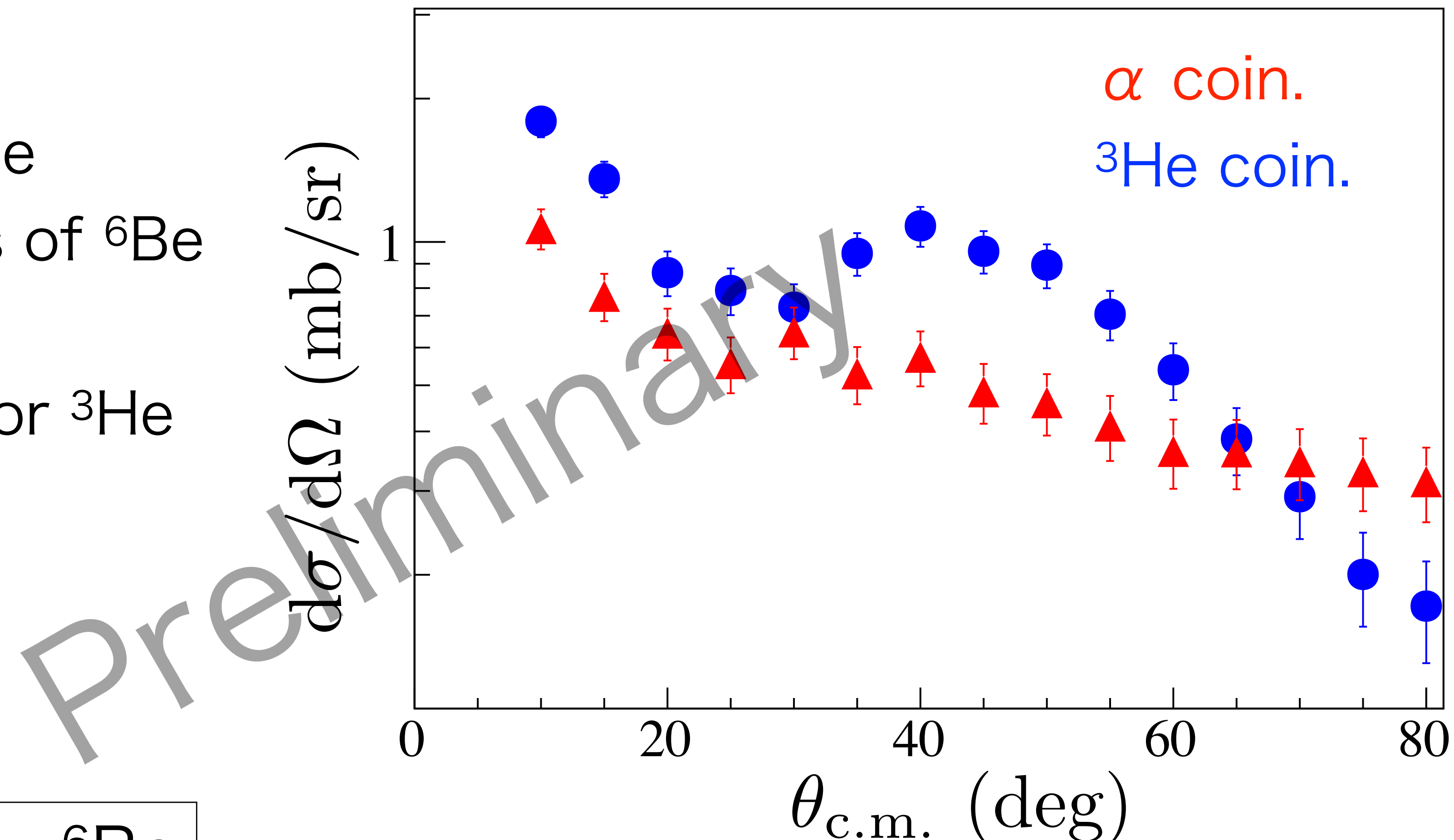
Angular distribution

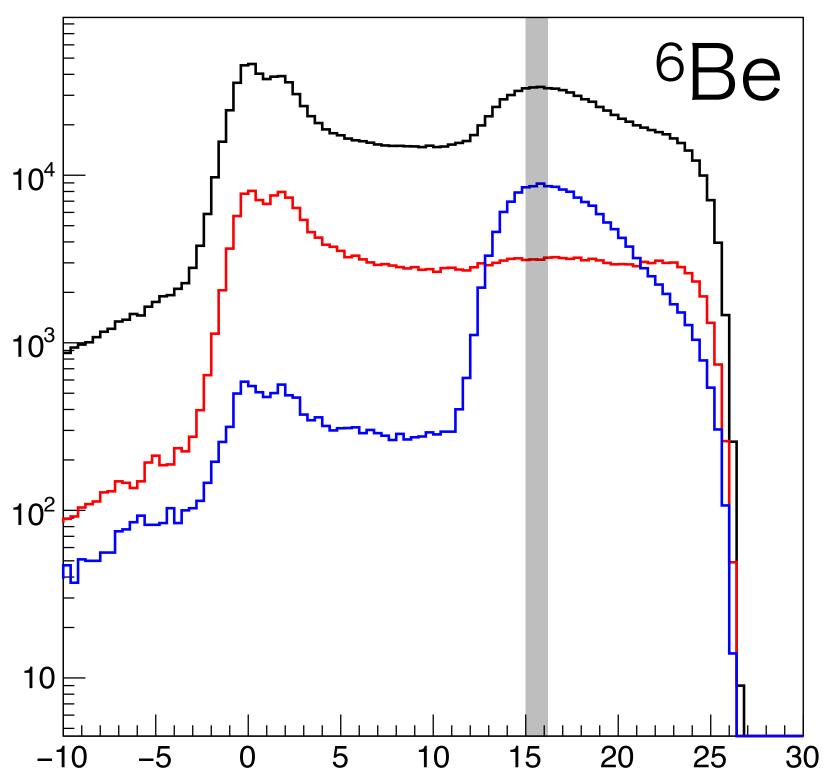
High statistics for ^{6}Be

Angular distributions of ^{6}Be

Ex = 15-16 MeV

Coincidence with α or ^{3}He





^{3}He : Diffraction pattern ->

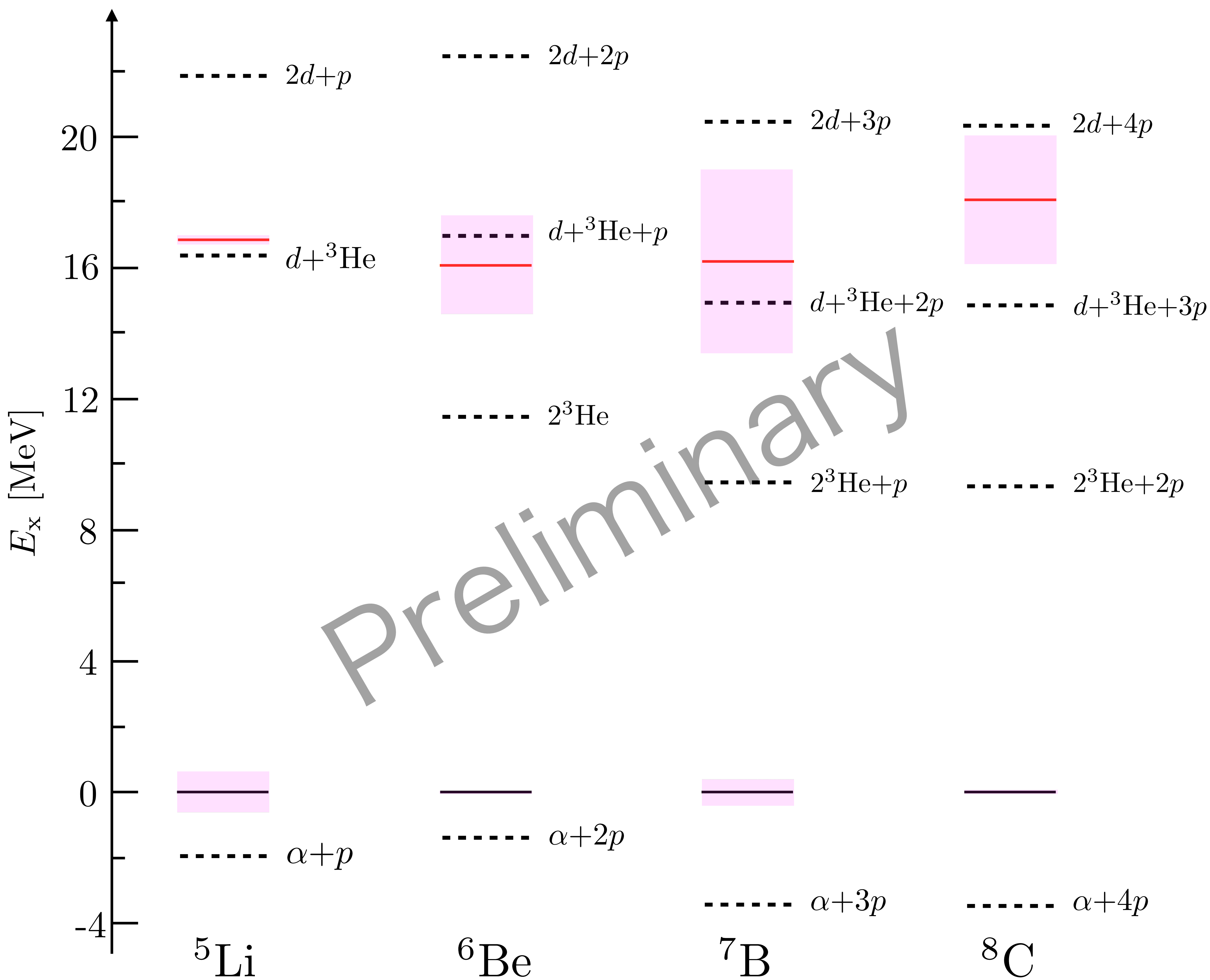
Resonance from neutron transfer ?

α :Characterless distribution ->

Non-resonance (phase space)?

Analysis ongoing …

Resonances around 17MeV



- 3/2+ state in ^{5}Li
- is known at 16.87 MeV
- Systematically observed around 17 MeV for ^{5}Li, ^{6}Be, ^{7}B and ^{8}C
- The main decay mode is ^{3}He emission in ^{6}Be, not α emission in spite of Q value

Collaborators of E738

S. Koyama[1,4], D. Suzuki[2], M. Assié[3], L. Lalanne[4,3], O. Sorlin[4], D. Beaumel[3], Y. Blumenfeld[3], L. Caceres[4], F. De Oliveira[4], F. Delaunay[5], F. Flavigny[5,3], S. Franchoo[3], J. Gibelin[5], V. Girardalcindor[4,3], J. Guillot[3,] F. Hammache[3], A. Kamenyero[4], O. Kamolou[4], N. Kitamura[6], V. Lapoux[7],A. Lemasson[4], A. Matta[5], B. Mauss[2,4], P. Morfouace[4,7], M. Niikura[1], H. Otsu[2], J. Pancin[4], T. Roger[4], T. Y. Saito[1], C. Stodel[4] ,J. C. Thomas[4]

1. University of Tokyo
2. RIKEN Nishina Center
3. IJCLab
4. GANIL
5. Laboratoire de Physique Corpusculaire de Caen
6. Center of Nuclear Study, University of Tokyo
7. CEA Saclay
8. TU Darmstadt
9. University of Tennessee

Summary

- Missing mass spectroscopy of ^{8}C were performed at GANIL.
- A secondary beam of ^{9}C was produced by the LISE spectrometer was used and one neutron transfer (p,d) reaction was measured.
- First 2^{+} excited state in ^{8}C was observed.
- The mirror energy difference of this state is comparable with that of other 2^{+} states of even-even nuclei.
- The effect of continuum coupling is important to understand the MED by a simple model.
- Ex ~ 17 MeV are observed in N=2 isotone
- ^{3}He clustering? Analysis on-going…

Experimental results of ^{8}He and ^{8}C

$^{8}_{2}\mathrm{He}_{6}$

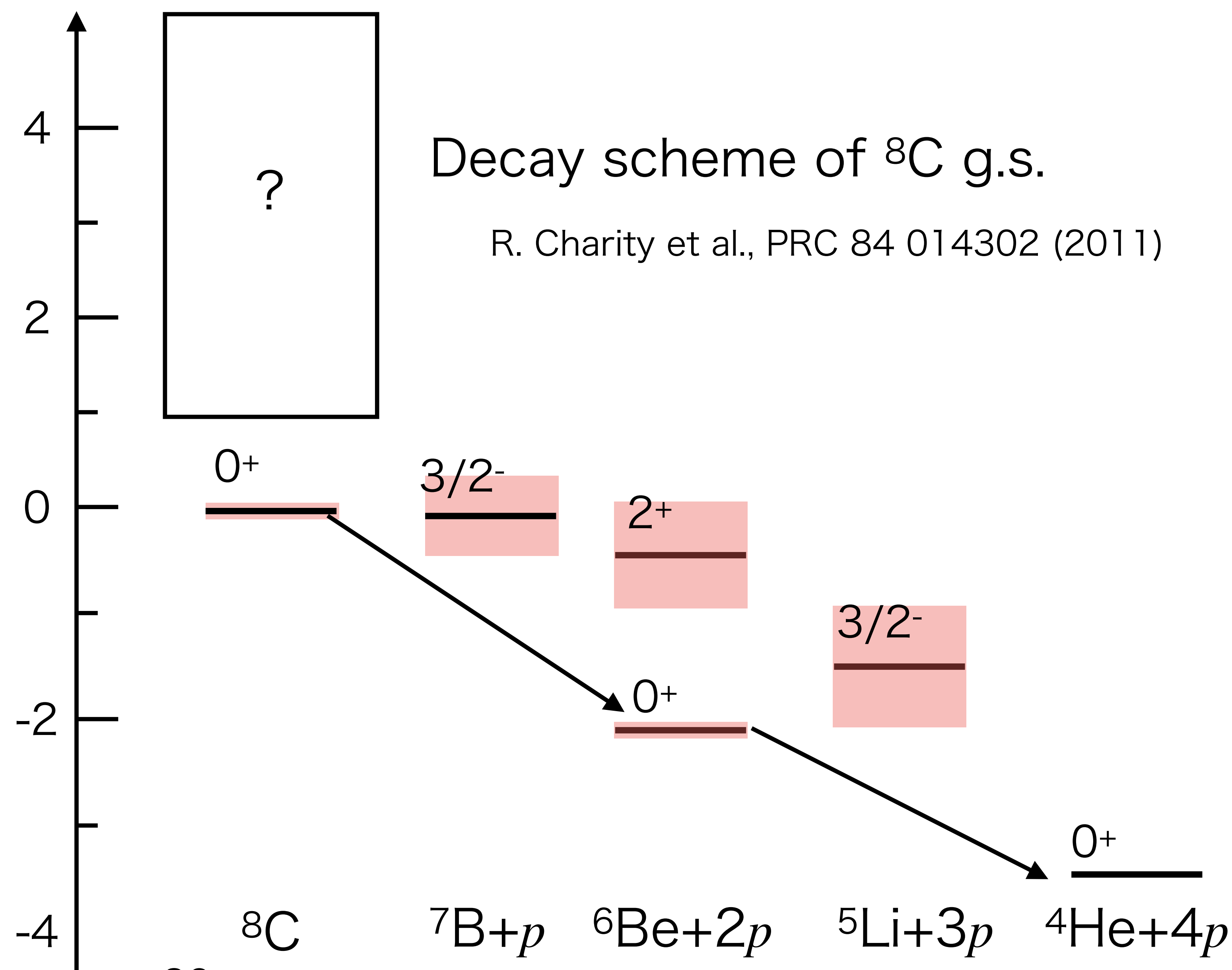
- Bound g.s.
  - Smaller charge radius than ^{6}He
- Some excited states observed
- …

P. Mueller et al., PRL 99 252501 (2007)

mirror ↕

$^{8}_{6}\mathrm{C}_{2}$

- 4 proton unbound g.s.
- Narrow decay width of Γ=130(50) keV
- Decay scheme of ^{8}C g.s. was measured to be ^{8}C -> ^{6}Be + 2p -> ^{4}He+4p with ~ 100% branch
- No excited state has been observed



Unbound region

- V_0 = -45 ~ -40 MeV
- MED becomes smaller
- ^{8}C 2^+ constant, while ^{8}He 2^+ decreasing rapidly
- ^{8}C 2^+ is above Coulomb barrier while ^{8}He 2^+ is still below centrifugal barrier
- Both MED and Ex well reproduced at V_0 ~ 42 MeV

$\Delta Ex = Ex(^8C) - Ex(^8He)$

$= (E_{p1/2} - E_{p3/2})_{^8C} - (E_{p1/2} - E_{p3/2})_{^8He}$